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Mobileye 2021: Robotaxi and/or Consumer AV?

In March 2021, Amnon Shashua, co-founder and CEO of Israel-based Mobileye, was preparing to meet with Intel's new CEO, Pat Gelsinger, to review plans for the future. Mobileye had been acquired by California-based Intel in 2017, but still operated independently. Gelsinger had rejoined Intel as CEO in February 2021 after a 12-year hiatus during which he served as president of EMC and CEO of VMWare. Gelsinger wanted to know from Shashua: what could Mobileye do for Intel, and what could Intel do for Mobileye?

Shashua thought Mobileye was at an inflection point: while his company was the global leader in vision technology for Advanced Driver Assistance Systems (ADAS), his ambition was much bigger. Mobileye held around 70% of the ADAS market, with $1 billion in revenue in 2020, up 100% in three years. The company's ADAS chip, EyeQ, which combined optical vision software with motion detection algorithms, was used in 285 models across 20 car manufacturers. But ADAS was only Shashua's first step. His dream was to lead the autonomous vehicle (AV) revolution. It was this vision that led Intel to acquire Mobileye. While Mobileye represented just over 1% of Intel's 2020 revenue of $77.8 billion, AVs could drive significant revenues for Intel by 2030, with Mobileye leading the way.

Shashua's challenge was that consumer AVs were not ready for prime time in 2021. Concerns over safety, regulation, cost, and consumer acceptance pushed out the big revenue opportunities for at least five years. A nearer term use case for AVs was the robotaxi market — fully autonomous, driverless taxis. Shashua and his team were excited about the potential of robotaxis to change the future of mobility. Original equipment manufacturers (OEMs), tech companies, and startups were all rushing to participate in what Mobileye projected to be a $160 billion market by 2030. Mobileye believed that it could generate at least $15 billion in annual robotaxi revenue by the end of the decade. Equally important, Shashua viewed robotaxis as a necessary first step toward consumer AVs. Mobileye could use its experience in robotaxis to improve the technology, address regulatory challenges, and build high definition maps. Mobileye was set to launch its first robotaxi pilot in Israel in 2022.

The long-term question facing Mobileye was whether to: 1) invest billions of dollars to build-out a global, vertically integrated robotaxi business; 2) use robotaxis as an opportunity learn and then revert back to a horizontal supplier of AV chips and software; and/or 3) do both? Each strategic choice had different capital requirements, risk profiles, and margin opportunities. Shashua needed to decide which direction to recommend to Gelsinger.

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Autonomous Vehicle Industry

Since the early 2000s excitement over the prospect of a truly autonomous car — one that could navigate and drive using on-board sensors that interpreted and responded to the environment without the need for any human intervention — had consumed the automotive industry. Full autonomy was the final step along a continuum of automated assistance that ranged from simply *supporting* the human driver to fully *replacing* the human driver. In 2014 the Society of Automotive Engineers (SAE) developed a widely adopted classification system which defined six levels of autonomy, ranging from Level 0 to Level 5, based on the degree of human intervention required (see **Exhibit 1**).[1] By 2021, the automotive industry was offering Level 2+ autonomy through a series of advanced driver assistance systems (ADAS) such as lane assist, blind side assist, and adaptive cruise control that supported the human driver in decision making. Even Tesla's "Full Self Driving" system was technically only classified as Level 2 automation — lower than the name implied. While the industry had made attempts to reach Level 3, none had yet been successful. In 2020 Audi scrapped plans for Level 3 automation in its Traffic Jam Pilot system for its model A8 due to regulatory delays and liability concerns. The unbridled excitement over the prospect of AV had led to unrealistic projections early on that Level 5 AV vehicles would be on the roads by 2021. More recent projections coalesced around 2030 as a more likely timeframe for wide-spread consumer Level 5 autonomy.[2,3]

Excitement over autonomous vehicles stemmed from a host of advantages they offered over human driven cars. One of the key benefits was safety. A national survey of police-reported crashes showed that driver error contributed to 9 out of 10 crashes. With their predictable, automated decision making, autonomous vehicles were projected to reduce crashes by 90%, resulting in savings of approximately $190 billion per year.[4] Furthermore, autonomous vehicles were projected to reduce fuel consumption and emissions. In the U.S. alone, 3 billion gallons of fuel were wasted each year due to traffic jams and poor route choice, which autonomous vehicles would be programmed to avoid, resulting in a projected 60% reduction in emissions.[5] Autonomous vehicles also had the ability to "platoon" (follow closely behind a chain of AV vehicles) and save gasoline.[6] Reduced congestion would also free up time and lead to increased productivity. Americans spent an estimated 6.9 billion hours in traffic delays in 2014 which could be dramatically reduced with autonomous vehicles.[7] Finally, autonomous vehicles offered improved accessibility and mobility — especially for the elderly and disabled. In the U.S. alone there were 49 million Americans over the age of 65 and another 53 million with some form of disability.[8]

Use Cases

There were a number of potential commercial use cases for autonomous vehicles with varying timelines for potential adoption. Autonomous vehicles were expected to play a role in logistics and goods delivery, especially in the "last mile delivery" (LMD) of goods, which accounted for 28% of total logistics costs.[9] The major expense associated with LMD was the cost of the driver, so by replacing drivers with robotic-driven vehicles, the operating costs would decline significantly. Long haul trucking was another likely application of AV. Approximately 65% of goods in the U.S. were delivered by trucks, with the human driver accounting for the bulk of operating expenses. Estimates suggested that 45% of operating costs could be reduced by replacing a human driver with a self-driving truck.[10] Agriculture and mining were other possible use cases with advantages for addressing declining workforce populations in those industries, safety of workers, and productivity gains.

Perhaps the most industry excitement focused on the potential for robotaxis. Robot taxis (shortened to "robotaxis") were self-driving taxis operated by on-demand and ridesharing services. In essence they would be an extension of ride-hailing business such as Uber or Didi, but without a driver. Reducing the need for individual car ownership, increased road safety, decreased traffic congestion, and reduced burden on city parking were all hailed as potential benefits bolstering the robotaxi market. Historically, the traditional taxi business model did not offer high margins, but the economics for robotaxi were hoped to be better. Removing the driver from the car would save substantial operational costs; moreover, central fleet control would optimize the ride allocation for the vehicle and improve the ratio between paid vs. unpaid miles (at the fleet level). Several studies had shown that robotaxis could be one of the most rapidly adopted, global applications of autonomous vehicles. While most robotaxi services were still in the testing stage in 2021, analysts forecasted that commercial operations would start to scale in 2023.[11]

AV Players

The lure of the AV industry had attracted OEMs, tech giants, and startups. Shashua believed that AVs would fundamentally alter the structure of the auto industry. However, the technical challenges were enormous. "Smartphones," he noted, "had very advanced technology, which occasionally failed. Passenger planes, on the other hand, could never fail. The challenge is that AVs are a combination: Cutting edge technology which can never fail." This created a big hurdle for OEMs, who struggled to attract the engineering talent. Shashua explained:

> A few years ago, car companies just hired engineers and they thought they could do autonomy themselves. The problem is that car companies' DNA is not advanced software technology…They will need deep partnerships if they want to avoid losing their business to companies like Tesla and Apple…Some OEMs are now pursuing partnerships. However, others have not gone through this phase yet, and they don't know what they don't know.

The result was that many OEMs struggled with AV development. Erez Dagan, Mobileye's Executive Vice President for Product & Strategy, noted that most (though not all) OEMs were "highly risk averse. The standards compliance teams at OEMs slow them down. They hesitate to make bold choices." In an effort to remedy this problem, a bevy of OEM partnerships and acquisitions had been announced in recent years. In 2016, for example, General Motors acquired AV startup Cruise for a reported $1 billion. In 2018, Honda joined forces with GM and Cruise.[12] In 2019, Volkswagen agreed to invest $4.1 billion into Ford's Argo AI self-driving unit;[13] and Fiat Chrysler began working with AV startup Aurora Innovation, which then acquired Uber's self-driving car unit in 2020. Hyundai and Kia Motors also agreed to invest in Aurora. And in 2020, Renault and Nissan partnered with Alphabet's self-driving car unit, Waymo, to develop cars and trucks for Japan and France.[14] Tesla (as well as Mobileye and Intel) were the exceptions, pursuing the AV market on their own.

Technology

There were several enabling technologies paving the way to fully autonomous vehicles. The full tech stack included hardware, software, and AI used in three key sensors:

Cameras provided high resolution images of the surrounding area, including traffic signals, lane markings, and road signs. It was not uncommon for up to 12 cameras to be used. Cameras were relatively low-cost which made them a good fit for the consumer AV market, but on the negative side, they were hindered by low light, direct sunlight, and inclement weather. Vision systems also struggled with depth perception. However, some companies, most notably Tesla and Mobileye, were strong believers in the power of cameras. In fact, Tesla primarily relied on cameras.

