The Future of Exterior Lighting

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About the authors

Hector Fratty has made his entire career in vehicle lighting. Until 2006 he was Valeo Lighting Systems' R&D chief, managing a staff of 650 engineers and technicians. Then, he headed the Valeo Lighting Expert Committee until the end of March 2008. He is now President of Driving Vision News, the global vehicle lighting and driver assistance industry's technical journal of record. He presides over the highly-regarded biennial VISION Congress international vehicle lighting and driver assistance symposium. He also a member of the ISAL steering committee, which guides and administers ISAL, the International Symposium on Automotive Lighting organised by Technische Universität Darmstadt in Germany.

Leo Metzemaekers worked 29 years at Philips (including 2 years at Lumileds), 19 of them in automotive (Lighting and Optical Storage) and 10 years in Consumer Electronics. He held international positions in Development, Marketing & Sales and Strategy & Business Development. Since October 2016 he works as an independent Advisor in automotive sales & marketing, strategy, and business development.

Ralf Schaefer worked more than 34 years for Philips Lighting, from which he served Philips Automotive Lighting for 22 Years. He held different positions in research, development, product marketing and business management until his retirement, since which he keeps himself busy as partner and advisor to the vehicle lighting community.

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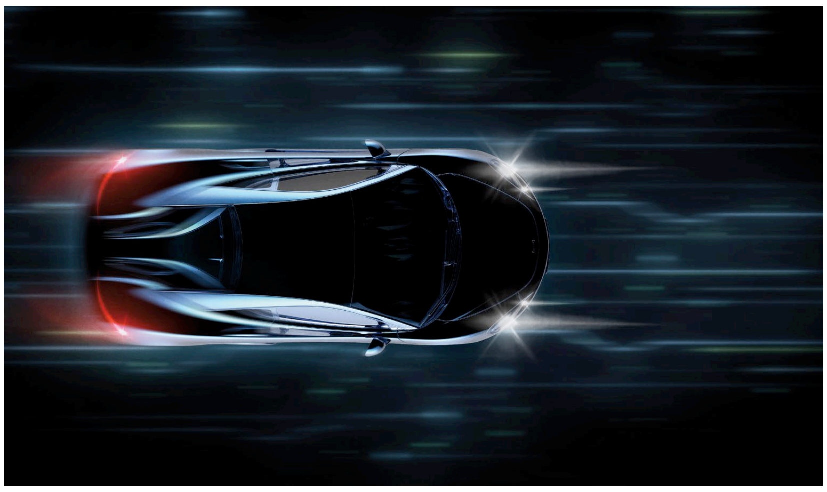
Jean-Paul Charret worked during his entire career in R&D, in different fields like toll highways systems design and medical imaging systems design, at companies like Alcatel, Thomson, and General Electric where he led a global R&D team. He joined Valeo in 1995 and since then has been dedicated to vehicle lighting. First as Advanced Engineering Director, then as Project an R&D Director of Valeo Sylvania in America, then he replaced Hector Fratty in March 2006 as Global R&D Director for Valeo Lighting Systems until his retirement in June 2011. He is still working part time as consultant in Vehicle Lighting Systems activities.

Daniel Stern, DVN's Chief Editor based in Vancouver, Canada, is one of the five greatest lighting experts in North America. He is an appointed member of the US transportation Research Board Visibility Committee, which steers North America research on matters related to automotive conspicuity, lighting performance and regulation. He attends and participates in the world's automotive symposia.

Introduction and Target of the Report



Currently there's a great deal of public discussion about current and looming changes in the automotive industry with the arrival of electric vehicles, autonomous driving, and vehicle communication to other vehicles, drivers, road users and infrastructure.

Listening to opinions in the vehicle lighting community, DVN explored the influences of these new factors on exterior lighting in order to provide guidance for the lighting community to successfully negotiate the transition into the coming decade.

Two years ago, DVN led a study using an array of tools in carrying out this guidance. Taking the information of the study and adding new information from these two last years, this report provides a solid basis to define the strategy and path to success within the specifics of your business area.

EXECUTIVE SUMMARY

Several trends have been identified, both in society and in the automotive industry: urbanisation and mega cities, the burgeoning sharing economy including car sharing and ride sharing, environmental protection and sustainability, ageing population, ADAS, AVs and EVs, digitalisation, communication, AI, and the world's various zero-crash initiatives.

There will be an indefinitely long period during which human-driven, semi-autonomous, and autonomous vehicles will share the world's roadways. The basic see-and-be-seen functions will be joined by an element of sophisticated communications surpassing that of today's vehicle lighting systems, and it seems attractive and efficient for the industry to have a globally harmonised regulation system. It may well happen that some major regional markets will not wait for others, and will go ahead with local regulations that might be in conflict with those of other regions, or with developing international consensus on the matter.

Relevant trends include:

1. ADB (Adaptive Driving Beam, also called glare-free high beam)

We predict that ADB prevalence will grow from 1% in 2016 to 15% by 2025, assuming worldwide regulatory acceptance. There will be de luxe high-end systems and entry-level basic applications. ADB offers great benefits in safety and convenience for many driving conditions; however, to bolster ADB uptake and prevalence, additional work must be done to identify and create additional user benefits for use in mega-cities where traffic flows at speeds below the activation threshold for many of today's systems.

2. Communication functions

Exterior lighting is moving from the basic functions to the level of being a major safety communication tool. New communication with light will provide additional safety and convenience. Road projections, animations, and pictograms will play an important role in how to communicate. This kind of new communication will be one of the most important areas contributing to the growth of vehicular lighting in the next decade.

3. Dynamic signal lights

The main current trend is to introduce more animated signals and otherwise unconventional light-in-motion effects. Animation is already allowed for turn signals, and for ARS (Adaptive Rear-lighting Systems) with the possibility to enlarge or brighten the lit area in accord with prevailing conditions. In the next decade, communication and safety needs will drive increased application of light-in-motion effects, that is if, as, and when regulations will change to permit it.

4. Styling

Styling will remain a prime driver led by appearance differentiation, dynamics, and signature with new styling and technology.

As to light sources, LED will be the dominant technology for front and rear lights on vehicles.
Laser with the current application as long range beam will remain a niche application, but in combination with a scanning system (Laser + MEMS) for projection, broader opportunities will come up in the first half of next decade.
OLED shows no clear indications that it will become a mainstream light source for rear lighting.

The value chain is changing with the increase of the gap between future requirements by automakers on advanced lighting systems and currently-available capabilities and resources at tier-1 lighting suppliers. New large suppliers ("super integrators" or "tier-0.5" suppliers) may integrate current tier-1 lighting suppliers in their activities, or via other forms of new coöperation.

