Automotive Cameras for Lighting and Vision Systems

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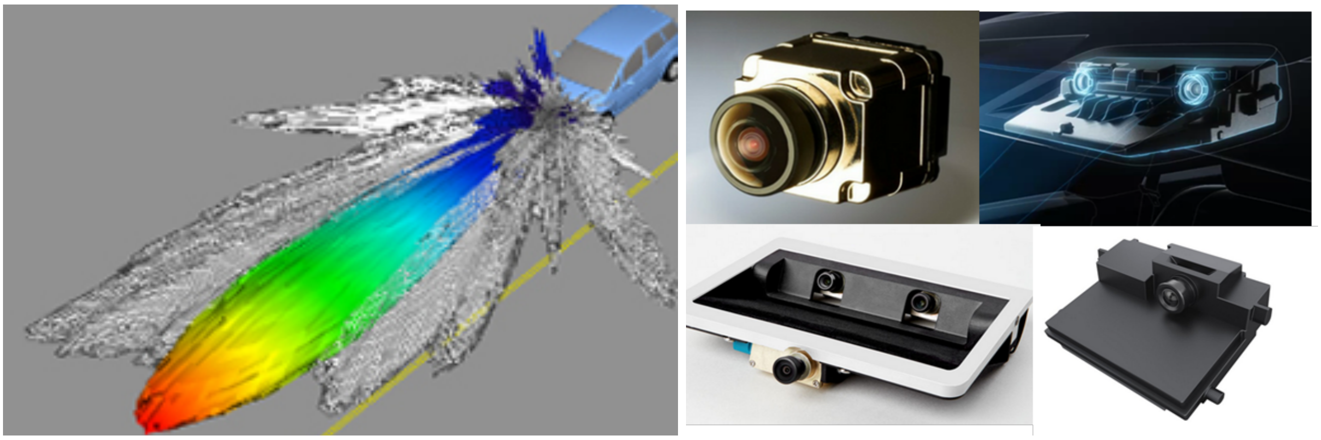

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About the author

Jean-Paul Ravier graduated from ISAE SUPAERO (the Institute for Space and Aeronautics Engineering) and IAE Paris (Institute for Administration of Enterprises).

He worked for over 41 years at Valeo, including 29 years at Valeo Lighting where he held a variety of management positions first in IT and finance, and then in R & D, projects, and innovation, including in Japan from 2005 to 2009 at Ichikoh as a board member and managing director. He retired from Valeo in 2013. Shortly thereafter he was appointed chair of the ELS programme (Embedded Lighting Systems) for Advanced Master training and Research in Lighting at the Institut d'Optique Graduate School, ESTACA and Strate School of design. He held that position through the end of 2017. He is now DVN's Development Advisor.

Author's foreword

To build this report, I am deeply thankful to all the companies and people who have helped me to realise this study, particularly to Yole[1] that has allowed us to reproduce some charts for their studies, to Pierre Cambou, Activity Leader for Imaging at Yole for his great knowledge and expertise that we appreciated during his interview, to Joachim Mathes, R&D and Product Marketing Director at Valeo Driving Assistance for his interview, to Daniel Stern for editing, and of course to DVN President Hector Fratty for his advice and support.

YOLE Développement

[1] Yole Développement group provides market research, technology analysis, strategy consulting, targeted media, and financial advisory services with a global vision and a large customer base. Yole are particularly specialised in imaging, sensors, actuators, semiconductors, solid state lighting, and materiel for electronics, displays, and software.

Executive Summary

ADAS (advanced driver assistance systems) and AD (autonomous driving) are now some of the main directions for the automotive industry to improve safety and comfort for drivers and road users.

These systems depend on sensors to gather information to be processed by sophisticated computers. Currently—and likely for quite a while—cameras are the main sensors used, as they can give a reasonably precise view of the environment at an affordable cost. Other sensors found on cars include radars, lidars, and sonars. Radars are often used for functions such as AEB (automatic emergency braking) and BSD (blind spot detection). Lidars are just emerging for front detection, and sonars are mainly used for parking assistance. These sensors are chosen for specific functions or to improve the reliability of the information given by cameras, but none has the versatility of cameras, which are thus indispensable for ADAS and autonomous driving. Too, there is a cost factor, and cameras are competitive in that sense; low-range cars, because of their build cost constraints, tend to use only cameras to drive some very useful functions for safety as AEB. Medium-range cars' systems still use cameras, but bolster performance and accuracy with radars and rangers that are usually simplified lidar with one beam. And high-range cars are beginning to use lidar, though at this point it remains very expensive. The development of autonomous cars at levels 4 and 5 will likely see the use of cameras, radars, and lidars jointly in the same car for redundancy, which is obligatory to achieve adequate safety performance and dependability.

The global market for cameras is currently dominated by their use in the smartphone market with roughly 90% of applications. The market for automotive cameras was around USD $2bn and 10% of the global camera market in 2016, but the automotive camera market is now growing much more rapidly at a rate of 20% per year in volume. Present projections have the market reaching 800 million cameras in 2030. This market is pulled by end users' strong interest in the real safety benefits of ADAS and AD, and it is pushed by the assessments and regulations already applied or under preparation in different countries.

Front cameras are the most complex ones in automotive service, and Yole estimate their market value at $10bn by 2030. Other cameras, particularly surround cameras, are forecast to make another $10bn market in 2030.

Technical progress for cameras is under way on all their main components. The optics will shrink, perhaps with plastic lenses if thermal issues can be solved, or even with no more lenses over the longer term. The sensors will come to have higher definition, much above the current best 8-megapixel level. We'll see more and more sophisticated solutions integrating several sensors working together for enhanced possibilities, for instance with 3D, distance measurement, very high sensitivity towards quantum imaging counting each photon, and multispectral systems for better recognition of objects. We're also likely to see image processing and, more generally, sensor fusion systems and artificial intelligence becoming one of the most differentiating factors of competitivity, given that many actors such as the leader Intel/Mobileye are investing hugely in R&D.

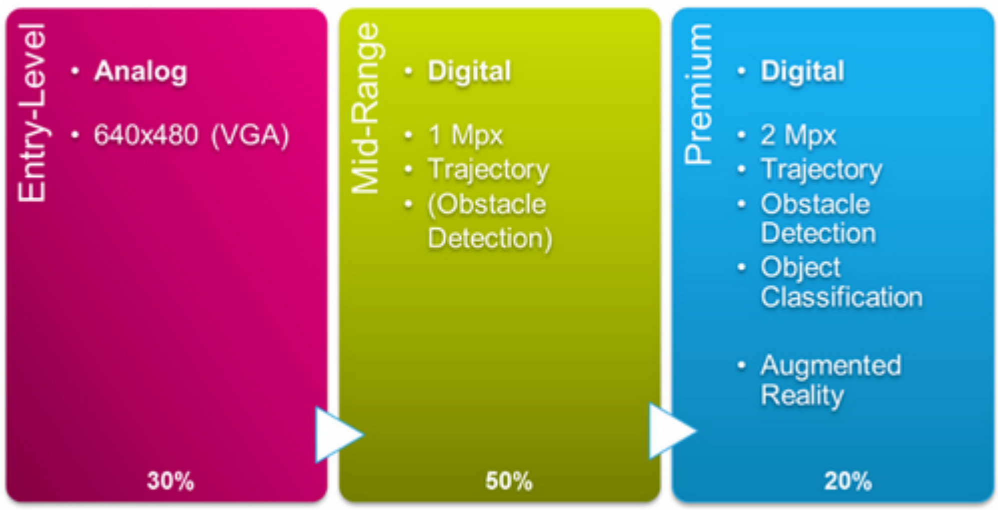
Introduction

Cameras are now more and more used for automotive applications to enhance safety and comfort. They are augmenting and even replacing human vision, limited as it is by human failings such as fatigue, inattention, age-related deterioration, and the simple fact that a human in the driving seat simply cannot see in all of the necessary directions, especially not all at the same time.

The first still video camera was introduced in 1975 by Kodak. It had a resolution of 0.01 megapixels, weighed 4 kg, and needed 30 seconds to shoot a picture. The first really commercial still video camera was the Sony Mavica (**Ma**gnetic **Vi**deo **Ca**mera) in 1981, with a CCD size of 570 × 490 pixels. Like the Kodak item, it was an analog camera.

Now digital cameras have substantially supplanted analog cameras. For automotive applications, entry-level cameras with VGA (Video Graphics Array) definition of 640 × 480 could still have a 30% market share. Simple digital cameras with around 1 megapixel are the current mainstream, with around 50% of the market. Their resolution is sufficient to be used for obstacle detection. Premium digital cameras with 2 megapixels or more have a 20% market share and can be used for trajectory analysis, obstacle detection, object recognition, and augmented reality.

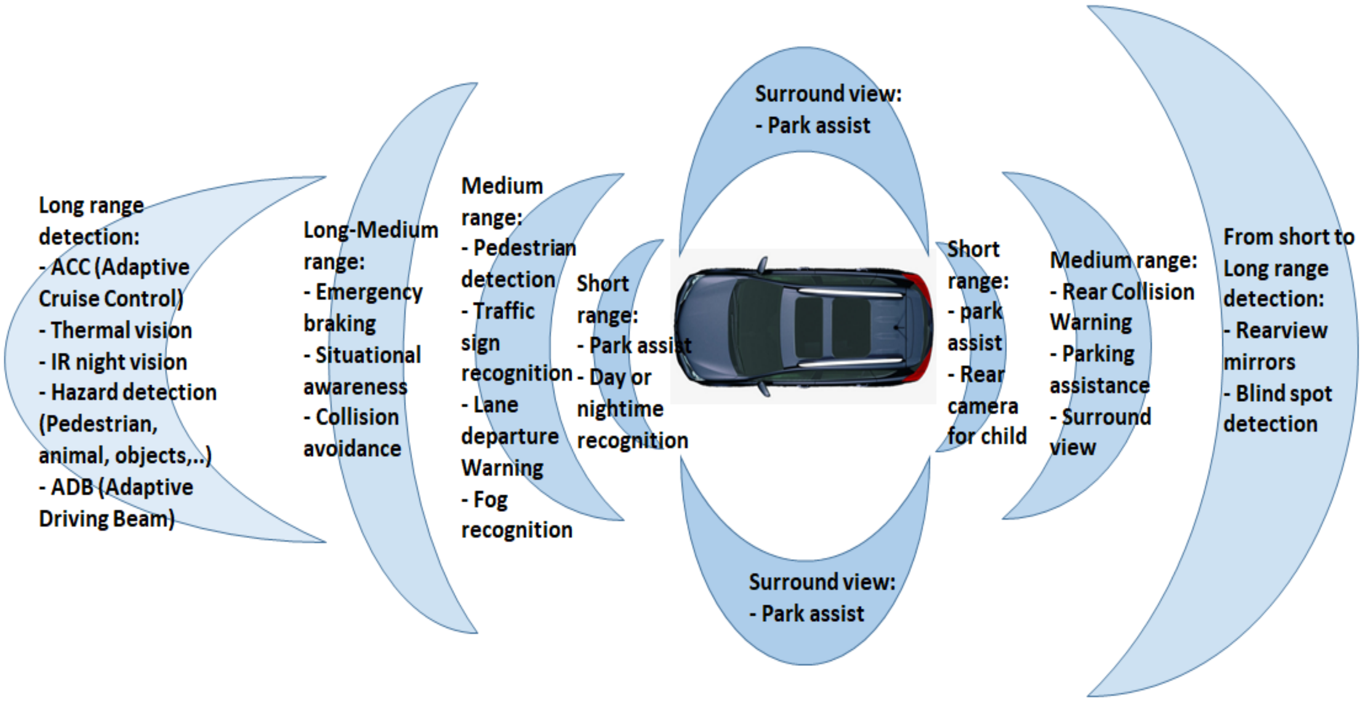
The market is progressively eliminating analog cameras and increasing the share of the more complex cameras as the new functions installed have much higher demands, with a very strong CAGR of roughly 20% till 2022.



Cameras currently central to ADAS functions and surround view for park-assist will be even more important with future AD-capable vehicles over the next decade. For optimal safety, they will certainly be used alongside other sensors such as radars and likely lidars, but cameras will surely remain the main sensors as they have the best definition, the nearest perception to human eyes, and the lowest costs.

Automotive camera applications

Cameras have many automotive applications that can be classified in three main categories as forward-facing, rear-vision, or surround cameras.



For some of these applications, cameras can be the lone sensor; for other applications lidars, radars, and sonars might be competitive or cooperative with cameras, but the cameras are nevertheless currently the only kind of sensor that cannot be replaced totally. In some cases, particularly for forward cameras, several functions can be achieved with a single camera, improving the cost/benefit ratio and alleviating packaging pressure.

Forward-facing cameras

The main target of a forward-facing camera is to help with collision avoidance by contributing to a good situational awareness and a good hazard detection of pedestrians, bicyclists and motorcyclists, cars, and other potential dangers. Thanks to this recognition, there are many essential functions in forward direction for safety that can be performed by cameras:

- ACC (Automatic Cruise Control) to maintain a safe speed and a safe distance to other vehicles
- FCW (Forward Collision Warning)
- AEB (Automatic Emergency Braking) to slow the vehicle and try to stop it to avoid a crash
- TSR (Traffic sign recognition) particularly for speed limit recognition
- LDW (Lane Departure Warning) to inform the driver when the vehicle is leaving its lane and LKA (Lane Keep Assist)
- TJA (Traffic Jam Assist)
- PCW (Pedestrian Collision Warning)
- ADB (Adaptive Driving Beam) to have a glare free high beam or IHC (Intelligent Headlight Control)
- Automatic LB/HB by day time and night time recognition
- Automatic wiper activation
- Active scan suspension by anticipating the optimised suspension damping.

Cameras are therefore the central sensor for ADAS functions helping the driver for levels 1 to 3, and will retain their primacy for level-4 and -5 autonomous driving.

Camera ability for long range detection

Cameras have some difficulties for long range detection, especially in adverse weather.
Radars and lidars presently offer more precise and reliable information for distance measurements. On the other hand, these systems are currently unable to give precise information about the nature of the object detected. A current limitation of cameras for long-range detection is the number of pixels available: a camera having a horizontal definition of 1000 pixels and a field of view of 80° will see a 15 cm large object at 100 m, for instance the leg of a person, by only one pixel, with resultant poor chance for a good identification. But future cameras will have much higher resolution—more pixels—and so better detection and recognition ability. There is, however, still a long way to go before cameras compete totally with human vision, which has a resolution equivalent to about 576 megapixels.

Camera ability to measure distances:

The other drawback of standard cameras is their difficulty in measuring the real distances to potential obstacles. This can be partially solved by the new generation of stereo or 3D cameras, these being currently a strong trend for forward cameras, today at least for high range and medium cars.

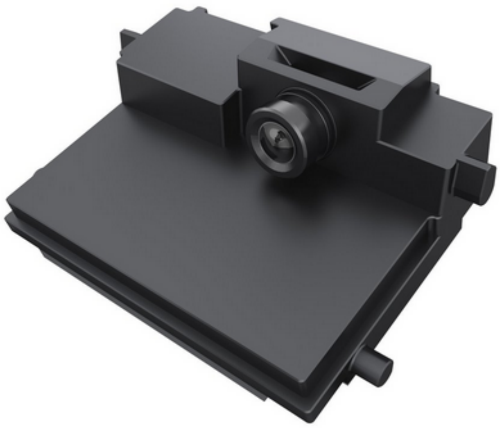
To illustrate these new possibilities, Mobileye—the leader for camera software—are currently performing tests for autonomous driving in Israeli with only cameras, working on distance evaluation. But they consider nevertheless that at least one other sensor, a radar or a lidar or both, will be necessary to ensure adequate safety by dint of information redundancy.

Camera as main sensor for ADB
ADB (Adaptive Driving Beam) or glare-free high beam systems send light everywhere except where cameras have recognised other traffic participants, who are dynamically shadowed out of the beam. Front-facing cameras and their associated data processing are crucial to give the lighting system the right information, which it needs to clearly identify and keep track of other traffic participants and their positions, avoiding confusing taillamps for traffic lights, discerning road signals and other cars, etc. While at night cameras might have better sensitivity than human eyes, a good lighting system will systematically help cameras give better detection and recognition particularly for objects having a low contrast with the scene.