LiDAR (Light Detection and Ranging) was similar to radar, but instead of sending out radio waves, it sent out pulses of infrared light and measured the time it took for the light to bounce off an object and come back to the sensor. Millions of pulses could be sent per second, allowing it to create an accurate 3D representation of the surrounding area. An advantage of LiDAR was that it was not dependent on specific lighting conditions since it created its own light. However, LiDAR did not offer the same image resolution as a camera and historically, it was very expensive. The large 64-laser unit LiDAR seen on top of AV test cars from Waymo originally cost $75,000, making it a nonstarter for consumer AV. However, new LiDARs used "solid state" technology which involved no moving parts. LiDAR manufacturer Velodyne announced that it hoped to sell a solid-state LiDAR in 2022 for $500, dramatically reducing the costs.[15]

Radar (Radio Detection and Ranging) was an older technology, that been used for decades in cars as part of driver assist systems. Radars were usually placed in the front bumper of a car and sent out electromagnetic waves that reflected back when they hit an object. The time that it took for the wave to leave and bounce back determined the distance to the object. Similar to LiDAR, radar was not impacted by weather, but radar could travel much longer distances (hundreds of yards) than LiDAR and could track the speed and direction of moving objects. It also was relatively inexpensive, with units costing between $30 to $100, about one-tenth of the cost of Lidar.[16] However radar had relatively low resolution and other limitations that made it difficult to identify moving objects. Kevin Rosenblum, Mobileye's Senior Director Sensor Fusion, colorfully commented that, "radar today sucks," but next generation radar, called "software defined imaging radar," would make it much more useful.

Given the advantages and disadvantages inherent in each technology, most industry observers believed that full autonomy would require redundancy in these systems; if one system failed or became hindered by environmental conditions, another would be able to take over and guide the car.

Beyond Technology: Other AV Barriers

While the industry was making progress on the technology, other barriers remained. Safety was a critical gating item. Human drivers were involved in a police reported accident about every 500,000 miles.[a][17,18] Autonomous vehicles would need to beat this threshold of safety to be approved by regulators. Engineers had been able to train the "neural net" in AVs to assess 95% of situations correctly, but the leap from 95% to over 99% was incredibly difficult. Solving for the extraordinary number of "edge cases" would take time, testing, and significant resources. One alternative to road testing AVs was to use simulated computer-generated testing in a lab. In theory, simulations could expose a massive number of "edge-case" permutations. However, Mobileye's Rosenblum argued that, "simulations are good for doing research, but simulations cannot guarantee the car will safely handle black swans and edge cases in the real world."

Getting regulatory approval was another challenge. In the U.S., there were no national regulations guiding autonomous vehicles. Instead, it was a state-by-state patchwork of regulations that guided the industry. By 2021, 38 states had passed legislation or issued executive orders regarding autonomous vehicles.[19] Seven states offered fully autonomous self-driving car testing on public roads in 2019, while 30 others allowed for testing with a safety driver. Internationally, regulations differed across countries, adding to the complexity of global adoption. In 2020, 53 countries in the European Union, Asia and Africa, agreed to common, binding regulation for Level 3 automation. The regulation covered what roads it could be deployed on, a speed limit of 60 kilometers per hour (37 mph), the need for a "black box" to record information when the autonomous system is activated, and installation of a Driver

[a] Calculated as: 3.23 trillion total vehicle miles traveled in 2019 divided by 6.76 million police reported crashes in 2019

Availability Recognition System which monitored the driver's capability to take back control of the vehicle by checking for eye blinking and eye closure.[20]

For consumer AVs, the cost of the underlying technology created an additional barrier to consumer adoption. While prices of individual components were coming down, the entire AV hardware and software system was still estimated to cost far more than expected consumer willingness to pay. Costs were less important for robotaxis, which theoretically would have much higher utilization (usually estimated around 60% of the day) compared to a personal vehicle (with less than 10% utilization/day).

Finally, not everyone was confident that consumers would widely accept AVs. A 2019 global research report by Capgemini found that only 25% of consumers would prefer to drive in a self-driving car within a year's time. Consumers expressed concerns about safety, with 73% of respondents saying that vehicle safety would impact their decision to buy or embrace self-driving vehicles. Furthermore, when asked what emotion described respondents' feelings about self-driving cars, 48% said "fear" and 43% said "loss of control/helplessness," while only 28% said "confidence."[21] Differences could be seen by country: Consumers in China were the most positive about AV, while British consumers were most hesitant.[22]

Mobileye: From ADAS to AVs

While AVs attracted investments from venture capital, technology companies, and every major player in the auto supply chain, Mobileye got its start with a focus on bringing cutting edge vision technology to make driving safer. Mobileye was founded in 1999 by Amnon Shashua, a professor at the Hebrew University of Jerusalem, and Israeli entrepreneur Ziv Aviram. Shashua was described by his partner, Aviram, as a "brilliant computer scientist" who made Mobileye possible. Soft-spoken, but confident, the Hebrew University professor received his Ph.D. from MIT's Artificial Intelligence Lab in 1993. Ziv Aviram was an industrial engineer who had emigrated from Russia to Israel when he was 9 years old. Described by Shashua as a "financial and managerial genius," Aviram believed that management was a profession which could be applied across industries. Aviram had previously been CEO of Israel's largest bookstore chain, CEO of the country's biggest shoe retailer, and the CEO of a water park.

Mobileye built its business with a contrarian strategy for ADAS. While competitors bet on radar, lasers, or multiple cameras as the sensor of choice, Shashua and Aviram believed that a single, inexpensive camera combined with sophisticated software could reduce collisions and save lives. Mobileye's camera system scanned the road ahead, identified obstacles, road signs, and traffic lights, and then interpreted the image and sent signals to the driver or other car systems to take action. Mobileye was a "Tier 2 supplier" in the automotive industry, meaning that it sold its chip and software to Tier 1 suppliers (e.g., Delphi, ZF, Valeo) who integrated Mobileye's technology into a solution for a car or truck. While Mobileye marketed its solution directly to car companies, Tier 1 suppliers integrated the product for OEMs. Mobileye historically refused to work with any Tier 1 or OEM that retained its own vision-based ADAS program.

In 2004, Mobileye developed its EyeQ chip, referred to as a "system on a chip" since it fused camera sensor data with motion detection algorithms. The EyeQ enabled some of the first implementations of important ADAS breakthroughs, including a Pedestrian Collision Warning feature in 2010, an Autonomous Emergency Braking System in 2013, and Adaptive Cruise Control in 2013. Mobileye went public in August 2014, at a $5.3 billion valuation, which quickly rose to $11 billion a month later, making it the third largest Israeli company as measured by market capitalization at the time.

Acquisition by Intel

Shashua and Aviram's vision was to build a leading position in ADAS, and then add more sophisticated hardware and software for AVs. By 2017, Mobileye had nearly 80% share of the global market for driver-assistance and anti-collision systems and was a considered a major contender in the future AV market. Mobileye's success sparked interest from Intel, which acquired Mobileye for $15.3 billion in 2017. Intel projected that the market for vehicle systems and data services for autonomous driving would become a $70 billion opportunity by 2030. Intel's CEO at the time, Brian Krzanich, wanted to expand Intel's reach beyond its mature PC business.[23] Krzanich commented:

> Intel provides critical foundational technologies for autonomous driving, including plotting the car's path and making real-time driving decisions. Mobileye brings the industry's best automotive-grade computer vision and strong momentum with automakers and suppliers. Together, we can accelerate the future of autonomous driving with improved performance in a cloud-to-car solution at a lower cost for automakers."[24]

He added, "This acquisition merges the intelligent eyes of the autonomous car with the intelligent brain that actually drives the car."[25] Aviram discussed the potential of the two companies:

> We expect the growth towards autonomous driving to be transformative. It will provide consumers with safer, more flexible, and less costly transportation options, and provide incremental business model opportunities for our automaker customers. By pooling together our infrastructure and resources, we can enhance and accelerate our combined know-how in the areas of mapping, virtual driving, simulators, development tool chains, hardware, data centers, and high-performance computing platforms.[26]

Steps Towards AV

Following the acquisition, Mobileye remained largely independent. In fact, Intel gave Mobileye responsibility for all of Intel's automated driving technology. Shashua stayed on as chief executive of the unit, while Aviram retired. (Shashua and Aviram remained Chairman and CEO in another company they had started together, called OrCam, which used vision technology to help the visually impaired.) With technology support and capital from Intel, Mobileye formally announced its strategy to move beyond ADAS to address the three pillars of autonomous driving: mapping, sensing, and driving policy.[27]

Road Experience Management (REM) – AV Maps: One of the biggest challenges for AVs was the need for high definition (HD) maps. Traditional navigational maps were sufficient for human use, but autonomous vehicles would require HD maps that provided a precise 3D representation of the surrounding area, with centimeter level accuracy. Most AV companies spent enormous time and resources driving specially equipped cars, multiple times over the same route, to create those HD maps. In 2015, Shashua had a different idea. He believed that Mobileye was uniquely capable of collecting data for HD maps since it could crowdsource road-level data through the front camera installed in cars with its ADAS systems. Based on this premise, Mobileye created REM Roadbook, its crowdsourced mapping product. Mobileye gave OEMs an incentive to share the mapping data from its fleets of cars by offering a modest discount on the Mobileye camera and EyeQ chip for those who shared data. Mobileye was able to secure agreements with several companies, including Volkswagen, BMW, and Nissan to collect mapping data from its on-board cameras. By 2022, Mobileye expected that 2 million cars would be supplying them with road data, growing to 5 million cars by 2024.