1. Society and Industry Trends

The trends in our society and the automotive industry will be the major drivers for future change, resulting in an ongoing series of opportunities, challenges, and threats for all stakeholders. Here we look at how societal changes interact with automotive industry trends to affect the vehicle lighting industry.

1.1 Societal trends

Urbanisation and mega cities

There is a clear demographic shift in where cars are sold and used. Especially in Asia, most distance is driven in highly urbanised areas, but also in Western Europe and America people will live more and more in urbanised areas. It's clear that driving in an urbanised area will have different lighting requirements compared to driving in a rural area. Many lighting systems are optimised for driving in rural areas and at high speeds.

The sharing economy

As a social trend it's getting more and more common to use products only when they're needed, without owning them—which implies sharing with other people. Sharing goods will lead to more efficient usage and hence a smaller ecological footprint because they will be produced in smaller numbers and under more sustainable practices. This social trend is cascading down rapidly to the automotive industry as well by introducing the concept of car sharing versus car ownership.

Environmental protection and sustainability

In all regions automakers will face very strong pressure for reduced emission and fuel consumption. Automakers will have to pay significant penalties in case fleet level targets are not met. Details in legislation differ from region to region. The main contribution from the lighting industry will be in switching over to more energy-efficient technology. To stimulate this transition automakers can claim credits in some regions when using LED lighting technology. Currently LED high and low beams are creditable eco innovations in Europe, for example.
If an automaker will exceed their emission targets at the fleet level, they can face a penalty of €150 per g/km CO_2. We forecast that even generalist automakers will make LED headlighting available, at least as an option, for all models, allowing them to use every gram of CO_2 worth of credit to control fleet-level emissions. In the longer run, LED will become standard, hence will not be treated as an eco innovation any more.

Personalisation

Individuals want to express themselves and share their flair with others—just take a look at social media! Of course, the interior of a car is a perfect space for creating a more personal atmosphere, which can also be made adaptable to the mood of the driver—and in a later stage this concept can be adapted even more when driven in autonomous mode. In lighting, the use of digital light controlled by software will open the door for new features and personalisation of light, including in publicly-visible ways.

Demographics: ageing population

Globally there is a clear trend towards an ageing population across developed and developing countries alike; the difference is in the starting mix of population. The implication of an ageing populace: car lights will need to work better, in ways that matter to older persons.

1.2 Automotive Industry trends

ADAS and autonomous driving (AD)

AD will change the automotive realm radically. A new landscape is under construction wherein new technologies are being developed, new business models are being created, new partnerships and alliances are being formed, and new legislation is under review. It is important to understand that AD will not happen overnight, it will be gradual with different levels of autonomy and different modalities. For the foreseeable future there will be a mix of autonomous, semi-autonomous, and human-driven vehicles on the road. Moreover, even once level-5 autonomous driving will be achieved, the need will remain for exterior lighting on cars. Exterior lighting will create the best conditions for the sensors and cameras to perform well and not to glare or elsewise interfere with other cars' sensors.

Electric vehicles (EV)

It's no longer a question of whether EVs will be a success; that answer is already known, and it is yes. Now it's more about how fast they will arrive. This arrival will be strongly driven by governmental pushes on fleet fuel consumption targets and CO_2 fleet emission targets, tax incentives, infrastructure build-out (charging stations…) and suchlike. We investigated if EVs will have different or additional requirements and opportunities for exterior lighting; the answer is clearly no.

Car sharing

The trend from a sharing economy will also impact the automotive industry. Many new companies and coöperative ventures with large automakers have been set up to facilitate the concept of car sharing. In this study we identify what new opportunities in lighting will appear in the emerging segment of cars to be used in a sharing mode. Opportunities in the HMI (human-machine interface) to use lighting to facilitate intuitive operation and understanding of a vehicle's functions and capabilities, and also in welcome scenarios for non-owner temporary car users.

Digitalisation & communication

Headlight beams will be built up of pixels which can be individually controlled in real time by software and sensors. Digitalisation will be one of the most important enablers for future generations of new lighting applications, and to facilitate vehicle-to-vehicle communications. Many new functions will be made possible, supporting the trends presently being presented. We anticipate that the digitalisation of light will make big opportunities for new features and business models, and in the value chain of headlighting systems.

Artificial intelligence

Increased processing power and the increasing availability of enormous amounts of data will drive new ways to control systems and machines. Control systems used to be defined by fixed algorithms; this strategy is quickly growing obsolete for complex tasks with many variables, such as autonomous driving. Hand in hand with the digitalisation of light, artificial intelligence will play a role in defining the most advanced new lighting control systems.

The zero-crash/zero-fatality impetus

Increased safety for passengers and other road users is probably the strongest driver (next to styling) for the development of more advanced lighting systems. Intelligence that increases safety will be the strongest driver for the development of highly advanced ADB systems, in combination with high-luminance light sources and new devices such as µAFS, MEMS, DMD, and LCD technology.

2. Exterior Lighting Technological Trends

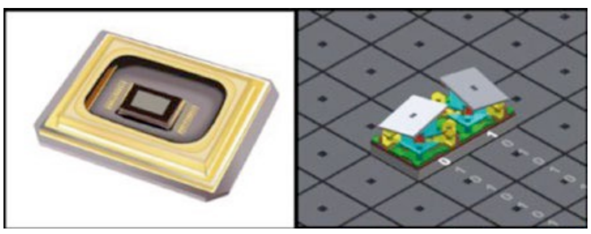
New technologies are expected to develop and grow in the next decade thanks the progress of upcoming innovations.

2.1 Lighting components and subsystem technologies

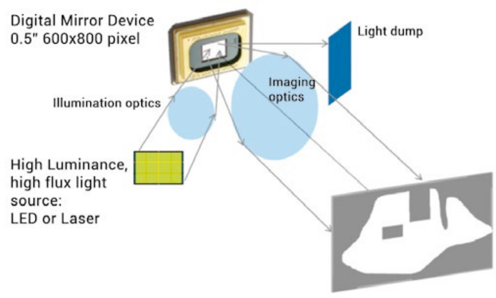
New or improved components are a key enabler for the design and commercialisation of innovative systems, subsystems, and functions. Two main families of components are driving such innovations in subsystems: optical components and light sources.