Types of forward facing cameras

Standard Monocular cameras are still the main kind, with multifunction abilities. The new assessments for the evaluation of car safety, for instance by EuroNCAP taking into account these safety functions, are strongly pushing for the installation of these cameras on a majority of new cars.

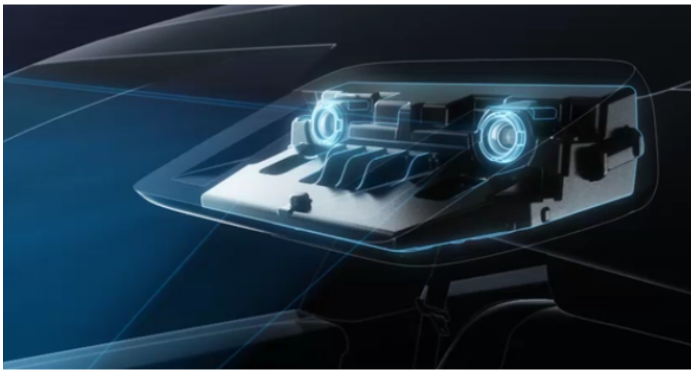
ZF monocular forward camera



Future Continental 2020 Monocular camera

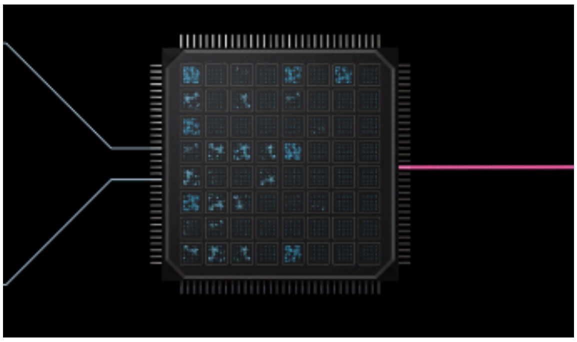
The use of **Stereo - 3D cameras** is currently a strong trend particularly for high-range cars, but with increasing application in middle-range cars. These cameras can give more precise information about the distances to objects.

Continental stereo camera

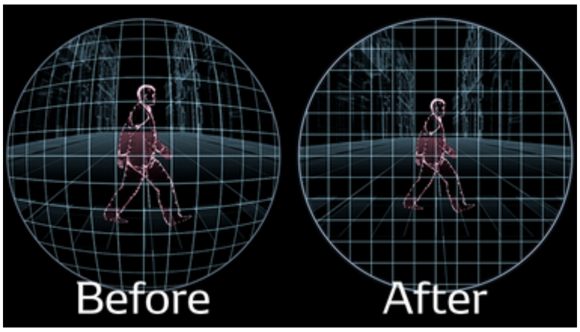


Denso stereo vision system for minicars

Principles of stereo vision:



To accurately measure the vehicle's distance from an object, images from the left and right lenses are processed, requiring a large amount of data to be calculated at one time



An accurate parallax image, created by combining two images together, is required to measure the distance to an object (image: Denso)

Multiple focal distances

Another trend is to have several cameras with different focal distances, one for telephoto range and another for a larger field of view—similar to premium smartphones. The Volvo triple camera, for instance, has a broad 140° view, a normal 45° view, and a narrow 34° view for depth perception and distant object detection.

Volvo triple camera

Implementation of cameras

Forward-facing cameras are generally installed between the rearview mirror and the windshield to have the benefit of a position cleaned by wipers. As this area is limited by the driver's needs for his vision and by regulation, the cameras must be compact. Suppliers like Continental are proposing the installation of the camera and the lidar in a unitised package in this area.

Subaru EyeSight dual colour cameras for ACC and AEB

Continental forward camera with lidar

Active scan suspension is now a new function using the information from the multifunction camera to detect street holes and bumps. Such a function is for instance implemented on the PSA DS7

Camera integrated in headlamps
A camera integrated in the headlamp can give crucial information when leaving a parking lot while the view is blocked for instance by a truck. This forward camera position in such a case gives a strong advantage. This solution, having been introduced some years ago in Japan and subsequently fallen out of favour, is nevertheless potentially important for the future.

Rear Vision Cameras

Though perhaps not as crucial as forward cameras particularly for autonomous driving, cameras used for the rear vision are also becoming important for functions including replacement of traditional rearview and sideview mirrors; BSD (blind spot detection, though this is oftener realised with radar sensors); RCW (rear collision warning) and rear-vision systems intended to help the driver avoid reversing over children too small to be seen through the backglass or in the mirror.

Rear view mirrors

The replacement of traditional glass mirrors by cameras with displays is now allowed by the UN Regulations and under Japan's regulations; U.S. approval is still pending. One advantage is reduced aerodynamic drag, thus reducing CO_2 emission by 1 to 1.3 g/km.

Rearview mirror with camera and display (image: Panasonic)

Also, sideview cameras reduce the total width of the vehicle. Though at the same time, lighting equipment currently integral to side mirrors—turn signal repeaters, puddle lights, and so on—might have to be relocated if the camera is highly integrated, as on the new Audi e-tron shown here.

It's the first 100% electric SUV, with ordering open and deliveries slated for the end of this year. Sideview cameras will be an available option, which shows this technical solution is still expensive and so will appear first with reduced quantities on high-range cars.

Surround cameras

Surround cameras for a 360° view are increasingly implemented even on medium-range cars. Their main purpose is to assist drivers for parking by giving a complete, bird's-eye view around the vehicle. To realise this function takes four to six cameras: generally one under each side mirror, one at the back side of the trunk, and the last one could be the main multifunction forward-facing camera.

The corresponding images can be displayed to help the driver, or can be directly used by an automatic parking system not requiring human action.

Valeo 360° camera

Volvo XC90 360° surround view

Currently most systems display in 2D, but virtual 3D rendering is now the new trend for high-range cars. For these applications, a very wide dynamic range of 130 dB is required to have clear images even in sunny conditions, and a frame rate of 30 frames per second is the minimum for a smooth rendering.

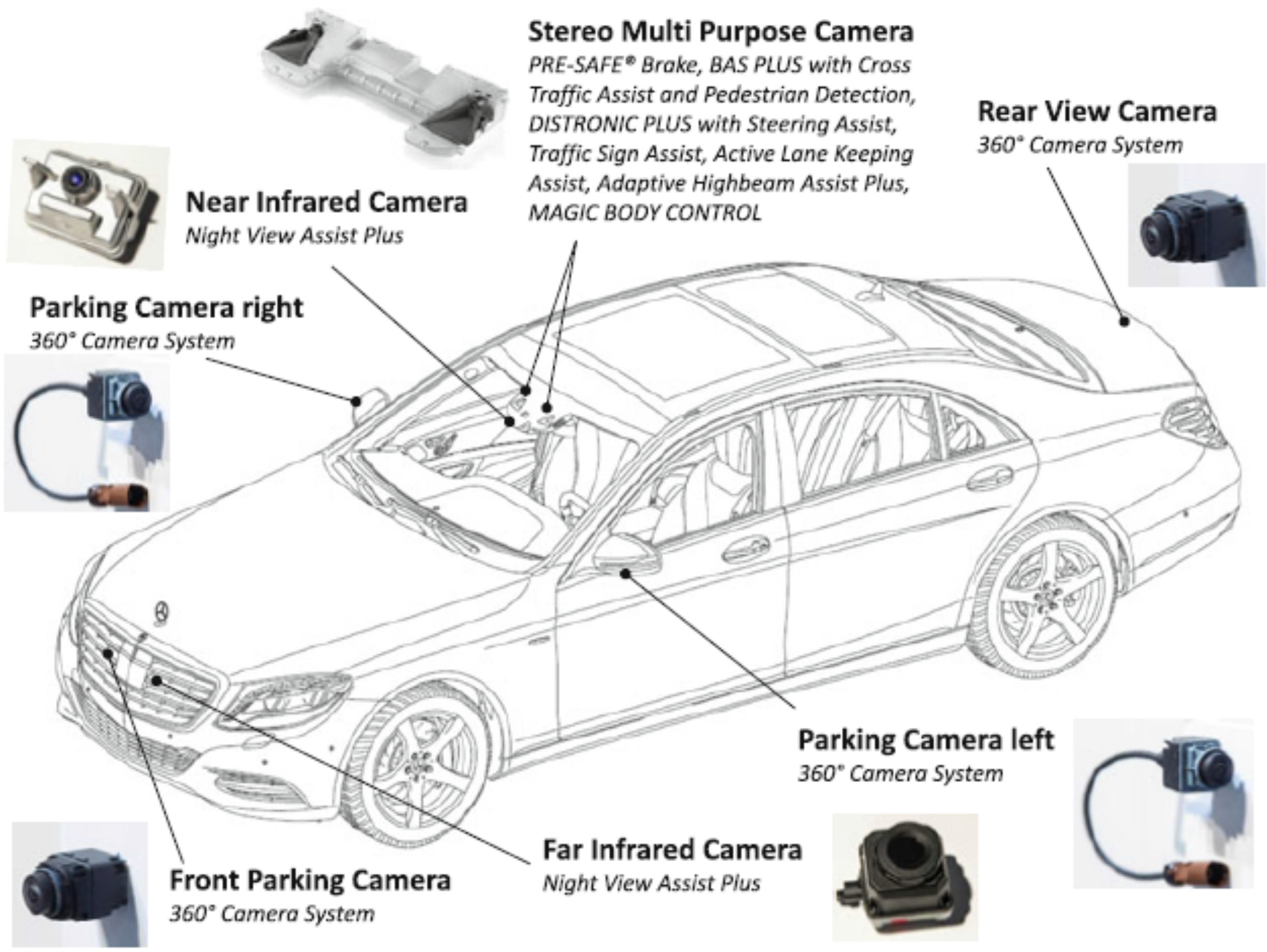
Interior cameras

Cameras can also be used inside cars for other safety functions, such as driver drowsiness detection. Cameras are used to image the driver's face and behaviour and keep track of eye gaze and blink patterns, to monitor for drowsiness or inattention. And cameras can keep an electric eye on children sitting in the back seat, so the driver needn't turn around to look at them and can keep eyes on the road. Too, by dint of cameras and their recognition of vehicle occupant size and position, airbag deployment can be adjusted in case of a crash.

Cameras are also at the centre of solutions to improve the comfort of people inside the car, for instance by illuminating the precise area where passengers are reading, thus limiting the risk of glare for others including the driver.

Camera Count per Car

The number of cameras per car can be up to 10 for high range cars to achieve all the functions. Here's an example showing the camera content of the Mercedes S-Class:



In the S-Class, camera equipment powers extended driving assistance functions:

- Active Distance Assist and Active Steering Assist to keep a safe distance and steering with the vehicle speed being automatically adjusted in bends and at road junctions;
- Active Emergency Stop Assist
- Active Lane Change Assist
- Active Speed Limit Assist

Dr. Michael Hafner, Head of Automated Driving and Active Safety at Mercedes-Benz, says "We are approaching the goal of automated driving more purposefully and faster than many people suspect"

The number of cameras per car will increase with the development of ADAS functions and autonomous driving in the near future. Currently, high-range cars have already around 10 cameras; the standard for the majority of cars could reach six to 10 cameras in 2025-2030.

Source: Yole/Autoliv

The application for cameras is summarised in this Yole chart:

	Device/Application	Technology
For AD	Driver monitoring	Camera
For infotainment display	Gesture recognition	3D Camera
	Rearview/Backup	Camera
	360° surround	Camera
	Side mirror replacement	Camera
For AD & ADAS	Forward ADAS	Mono camera
	Forward ADAS	Stereo camera
	Forward ADAS	Triple camera
	Night vision	LWIR camera

Imaging sensors and lidars

Imaging sensors detect and convey the information that constitutes an image. Cameras can naturally be classified within this larger category. But now, some lidars can also be considered as imaging sensors thanks to their resolution that could reach one megapixel. The imaging systems for automotive would in this condition cover visible light cameras, 3D cameras, night vision cameras with near or far infrared, and lidars.

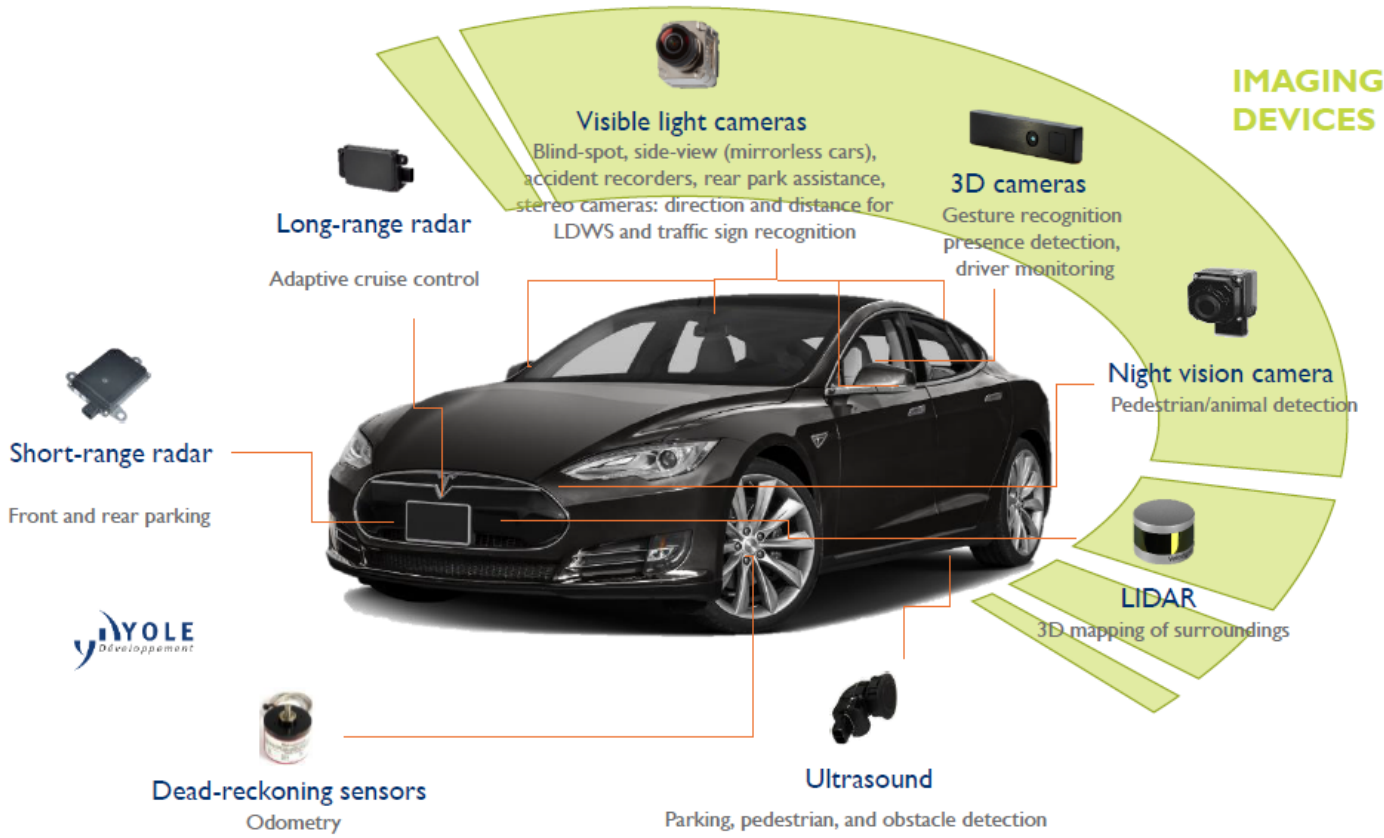


image: Yole

Lidars measure the time of flight of the laser light they put out, so as to measure distances relatively precisely and with a good reliability. The laser light is powerful and in a narrow wavelength range—generally 905 nm or 1550 nm with a better efficiency—reducing the risk of confusion with other sources. But they are competing with the new stereo cameras or camera-based TOF (time of flight) systems that can also measure distances well. The main drawback of lidars is their high cost of up to thousands of dollars, though that is trending lower. As their costs decrease and as advancing autonomous driving makes redundancy of information necessary, lidars will likely equip many future AD vehicles. The majority of lidars are still currently mechanical, the beam being moved by motors. A new generation of solid state lidar is emerging, but still expensive with currently no real functional added value. This technology will nevertheless certainly be the future of lidars as potentially more simple, compact and reliable.
Simplified lidars with a unique fixed beam are too proposed for instance by Continental. These devices called rangers are naturally relatively cheap, but cannot be considered as imagers.