By crowdsourcing and automating the HD mapping process through the millions of miles driven daily by vehicles equipped with its ADAS, Mobileye had a big potential advantage over other mapping companies. For example, Mobileye was able to map Israel in just 3 weeks using 3,000 vehicles. The company believed it would have complete global HD maps by 2024. Mobileye's crowdsourcing approach also enabled constant updates at a very low cost. While scanning the landscape with a high definition camera would require massive bandwidth to update the maps, the REM system would scan the road, identify any changes from the last update, and only send 10 kilobits of data to the cloud. Another competitive advantage over third party mapping companies was that Mobileye's internal mapping team was working closely with Mobileye's AV team to understand exactly what information and features were needed from the maps to support AV decision making. Nimrod Nehushtan, Director of REM Product, elaborated, "We don't have to hypothesize on what will work. We can directly test our map and experiment with it. In the last year, we added 30 features to our map, all of which are necessary and valuable for autonomous driving."

Mobileye planned to monetize its HD maps by licensing REM Roadbook to OEMs, creating a potential revenue opportunity of hundreds of millions of dollars. Other potential customers for REM Roadbook included cities, road operators, and transportation authorities. Since Mobileye constantly refreshed its maps through crowdsourcing, it could provide almost real time data on road networks, pavement conditions, and traffic flow. This could enable cities to efficiently monitor their infrastructure and make roads safer. However, Mobileye did not plan to license its REM Roadbook to other robotaxi companies.

Responsibility-Sensitive Safety (RSS): Mobileye recognized that for the vision of autonomous vehicles to become a reality, the AV industry, governments, and the public would need to agree upon common standards for safety. If the key players couldn't agree on those standards, it would hold up AV deployment. As a starting point for helping the industry collaborate on defining safety standards, Mobileye published its Responsibility-Sensitive Safety (RSS) model in 2017.[28] The RSS was a mathematical model that mimicked how humans made safety decisions. It was based on a set of common sense rules of how humans think about what it means to drive safely. The RSS had five foundational tenets:

Safe distance: don't hit the car in front of you

Cutting in: don't cut in recklessly

Right of way: right of way is given, not taken

Limited visibility: be cautious in areas with limited visibility

Avoid crashes: if you can avoid a crash without causing another one, you must

The RSS sought to balance safety and utility. As Shashua explained, "If you drive too carefully you are not useful, but you also cannot drive recklessly. We need to determine mathematically, what is the dividing line between being too careful and too reckless? That is what RSS is all about." As an example, for lane merges, RSS determined the boundary between "assertive" vs "dangerous" maneuvers and specified a minimum required gap between vehicles before an AV could change lanes. Mobileye's RSS proposal was technology-neutral, so that it could be used as a platform for developing regulations across the industry. Intel was influential is promoting RSS to regulatory bodies and industry players, and in 2019, Intel was chosen to lead the IEEE (Institute of Electrical and Electronics Engineers) working group to develop AV decision making standards, using the RSS as a basic framework.

Launch of SuperVision: In 2020, Mobileye announced a major new product called SuperVision, a full stack, camera-only ADAS system that offered 360-degree surround camera coverage, coupled with driving policy and navigation technology (based on the REM Roadbook maps). SuperVision consisted of two EyeQ chips and 11 cameras (7 long range and 4 short range) all with varying fields of view. This was a significant enhancement from Mobileye's traditional single front facing camera system. SuperVision allowed for the highest-level autonomy that Mobileye had yet achieved. In fact, the SuperVision technology had been tested in Level 4 vehicles. However, in the near term, SuperVision would be used as part of advanced ADAS systems for Level 2+ cars. Recognizing its potential, Chinese automaker, Geely, signed an agreement with Mobileye to use SuperVision in 400,000 electric vehicles starting in 2021.

Pursuit of True Redundancy: While Mobileye had proven that SuperVision was capable of Level 4 autonomy, the company also realized that technological redundancy would ultimately be necessary to achieve the safety standards required for autonomous vehicles. Rosenblum argued that Mobileye's "key value proposition is scaling up from ADAS to premium ADAS to consumer AVs by having two, independent redundant systems." Mobileye used the automotive industry metric of "mean time between failures" (MTBF) to determine safety levels. The estimated probability of a fatality in a human driven car was one in one million hours driven. Knowing that AVs would need to *surpass* human level safety levels, Mobileye had set its own bar for autonomous vehicle safety at one fatality in ten million hours.

To achieve this level of MTBF, Mobileye made the strategic decision to pursue technological redundancy for AVs by building two independent self-driving systems — one based on cameras and the other based on a combination of next generation LiDAR and Radar that Intel was helping Mobileye develop. If each of the two systems could conservatively travel for over 3,000 hours (10^3.5) without a crash, Mobileye reasoned that combining the two systems in a car could achieve a MTBF of one in 10 million hours (10^3.5 x 10^3.5 = 10^7), well above human standards, and likely acceptable to regulators.[29] As Shashua explained, Mobileye's approach to true redundancy "is like having both iOS and Android smartphones in my pocket and asking myself: What is the probability that they both crash simultaneously?"[30] Some industry observers questioned Mobileye's calculation of MTBF. The approach assumed that the two systems were statistically independent, which might not be the case.[31] Mobileye planned to test the two systems separately and demonstrate their respective safety performance levels before combining them into a "super-system" that exponentially increased safety levels. The camera-only system would become the backbone of the system, while the radar/LiDAR subsystem would serve as a diversified and redundant safety backup.[32] Mobileye planned to use its True Redundancy system in its future robotaxi rollout.

Mobileye projected that the cost of the whole self-driving system (REM Roadbook, RSS, and True Redundancy systems) would ultimately be $3,500 per vehicle. However, in the short-term, the cost of a full SDS was estimated to be roughly five times that for Mobileye, and almost ten times that for Waymo and Cruise.[33] Dagan argued that Mobileye's long-term cost advantage, which partly came from Intel's ability to deliver next generation low cost LiDAR and radar, could lead to "dramatic differences in returns" as well as give Mobileye the flexibility to compete more aggressively on price with incumbent taxi and ride sharing companies.

Mobileye's Robotaxi Strategy

While Shashua's ultimate goal was to deliver consumer AVs, it would take several years to demonstrate safety, bring costs into line with consumers' willingness-to-pay, and get the regulations in place. However, robotaxis represented a nearer-term opportunity. Since robotaxi fleet operators could amortize that cost over the number of rides taken, the price of the vehicle was much less important.[34] On the regulatory front, Shashua and his team believed it would be easier for regulators to monitor and regulate a handful of fleet operators rather than millions of individual owners of AVs.[35] Finally, AVs required HD maps for anywhere they traveled, but early HD mapping efforts had been largely limited to cities. As a result, existing HD mapping was better suited for robotaxis operating in "geo-fenced" cities[b] than to consumer AVs that would need to drive in urban, suburban, and rural areas.

Perhaps most important, robotaxis would serve as an R&D lab for AV experimentation, testing, and learning. Shashua explained, "Robotaxis are a necessary steppingstone for driverless cars."[36] He added, "The auto industry is gradually realizing that autonomy must wait until regulation and technology reach equilibrium and the best place to get this done is through the robotaxi phase… When the factors of cost, regulation and scale are taken together, it is understandable why series production passenger cars will not become possible until after the robotaxi phase."[37] (See **Exhibit 2**.)

Robotaxi Economics

A large part of the excitement behind robotaxis was the potential for a lower cost alternative to other transportation options (see **Exhibit 3)**. Fujitsu projected that an autonomous robotaxi would cost approximately $.35 per mile by 2025, compared with $3.50 for a human driven taxi, $1.50 for an Uber, and $.75 for a privately owned vehicle.[38] However, there was debate over these economics. A study published in 2019 by MIT researchers, which analyzed robotaxi costs using San Francisco as their test market, found that the price for an autonomous taxi would range from $1.58 to $6.01 per mile.[39] Robotaxi costs were analyzed according to the following formula:

$$\text{Cost per mile} = \frac{\text{financing + licensing + insurance + maintenance + cleaning + fuel + safety oversight + profit}}{\text{utilization rate}}$$

Vehicle financing included the amortized cost of the financing costs of acquiring an AV. Licensing included the fees paid to regulatory bodies by commercial fleet operators to offer robotaxi services. Insurance included coverage for accidents and thefts. Maintenance included the cost of inspecting and maintaining the robotaxi vehicle. Fuel costs were based on the assumption that robotaxis would have a hybrid powertrain. Safety oversight included the cost of human supervisory control over AV vehicles from a central location. It was assumed that one supervisor could monitor a maximum of 50 AVs. Profit included the return that fleet operators would realize from the business. Finally, utilization rate was defined as the percentage of miles traveled with a fare paying passenger onboard.[40]

Utilization rates were a key driver of robotaxi economics. The utilization rate for traditional taxis in the U.S. was around 50% and even Uber's New York City utilization rate was only 58%.[41,42] However, utilization rates in some other parts of the world were slightly higher than the U.S. average: China 58%, Singapore 66%.[43] There were also other ways to improve robotaxi economics. Ridesharing was more cost effective than transporting individual passengers. Furthermore, supervisor costs could be reduced if AI programs could be used to monitor more cars simultaneously. There were also additional revenue opportunities that could be tapped. For example, robotaxis could also offer food delivery with their excess capacity and riders could purchase entertainment or other add-on features on board.