Optical Component Technologies & Subsystems
A considerable amount of new technology is under active development for new optical components. These technologies in themselves are not new; they are known from other industries, but they have to be made fit for the specific automotive requirements. They include:

DMD (Digital Mirror Devices)



DMD unit (L) and sketch of a micro-mirror cell (R)

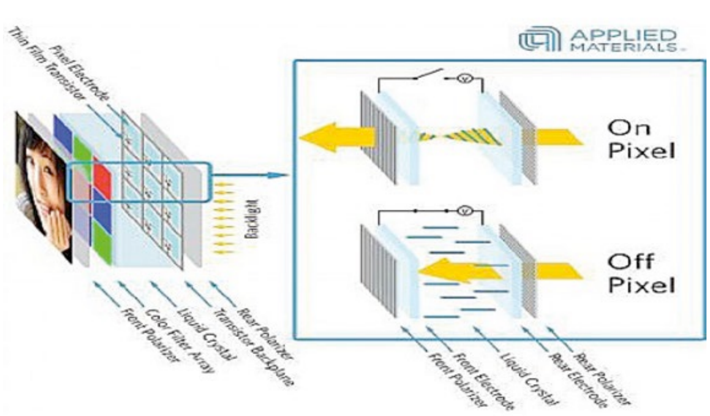


Operational principle of a DMD system

This technology is widely used in video projector systems. A DMD has up to two million micro-mirror cells, each 10 to 20 µm across and electronically controlled to move between "on" and "off" states. For automotive use currently only one supplier has a product on the market. Light is incident homogeneously on the DMD array. Depending on the electronically-controlled state of the individual micro-mirrors, the light is directed to an optical system for imaging or to a light dump. In this manner, time-dependent variable images can be formed.

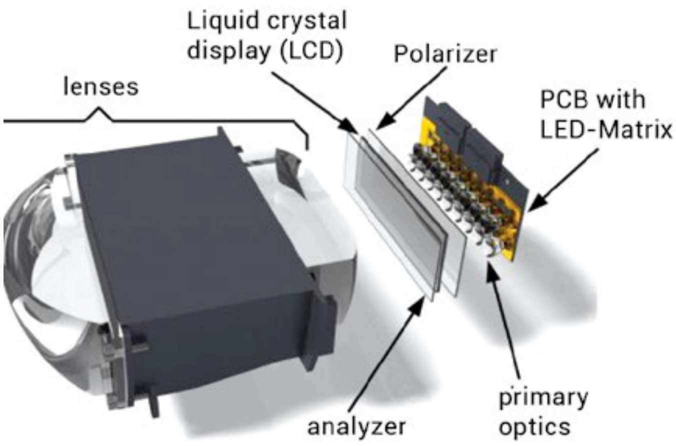
Technological challenges are the heat transfer from the mirrors and achieving uniform coating of the mirrors. An advantage is that no polarised light is needed, therefore efficiency can be high compared to technologies based on polarised light. Nevertheless, part of the usable incident light is wasted in a light dump. Another challenge of such systems is to build them compactly enough. Due to the small ±10° deflection angle of the micro-mirrors, the size and distance of illumination optics, imaging optics and light dump in relation to the DMD size has to be chosen adequately for reasonable functioning of the system. Right now the total surface of the optically active area is still limited, so first applications will be in auxiliary functions and not the main illumination; the three different DMD lights presented by OEMs or set makers to DVN in 2017 were only a complement to the main light. Their function was to improve the resolution to communicate to drivers, pedestrians, and other vehicles.

LCD (Liquid Crystal Displays)
LCDs are a well-known technology; they've been ubiquitous since the 1970s.



← ***Operational principle of an LCD Panel (a television screen)***

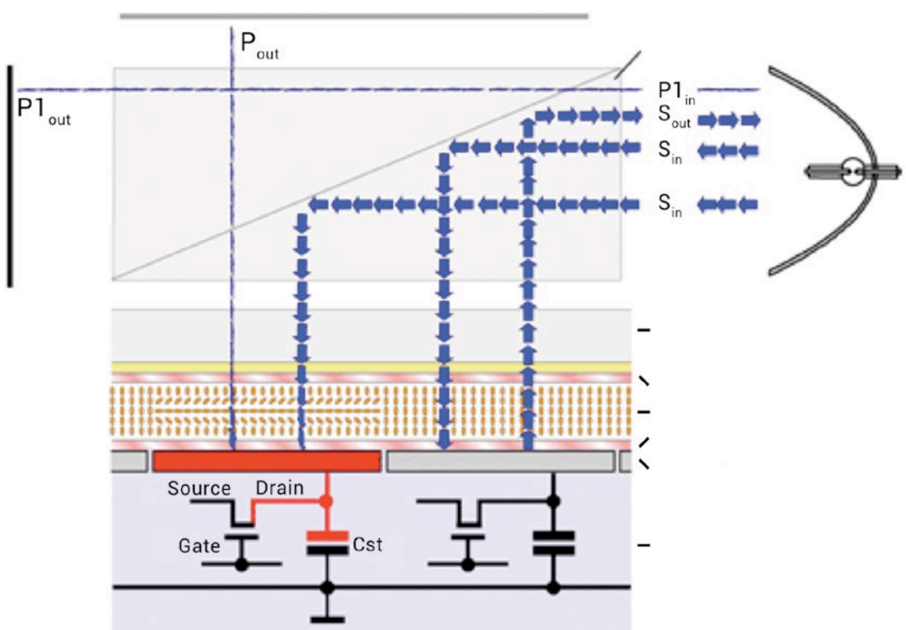
The principle of an LCD: an assembly of electrodes and liquid crystals are sealed between two glass-mounted polarising foils orientated at right angles to each other. If the applied voltage is zero, no change of polarisation occurs and no light can pass. When voltage is applied, the polarisation of the incident light changes by 90° and light can pass. An LCD screen consists of a huge number of such small pixels with sizes in the range 20 to 100µm.



← ***LCD system component stack***

For automotive applications with white light, no colour filter is used; the image after the front polariser is directly projected on the road. The light from an LED matrix with primary optics is incident on the LCD unit with the two polarising foils (polariser and analyser). The image of the LCD screen is then projected by secondary optics onto the road. LCDs are well-known and mature technology from other industries. System depth is rather shallow, an advantage in packaging. The main disadvantage is that polarisation is involved, therefore part of the incident light is wasted. The LCD headlamp developed during the VoLiFa project is self-contained with no additional hardware needed. It showed great possibilities with 650 Lm and 43,750 cd today and 1,000 Lm and 93,750 Lx expected…but there's been no new information announced over the last two years' time.

LCoS (Liquid Crystal on Silicon)



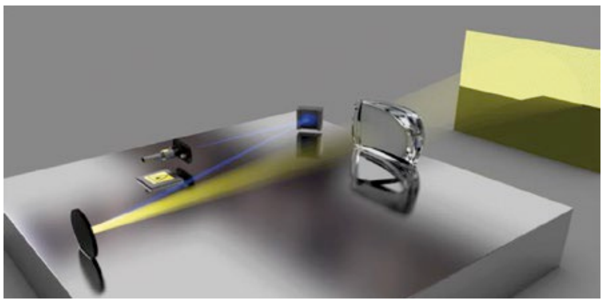
← ***Principle layout of an LCoS system***

Like LCD, LCoS is a technology from the entertainment industry. And, like LCD, it works with polarised light. The departure from LCD is that LCoS is based on reflection instead of transmission of light. A polarising beam splitter separates the two polarisation directions. One direction passes; the other is reflected onto the liquid crystal cells. If the cell is in the "off" mode, light is reflected back to the light source. In the "on" mode the light can pass through the beam splitter and hits a screen. Each pixel cell is 5 to 20 microns across. The inherent efficiency of LCoS is higher than LCD, but due to the more complex optical setup the resulting system efficiency is similar.