Radars in their current form cannot really be considered as imaging sensors; their definition is not precise enough to produce a real image.

Regulations and incentives

ADAS are safety-orientated, and so are increasingly regulated. Some regulations require functions like rear-vision cameras in the USA, while other regulations specify performance requirements for camera-based systems to replace another device, for instance instead of mirrors. These safety features are also encouraged by market-based incentives such as the world's various NCAPs. These regulations and assessment programmes are pushing the use of ADAS, and more particularly the use of cameras as they are currently the core sensor for these systems.

On 31 March 2014, NHTSA (the US auto safety regulatory agency) announced that all new vehicles under 10,000 pounds (4,500 kg) will have to have rear-vision cameras by May 2018. Systems installed under this regulation must survey an area of 3 m width and 6 m length behind the vehicle. The aim is to address crashes with pedestrians—notably small children—in the area immediately behind a reversing vehicle.

Rearview and sideview mirrors are legally required on vehicles virtually everywhere in the world. UN Regulation № 46 was the world's first apposite regulation to permit all mandatory mirrors for passenger cars, commercial vehicles, and buses to be replaced by camera monitor systems (CMS). The amended regulation is based on the new international standard ISO 16505, "Ergonomic and performance aspects of Camera Monitor Systems—Requirements and Test Procedures". ISO 16505 technically defines the cameras and the displays in terms of implementation, monitor image isotropy (uniformity in all orientations), luminance and contrast rendering, greyscale rendering, colour rendering, artifacts like smearing, blooming, lens flare, or point light sources, sharpness and field of view, geometric distortion, flicker, time behaviour with the frame rate, the image formation time, and the system latency.
UN R46 is applicable throughout Europe, but some countries that use UN Regulations for car safety have not yet adopted it. CMS are permitted in Japan, but—like ADB—not yet in America.

Other cameras are not regulated in such detail. Nevertheless they must meet other regulations including:

- UN R10 for electromagnetic compatibility
- UN R21 for interior fittings
- UN R48 for installation of lighting systems (turn signal repeaters ordinarily placed on outside mirrors need another appropriate location with CMS)
- UN R95 for lateral collision protection
- UN R125 for forward field of vision

UN Regulation for AEB (Automatic Emergency Braking):
There are discussions ongoing to introduce a new regulation for AEB as some studies indicate the risk of accidents could be reduced by 50% with AEB. This regulation could enter into force in 2020 for countries following UN Regulations. Naturally, in that case the number of car cameras will strongly increase, even if this function could also be realised with radars.

EuroNCAP safety ratings
EuroNCAP (New Car Assessment Programme, an organization involved in automotive safety rating in European countries—other countries have their own analogous NCAPs) assesses different ADAS functions for active safety mainly based on cameras:

Speed assistance systems: NCAP interest started in 2009 and was updated in 2018,
- informing the driver of the present speed limit;
- warning the driver when the car's speed is above the set speed threshold;
- actively preventing the car from exceeding or maintaining the set speed.

The most advanced systems, either speed limiters or intelligent Adaptive Cruise Control (ACC), combine all of these functions, where setting the speed can be done by simply confirming the speed limit detected and shown by the vehicle on the basis of speed sign recognition or digital map data.

AEB (Automatic Emergency Braking) interurban systems helping the driver to avoid high speed rear-end crashes, introduced in NCAP in 2014 and updated in 2018

Lane Keep Assist (LKA) systems helping to correct the course of a vehicle that is gradually veering out of its lane, introduced in NCAP in 2014 and updated in 2018

EuroNCAP has decided to include nighttime pedestrians as targets for automatic braking collision avoidance systems in 2018. Going forward, this will drive increased demand for high-sensitivity, high-quality image capture capabilities and will also push for enhanced lighting systems for instance with ADB.

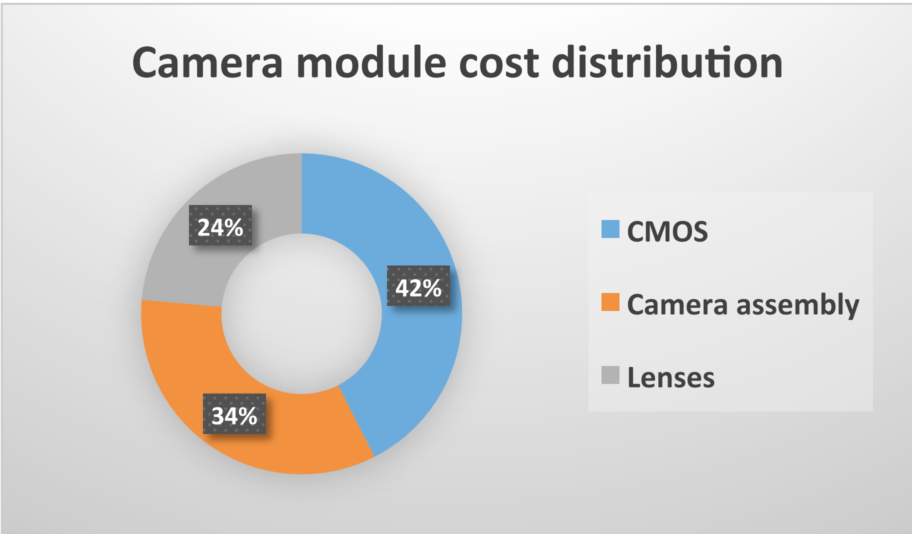
In Japan from April 2018 on, ADB using a camera as the main sensor will be covered by JNCAP as a reason for an additional point. From April 2019 on, ADB activation will be counted as an element in assessing automatic emergency braking systems for nighttime pedestrians.

Market for automotive cameras

Cameras were first used for photography, and during many years this was the main application with devices dedicated to this lone function. More recently, smartphones were introduced with many functions including photography with one camera module integrated, then another one for selfies, and now two or even more for front photography are becoming standard. For automotive applications, camera modules were introduced several years ago, but applications were limited for quite some time. Now as prices have dropped and as many new functions for safety require electric eyes, this market is booming.

The worldwide market for car cameras has been evaluated by Yole at USD $23.4bn in 2016 and that could reach $47bn in 2022 with an annual growth around +12% in value. This market is still dominated by the huge market for smartphones, but the current applications for automotive that are representing currrently around "only" 10% in value have now a much stronger annual growth.

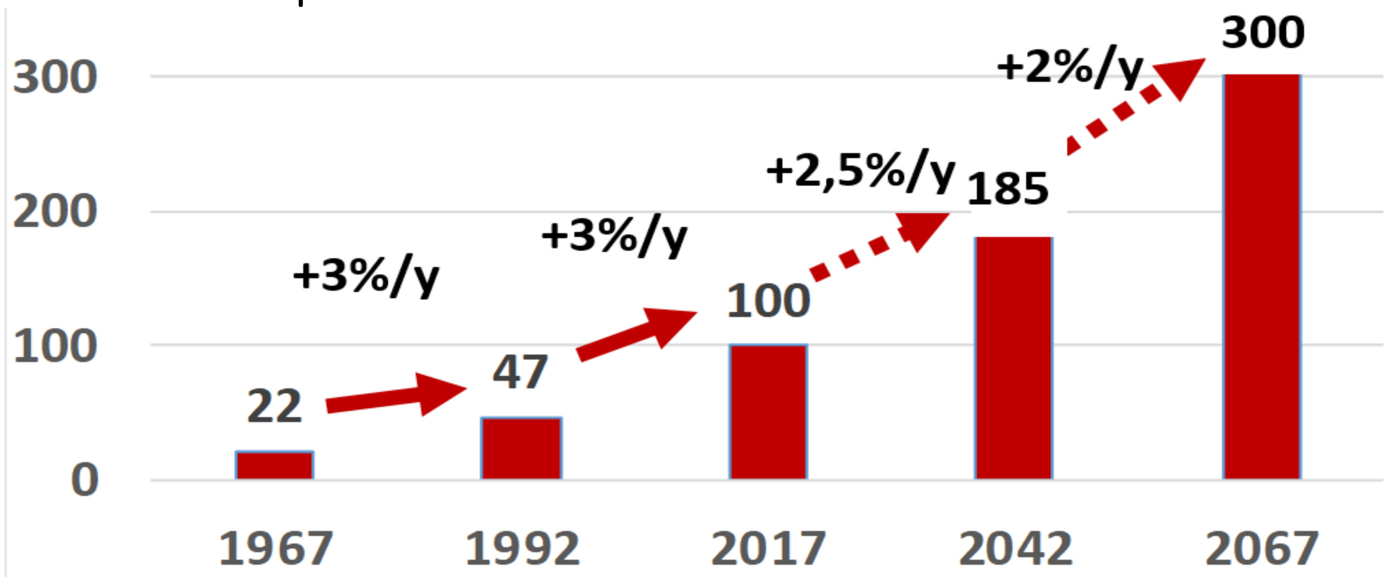
CMOS image sensors are the main part in value of camera modules with around 42% of the total cost. The global price of a camera system is currently estimated at around $100, compared to a radar at $60 and to a lidar at above $1000.



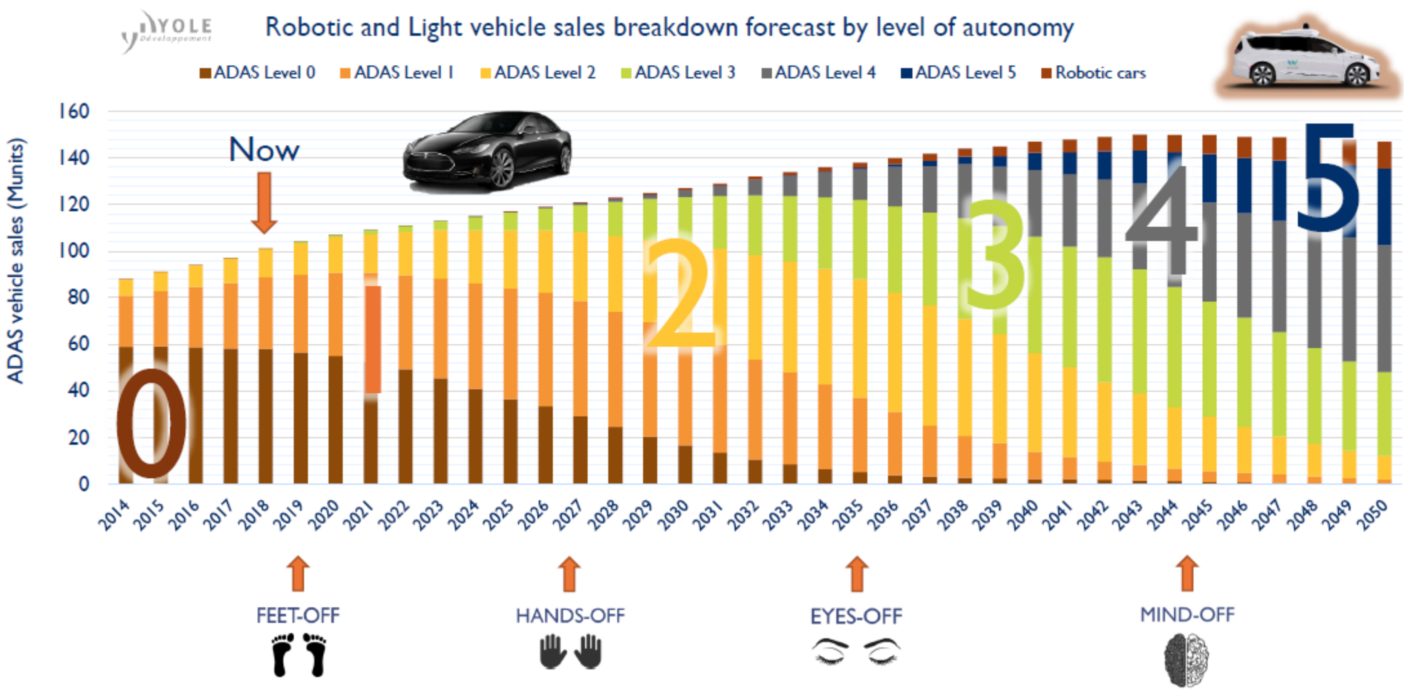
For automotive applications, the quantity of modules is forecast to multiply by 10 from 2016 to 2030. This increase can be explained by the continuation of the global automotive production trend of +2.5% per year. But the main reason of the increase is the acceleration of penetration of ADAS and AVs with their need for multiple cameras.

In the following chart, the slight deceleration for car production increase is explained by new societal trends like car sharing, initiatives to increase public transport, and reduced attractivity of automobile ownership in more advanced coutries. At the opposite, developing countries are avidly buying cars. So even if the global worldwide production will not double every twenty five years as during the last half-century, car production is supposed to reach a high level of 185 millions cars in 2042.

Global automobile production estimated



Yole are a little more pessimistic in their forecast with 150 million cars in 2042. Nevertheless, this level is a first important factor for the number of cameras used in automotive applications. The second factor, much more important, is the transition towards higher ADAS levels as illustrated in the following graph from Yole:

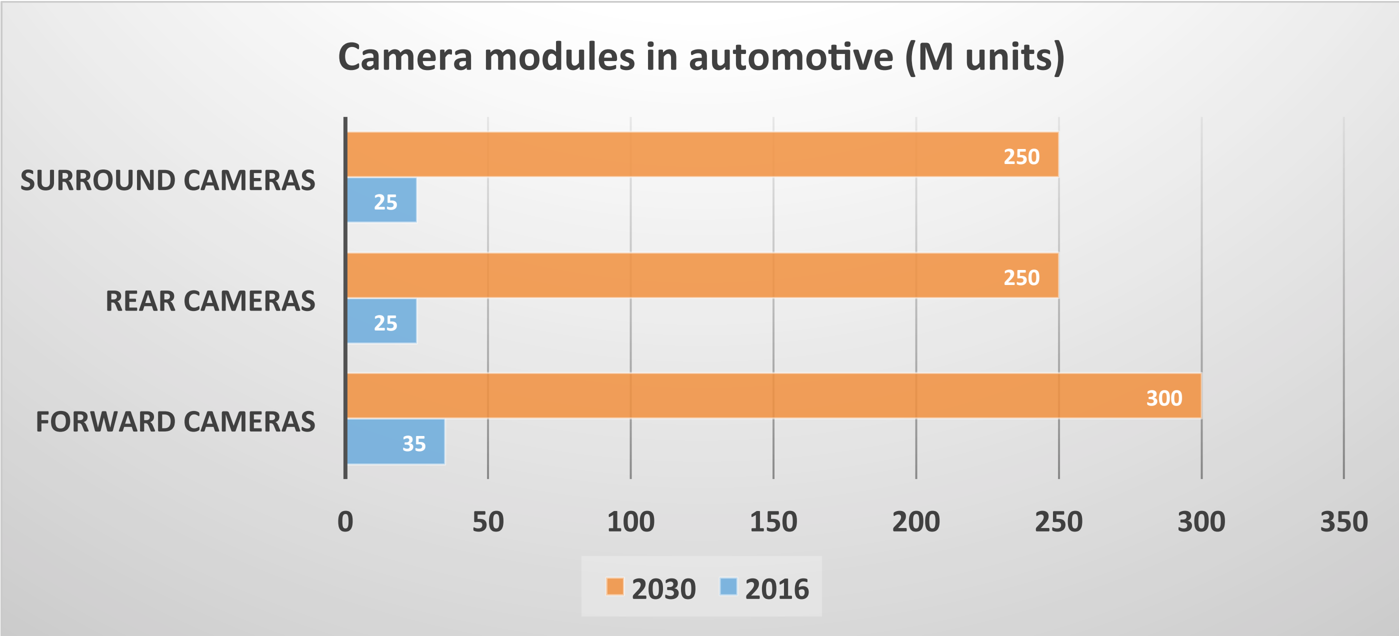


Naturally, the higher the ADAS level, the more cameras installed and the greater their complexity to ensure good safety performance. On the above graph, we can see that level-4 and -5 autonomy will slowly emerge from 2020, but will not have significant quantities before 2030. Robotic cars for taxi replacement or for shuttles will certainly be their first markets. So during at least the two coming decades, the huge majority of vehicles will be vehicles with an ADAS equipment from level 1 to level 3.