[b] Unlike a regular taxi, which in theory could take a passenger anywhere, robotaxis could only travel in areas with special, high definition maps. As a result, early robotaxis would need to be "geo-fenced" and only available on a more limited number of routes.

Mobileye would soon determine the real economics of robotaxi after it deployed a fleet of 50 to 100 robotaxis in Israel in early 2022 (see **Exhibit 4** for Mobileye's robotaxi prototype). Shortly after, similar deployments were planned for Germany, France, UAE, South Korea, and other European countries. In 2023, Mobileye planned to launch in Osaka, Japan and in the U.S. The ROI from these investments was also sensitive to pricing pressure from competitors: Would the robotaxi look like the ridesharing business in the U.S., where Uber and Lyft had intense price competition for many years, or more like Didi in China, where prices stabilized after Uber's departure?

Taxi and Rideshare Economics

Robotaxi economics had the potential to be superior to traditional taxi economics and rideshare economics. In most cities, traditional taxi drivers required a medallion to have the right to drive a taxi. Medallions were issued by cities themselves, with the goal of limiting supply to support prices. For example, New York City had 13,000 medallions and Boston had just 1,825.[44,45] Due to their limited supply, taxi medallions were a valuable asset, trading for upwards of hundreds of thousands of dollars, affordable only to investors or fleet owners. Individual taxi drivers typically leased medallions on a daily or weekly basis. The daily price for a medallion lease ranged from $75 to $150 per day, depending on location.[46] Taxi drivers were also typically responsible for paying for gas and general liability insurance. Cab operators insured the vehicle and covered maintenance costs.[47] Taxi drivers kept every fare dollar and all tips. Utilization rates and wait times impacted taxi driver revenues. Taxi pricing was usually regulated by city ordinances. Pricing was based on an initial charge ranging from $2.00 to $4.00, a per mile charge when moving, ranging from $2.00 to $4.00, and a per minute charge when idling (not moving at all).[48] The all-in cost for a 5-mile trip was between $3.00 to $5.00 per mile in the U.S., depending on the city.[49] Most taxi services had margins ranging from 3-10%.[50] Before the entry of Uber and Lyft, margins were helped by regulation and the medallion system, which constrained supply.

In contrast, rideshare drivers paid a percentage of each fare to the ride-hailing operator, thereby reducing fixed costs in comparison to leasing a medallion. The commission taken by operators was typically around 25%.[51] Ridesharing drivers were responsible for buying and maintaining their own car, paying for gas, and paying for insurance. The price of a ride through a ridesharing company was comprised of four components: 1) a flat fee charged at the beginning of the ride, 2) a per mile charge, 3) a per minute charge, and 4) a booking fee, which went directly to the rideshare operator, not the driver.[52,53] On average, Uber and Lyft prices were around $2.00 per mile in the U.S.[54] Ridesharing, however, was historically unprofitable: the cost of recruiting drivers and enticing passengers led to multibillion dollar losses at Uber and Lyft.

Robotaxi Competition

Shashua was not particularly concerned with competition in robotaxis. He noted, "it's a huge market, and there's no winner-take-all." The competitors he worried most about were Tesla and Apple. Shashua viewed Tesla as a "big disruptor" in the auto industry; and Apple's consumer expertise, design strengths, and brand would make it a formidable player, if it chose to enter. Nonetheless, a large number of OEMs, tech firms, and startups were expected to enter the space. After General Motors acquired Cruise in 2016, the company developed a Level 4 to 5 AV for the robotaxi market, named Cruise Origin. Cruise planned to launch its U.S. robotaxi service in San Francisco (no announced date) and its first international robotaxi in Dubai in 2023.[55] Ford's AV tech company, Argo AI, was developing a robotaxi and delivery service which was being tested in Miami, Austin, and Washington, DC, but due to COVID-19, Ford had delayed the official launch until 2022.

Waymo, Alphabet's self-driving car unit, was the most visible competitor. It began operating its robotaxi service, Waymo One, in Phoenix, Arizona in 2018. It was speculated that San Francisco would be Waymo's next market rollout. Mobileye's approach was quite different from Waymo, according to Johann Jungwirth, Vice President of Mobility-as-a-Service (MaaS). He noted that "unlike Waymo and others, we are agnostic to the type of vehicle, and we have the ability to implement the entire vertical stack," (which is discussed in more detail below). Other big players included Alibaba-backed AV startup AutoX, which launched its robotaxi service in Shanghai in 2020, and in Shenzhen in January 2021. AutoX faced competition in China from Didi, China's largest ride-hailing platform, which had launched its robotaxi pilot in Shanghai in June 2020.[56] Amazon acquired AV tech company Zoox in June 2020. Amazon was testing its robotaxi in San Francisco and Las Vegas, but had not yet announced an official launch date.[57] The company planned to operate its robotaxi in other countries as well. Aicha Evans, Zoox CEO commented, "This is really about re-imagining transportation. Not only do we have the capital required, we have the long-term vision."[58]

Capital was a key consideration, since the R&D costs involved in developing a robotaxi could potentially reach billions of dollars.[59] It was speculated that cost issues drove Uber and Lyft to stop their own robotaxi development. In December 2020, Uber sold its robotaxi division to Aurora, and Lyft was expected to announce that it would sell its autonomous taxi unit to Toyota.[60] Given the high capital requirements, further consolidation was expected in the market.

Mobility-as-a-Service

Building a robotaxi business went far beyond a self-driving system. Robotaxi operators would need the self-driving vehicle, tele-operations and fleet operations, a mobility intelligence platform, and the ride experience itself. These components came together under the umbrella of MaaS.

MaaS was defined as a unified gateway that enabled end users to digitally connect to a variety of mobility services to plan, book, and pay for transportation on demand. MaaS included both public transportation options (e.g., trains, buses) and private transportation (e.g., taxis, bicycles, scooters). By linking these services together, MaaS hoped to offer end-to-end trip planning by arranging the most suitable transport modality across all types. Societal advantages of MaaS included lower costs, reduced traffic congestion, reduced emissions, and increased transit network efficiencies (see **Exhibit 5**). The evolution from private car ownership to MaaS was already underway, fueled by the rise in a variety of mobility transport options, including ridesharing, bicycle-sharing, scooter-sharing, car-sharing, and on demand pop-up bus services. Mobileye projected that MaaS would be a $550 billion market by 2030 (see **Exhibit 6**).

Mobileye's vision of MaaS had five value layers, and each robotaxi operation would need to decide if they would offer the entire stack or play in only one layer (see **Exhibit 7** for competitor approaches to MaaS). The "full-stack" player required:

1) **The self-driving system software (SDS):** the full AV system kit, including SDS software, SDS hardware and HD maps and data services.

2) **Self-driving vehicles**: Level 4+ base vehicle, rider sensing, MaaS UX hardware.

3) **Fleet operations and tele-operations:** fleet operations were brick and mortar service operations that handled storage, maintenance, repair, charging, and cleaning of vehicles. Tele-operations were command and control centers that had humans on hand for back-up AV decision support, such as road decisions and routing decisions.

4) **Mobility intelligence platform and services:** fleet utilization models and algorithms (ride requests, vehicle location, environmental conditions, customer wait time and pricing elasticity, and demand prediction).

5) **Service and in-ride experience:** the in-vehicle user experience (e.g., productivity, relaxation, entertainment experiences) and user feeling of psychological safety.

Mobileye was committed to being a full-stack MaaS player through the development of all five value layers of the value chain. As the company stated: "Developing MaaS and driving it to quick convergence is critical to secure our SDS product fit, and to dominate the consumer AV ramp up ahead of the industry learning curve."[61] For some layers, Mobileye would develop its own solution, but for others it planned to partner or outsource. For example, Mobileye announced a joint venture with Volkswagen to build the self-driving vehicle (Layer 2)[c] for the robotaxi trial in Israel, and according to Jungwirth, Mobileye's plan would outsource some of the fleet operations and tele-operations to Champion Motors (Layer 3).

To address the mobility intelligence platform (Layer 4), Intel acquired Moovit in 2020 for $900 million. Moovit was a consumer-facing urban mobility app that integrated all forms of urban transportation, including public transit, ride-hailing services (Uber, Lyft), bicycles, scooters, car-sharing, and carpooling. The app yielded a personalized trip plan for a user to get from point A to point B that could include several modalities. Moovit combined schedule information from public transit operators with live information from users to give a real-time picture of what was going on (see **Exhibit 8** for a picture of the Moovit app). The company had partnerships with 7,500 local public transit operators to get real-time data from its vehicles, as well as 320 other mobility partners, such as ride-hailing services. The company also leveraged the efforts of over 720,000 volunteers, referred to as "Mooviters," who provided local transportation schedules and verified public transportation stops for cities that would otherwise be unserved.[62] The Moovit app was hailed as the "Best Local App" by Google in 2016 and one of Apple's picks for Best App in 2017. [63] By 2020, Moovit had 950 million users.