LCoS systems exhibit strongly advantageous heat management characteristics compared to LCD. Due to the reflection principle, hardly any light is absorbed. Moreover, LCoS with its silicon substrate can be directly mounted on a heat sink for efficient heat transfer.

Scanning laser systems with MOEMS (Micro-Opto-Electromechanical System)

Despite the similar designation, MOEMS are not a subtype of MEMS; they combine MEMS with micro-optics. A blue laser beam is incident on a MOEMS, which reflects it onto a yellow phosphor. The moving MOEMS scans over the phosphor, and at each position white light is generated as an admixture of the blue laser light and the yellow phosphor light. Therefore a sort of pixellation of the pattern on the phosphor takes place and can be imaged on the road by normal automotive projection or reflection optics.



← ***Lab setup showing the basic function of scanning laser + MOEMS***

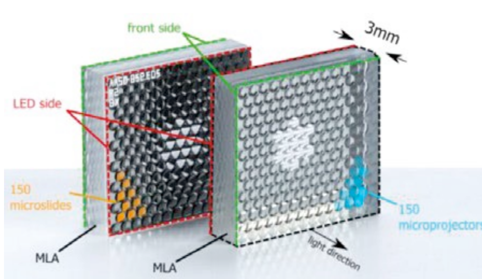
MEMS technology is flourishing in the automotive industry for a number of applications in acceleration sensors, gyroscopes etc. It is a semiconductor technology led by big suppliers, while research bodies like the Fraunhofer Institute put considerable resources into it. The new element for vehicle lighting applications is optical: the MEMS device is combined with a highly reflective mirror, adding the O for Optics to arrive at MOEMS. The mirrors can be moved in two directions. In resonant mode they usually operate with frequencies of 1-20 Khz. To show feasibility, potential and obstacles of a scanning laser based headlight, the German Federal Ministry of Education and Research (BMBF) founded the project iLaS (intelligent laser based adaptive headlight system) with the partners Audi, Bosch, Osram, KIT, and ZKW.

Laser scanning allows true energy-neutral redistribution and accumulation of light and related multi-channel luminous intensity distributions, with benefits including system efficiency, light performance, system far-field light output and electronic / MOEMS synchronisation functionality. MOEMS units are available in different sizes and with different operational principles, with mirror sizes ranging from 2 to 20 mm. An essential technology is that all units are vacuum-encapsulated under special glass covers to avoid corrosion and allow higher movement frequencies due to reduction of air resistance.

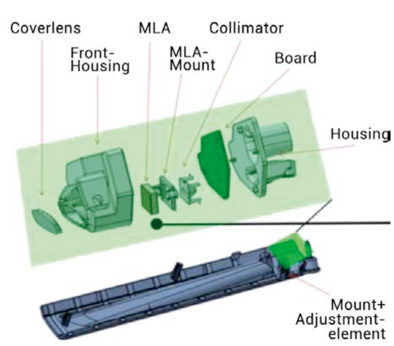
Some crosstalk between adjacent phosphor areas can occur, reducing contrast. A potential solution: pixellation of the phosphor by filling structures engraved in silicon wafers.

MLA (Micro Lens Arrays)

This technology is evolving in portable entertainment units' micro-projectors. For vehicle lighting use it has first come to the market with the welcome/exit light of the new BMW 7-Series.



Micro lens arrays



MLA system component layout

MLA components can be made of plastic, glass, or fused silica depending on application requirements. Size and shape of the micro lenses are variable across the MLA, so customised designs for a special application are possible. The component layout of an MLA system is shown in the figure on the right. Light from an LED board is collimated on the MLA. The light output of the MLA is then imaged on the road or pedestrian walk surface. This system is extremely compact and gives a high resolution in the near field around the car.

Holograms

A hologram foil consists of a stack of three layers. A light-sensitive, self-developing photopolymer film is deposited on a substrate of cellulose triacetate film (TAC). The photosensitive layer is then protected by a cover of polyethylene film. The foils are engraved with phase-sensitive holograms by visible laser light. In one hologram foil a limited number of different hologram pictures can be engraved.

← ***Tail light with flakes-design hologram***

Light from an LED illuminates the hologram via a reflector with micro optics to generate a parallel wave front. In this way the phase- sensitive information in the hologram is converted to virtual images around the hologram plane, creating the impression of depth.
Holograms offer slim thickness (<1 mm), light weight, and flexibility regarding new design concepts. As holograms are commonly used with laser illumination, the usage of divergent white light sources, e.g. phosphor-converted diodes, is an important challenge.

3-D Technology

← ***3D effect in a tail light***

Beyond more and more homogenous production rear lamps, automakers are asking for the next evolution or better revolution with marketing required "wow" effect. Technologies like holography, diffraction or light-field promise this evolution. Two directions are considered:

- Mirror tunnel systems, already used in production lamps, reflect light rays between a rear mirror and a semi-transparent front mirror to create a light tunnel effect. The size and geometry of the mirrors define the number of reflections and the direction in which the reflections open the tunnel.
- An alternate 3D-light in rear lamps uses either optical elements in a 3D-arrangement or optical parts with 3D-shaped geometries. The sculptural design of the rear lamp can be pronounced by a 3-D shaped outer lens.

Beside these established solutions, new technologies enter the automotive market.

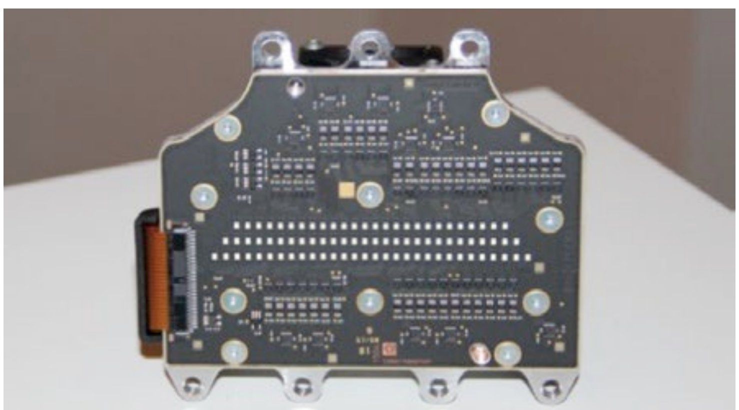
Light Source Technologies

As a second major source for innovation, light source evolution has sped up in recent years and will carry on as a strong driver. LED sources continue to grow more and more sophisticated, and laser-based sources are coming onstream as well. In this chapter we discuss the main innovative approaches for new and improved light sources.