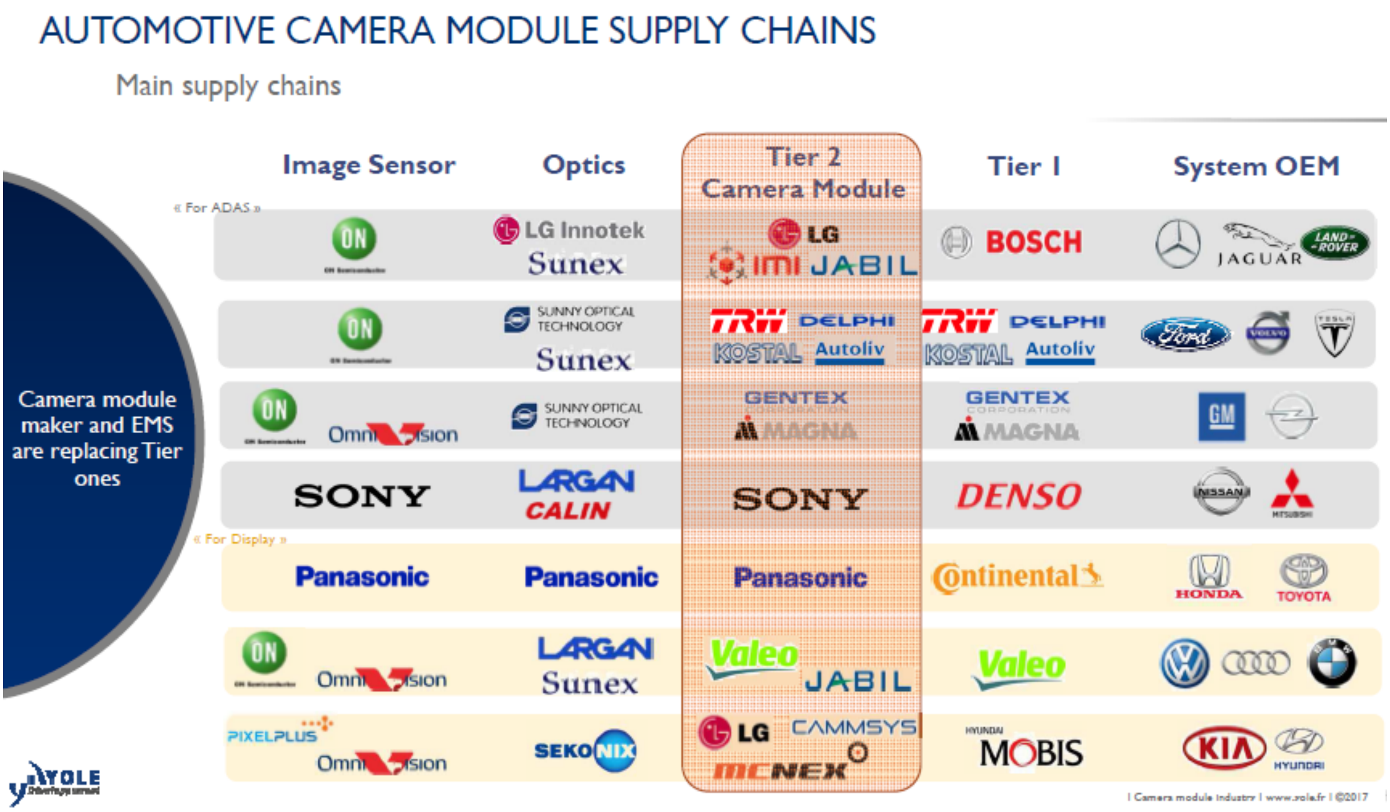
For the record, these ADAS levels were defined by SAE with these definitions:

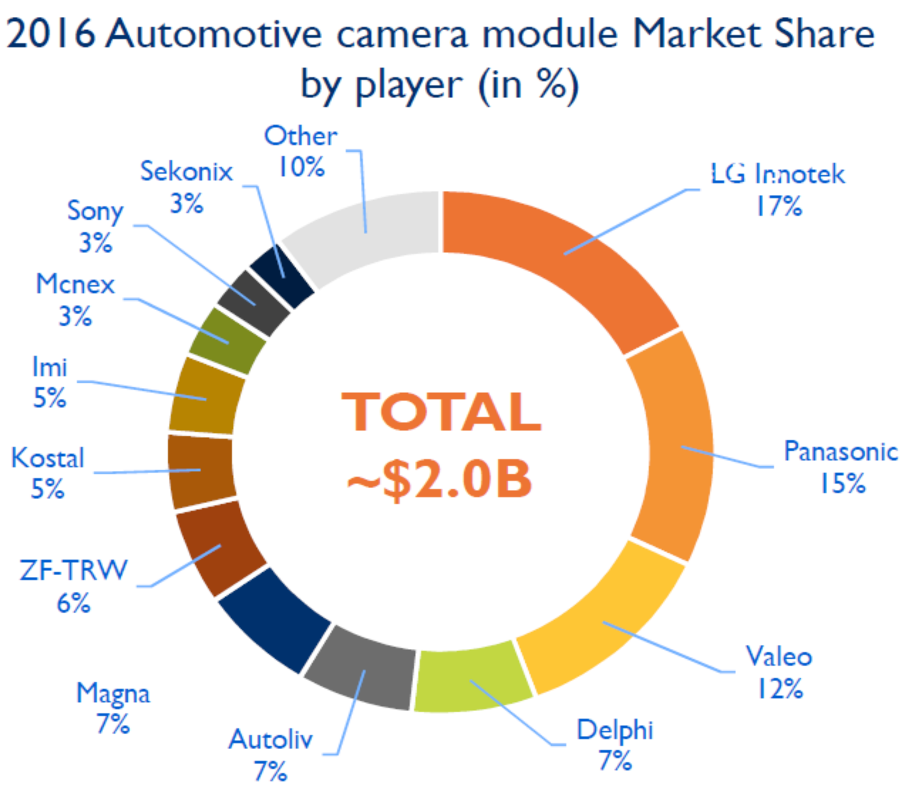
- Level 0: Automated system issues warnings and may momentarily intervene but has no sustained vehicle control.
- Level 1 ("hands on"): The driver and the automated system share control of the vehicle. Examples are Adaptive Cruise Control (ACC), where the driver controls steering and the automated system controls speed; and Parking Assistance, where steering is automated while speed is under manual control. The driver must be ready to retake full control at any time. Lane Keeping Assistance (LKA) Type II is a further example of level 1 self driving.
- Level 2 ("hands off"): The automated system takes full control of the vehicle (accelerating, braking, and steering). The driver must monitor the driving and be prepared to intervene immediately at any time if the automated system fails to respond properly. The shorthand "hands off" is not meant to be taken literally. In fact, contact between hand and wheel is often mandatory during SAE 2 driving, to confirm that the driver is ready to intervene.
- Level 3 ("eyes off"): The driver can safely turn their attention away from the driving tasks, e.g. the driver can text or watch a movie. The vehicle will handle situations that call for an immediate response, like emergency braking. The driver must still be prepared to intervene within some limited time, specified by the manufacturer, when called upon by the vehicle to do so.
  As an example, the 2018 Audi A8 Luxury Sedan was the first commercial car to claim to be capable of level 3 self driving. This particular car has a so-called Traffic Jam Pilot. When activated by the human driver, the car takes full control of all aspects of driving in slow-moving traffic at up to 60 kilometres per hour (37 mph). The function works only on highways with a physical barrier separating one stream of traffic from oncoming traffic.
- Level 4 ("mind off"): As level 3, but no driver attention is ever required for safety, i.e. the driver may safely go to sleep or leave the driver's seat. Self driving is supported only in limited spatial areas (geofenced) or under special circumstances, like traffic jams. Outside of these areas or circumstances, the vehicle must be able to safely abort the trip, i.e. park the car, if the driver does not retake control.
- Level 5 ("steering wheel optional"): No human intervention is required at all. An example would be a robotic taxi.

With this environment, the number of cameras installed on cars is currently increasing at a strong +20% per year. From a market of 85 millions in 2016, it could increase to 170 millions in 2020, and could reach 800 millions in 2030, including 300 million for forward facing cameras and 500 millions for surround and rear cameras. Forward cameras could at that time have sales of $10bn and rear cameras and surround cameras another $10bn in sales, according to Yole.


Camera modules in automotive (M units)
SURROUND CAMERAS
REAR CAMERAS
FORWARD CAMERAS
250
25
250
25
300
35
0
50
100
150
200
250
300
350
2030
2016

Camera module industry





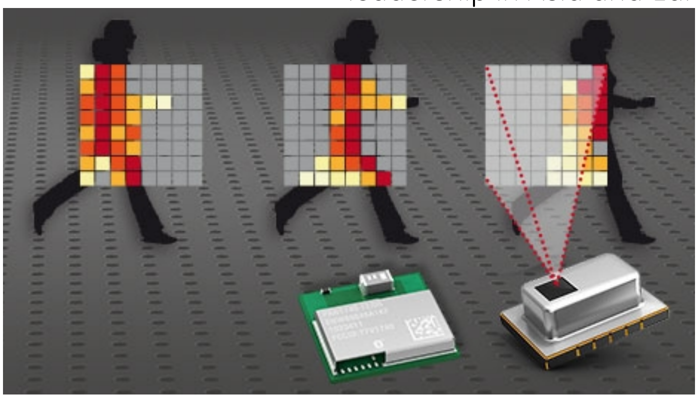
Source: Yole camera module industry 2017 report

Major makers

LG Innotek have made their initial move by providing single and stereo cameras to Mercedes. This technology was initially developed by Bosch, but LG did focus heavily on this activity when Mobile was struggling.

LG Cameras:
. For LDW, surround and rear
. Resolutions: VGA to Full-HD(2 Megapixel)
. Near infrared cameras (NIR) and algorithms for improving low illumination visibility to enhance recognition rate

Panasonic are the historical leader, and are well positioned to maintain leadership in Asia and Europe.



Panasonic manufacture a complete range of sensors for full-body tracking and gesture recognition, occupancy detection, light intensity, acceleration, object detection, and pressure measurement.

Valeo purchased Irish company Connaught Electronics in 2007. The innovative CMOS approach led to design wins with major European car manufacturers such as BMW and Volkswagen. Valeo are involved in all the applications of cameras, front camera with a partnership with Mobileye, rear cameras and surround cameras. Valeo are also proposing lidars and radars for a complete offer in ADAS systems.

Mcnex, a Korean supplier, made an early strategic move toward automotive camera modules and have installed themselves as a prime supplier of the Korean market. Mcnex make front and rear cameras, HD cameras (LVDS and Ethernet), stereo camera, and far IR cameras.

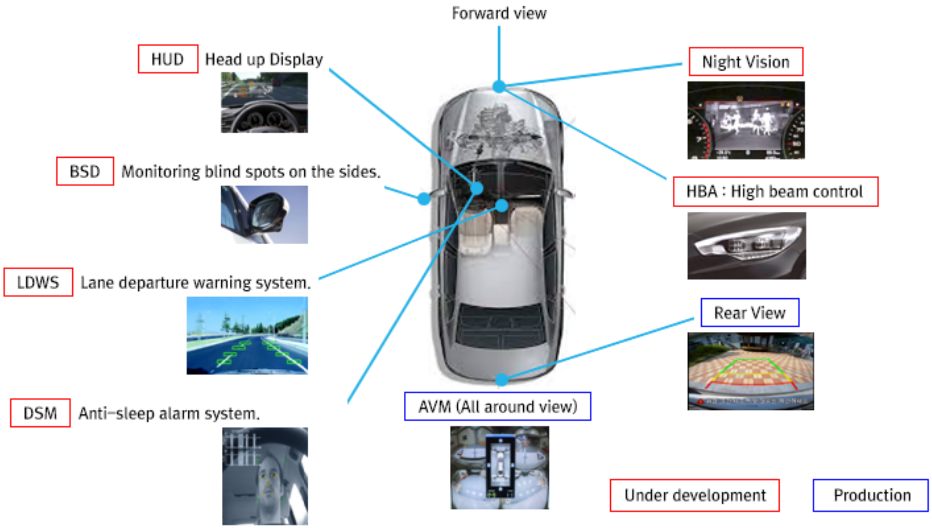
HD Ethernet camera

Far IR camera

Magna have long been leaders in the automotive camera market by developing their own supply chain in the US.

Sunny Optical Technology claim to be the world leader for shipment of automotive camera lenses with a market share of 30%.

Sekonix leveraged their optical expertise into automotive camera modules. 25% of their revenues are now coming from automotive camera modules, and their main customers are Korean and US tier 1 suppliers. Sekonix are now developing in all the sectors of automotive applications with cameras.



Sony are a longtime worldwide leader for sensors, first with CCD technology and now with CMOS, leading the market for smartphone imaging sensors.
Sony's automotive sensors range from 1.26 to 7.42 megapixels, with pixel size from 2.25 to 3.75 µm.

On Semiconductor are a spinoff of Motorola created in 1999. They now have a strong position for image sensors in automotive and are claiming to be the № 1 supplier of CMOS image sensors for viewing and ADAS, and integrated circuits for advanced front lighting systems.

Omnivision offer a wide range of image systems solutions for CMOS sensors, including high dynamic range and advanced image signal processing, global shutter technology for good sensitivity in near infrared, and backside illumination for high sensitivity, in chip-scale packages.

Mobileye are the leader for SoC (Systems on Chips) used for the intelligence of ADAS cameras and autonomous driving. Mobileye are an Intel company since 2017, and that year they delivered 8.7 million SoC, an increase of 45% compared to 2016.

Camera technology

A camera has several main components: the optical system, the sensor, and the data processing system.

Optics

The role of the optical system is to gather as much light as possible and to transfer it to the sensor with minimal deformation or distortion. The main optical parameters of a camera optical system are the field of view and the aperture. They are defined with the size of the sensor and the focal distance. With a given sensor size, a longer focal length means a narrower FoV (field of view), or with a given focal length, a bigger sensor gives a larger FoV. For instance, based on the Kyocera range of automotive lenses: with a ⅓" sensor, a focal length of 3.8 mm has a 75° horizontal field of view, and a longer focal length of 5.5 mm has a reduced horizontal field of view of 51°. With a more compact sensor of ¼", the 3.8 mm focal length has a horizontal field of view of 51°, so reduced compared to the bigger ⅓" sensor.

A large field of view is necessary for surround cameras to provide a 360° view. For front cameras, a large field of view is also useful for instance for detection of vehicles at a crossing. But it is also important to have a good definition in the axis for detection and recognition of objects that can be relatively small and far away. So a compromise is made, currently around 45° of FoV. The evolution of sensors with more pixels should allow to improve that compromise with an increased FoV. Another possibility to have both a large field of view and a good range is the use of cameras integrating several sensors with different fields of view.

The other important parameter of the optics is the aperture. The aperture is defined as the ratio between the focal length f and the effective entrance pupil, so a numerically lower aperture allows more light in. Generally for automotive lenses, the aperture is around $f/2$.