Part of Mobileye's interest in becoming a full-stack MaaS provider was to own the end user data. However, operating a B2C business was a significant departure from Mobileye's and Intel's traditional B2B focus. Dagan elaborated, "Robotaxis are not a B2B *devices* market, but an end user's *data* market. For Intel, it's a different perspective and a different monetization channel. At Mobileye, we believe that owning the transportation users is a significant asset."

Related Markets: RaaS, VaaS, and XaaS

Due to the uncertain economics of MaaS, Mobileye made the strategic decision to adopt a diversified go-to-market strategy that also included related business models, including Vehicles-as-a-Service (VaaS) and Rides-as-a-Service (RaaS) (see **Exhibit 9**). By pursuing a so-called "XaaS "(anything as a service) strategy, Mobileye could dynamically determine what level of vertical integration was economically optimal. VaaS and RaaS would involve collaborating with transit and network service operators (e.g., Uber, Lyft), which Mobileye hoped would help them gain dominance as the autonomous mobility provider of choice. These other models also might give Mobileye an opportunity to participate in certain markets where Mobileye could not, or chose not, to be a robotaxi player.

Rides-as-a-Service (RaaS) was a way for transportation network companies to balance supply and demand. If a service operator like Uber had an unmet demand, it could "summon" an automated

[c] As of Jan 2020, the Volkswagen minivan had faced delays, so Mobileye signed a deal with Nio (China's equivalent of Tesla) to supply dozens of Nio cars for the development and trials of the robotaxi fleet.

mobility solution by outsourcing to the highest bidder on the supply side. In other words, Mobileye would provide rides to fleet operators to fill un-addressable demand.[64] The business model they had in mind was a dynamic auction, similar to bidding on key words at Google. MaaS providers would bid on vehicles as needed.

Vehicles as a Service (VaaS) Mobileye referred to VaaS as the opportunity to sell or lease a fleet of autonomous vehicles/shuttles to a transit operator to be assimilated into the operator's existing fleet and control center.[65] Beyond transit operators, other potential VaaS customers included car rental companies or transportation network operators. As Jungwirth commented, "VaaS is specifically interesting to people who are good at operations, like public transport operators. It could also be interesting for transportation network companies in the long term, depending on whether they want to stay asset light or become asset heavy once the driver is out."

Mobileye's Long-Term Strategic Dilemma

By 2020, Mobileye was generating $1 billion in revenue from ADAS systems (see **Exhibit 10**). The company was positioned to compete across multiple parts of the AV value chain, including ADAS, HD Mapping, robotaxi, and SDS systems (see **Exhibit 11)**. However, as the AV market evolved, it was not clear how Mobileye should prioritize its efforts — on robotaxi or as a supplier of SDS systems.

In the short run, Mobileye was committed to entering the robotaxi business in 2022. Yet over the longer term, it was unclear how far Mobileye should go? Looking out to 2025-2026, should Mobileye focus on becoming a $5-$10 billion robotaxi company? Or should Mobileye use the robotaxi business as a steppingstone towards building a Level 4 to Level 5 AV system that it could supply to OEMs? Under the first approach, Mobileye would become a vertical industry player, while under the second, it would remain a horizontal supplier to OEMs, as it had been for ADAS systems. Shashua noted that, "Since we must go through this practice phase, why not also build a robotaxi business? This is why we bought Moovit. But are we fully committed to scale and become like Uber? I don't know. My dream is the consumer AV."

Gilad Lustig, Senior Director of Strategy, Mobileye, supported the MaaS/robotaxi direction, commenting:

> I think a full stack solution creates a lot of strategic advantages and gives us flexibility in offering multiple business cases (RaaS, VaaS) across derivative markets. It's hard to predict what position OEMs will take in the consumer autonomy space, so we should be able to offer a variety of solutions to be competitive. There is a scenario where robotaxi grows and provides — at least for urban centers — *all* the transportation needs, due to its price competitiveness, ease of use, and availability. It could replace a huge chunk of private car ownership.

Dagan had a more balanced view on Mobileye remaining a full-stack MaaS player over the long term:

> Robotaxi is a huge opportunity, but also a huge risk. It's a completely different business model to be a full-stack service provider with a massive capital investment, rather than a horizontal supplier of systems. However, we will definitely launch robotaxis in a few metropolitan areas and study the economics… The exact way MaaS margins are going to emerge across the value chain is yet to unfold. Our XaaS strategy should serve us well as a way to learn. By going to market with VaaS and RaaS as well as MaaS, we can

> identify the optimal level of vertical integration and monetize it. Of course, we will also have to monitor the regulation of robotaxis as a key success factor for consumer AV.

Another option was for Mobileye to do both — own the full-stack solution of MaaS/robotaxi *and* provide OEMs with autonomous driving systems. If Mobileye went this route, should it start selling AV systems to other robotaxi players? If big OEMs, such as GM and Toyota, ultimately would enter the robotaxi business, could Mobileye and Intel navigate the challenges of "co-opetition?"

Ultimately, Dagan was excited about the potential of the consumer AV market: "It's going to be a very rewarding market to play in. In Level 2+, there's no liability shift or risk exposure as there is in a Level 4 vehicle. In Level 2+ the driver stays engaged and is responsible, but full autonomy is very appealing. Consumer AV is much more organic to our DNA and would yield higher margins."

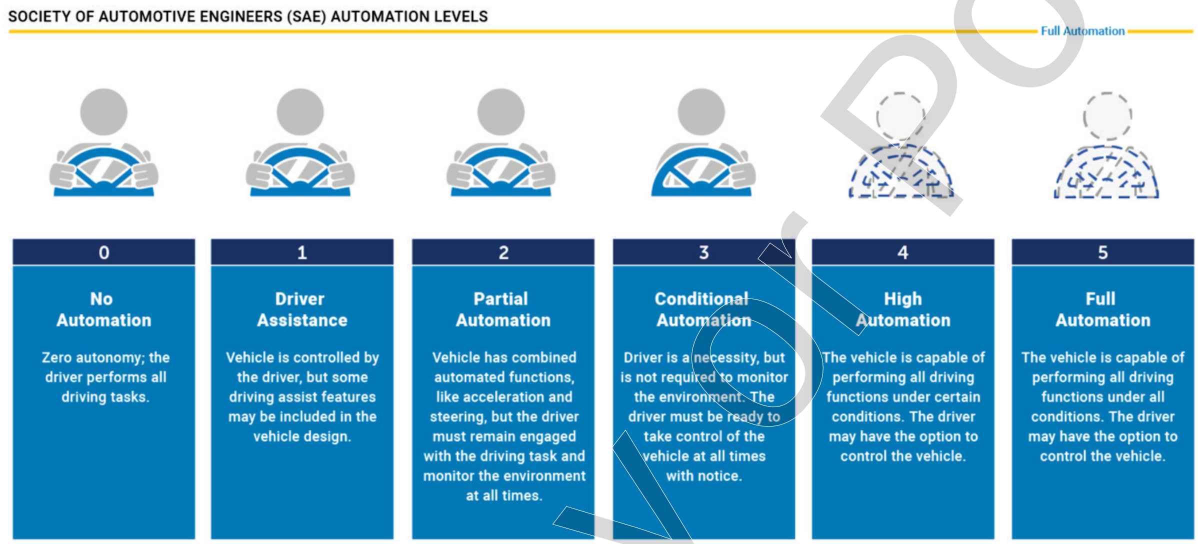
Nehushtan also saw a role for Mobileye in both markets, but acknowledged there were trade-offs:

> There is a revolution in progress for MaaS and a different revolution in play for consumer AVs. These are two different revolutions, and Mobileye should play in both. However, as we consider issues like cannibalization or other issues that will come up, we should consider what will be the right thing to do to promote these two visions and put Mobileye in a position where we can play a central role in these two revolutions.

One big uncertainty that remained was government regulation. As an SDS supplier, it was unlikely that Mobileye would be directly liable for accidents involving consumer AVs. However, as a vertically integrated, full stack MaaS provider, Mobileye would have to take on much greater liability risk and balance liability exposure with market opportunity. Dagan noted that, "We hope the regulator makes it easy math in terms of exposure. If, for example, the regulator says consumer AVs must have RSS and 10^8 MTBF, and we meet these two criteria, then we would be protected in the case of an accident." He was counting on regulators in Israel, who would be overseeing Mobileye's robotaxi trial, to recognize the societal value of robotaxi and administer the risk-taking accordingly, setting an example for other regulators worldwide. But when asked about what kept him up at night, Jungwirth replied: "Regulatory approvals. It is simple, we cannot launch without it."