HB (high-brightness) LEDs

In striving to compete with the new ultrahigh-brightness laser light sources, LED technology has evolved for higher-current operation. Instrumental for this development was a new approach to extract heat from the LED junction. The droop effect means high-brightness LEDs are a compromise between luminous efficacy and luminance. The general trend shows that luminance values above 200 MCd/m^2 are achievable with HB LEDs at a reduced luminous efficacy of about 70 Lm/W. This luminance is still about a factor 2-3 lower than reported from roadmaps of laser-based sources. Even in the long term it is doubtful that HB LEDs can compete with the luminance of laser-based sources, but there are certainly applications wherein HB LEDs will be important at least in the mid term due to their lower cost compared to laser-based sources at least in the next 5-7 years.

MLS (Matrix Light Sources)



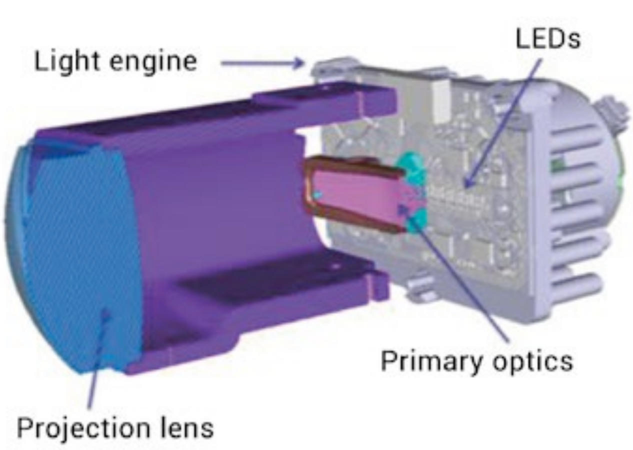
← ***84 LED Matrix Light Source (MLS)***

For this type of light sources a row or matrix of individual light points (pixels) is placed on a PCB. The LEDs can be singly addressed—switched on and off independently of each other. These light sources can be set up with or without electronics included. Their range is believed to be limited to about 100 LED pixels. Typical applications are current ADB systems with matrix beam.

MMLS (Micro Matrix Light Sources or "Micro-AFS")

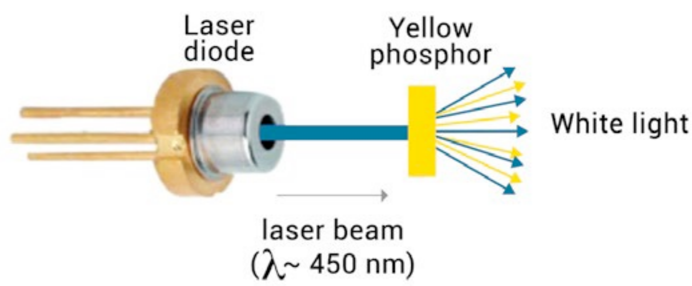
This type of light source is based on a pure silicon technology. Instead of a simple silicon carrier as in normal LEDs, a silicon carrier including CMOS switches is used. The LED pixel array is then grown on this carrier and the pixels can be individually addressed by the CMOS switches.

In laboratory research projects, MMLS with up to 1,024 individually-addressable pixels have been realised. Industrial availability is estimated around 2020. At this stage there is no technical reason to assume significant hurdles even for finer array structures. We track industry consensus projections at more than 100 kilopixels within 5-7 years. MMLS will then be placed on circuit boards. Several of these sources can be combined to create even more variation possibilities in the beam.



The light from the MMLS LED board is pre-shaped by primary optics which may be part of the LED board or placed separately. For imaging on the road, normal projection or reflection optics can be used. This type of system boasts simple construction and high efficiency compared to systems with mirrors or absorbers between light source and imaging optics. A disadvantage for the time being is that only light sources with about 100 matrix elements are available on the market for industrial production use. It is expected that light sources with higher pixel count will come to the market continuously in the next 2-7 years.

Laser



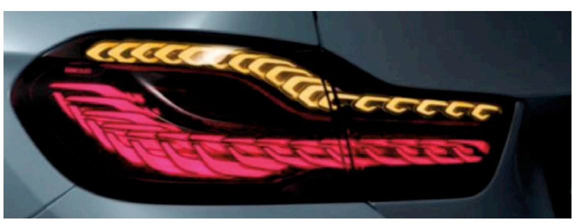
← ***Blue laser light conversion with yellow phosphor***

The light output of this technology originates from the combination of a blue laser with a yellow phosphor. The laser irradiates the phosphor, part of the light passes as scattered blue radiation, and the other part is converted by the phosphor to yellow light; the admixed result is white light.

Presently, laser diodes with about 2 W blue radiation are available for automotive use; in a next step a blue output of about 4 W is expected. In case of even higher wattages the packaging structure must change to a flatter topology for heat transfer reasons.
Nichia recently announced automotive laser diodes which directly emit white light, and the indicated future performance is clearly superior to HB LEDs. Key questions are how white laser diodes compare to blue diode/yellow phosphor systems in terms of performance, cost, and application logistics. Direct projection of white laser light on the road seems unlikely (for safety reasons) so diffusers are likely to be applied.

OLED

OLEDs—Organic Light-Emitting Diodes—are flat light sources with much lower luminance than LEDs. They have mainly been developed for decorative purposes. The figure shows the structure of an OLED. The basis is a glass plate covered by a transparent TCO electrode. On this structure the organic layers for light generation are deposited, and on top of those the second electrode is placed. The whole structure is hermetically sealed, because the organic layers would be destroyed by contact with air. For automotive use OLEDs are in a very early stage and their main draw is to create signalling functions with distinctive styling features which cannot be achieved with other technologies.



Scientists have recently succeeded in using a new active principle to reduce the number of different layers in OLEDs to just one. With their first prototype, the scientists were able to show that with a voltage of only 2.9 volts, their OLED can generate a brightness of emitted light of 10,000 cd/m^2, about 100 times the brightness of modern screens.

2.2 Comparison of Technologies

Technologies can be assessed by four main criteria: near-field illumination range, resolution, efficiency, and operating temperature range.

• Near-field illumination range
MLA has the leading advantage here. The main near-field tasks are communication to other road users and illumination for cameras. MLA can be constructed very compactly, so can be placed within tight space constraints. MLA is also less costly than other technologies. Present systems are static, but future developments will bring dynamic MLAs. For mid- and far-field illumination and communication, other systems are preferable.