Sunny Optical Technology lenses

Jabil optics camera

Future directions for lens technology

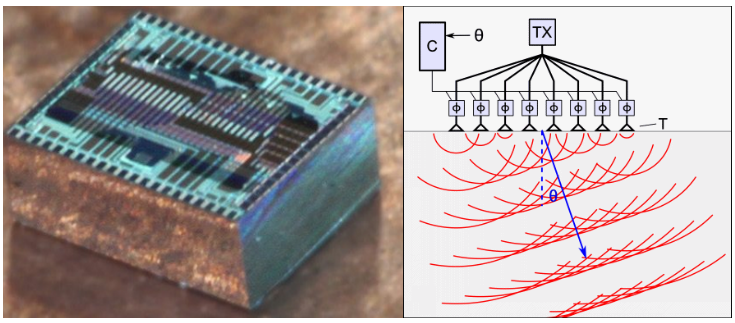
Material: Currently, the best lenses are made of glass. Some manufacturers like Sunny are using a manufacturing process similar to plastic molding with a softened glass at transition temperature with inserts to shape aspheric surfaces. Perhaps, however, plastic lenses could be more used in the future if their quality and particularly their thermal resistance would improve; that is still currently a challenge.

High precision lens module: As sensor definition is rising to 2 megapixels and soon 8 megapixels or more, it is necessary to have in parallel lens modules with very high precision to put all these pixels to good use. Flare-free lenses and large-FoV fisheye type lenses are other current targets for development.

Long-term research is under way to improve compactness as with conventional lenses, the dimensions of the optical system are imposed by the laws of optics: the quantity of light available for the sensor is proportional to the surface of the lens, and as we have seen previously, the focal distance is in relation to the size of the sensor and the field of view. This means the optical system requires space!
New directions would use revolutionary principles, for instance with broadband achromatic metalenses for focusing and imaging in the visible or with an ultra-thin phase array system. The key goal of metalens research is to achieve wavefront shaping of light using optical elements with single layer of nanostructures with thicknesses on the order of the wavelength. The challenge is to have a diffraction-limited achromatic focusing and achromatic imaging from 470 to 670nm, with high efficiency (currently limited to around 20%).

The other direction with ultra-thin phase array systems is under development by Cal Tech researchers. This type of camera doesn't require any lenses; curved glass is replaced by something that does the same job computationally: an ultra-thin optical phased array. The lensless camera is made from thin light-sensitive silicon components integrated on a silicon chip. Light waves are received by each element in the array and destructively interfere from all but one of the directions. In that direction, the waves amplify each other to create a focused "gaze" that can be electronically controlled.

However, these new technologies are still in the research phase, and not really targeting automotive where applications if any should be at very long term.



Phase array imaging

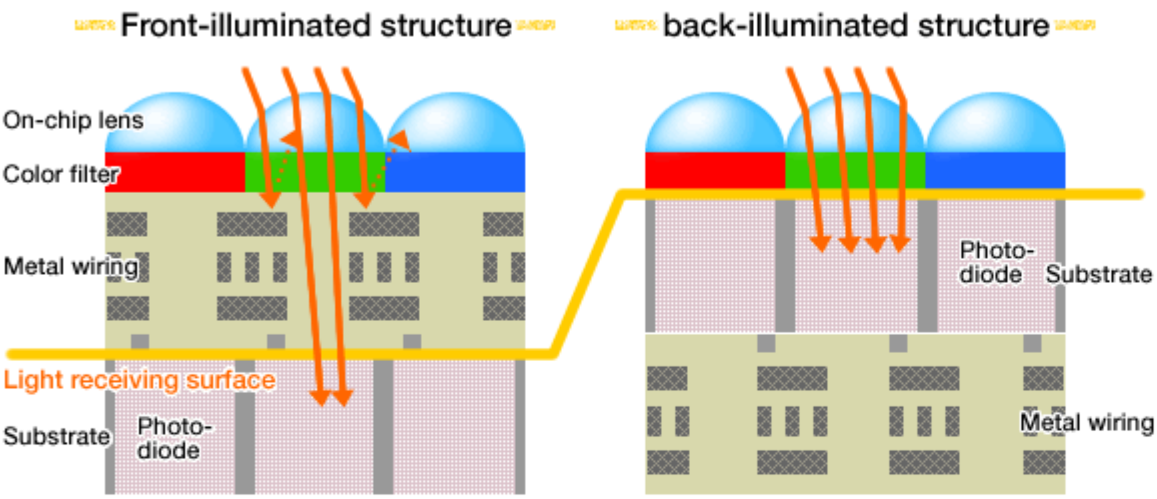
Image sensors

The image sensor (or imaging sensor) detects and conveys the information that constitutes the image. It does that by converting the light waves into signals. The waves can be visible light or other electromagnetic radiation. Image sensors were initially analog, but now they are essentially digital. They are naturally at the heart of camera modules, but they can be used also for other applications—for instance medical imaging equipment, night vision equipment with thermal imaging devices, radar, sonar, and others.

Early analog sensors for visible light were video camera tubes. CCD (Charge-Coupled Devices) replaced them in the seventies. Now CMOS active pixels sensors (Complementary Metal–Oxide Semiconductor) or N-type metal-oxide-semiconductor (NMOS, Live MOS) are the main technologies particularly for automotive applications.

CMOS versus CCD

CMOS sensors are the most popular as they are cheaper, smaller, and use less power compared to CCD. For a long time CCDs gave the best quality with particularly good signal:noise ratio, but now CMOS technology has made big improvements and CMOS sensors are available for a large majority of applications. CCD sensors are still used for high-end broadcast-quality video cameras. But for automotive front cameras their main defects are blooming and smearing effects due to saturation of the cells in relation to the discharge done line per line. CMOS image sensors have an amplifier for each pixel compared to the few amplifiers of a CCD. This results in less area for the capture of photons than a CCD, but this problem has been overcome by using micro lenses in front of each photodiode, which focus light into the photodiode. Some CMOS imaging sensors also use back-side illumination to increase the number of photons that hit the photodiode.



This Sony image illustrates the differences between conventional sensors and the more performant new back illuminated sensors.

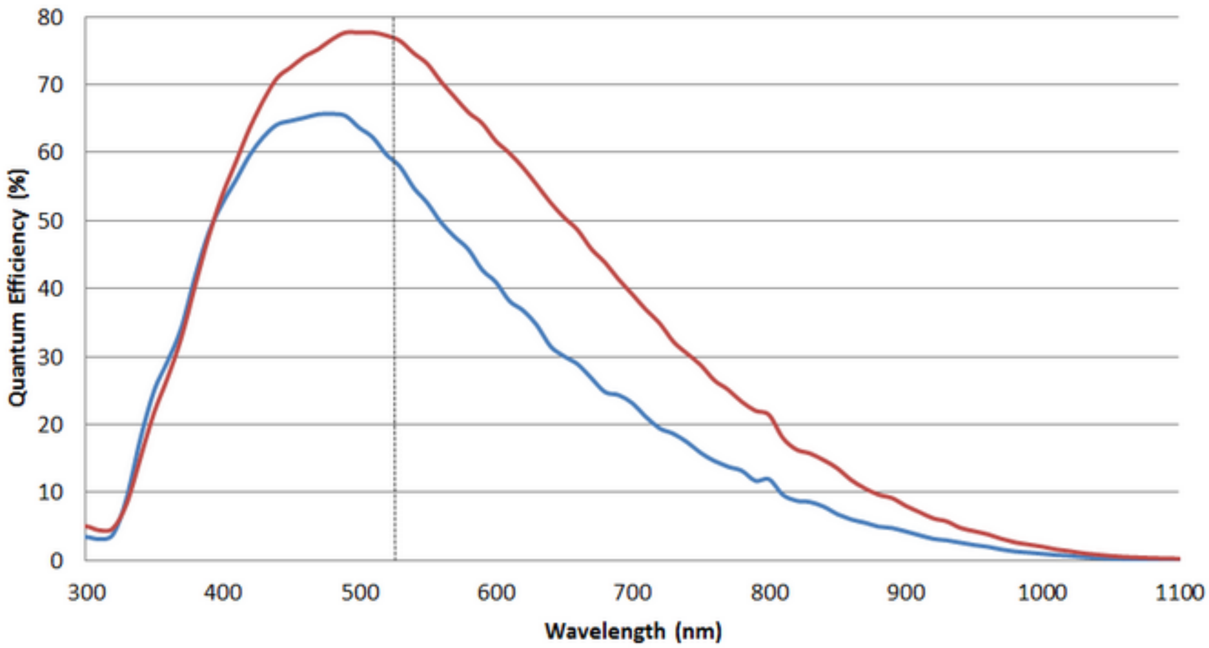
Theoretical calculation for sensors

The number of photoelectrons generated by the light received by a sensor is in relation to:

- The luminance of the scene L
- The quantum efficiency η defining the efficiency of the sensor at each wavelength: now with new sensors this value can be around 50% or more, showing that important improvements in this area will be more difficult in the future
- The wavelength λ (m)
- The Planck constant h (J/S)
- The speed of the light c (m/s)
- The dimensions of each pixel p_x, p_y . Naturally bigger is the pixel area, more light is captured, but the total size of the sensor and so the size of the camera is in that case increased needing a compromise. Currently typical size of sensors pixels for automotive application can vary from 3 to 6 microns.
- The time of integration between two lectures t_{int}. The longer the time of integration, the better is the light captured, but at the price of the frame rate that can be important to have a fluid rendering, obliging another compromise.

The number of photoelectrons N_{e^-} generated in a pixel is finally given by the equation:

$$N_{e^-} = \frac{\eta\lambda}{hc}\frac{\pi T_{op} L}{4N^2} p_x p_y t_{int}$$

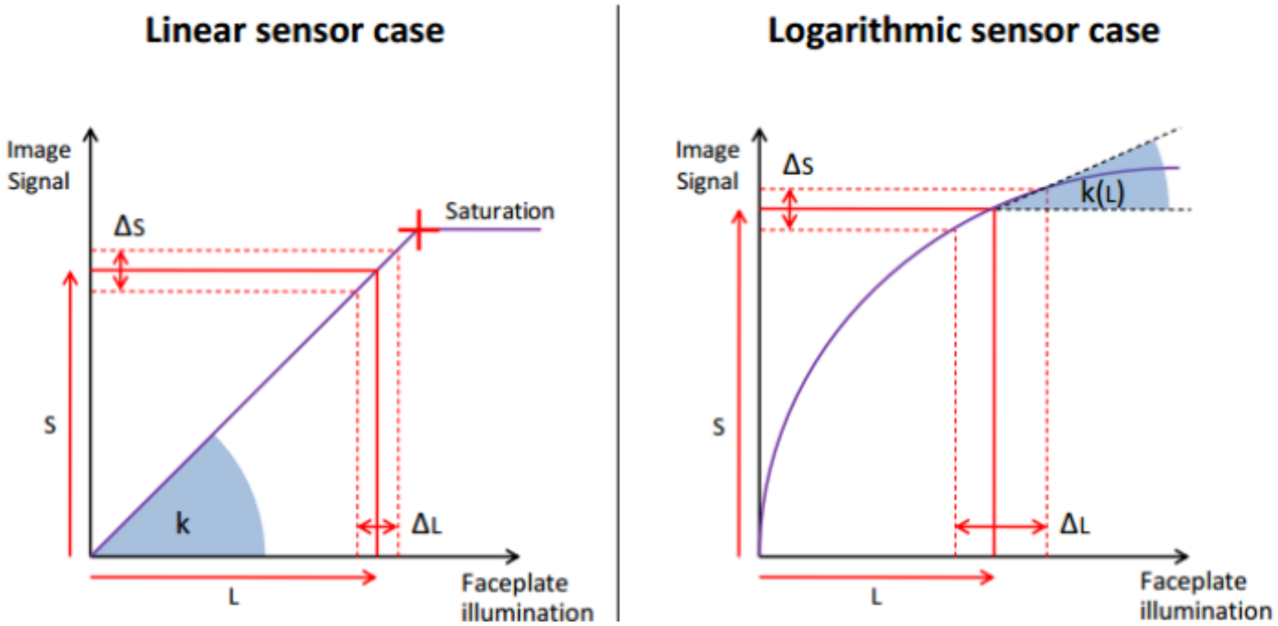


This graph compares the quantum efficiency of two Sony sensors, the blue one being a CCD sensor, and the red one a GS CMOS sensor with 2.3MP and a pixel size of 5.86 microns, so with relatively large pixels. These curves show the huge improvements of CMOS sensors during the last ten years.
Also shown: for use with infrared light, for instance for a night vision with near IR, a relatively large amount of IR light has to be sent as a normal sensor is significantly less sensitive for these wavelengths.

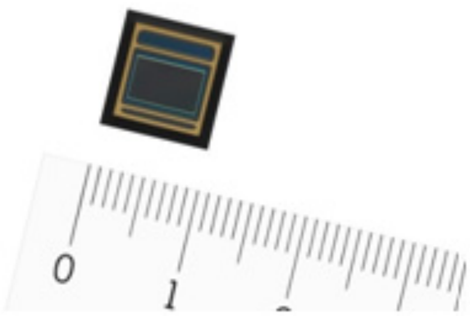
Other important specifications for sensors are the dark noise that could be important in case of low light level, the saturation capacity and so the dynamic range, this being very important for automotive front cameras during the night as we can have 120 db or more between the lowest and highest light levels within the FoV.

Improvement of dynamic range

There are several possibilities to improve the dynamic range, particularly to avoid sensor glare during the night. One of the most potential interesting solutions is the use of logarithmic sensor.
Their sensitivity being progressively reduced with high level of light for instance with high beams during night time, so they are less sensitive to glare.



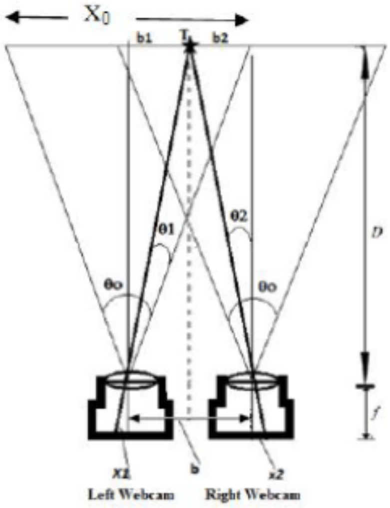
For automotive, another important specification for sensor during night time is a good flicker mitigation function that reduces flickering when shooting LED signs and traffic signals. The dynamic range can be improved with a good HDR (High Dynamic Range) sensor. For instance, Sony introduced in mass production in March 2018 a new sensor, the IMX390CQV shown here, for automotive applications with a dynamic range of 120 db, 2.45 megapixels of 3 × 3 µm, and a sensitivity of 0.1 lx (equivalent to moonlight).

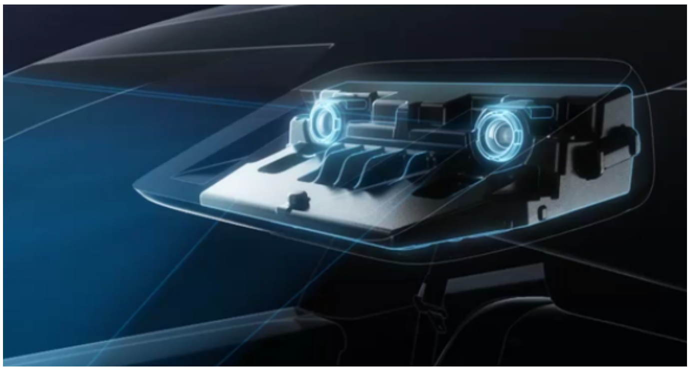


Distance measurements with sensors

Stereo vision sensors

The basic principle for distance measurement is triangulation calculation thanks to two cameras perfectly aligned. With such a system, an object will be imaged in two different positions on the two sensors. With the knowledge of the field of view and the distance between the two sensors, this difference of positioning gives the distance from the camera to the object. To obtain good accuracy, it is necessary to have a perfect alignment of the sensors and a distance from one sensor to the other as large as possible. The advantages of stereo vision systems is that they can use the existing light and so they work well during daytime and nighttime. The drawback is the cost higher than a simple camera first due to the presence of two cameras, but also due to the much more complex data processing necessary for the comparison of the two images, the recognition of the same objects and the identification of their positioning on the sensors.





Denso stereo camera

Sensors with TOF (Time of flight) for measure of distance

Traditional CMOS sensors for cameras use only an external light that illuminates the objects detected, the light being reflected on these objects and captured then by the sensor. Consequently there is no possibility to estimate the distance by the time of flight of the corresponding light except by using stereo vision systems.