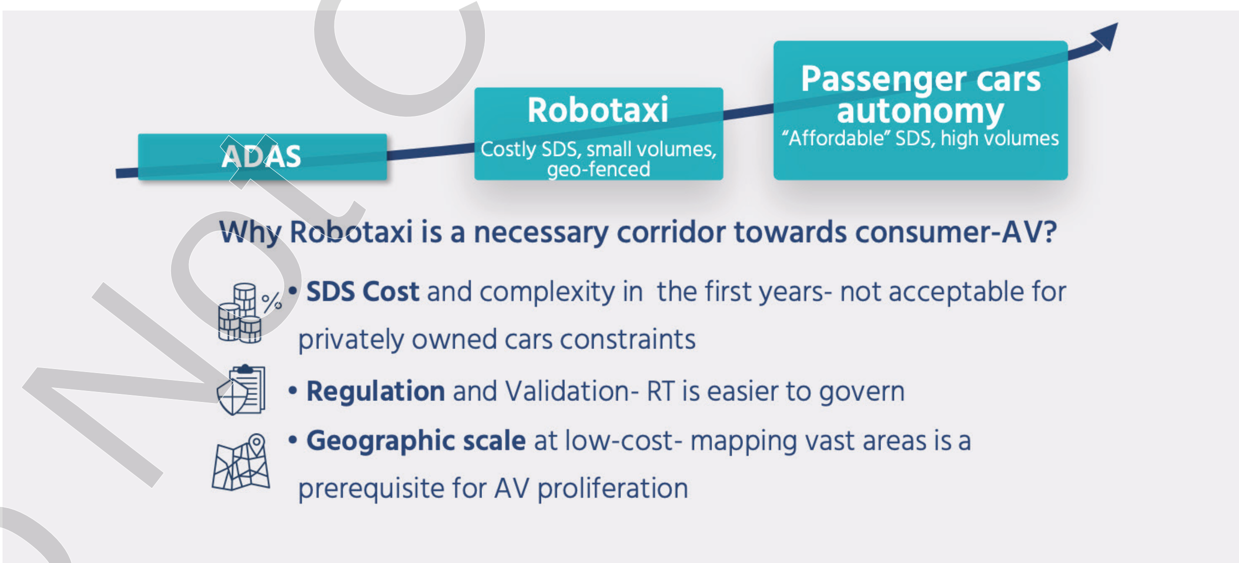
Shashua weighed the three options as he prepared for his meeting with Gelsinger. Shashua's long term vision had always been consumer AV, but robotaxis represented a larger opportunity in the short run and had the potential to reduce or obviate the need for privately owned automobiles in the long run. However, internal estimates suggested that it would cost at least $1 billion in negative cashflow to rollout to 400 cities, around seven years to get to cumulative cash positive, and Mobileye would probably require an additional few billion dollars in acquisitions (see **Exhibit 12** and **Exhibit 13** for Intel's financial statements). Ultimately, broad geographic exposure was critical: self-driving systems had to operate safely everywhere in the world, not just a few cities or even countries. Traffic rules and driving conditions varied dramatically in different geographies. As a result, capital costs over the decade, mainly for a large global fleet of 200,000+ self-driving cars, would likely cost over $10 billion. This was no small ask. Since Gelsinger had not been at Intel when it acquired Mobileye, Shashua wanted to help educate Gelsinger about where Mobileye fit within Intel's overall strategy. During most of Intel's history, the company had been a horizontal semiconductor company which avoided vertically integrating into its customers' businesses. Should Shashua make the case that it was time for a change — and Intel should run a full-stack vertical robotaxi company? Or should the long-term goal be to become a horizontal supplier of AV software and hardware to OEMs? Or should Mobileye and Intel do both?

Exhibit 1



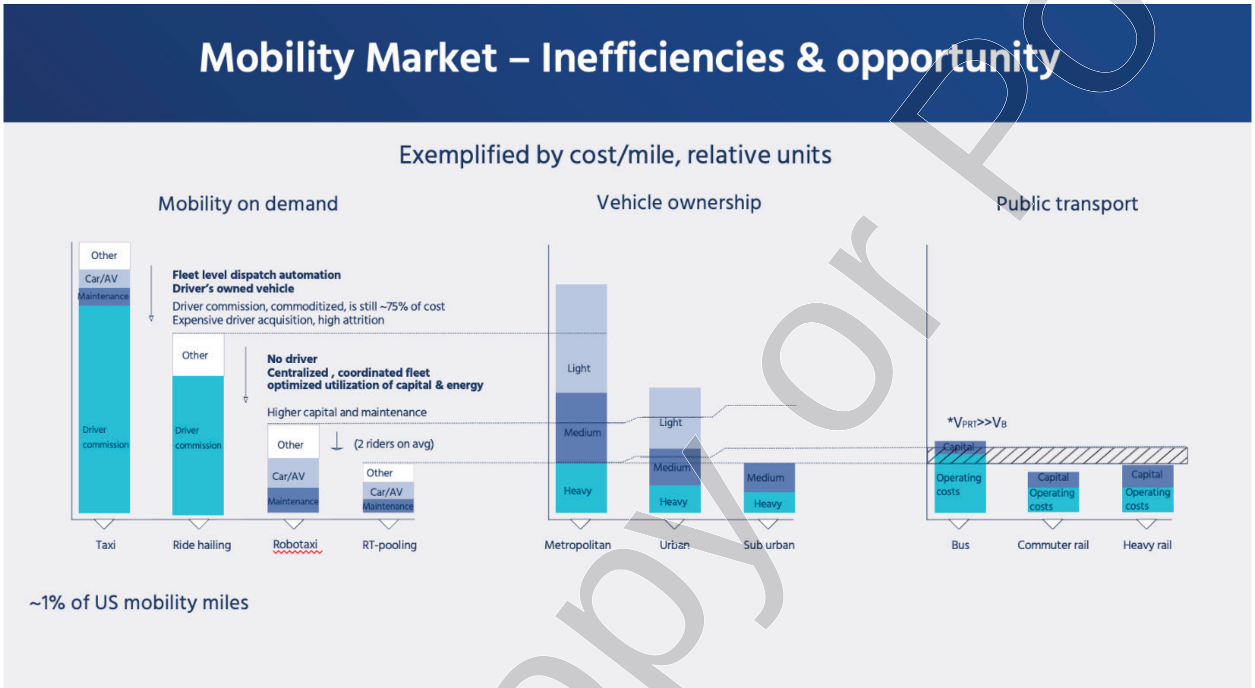
Source: nhtsa.gov, https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety, accessed April 24, 2021.

Exhibit 2 How Robotaxi Fit Within the Evolution of AV Technology



Source: Company documents.

Exhibit 3 Comparison of Costs Across Transportation Options



Source: Company documents.

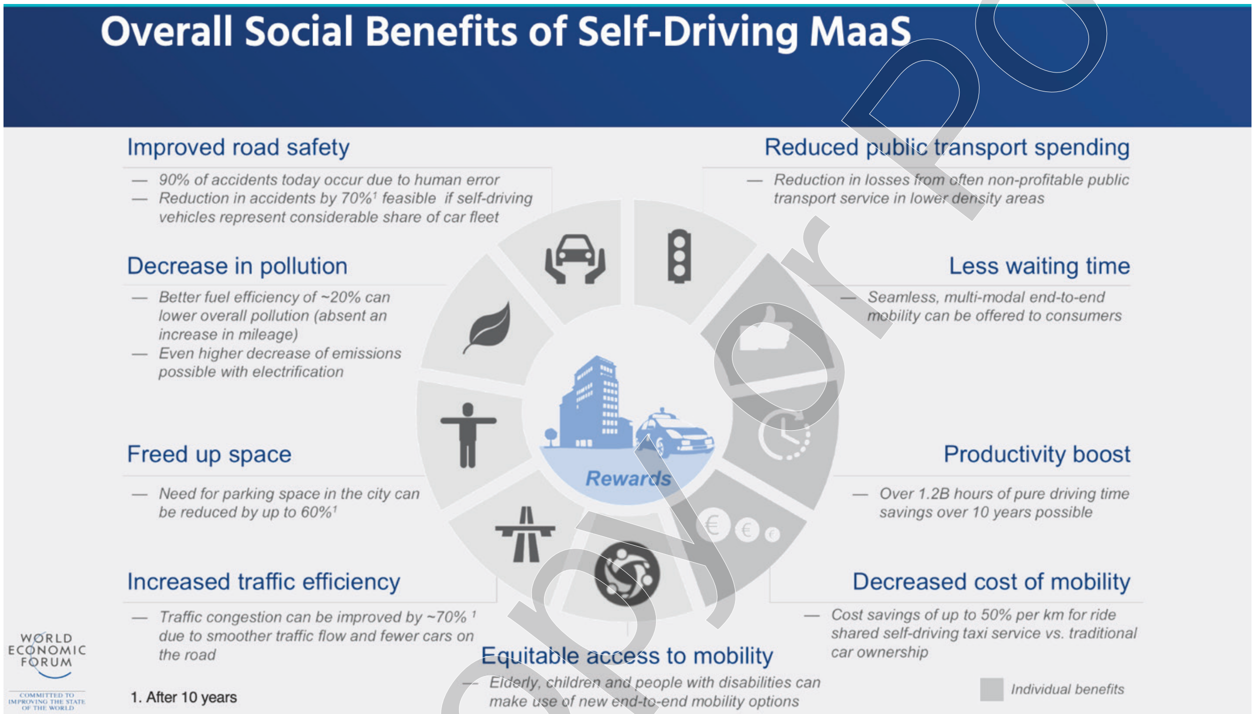
Exhibit 4 Mobileye's Robotaxi Prototype: 6 passenger vehicle and 16-passenger shuttle