• Resolution
Presently DMD is the only system providing ultrahigh resolution. LCD and LCoS today can provide high resolution with the potential to develop to ultrahigh at least for LCoS. Scanning laser systems provide high resolution, although in this case the definition of "pixel" is not quite fully applicable, due to the dynamic and continuous light generation approach. Existing systems using matrix light sources on PCBs give low or medium resolution depending on their numbers of singly-addressable LEDs. Further development of this technology's resolution is not likely. Systems based on current prototypes of micro-matrix light sources are beginning to reach high resolution. Further stepwise development through high to ultrahigh resolution is forecast within a 7-10 year timeframe.

• **Efficiency (in subtractive and additive systems)**
Subtractive systems—DMD, LCD, and LCoS—are all only using part of the light delivered by the light source, because they send some light into a light dump or reduce light by polarisation. These systems are thus "subtractive", and they have an efficiency disadvantage compared to technologies which use all the light from the light source. There are attempts under way to overcome this disadvantage for the case of polarisation, though the reduced inefficiency brings higher complexity and cost. LCD achievements of the VoLiFa project show impressive possibilities of efficiency improvements.
Additive systems—MOEMS and (micro) matrix light sources—can in principle use all the light from the light source to image on the road, not counting the usual optical losses. In these "additive" systems, no substantial subtraction of light is present.

• **Operating temperature range**
DMD, LCD, and LCoS in their present developmental stages are subject to temperature range limitations. The two liquid crystal technologies (LCD, LCoS) cannot withstand low temperatures because the crystals become solid; new material mixtures are under development to address this. At high temperature, the crystals can become isotropic so they no longer work; LCoS here has the advantage of low light absorption and good dissipation by heat sinks directly mounted to the product. DMD technology has limited tolerance of high temperatures; due to high-frequency movement of the micro-mirrors, solid thermal conduction to the surroundings is crucial.
MOEMS and (micro) matrix systems are less critical with respect to temperature range. Matrix light systems with circuit board technology can withstand the automotive temperature range.

DMDs will pave the way for high and ultrahigh-resolution projection. They have the capability to be first to the market, but they have intrinsic disadvantages as subtractive systems, which will allow them only limited application in the medium to long term. MOEMS and micro-matrix systems are both moving in the medium-long term to high and ultrahigh resolution; additive systems are best positioned to be the main technologies after 2025.

Comparison of technologies for signalling
For signalling functions the different technologies can be assessed by four main criteria:

• **Styling opportunities**. Mid-power LEDs allow big variations in styling including an enormous range of colour even (e.g., deep "super red" light, numerous different amber/yellow variants). Recently also rear lamp designs giving 3D impression have been realised. Mid-power LEDs are a reliable and cost-effective light source. OLED is not yet applicable for all functions, and the roadmap is not clear. Hologram prototypes offer huge design potential with their unparallelled 3D floating-in-space image capabilities. GLT (graphic light technology) is an enabler to combine advanced styling without sacrificing functional performance at a reasonable performance/cost ratio.

• **Dynamic functions** From a performance/cost perspective, mid-power LEDs are best suited to serve simple dynamic functions as applied for the likes of ARS or progressive turn indicators. GLT is supporting LEDs in this aspect. In case of more complex animations, OLEDs and holograms enter the picture. They have the potential of finer structured images, but at high light intensity the structuring may not be visible.

• **Communication** Arrays of mid-power LEDs can provide simple messages (words, simple pictograms) with low resolution. More complex structures are difficult. OLEDs are capable to do the same, but intensity remains a constraint—as does performance/cost ratio. Holograms are best situated to display finely-structured images, and multiple predefined images in one hologram are possible.

• **System packaging volume and depth** Mid-power LEDs bring a packaging depth in the range of 10 cm; GLT can reduce this. If all functions can be realised with OLEDs or holograms, extremely thin rear lamps in the range of several mm could be realised, if driver electronics are placed outside of the lamp. In this manner it might be possible to place rear lights on top of the sheetmetal, without openings in the car body.

2.3 Approaches for mainstream LED migration from filament lamps

Cost is the main bottleneck for broad filament-to-LED migration. Automaker consensus is that a widespread general implementation of LEDs will occur once the LED system cost premium over incandescent drops to about 30%. LED cost reduction strategies can be applied on a variety of fronts:

Modules

← ***LED modules***

A first step to achieve cost reduction for LED systems is to go for a modular concept. Instead of designing optical solutions and components for every model, makers will base their LED systems on modules which can be used across vehicle platforms. This approach may somewhat constrain the freedom of stylists, but the cost reduction will be a tangible reward.

LED efficacy

Another key path to reduced system cost will be the ongoing increase of LED efficacy. The math is simple: more lumens per watt means an LED chip count reduction for whatever level of performance—and the knock-on effects of reduced chip count can further drive down cost (lower power consumption = thinner wires, less power dissipation = smaller heat sinks, etc). With current technology, a plateau at about 150 Lm/W is expected around 2025, reducing LED chip count by about 20% versus today's levels. Advanced research indicates the potential of a further step in efficacy to about 250 Lm/W on a timeframe of about 10 years. This would bring another cost reduction potential of 40% on LED cost.

The cost-lowering effect of efficacy increase via heat sink volume reduction warrants further detail: with better efficacy and better thermal contact between LEDs and their surroundings, heat sink volume and mass can be reduced leading to further considerable cost benefits. Moreover, driver electronics will go down in cost due to increased integration and scale.

LED cost

A general guideline on LED cost trends can be deduced from Haitz's Law. This rule applies to general lighting LEDs, but also will apply to automotive LEDs in a relative sense, because the basic value of cost per lumen will be different due to more stringent requirements for automotive service. In line with this prediction also for automotive use, LED costs per surface will be driven down by three effects:

- Wafer sizes for LED manufacturing will further increase, meaning the production of more chips within the same processing time;
- Overhead costs will go down with increasing production mainly due to growth in non-automotive areas, and
- Increased competition by more makers entering the automotive field will increase downward price pressure.

2.4 Other technologies

Some technologies, which have not been on the menu for vehicle lighting in the past, will have a decisive impact on the core lighting system performance in the future.

Modularisation, miniaturisation, and integration

Lighting systems are growing more complex and comprising more and more components and subassemblies. This will complicate supply chains and pose quality and cost challenges. One strategy to address these challenges is to integrate components and subassemblies into modules which can be tested separately. This will also reduce the number of interfaces (connections) in the system and thus can improve reliability and cost. A striking example is the move from plain LED sources to matrix sources to micro-matrix sources, as discussed previously in this report.