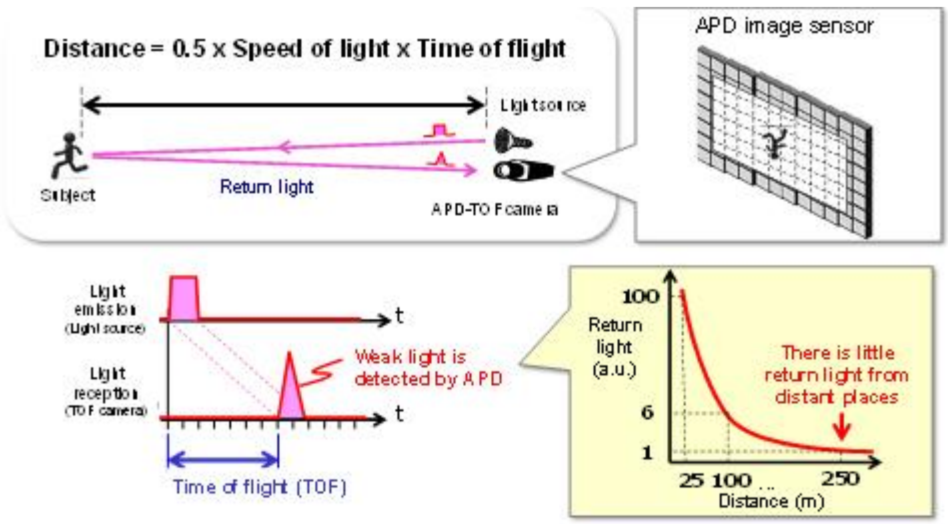
Lidar (Light Detection And Ranging) systems measure the time of flight by dint of laser emission. In addition to the laser transmitter, the system requires a highly sensitive receiver. Used primarily to measure distances to stationary as well as moving objects, the system employs special procedures to provide three-dimensional images of the detected objects. Initially, the laser emitter was mechanically swivelled to scan the targeted field with a limited number of photodiodes receptors. Now the new trends is the use of infrared lidar systems with Micro-Electro-Mechanical System (MEMS) to do the rotation of the laser beam, or even a solid-state lidar. With these developments, the number of points measured is significantly increased, but there is still a limited definition compared to cameras. The best ones have a resolution of 1 megapixel, but at a very high price.

Camera sensor with time of flight measurement

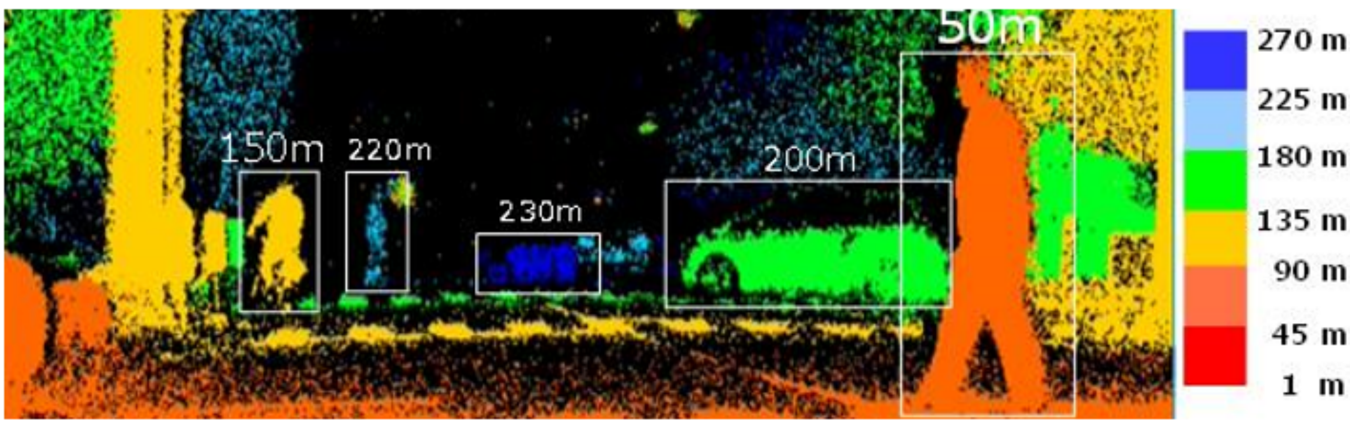
A new type of camera sensor is now proposed, able to give information about distances of objects. To measure the time of flight, a pulsed light is regularly emitted, but unlike lidar using a laser light, the emitted light is uniformly covering all the field of view of the camera. The sensor so measures the time between the emission and the reception of the light. In that case, the sensor needs to be very sensitive, much more than traditional sensors. To do so, manufacturers are using avalanche photodiodes able to multiply by up to 10,000 the number of photoelectrons generated by a lone photon.

New APD Panasonic sensor

In this way, Panasonic announced in June 2018 a new APD image sensor with a definition of 250,000 pixels (0.25 MP) and a sensitivity of 0.1 lx. The interest of this kind of sensor is that they could theoretically be used with no complementary light from the car, so virtually with no headlamps during night time. Nevertheless, the still relatively low definition, the risk of glare from other light sources and the use during daytime have to be evaluated to define if they could be interesting for ADAS and AVs in the future.



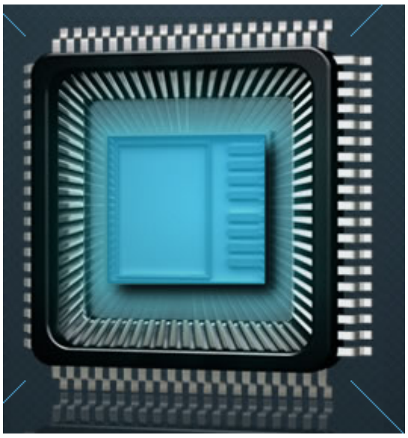
Panasonic explanation of the new PFD high definition sensor

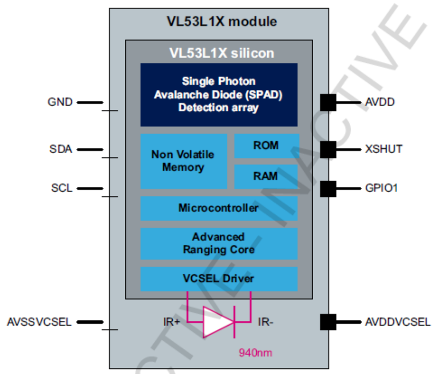


3D range image obtained at night by the TOF image sensor

Previously, other semiconductors manufacturers have also presented interesting new chips:

PMD Infineon with 3D ToF ability. Its definition is 224 × 171 (40 kilopixels) with a pixel size of 17.5 microns, so relatively large, the chip occupying a surface of 29 mm². The price of this chip is estimated at $5.





ST Microelectronics announced what they call the first 3D stacked BSI (Back side illumination) SPAD (single photon avalanche diode) capable of both single photon counting (SPC) intensity and time resolved imaging.
The definition of the ST VL 53L1X module is still relatively limited at 128 × 120 with a pixel size of 7.83 microns.

Thanks to these kinds of new developments and others, new CMOS image sensors have better sensitivity with larger pixels, increased frame rate with larger and faster memory, improved depth resolution, and improved frequency bandwidth with optimised optical filters.

Advanced research for sensors

Dynamic Vision Sensors or event cameras, initially presented by IBM and Inilabs and mainly developed now by Samsung, could be a very important future alternative to traditional sensors based on a neuromorphic approach. Conventional vision sensors see the world as a series of frames relatively inefficiently as successive frames contain enormously redundant information, wasting energy, computational power and time. In addition, each frame imposes the same exposure time on every pixel, making it impossible to process scenes containing very dark and very bright regions.
Dynamic vision sensors in contrast works like the human retina. Power, data storage and computational requirements are drastically reduced, and the dynamic sensor range is increased by orders of magnitude due to the local processing no sending out of entire images at fixed frame rates. Only the local pixel-level changes caused by moving in a scene are transmitted at exactly the time they occur. The result is a stream of events at microsecond time resolution, equal or better than conventional high-speed vision sensors running at thousands of frames per second. The prototypes presented by different labs are very promising with an optic rate of 1 megahertz instead of 30-60 Hz for conventional cameras, a power consumption of 20 milliwatt instead of 1.5W, and even more, they could have a dynamic range of 140 dB perhaps able to avoid the kind of accident of the Tesla car in

2016 when the sun blinded the camera. Some prototypes based on these principles were presented by Samsung, but the work for miniaturisation and industrialisation is still ahead.

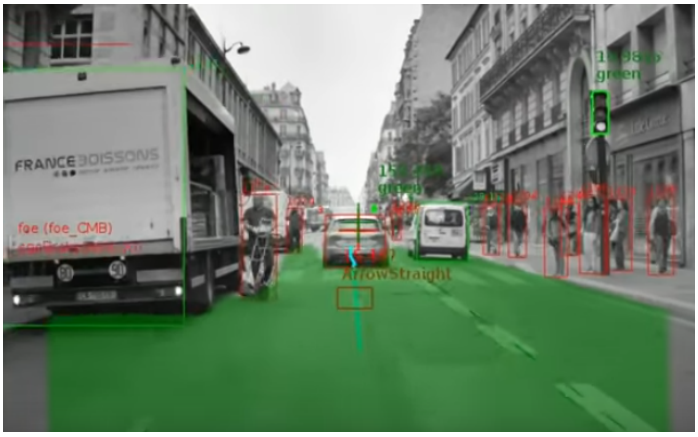
Other possible evolution of sensors
In February of 2018, researchers at Dartmouth College announced a new image sensing technology that the researchers call QIS, for Quanta Image Sensor. Instead of pixels, QIS chips have what the researchers call "jots". Each jot can detect a single particle of light, called a photon. The current imager has a definition of 1 megapixel and could run at 1,000 frames per second. This project, partially financed by the American Defense Advanced Research Projects Agency (DARPA) is still in the research phase and will not be available for automotive applications before many years have passed.

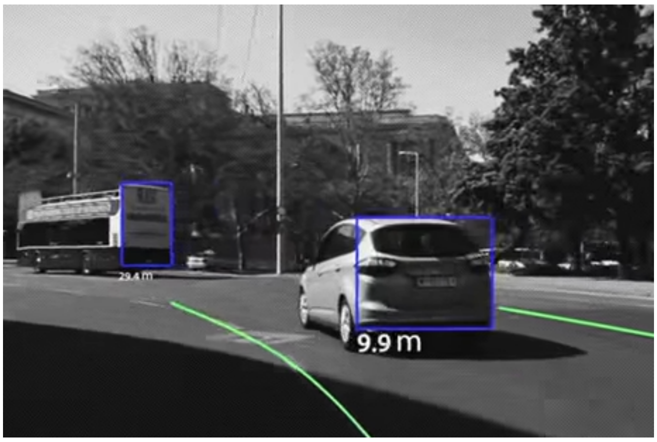
Data processing

The physical elements of a camera—the optical system and the sensor—are important, but perhaps even more important is the role of the data processing system.

The data processing is done at two levels: inside the camera, and in a remote unit. However, depending on the architecture choice, the distribution of the intelligence could be more centralised or more decentralised. Tasks generally done inside the data processing system of the camera include image decoding, lens correction, geometric transformation, video stream transcoding, video analytics, overlay, and image streaming. For surround cameras, the image aggregation and the image display are generally done in a central unit outside the camera.

For forward-facing cameras, that same list of tasks is done at the camera level, plus the possibility to integrate the intelligence for the detection and recognition of road users and objects such as car or truck recognition, pedestrian detection, traffic light detection, lane detection, and collision risk assessment.





The corresponding intelligence being more and more complex, particularly now for the preparation of the autonomous driving, the corresponding software is now generally put in SoC (System on Chip), mainly by the leader Mobileye with their EyeQ SoC, and by Nvidia, another important actor for autonomous driving SoC.

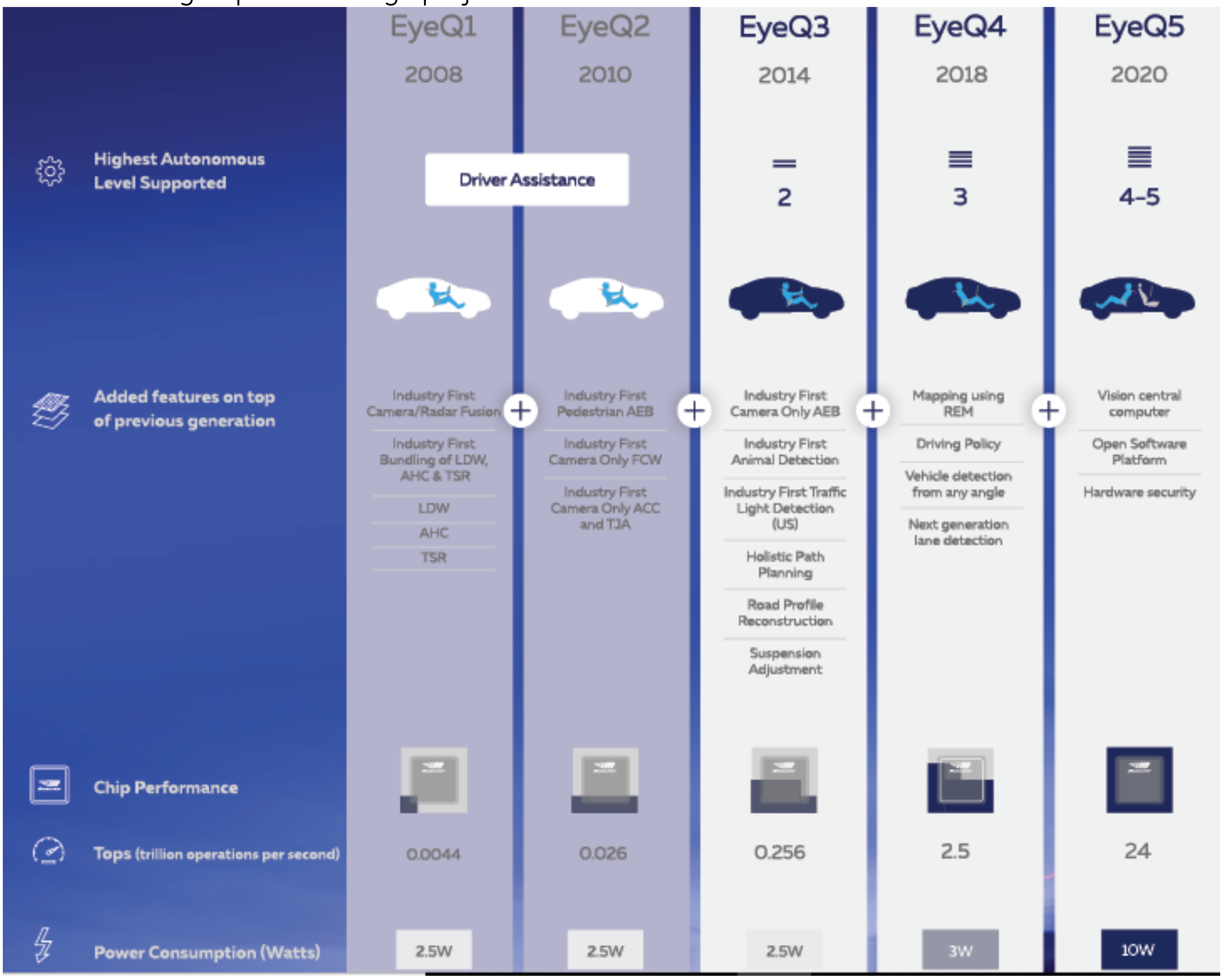
Mobileye

Mobileye are the current leader with a market share estimated at around 70%. The current generation EyeQ3 is adapted for 1.3 megapixels, and will be improved to support 1.7 megapixel in 2019.
Limited to monocular camera currently with a 50° FoV, it will support 100° in 2019.