Nio ES8-based L4 Self-Driving Vehicle
6 seats for riders

L4 Self-Driving Shuttle
for up to 16 riders (incl. ramp)

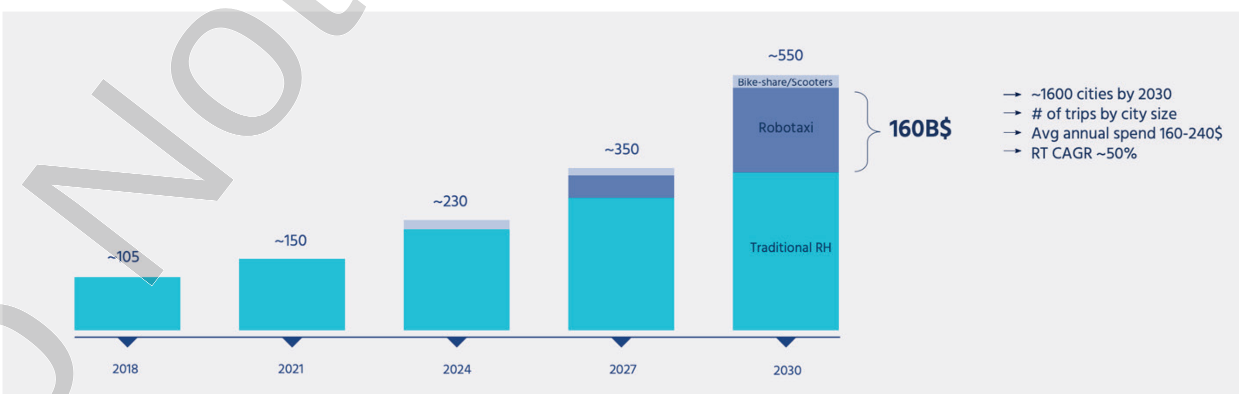
Source: Company documents.

Exhibit 5 Societal Benefits of MaaS



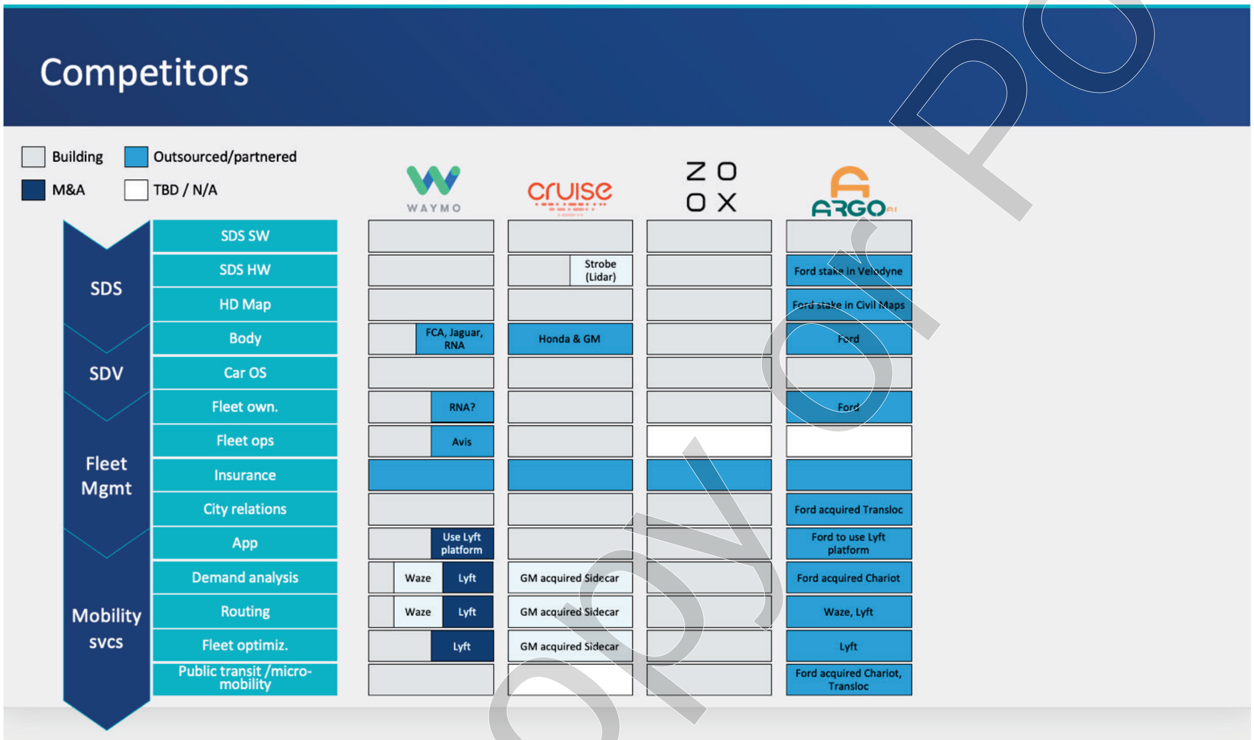
Source: Company documents.

Exhibit 6 MaaS Market Size Projection ($ billions)



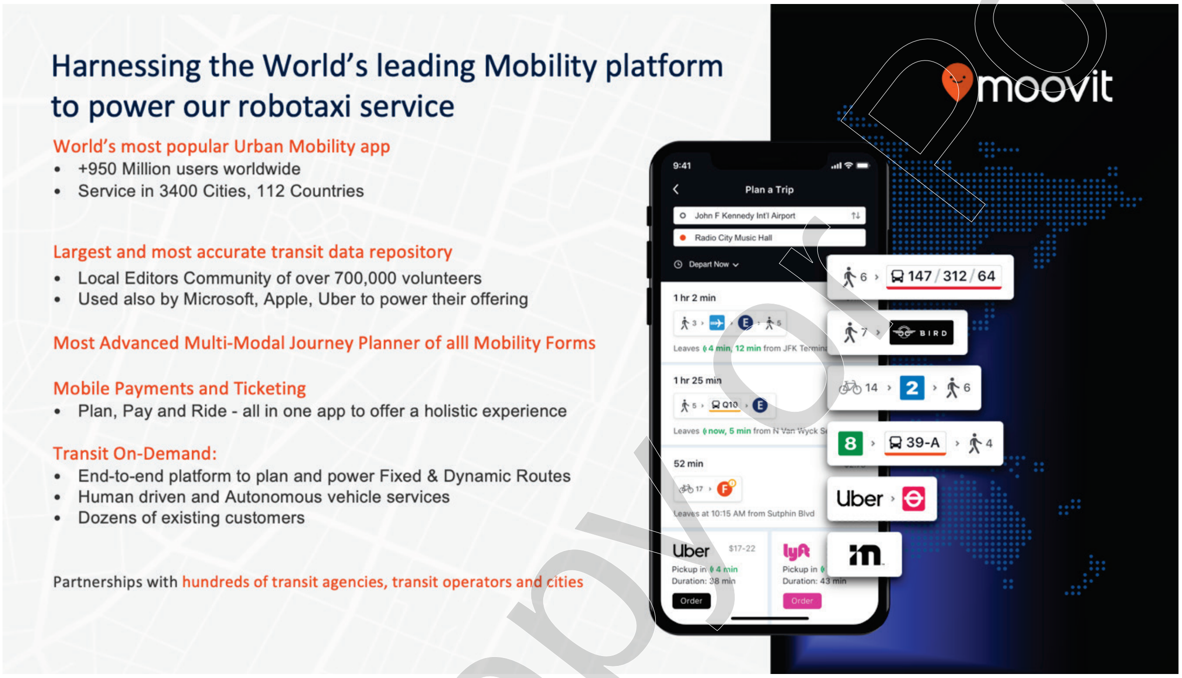
Source: Company documents.