← ***Koito headlamp with lidar sensor***

The miniaturisation of components and subassemblies will become practically mandatory. The trend is to increase the functional content of front and rear lamps with space constraints either shrinking (or at best not enlarging) due to vehicle exigencies and styling desires. An example is the wish of some manufacturers to include a lidar system or a camera—or both, or more; viz Marelli's latest Smart Corner system—into the headlamp, which will leave less space in the lamp for other components. Moreover, the integration of new lighting functionalities such as DMD projectors in a headlamp, as seen for example in the Mercedes S-Class prototype puts more packaging and volume pressure all components contained in the headlamp. The Koito headlamp shown here has a small solid-state lidar sensor successfully integrated. Lidar built in the headlight functions as a main sensor for advanced driving support system and autonomous vehicle system.

Computer power, software, data transfer

The trend toward intelligent, adaptive lighting systems implies a concommitant growing need for more computer power devoted to lighting. Data from a plurality of sensors must be analysed and transferred into actions of the lighting system. In this context four main factors must be considered:

- The data handling capabilities of CPUs will steadily increase according to Moore's Law, named for an Intel cofounder who posited that transistors per semiconductor surface area will double every 12–24 months. Currently the doubling period approaches 24 months. Additionally the speed of CPUs will not increase linearly with transistor count due to coördination tasks within the CPU. Nevertheless, computer power in general should show a stronger growth speed than automotive digitalisation. Depending on vehicle architecture, concepts with distributed local ECUs controlled by one master CPU are also under discussion.
- The controlling software is growing more and more complex with e.g. the rising number of pixels to be controlled by ever-more-detailed sensor input. This means the software is also more susceptible to malfunction—more lines of code mean more chances for bugs. Therefore, software testing for reliability, stability, and resistance to hacking, and timely release and deployment of updated software, are two major, important focal points for this type of software development in the future. Aeronautics is a benchmark industry for reliability, and the banking sector for resistance to hacking.
- The ever-increasing amount of data to be gathered and transferred will lead to strongly increasing demands on the board nets. The data rates to be transferred will come close to data rates necessary for television. Therefore there will be competition and "traffic" among the different functions in a vehicle to get priority for data transfer. A potential scenario for lighting could be that specialised, VGA-type data transfer lines are used for steering the lighting functions.
- Front and rear lamp topologies may well have to change. Presently LED driver electronics are mostly placed outside of the lamp. In the future the most likely scenario is that driver electronics will need to be placed close to the light sources or integrated in case of standard LEDs.

Simulation

Future vehicle lighting will be based on more complex, sophisticated and functionally-loaded lamp systems in the greater context of an increasingly-connected vehicle. To manage the heavy engineering workload necessary for the design of such systems, simulation- based techniques will have to take an even more dominant role than today. The known simulation tools in optical, thermal, mechanical, and electrical modelling will be further upgraded with the inclusion of new optical elements and light sources, and additional simulation tools will develop to focus on integration and communication with the lighting system in the digitally-controlled vehicle network. Another, even further reaching aspect of simulation is coming from the scientific community: reality-adapted models have been developed to simulate the reduction in nighttime crashes depending on road illumination under selectable surrounding conditions. This simulation technology will further develop into a major tool for decisions about functions, and for speeding up related regulatory processes.

Artificial intelligence (AI)

AI is beginning to be included during the testing and release phases of new vehicles. This will become more and more common—and practically mandatory for the release of autonomous vehicles. To embrace this technology is to take advantage of a major opportunity to build up a predictive tool for avoiding and resolving critical traffic situations, thus avoiding crashes. This will surely warrant strong attention and resources from shrewd and thoughtful makers. A first attempt in this direction has been reported for overtaking situations, involving lighting to facilitate the manoeuvre. In general, the appearance of AI can lead to revolutionary changes in the way exterior lighting will be specified, configured, applied, and operated in the future.

More technologies

There are specific technologies, materials, and components supporting vehicle lighting innovation. A comprehensive discussion of them all is outside the scope of this report, but here are some of the standouts:

• **3D printing** is a quickly progressing technology. In general lighting, printing of optics has entered the field; application of this technique for vehicle lighting will come onstream once accuracy, internal diffraction, and other challenges are addressed.

• The introduction of **optical silicones** over the past few years has provided exciting design and performance opportunities for adaptive driving beam systems, such as the multi-beam and matrix lighting. Optical silicone material and processing technologies continue to advance and open up new applications, as flexible light pipes beneficial for signature lighting. Silicone-on-glass is an emerging technology from the solar industry and in future may also impact vehicular lighting.

• **Diffractive foils** work with the principle of wave optics rather than ray optics. Their combination with other optical elements can create very homogeneous images.

• New membrane materials are currently under discussion to support moisture exclusion from automotive lamps. Such membranes applied in a sophisticated way for automotive vents can strongly contribute to reduced water condensation especially in areas with high humidity.

• The introductions of new technologies like LED, laser, or OLED has an impact on the material used in reflectors. **BMC** (Bulk Molding Compound or Glass-fibre thermoset polyester) has been used in the past mainly for dimensional stability and temperature resistance. With LEDs, reflector dimensions are very often smaller, and temperature is reduced versus halogen or HID. In general the first choice for reflector material is uncoated polycarbonate, but the local temperature close to the LED can be high enough to justify the use of heat resistant thermoplastic resins like APEC. For applications with few LEDs and bigger reflectors, the use of BMC is selected again for dimensional stability. For projector systems, glass was the only possible choice for the lens with halogen and HID, but with LEDs, again polycarbonate with multiple layers to build thick lenses is selected, for better reproducibility of shapes, including stylistic lenses and reduced weight. It also allows setmakers to build lenses in-house rather than buying from a specialist supplier like Docter or Bicom. However, polycarbonate lenses are optically inferior to glass; in particular, PC lenses exhibit more chromatic aberration, which can aggravate issues with colour fringe at the cutoff.

The impact on Signal lighting is not significant with the use of ABS (Acrylonitrile-Butadiene-Styrene) or ABS/PC for housings and PMMA (acrylic) for lenses.

2.5 Complementary and competing technologies

Radar and **lidar** are two technologies competing with lighting in the obstacle-detection field. These technologies are focussed on highly exact determination of obstacles' locations. Radar, especially, is insensitive to surrounding conditions like weather, but can work on long distances. These two technologies do have two key disadvantages compared to lighting: they cannot discriminate colours or "read" two-dimensional structures. Therefore, they cannot recognise vertical (road sign) or horizontal (road surface) traffic control and advisory markings. For these reasons they will support lighting,but cannot replace it on foreseeable time frames.

Similarly, **IR** (infrared) vision technology has the advantage of not glaring other road users and being less sensitive to weather conditions than visible-light vision, but it shares the key disadvantages of lidar and radar: no colour vision and no flat structure resolution.

Ultrasonics are a special technology for near field detection, not foreseen to compete with or support lighting.

WiFi technology can be deployed for communications between vehicles and other road users or even vehicles and road signs. Futurs scenarios imagine that road infrastructure additional to coloured signs could involve WiFi emitters for communications with vehicles. In a similar scenario, pedestrians could carry a special WiFi-based unit to communicate warnings or "go" signals with vehicles or even use their mobile phone for such communication.