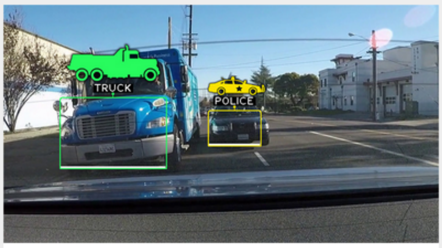
The new generation Eye Q4 introduced end 2017 on BMW 7 Series is already powerful, being adapted for level-3 autonomous driving this year, and is operating at 2.5 tops (trillion operation per second). This allows it to process data from eight cameras simultaneously including multifocal cameras.

The following generation EyeQ5 for level 4-5 in 2020 will be much more powerful and will operate at 24 tops with a power consumption of 10W.

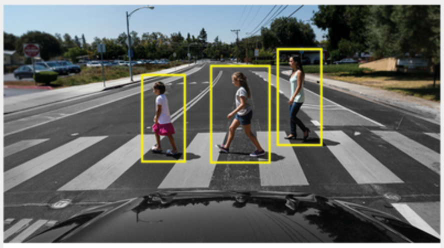
Here is Mobileye's product range projection:



Nvidia:
The Nvidia SoC prepared with ZF and Bosch is even more powerful at 30 tops, but with today a power consumption of 30W that is difficult to manage. These Nvidia images exemplify some capabilities:



Differentiation of Vehicle Types


Pedestrian Detection

Speed Limit Sign Recognition

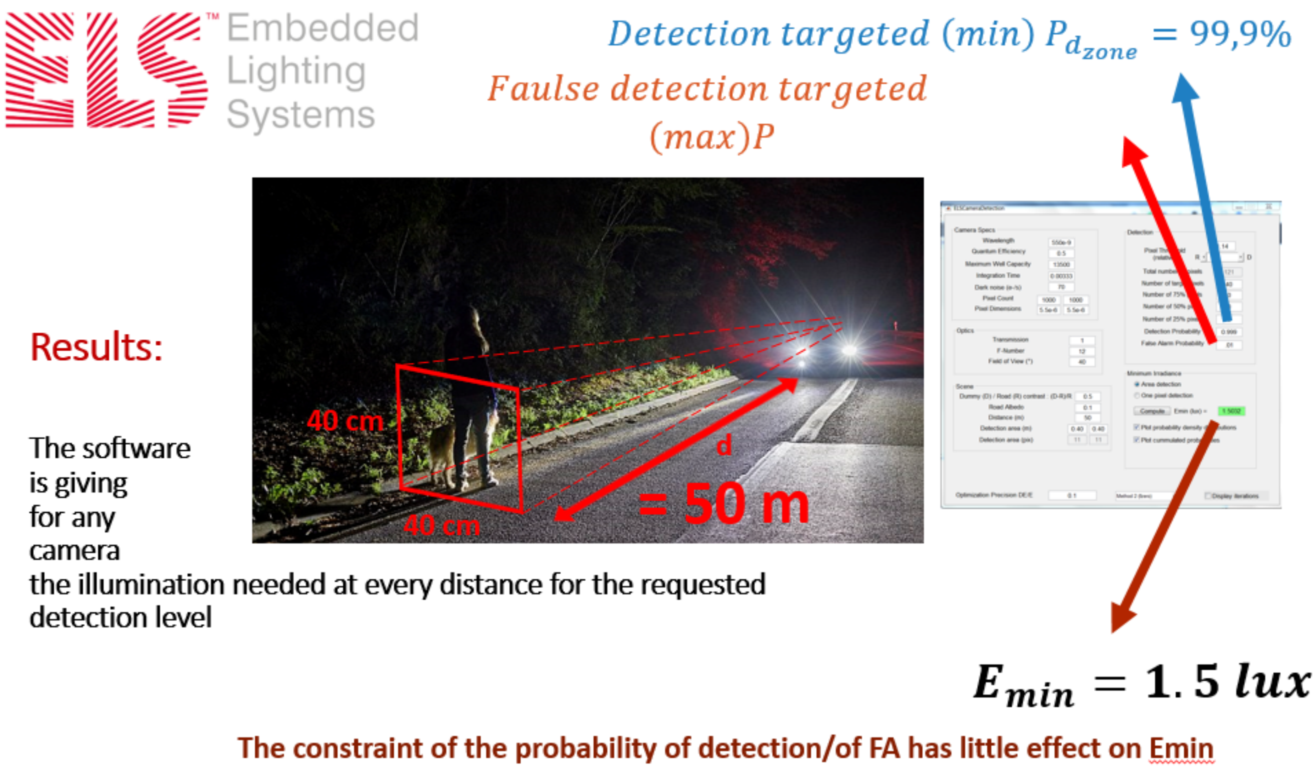
Cameras and lighting

During the next years, ADAS from level 1 to 3 will progressively equip the majority of cars, helping the driver to have safer trips. But the driver will still have to drive in some circumstances even in level 4, and so a good vision particularly during nighttime will stay very important, justifying a good lighting system. With autonomous driving, some are questioning the remaining need of a lighting system if the auto pilot can do everything. First, we are convinced that transported people will continue to need a good lighting system to see their environment, as it will give a better feeling of safety and avoid a kind of claustrophobia. The car lighting and signaling will too be necessary for other users to better see these cars, naturally as during many years, if there will be likely more and more autonomous cars, the majority of cars will remain traditional, without considering the fact that pedestrians or cyclists will never be equipped with "autonomous walking" or "autonomous biking".

Level of light needed by cameras

Another question with cameras used for ADAS or AD is whether cameras need a complementary lighting system from the car, and if so, how is a lighting system optimised for cameras?

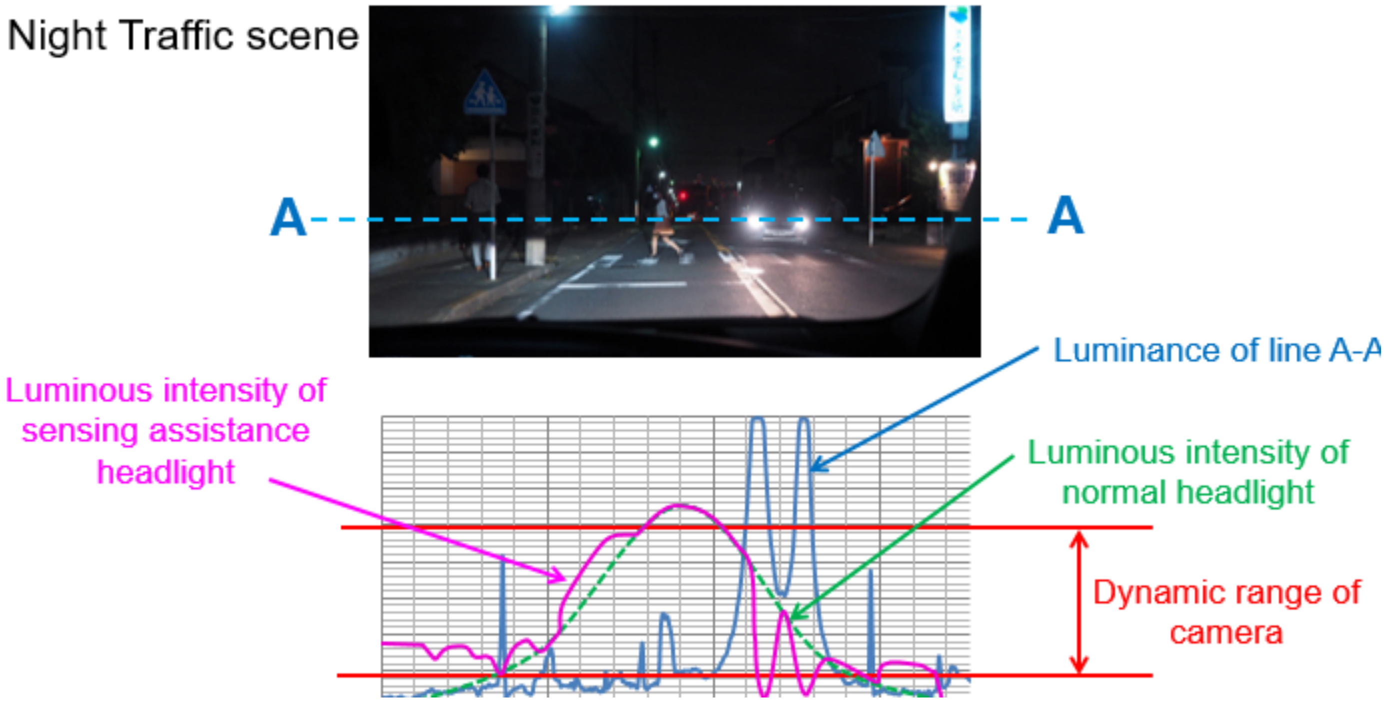
Currently, for sure, cameras installed for ADAS need complementary light. They can be more sensitive than human eyes and theoretically need less light. ELS (Embedded Lighting Systems) presented in 2017 at the Shanghai DVN workshop a study showing the level of light necessary for cameras. The software can be adapted to different models of cameras, and too to the level of detection targeted and the level of false detection accepted. In the example taken with a detection target of 99.9%, the illumination needed at 50 m was 1.5 lx, a level easily achievable with traditional lighting systems.



Nevertheless, better lighting means better detection and recognition of objects by the camera system, particularly if the potential danger (obstacle) has a low contrast compared to the environment. As these new systems will need to be 100% safe, a good lighting system will help to achieve this target.

ADB with autonomous driving

Another question could be: Are ADB systems still useful with autonomous driving? The answer is clearly yes, as ADB illuminates areas where no light is sent by low beam functions, so ADB will help to see obstacles ahead of the low beam cutoff line. Furthermore, Koito presented at the 2018 Tokyo DVN workshop an interesting use of advanced HD ADB supporting cameras by putting light where the limited dynamic range of cameras could fail, and so potentially improving the detection ratio.



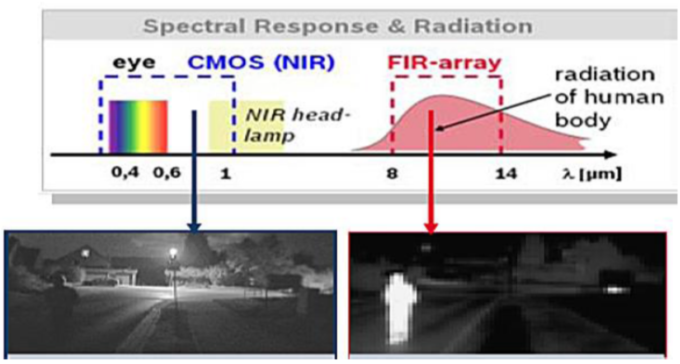
Koito source

Lighting for surround cameras and rearview cameras

Rearview cameras are safety requirements and a good illumination by the reversing lamps is important to have a better view. For the surround cameras mainly used for parking, lateral lighting could be useful, for instance light projected close to the car as found on some high-range cars.

Night vision with infrared

Two types of night vision system have been produced during the last two decades: with near infrared or with far infrared.



Near infrared (NIR) is realised with a complementary infrared beam. It was originally halogen beam with an IR filter. Now IREDs (infrared-emitting diodes, "infrared LEDs") are used. A normal CMOS camera can be used, but the results can be improved with a camera more specifically sensitive to IR.

Far infrared (FIR) uses the electromagnetic radiation coming from the scene itself, but a camera called bolometer is necessary.

The NIR systems are relatively affordable, as a normal camera can be used. And the image is more easily understandable as close to the normal vision. But NIR needs an IR emitter of some kind, now most commonly with IREDs giving typically the shape of a high beam function for a better range.

FIR systems are better for detecting pedestrians or animals, and give better range especially in adverse weather. But the special bolometer camera adds cost, and the image is not readily understandable by humans.

At first these systems output to a display to inform the driver. But driving only by looking at the display is quite impossible and really dangerous. Looking periodically at the display is not better, as the driver needs to take eyes off the road, and could miss an event displayed during the other periods.

But now with the intelligence put in ADAS systems and even more in AD cars, this night vision system can be very useful as there is no more need to transfer the information to a display, but only to the data processing system that can improve detection and recognition of objects with a better range without glaring other users and decide consequently the actions.

These new infrared systems can thus compete with ADB systems for the improvement of the range in case of automatic driving. Nevertheless, when manual driving is still used even partly, ADB will still be the best lighting solution.

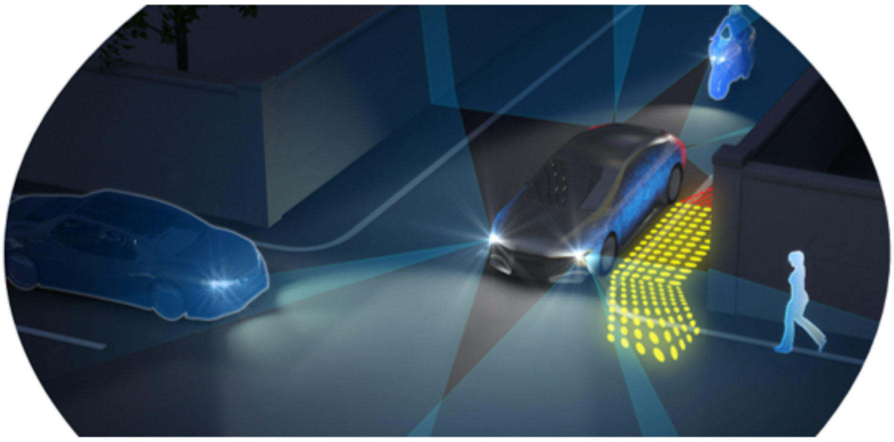
Communications by light

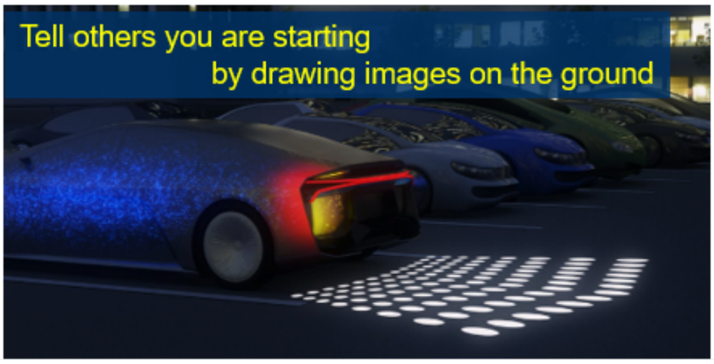
But it is in the domain of communication that the association of the lighting system of the vehicle and cameras will be of great importance. For ADAS systems and even more for AD, every complementary information will be very useful to achieve the target of zero crashes. These systems for instance will likely need a much more detailed mapping of the roads than is currently prepared by the likes of Mobileye, Google, Apple, and the rest. They will need more detailed information about the behaviour and the targeted trajectory of other vehicles. For that, transmission of information by lighting systems (LIFI or signals) will happen and naturally these signals will be received and analysed by cameras. There are a lot of studies currently in this direction for new signals and coded light potentially adapted to autonomous driving.

Communication by signal

For signals, much current work is under way in the GTB and in parallel in America to try to define a standard for new signals for autonomous driving information, for parking departure, for pedestrian exchange, and so on. The amount of information needs to be reduced, and the message clearly understood by people, even for elderly or young people. Naturally, cameras will have to understand these messages as well.

Here are examples of communication by signals presented by Koito during the 2018 DVN workshop in Tokyo:





Communication with coded light (LIFI)

Here the target is to have much more information exchanged with the possibility for instance to give the speed, the braking status, the intended direction, etc. Naturally in that case, humans have no more the possibility to catch these messages only perceived by cameras. For that, the light emitted by the front and the rear LEDs of the current lighting functions or from new devices could have their intensity

varying according to a code at a relatively high frequency, invisible to the human eye. This could be realised with no particular technical difficulties with LEDs which have instant on/off behaviour.
It is different for cameras that would need in that case a very high frame rate. The frame rate of current cameras being for the best at around 60 frames per second, it would be necessary to raise this level to around 1,000 fps to have a good enough level of transmissions exchanged. This level seems however achievable by some new techniques currently under development.

LIFI is still an emerging market with global sales estimated at only $80m in 2023 for all the applications. But the CAGR will be strong at around +75% and new solutions will certainly by invented to boost this market. For automotive applications, the difficulty will be to define solutions not imposing a unique standard regulated, as such a regulation is far to be defined and applied.