Exhibit 7 Competitor Approaches to MaaS



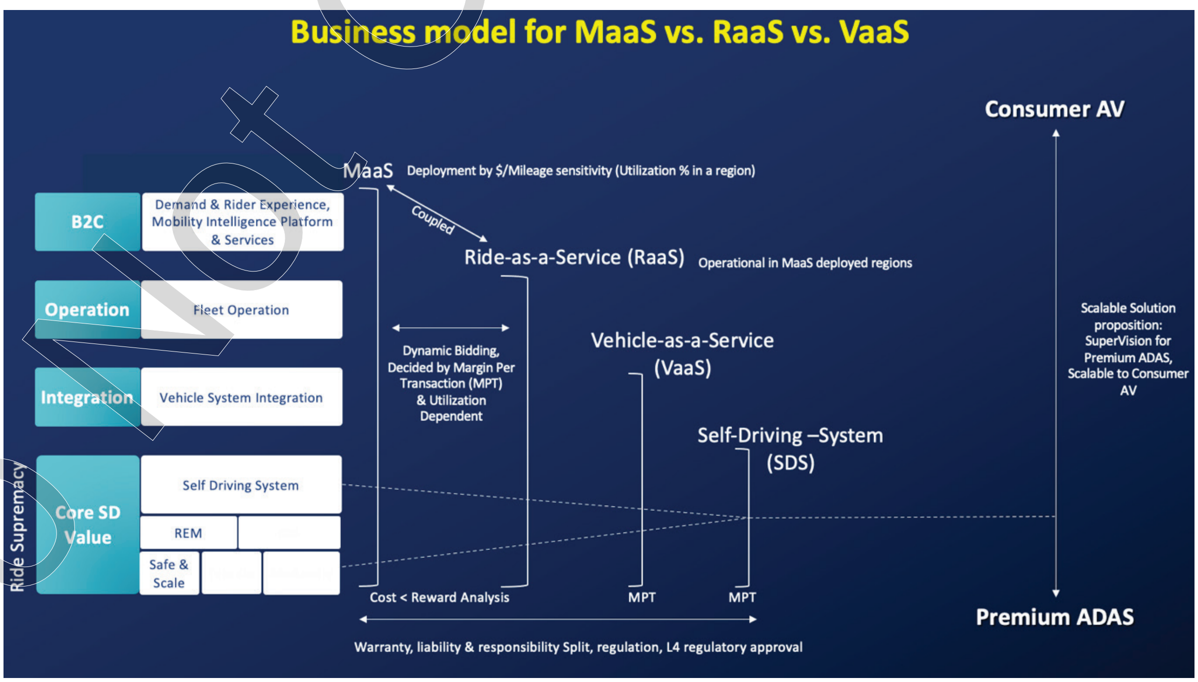
Source: Company documents.

Exhibit 8 Moovit App



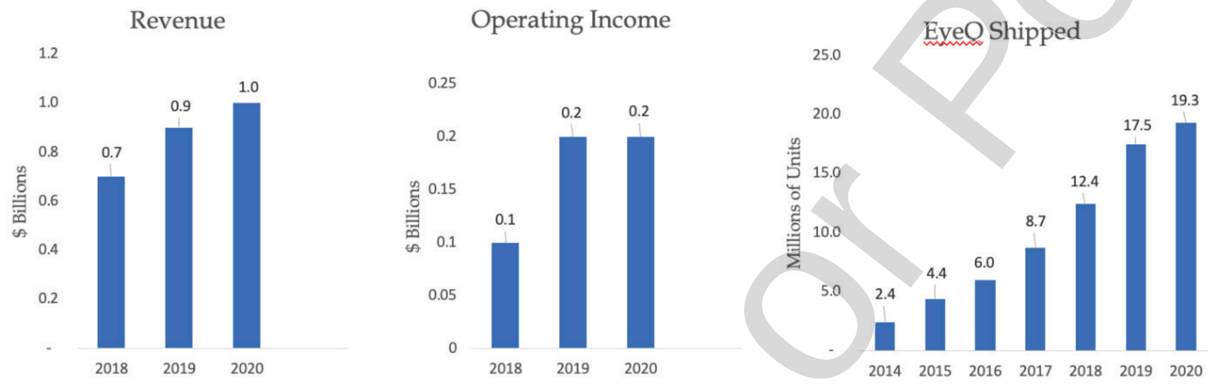
Source: Company documents.

Exhibit 9 MaaS vs. RaaS vs. VaaS



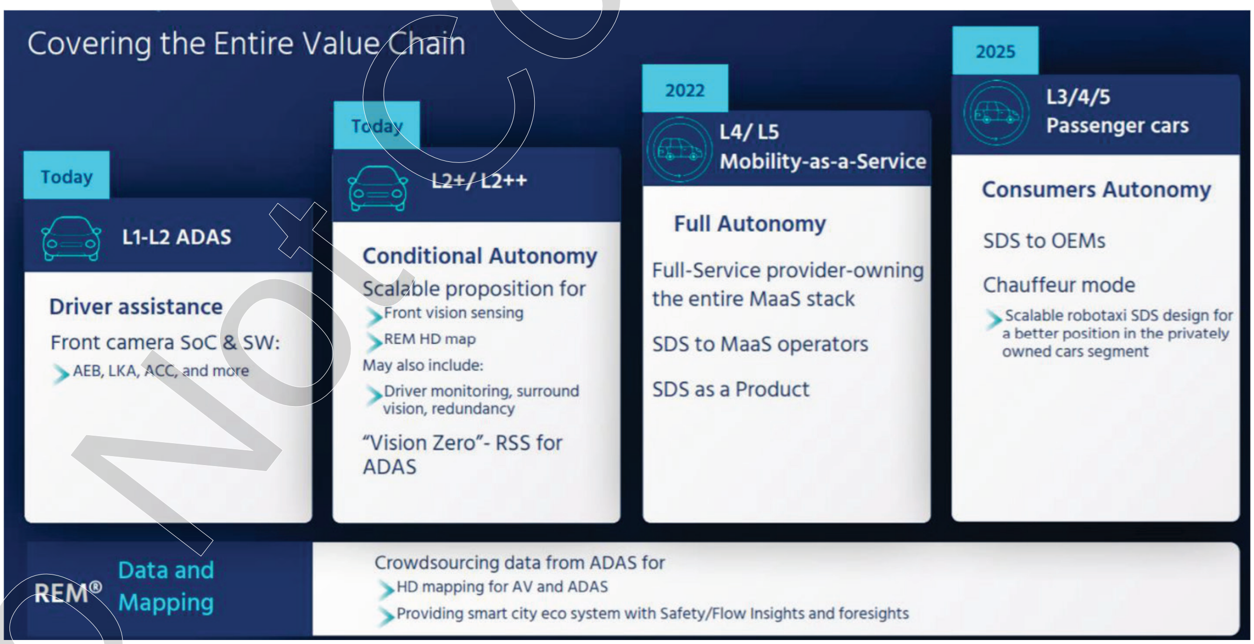
Source: Company documents.

Exhibit 10 Mobileye Financials



Source: Company documents.

Exhibit 11 Mobileye's Business Segments



Source: Company documents.

Exhibit 12 Intel Income Statement as of December 2020

Years Ended (In Millions, Except Per Share Amounts)	Dec 26, 2020	Dec 28, 2019	Dec 29, 2018
Net revenue	$ 77,867	$ 71,965	$ 70,848
Cost of sales	34,255	29,825	27,111
Gross margin	43,612	42,140	43,737
Research and development	13,556	13,362	13,543
Marketing, general and administrative	6,180	6,350	6,950
Restructuring and other charges	198	393	(72)
Operating expenses	19,934	20,105	20,421
Operating income	23,678	22,035	23,316
Gains (losses) on equity investments, net	1,904	1,539	(125)
Interest and other, net	(504)	484	126
Income before taxes	25,078	24,058	23,317
Provision for taxes	4,179	3,010	2,264
Net income	$ 20,899	$ 21,048	$ 21,053
Earnings per share—basic	$ 4.98	$ 4.77	$ 4.57
Earnings per share—diluted	$ 4.94	$ 4.71	$ 4.48
Weighted average shares of common stock outstanding:			
Basic	4,199	4,417	4,611
Diluted	4,232	4,473	4,701

Source: Company documents.

Exhibit 13 Intel Balance Sheet as of December 2020

(In Millions, Except Par Value)	Dec 26, 2020	Dec 28, 2019
Assets		
Current assets:		
Cash and cash equivalents	$ 5,865	$ 4,194
Short-term investments	2,292	1,082
Trading assets	15,738	7,847
Accounts receivable, net of allowance for doubtful accounts	6,782	7,659
Inventories	8,427	8,744
Assets held for sale	5,400	—
Other current assets	2,745	1,713
Total current assets	**47,249**	**31,239**
Property, plant and equipment, net	**56,584**	**55,386**
Equity investments	**5,152**	**3,967**
Other long-term investments	**2,192**	**3,276**
Goodwill	**26,971**	**26,276**
Identified intangible assets, net	**9,026**	**10,827**
Other long-term assets	**5,917**	**5,553**
Total assets	**$ 153,091**	**$ 136,524**
Liabilities, temporary equity, and stockholders' equity		
Current liabilities:		
Short-term debt	$ 2,504	$ 3,693
Accounts payable	5,581	4,128
Accrued compensation and benefits	3,999	3,853
Other accrued liabilities	12,670	10,636
Total current liabilities	**24,754**	**22,310**
Debt	**33,897**	**25,308**
Contract liabilities	**1,367**	**1,368**
Income taxes payable	**4,578**	**4,919**
Deferred income taxes	**3,843**	**2,044**
Other long-term liabilities	**3,614**	**2,916**
Commitments and Contingencies (Note 19)		
Temporary equity	**—**	**155**
Stockholders' equity:		
Preferred stock, $0.001 par value, 50 shares authorized; none issued	—	—
Common stock, $0.001 par value, 10,000 shares authorized; 4,062 shares issued and outstanding (4,290 issued and outstanding in 2019) and capital in excess of par value	25,556	25,261
Accumulated other comprehensive income (loss)	(751)	(1,280)
Retained earnings	56,233	53,523
Total stockholders' equity	**81,038**	**77,504**
Total liabilities, temporary equity, and stockholders' equity	**$ 153,091**	**$ 136,524**

Source: Company documents.

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