Integration of cameras in lighting products

The position of headlamps and rear lamps at the four corners of cars is unique and cameras could take advantage of it to improve the information for safe driving. It could be the case for front cameras in headlamps that can see potential dangers when a car is exiting from a parking lot with no visibility.
It could be the same for the back of the car when the car is reversing. These kinds of integration are not at all common currently, but with the development of autonomous driving, they could become obligatory to reduce the risk of crashing.

Situation at a crossing or at parking exit with other vehicles for instance trucks being parked in the street

Conversely, the **interior camera** is more often integrated in the interior lighting product to simplify the car assembly.

Interview

Joachim Mathes

Valeo

R&D and Product Marketing Director
Valeo Driving Assistance

DVN: Cameras are more and more used in cars. Can you tell us the applications targeted by Valeo?

J.M.: Rear Camera System, Surround Camera System, interior and exterior eMirrors, Multifunctional Front Cameras (behind the windshield), specific cameras for automated and autonomous driving (this includes both far-field cameras with ~100° FoV and near-field cameras with ~180° FoV).

DVN: What are the main regulations or safety assessments in the different countries that could help for the expansion of camera use?

J.M.: Regulation like the Back-over Protection Act in the US that mandates every car to have a rear camera. Global NCAP organisations demanding active safety features like AEB to reach 5 or even 4 stars (expected to be followed by regulators in some markets). Legislation enabling eMirrors and automated/autonomous driving.

DVN: What is your evaluation of the market of cameras for the car industry and its trend for next years?

J.M.: We will see a significant increase in the global average fitment rate for rear and surround view systems combined. Front cameras (behind the windshield) will become de facto standard fitment in developed markets. The rise of automated and autonomous vehicles will create new market opportunities for cameras feeding the machine vision of such systems.

DVN: And in this market, what is the position of Valeo?

J.M.: We see ourselves as the market leader for surround view systems and a major player for rear camera systems and windshield mounted front cameras. Leveraging our leadership in image quality, camera design, and volume production as well as machine vision algorithms, we see ourselves well positioned for the rising market for automated/autonomous vehicles.

DVN: For front lighting cameras, what is your evaluation for the trend for number of pixels?

J.M.: Windshield mounted front cameras will split into basically two market segments, one for active safety (like AEB) and basic automation up to SAE level 2 with ~2.5 megapixel, and one for more advanced functionality with ~8 megapixels.

DVN: What size for cameras are you targeting? Are plastic lenses an option for future cameras? Is there any interest to integrate a zoom function in the future?

J.M.: Satellite cameras for rear and surround view systems will get as small as the imager and the lens allows them to get. We see the next generation at about 20 cubic mm. The size of windshield mounted front cameras is following the embedded electronics and its related temperature management. Satellite version with centralised image processing will follow the form factor of the rear/surround cameras. Specific cameras for automated/autonomous vehicles can be significantly larger due to different (larger) imagers and lens designs. We do not plan pure plastic camera lenses due to their significantly reduced image quality especially over temperature. Image quality is not only important for the end-user satisfaction but is required as camera systems more and more serve safety and automated systems. This trend also drives an increasing demand for cleaning solutions where Valeo are also one of the leaders.

DVN: Do you think that 3D cameras or multi-cameras systems will take an important share of the market? Is Valeo developing such cameras?

J.M.: We believe that the majority of the market will be mono-camera systems with stereo camera prevailing in its niche. While a basic car will have 2 mono cameras (1 rear and 1 windshield mounted front camera), premium cars with a high-end automation package will feature over 10 cameras per car (including interior cameras).

DVN: For detection and recognition, what are the main differences between daytime and nighttime for cameras?

J.M.: As a camera is an optical sensor working in the visible light spectrum, these systems obviously work best in a well-lit environment. However the recent years have seen tremendous improvement in machine vision algorithms, so that the gap between day and night time performances has narrowed for most use cases. That being said, we believe that advanced safety features as well as and high and full automation require a redundant surround perception based on different sensing technologies.

DVN: What are you waiting for from the lighting industry to improve cameras efficiency for safety?

J.M.: Obviously a good headlamp system can facilitate the performance of vision-based systems. Already existing glare-free high beam systems (another field where Valeo are a leader) are therefore a good choice to support good functionality in the dark.

DVN: Night vision systems using IR are used since many years, but marginally as the resulting images sent to a display were not convenient for drivers. Do you think that now with integration in ADAS or AD systems, such a direction could have new developments? Do you think that normal cameras can be used for night vision IR systems or specific cameras will have to be used?

J.M.: We don't see IR-based night vision system gaining significant volume even if there are available at a currently increasing number of premium models. We believe that investment in a glare-free high beam system provides a much higher safety gain and end-user value. Next generation automated/autonomous vehicles however might require IR-based machine vision in addition to the "normal" cameras to support night time operation at maximum safety. Thermal cameras can increase safety even during daytime.

DVN: Cameras, lidars and radars are the main sensors for detection and recognition for ADAS and AD: what is your perception about the role and development of each in the future?
J.M.: Different sensing technologies like camera, radar, lidar, and ultrasonic do not compete but with supplement each other in a multi-redundant perception cocoon for near- and far-field and localisation. Currently we have a large number of different AD platforms under development. We believe that in the next five years we will see an accelerated consolidation of those platforms. In active safety (front AEB mainly), a camera plus radar will remain the dominant combination.

DVN: There are many cameras in new cars and concerning their position, what is your feeling about their implementation? Could headlamp, rear lamp, or high-mounted stop lamps be used more systematically for the implementation of some them?

J.M.: Location and integration in privately owned vehicles is mainly driven by vehicle design, thus we believe that it is best to offer highly standardised camera modules at the lowest possible cost. These will be integrated wherever the vehicle design places them best. In automated/autonomous vehicles the camera position is mainly driven by system performance. Lower vehicle volumes also favour standard modules.

Outlook

In the near future, the current evolutions of the market and the improvements of camera technologies are going to lead to the use of 2.5-megapixel cameras for AEB and basic automation, as well as for viewing applications to improve the image quality, and to the use of 8-megapixels cameras for advanced functionalities. Cameras will be more compact with a size of 20 cubic mm, and the number of cameras per car will continuously increase till 6 to 10 on average. The longer-term automotive future will be dominated by cars with high ADAS level above or AD. The technology of cameras will be strongly improved with not only 3D imaging, but to "4D" imaging time and "5D" imaging spectrum, thanks to their precise measurement of time of flight and to their ability to differentiate much more in detail the spectrum of electromagnetic waves received. Fusion with lidars possibly more often of solid state type at that time and with LWIR (Large Wave Infrared or far infrared) could become standard, associated to high sensitivity cameras with single photon detection. In 2030, however, these sophisticated technologies that are each at their early stage today will still be relatively expensive and still confined to use in relatively expensive cars.

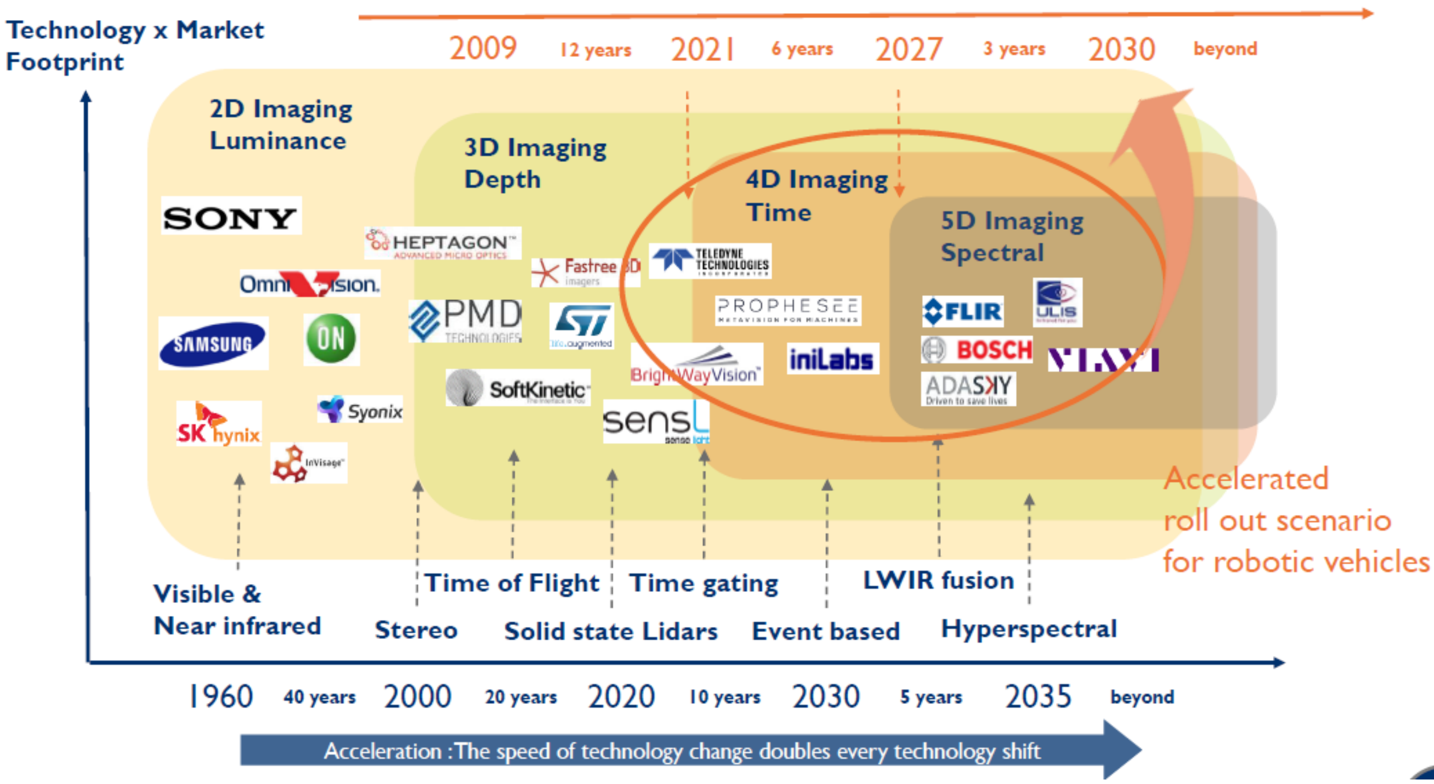
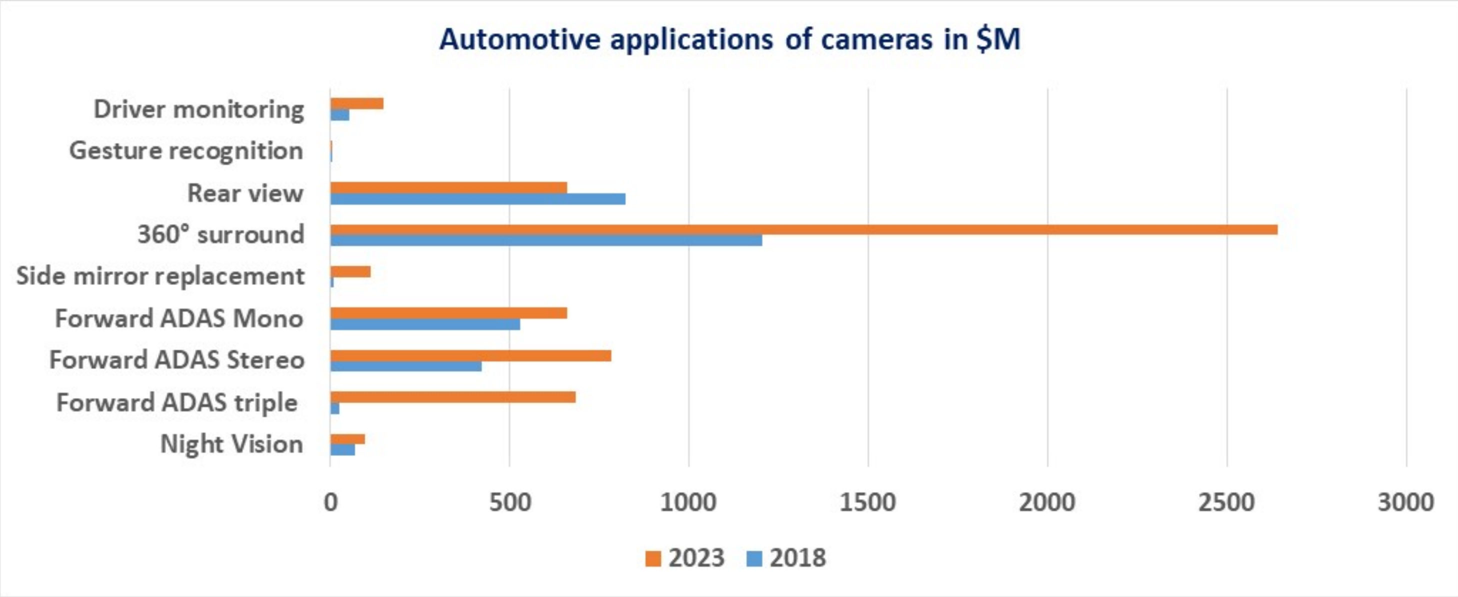


Image: Yole

During the next five years, there will be an important increase of the number of cameras used in the world for automotive applications, the most important developments being for 360° surround cameras and for front facing cameras, that will more than double the current figures.



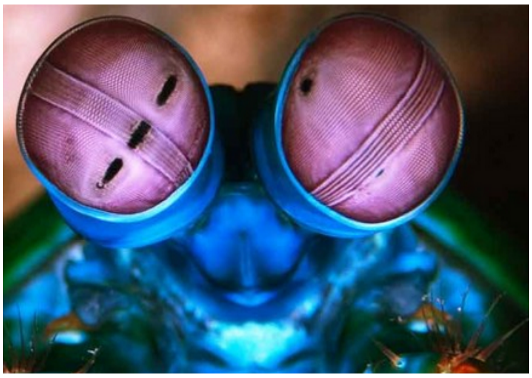
Conclusion

ADAS and autonomous driving are currently one of the main priorities of car makers at the same time as electric power and connectivity. And cameras are and will continue to be the main sensor for these functions. The market of automotive cameras is expanding very quickly, at a rate of +20% for quantities to reach 140 million cameras in 2020 and 800 million cameras in 2030, and +12% for sales as prices are decreasing, to reach $47bn in 2022. Technical improvements are also impressive with now more and more stereo cameras for better detection that would reach the level of sales of 4.3 million in 2021, with improved definition of sensors going to 8 or more megapixels, with better sensitivity going to the ability to detect each elementary photon and with very high frame rate able to ensure communication with light with other users or with the environment.

Nevertheless, compared to the eyes of animals created by nature with progressive improvements realised during many million years, cameras have still a long path of progress. For instance of resolution, human eyes have a resolution of 576 megapixels, far above the best 8 megapixels for automotive cameras, and over 11× the 50-megapixel level high-range professional photography cameras. For long distance view, eagles have a superb vision eight times better than humans allowing them to see a rabbit at 2 km with their multiple fovea and able to focus and zoom very quickly with a larger range of colours than humans, performance still not achievable currently with a camera of the size of their eyes. For low sensitivity, some animals are extraordinary. Take the carpenter bee, able to see at level as low as 0.000063 lux. Or even better, the American cockroach has light-sensitive cells found that can respond to less than one photon per second! Mantis shrimp have perhaps the most complex eyes with 16 types of cones allowing an extraordinary ability to differentiate colours and pick up on small changes in colour almost instantaneously. They take all the visual information they see into their brains at once without processing it, allowing very quick reaction, and they can detect polarised light.

So there is still huge possibility of progress for cameras. Nevertheless, as they are already currently and as they will be likely in the foreseeable future, perhaps precisely with a neuromorphic approach of dynamic vision sensors for instance, they are and will remain one of the main component for the new safety systems, and in 2030, will systematically equip every of the 140 million cars sold at that time in the world with around 6 cameras per car on average.

Owl eye



Mantis shrimp eyes

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