GPS, particularly the more accurate variety to be introduced in the next years, can support and augment the functionality of the exterior lighting system to adapt beam patterns to vertical and horizontal road curvature and suchlike. In this sense it is complementary and not competing.

Cameras for visible light are the most important technology in combination with exterior lighting. Currently exterior lighting and cameras are complementary to each in the sense that cameras, like human eyes, need light to function. A potential future scenario holds that the camera could direct the car's lighting to be better able to detect objects, road markings, and so on. Under these conditions a real symbiosis between lighting and cameras would exist. In this context it should be remarked once more that exterior lighting in the next decade has to serve illumination and safety (glare…) requirements of human beings and cameras. On the other hand with ever increasing detection and discrimination power of cameras through better hardware and software, the need for good lighting may eventually decrease. However, drivers and passengers will still need a different but good illumination of the environment.

3. Application and styling trends for exterior lighting

New and adapted functions for vehicle lighting are expected to develop and grow in the next decade. Special attention is given to the coexistence of human-driven, semi-autonomous, and fully-autonomous vehicles mixed in traffic. Additional influence may be exerted by electric vehicles and road infrastructure.

Society and industry trends must be incorporated in the design of new applications. Especially the needs of drivers and other road users must be respected and supported, and should guide the implementation of new or improved functions. This is important today, and will become even more so in the upcoming situation of mixed human-driven and autonomous vehicles. Another strong influence will be penalties for noncompliance with environmental rules and targets. We expect evolutionary developments with respect to exterior lighting.

Regulations are a key factor impacting application trends. New functions are evaluated under safety-based criteria. Supporting data are required, especially in North America. This process is time-consuming and in itself has an evolutionary character; some revolutionary elements would be helpful to the industry.

Technology enablers are a key basis for solid innovation in functional applications as well as styling. Current exterior lighting technology shows a high speed of innovation, but no real revolutionary impact on applications or styling is on the horizon. If revolutionary impacts develop, they will be based on software and artificial intelligence related technologies.

Stylists and designers will maintain a dominant influence on future lighting functions. As has long been the case, they will continue to grasp every opportunity through new lighting technologies and functions to make vehicle design more attractive. In general an evolutionary trend of light styling can be expected; in detail of course some revolutionary ideas will come up. A striking recent example is how the safety-based DRL function has come to serve as a main element of brand signature.

Competing and complementary technologies like these will influence the application of exterior lighting in the future. As a result, the application pool will give rise to improved functions in the traditional see-and-be-seen aspects of road illumination and signalling. Similarly, styling will benefit by new options. A new element entering the scene of exterior lighting is sophisticated communication going well above known signalling. This communication will focus not only on safety, but also will come to include convenience features. This newly expanded way of thinking about communication can be seen as revolutionary in the exterior lighting realm.

3.1 Illumination Functions

Low beam, high beam

In Europe and eventually in America, strong growth of ADB systems is expected. Nevertheless, a lot of vehicles will carry on being equipped with basic low/high beam functionality. Therefore, this function will remain for a long period of time, though increasingly augmented by automatic beam selectors. In Asia's mega cities, ADB in its current form does not show strong merits, so we expect in that region low/high beam systems will remain prevalent for the foreseeable future. A revolutionary game changer could be a derivative of ADB tuned to the needs of mega cities.

Cornering light

Cornering light is perceived as useful for traffic safety, especially avoiding pedestrians, cyclists, and other vulnerable, difficult-to-see road users. Enduser studies find that cornering lights are appreciated by about 75% of drivers. Technically a rather simple function, and an affordable one, its benefits are clear and will lead to a long life as a separate function, as integration into an ADB beam pattern may be not cost-effective.

Fog lamps

In the past fog light was the third illumination function, often sold as an option. Its efficiency was not obvious in fog but its light was appreciated thanks to its width. Today's headlamps produce very wide, very bright foreground light, rendering fog lamps functionally superfluous; they are more and more replaced by cornering lights of one kind or another. In the future, adverse weather light will remain important and sensors should be integrated in the fog lamps thank to its location at the bottom of the car.

AFS

Application of AFS, with its finite number of define beam distributions (town beam, motorway beam, country beam, foul weather beam, etc) will steeply decline, excepting the bad-weather beam. Rather these modalities of the AFS concept can and will be integrated into ADB systems.

ADB

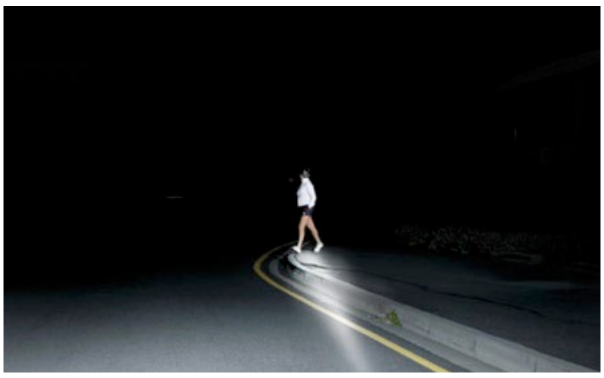
High end solutions will boast the ability to mask more cars simultaneously and a soft movement of the ADB beam pattern so as not to irritate the driver. Masking of non-driver other road users and dedicated illumination of road signs or obstacles are added functions presently under discussion. The technology needed for this high end application will be ultra high-resolution projection for the far field. Entry level solutions have the target to equip mid- and low-range vehicles with an affordable ADB system. Most importantly, there are regionally different opinions on the merits of ADB. In regions without many mega cities, such as North America and Europe, ADB is well accepted by end users (ADB is not yet available in America due to regulatory lag, but tests support this statement).

In China, Korea, and Japan with a lot of mega cities, the benefits of ADB are not clearly seen, as much driving is done at speeds lower than the ADB threshold.. Out of discussions in Asia the idea was born to try to define a special ADB functionality useful for mega cities. If this idea can be realised, it will be a revolutionary game changer for the desirability and deployment of ADB in Asia.

Laser high beam booster and spot marking lights

The laser high beam booster is impressive in theory and practice; it can throw light 600 metres down the road without adding foreground light. But this is of very limited practical advantage for most drivers; there aren't many roads in the world flat enough, fast enough, and empty enough to allow or require a 600-metre high beam. Potentially it may evolve into a combination of high beam with marking lights.

Spot marking lights



← ***Spot marking light***

These are much more practically attractive; they are a camera-driven system that detects pedestrians (or eventually animals, etc) outside the vehicle's headlight beam and highlights them with a spotlight beam, separate from the headlight beam, that also draws a line of light on the road surface to direct the driver's attention to the pedestrian while simultaneously alerting the pedestrian to the presence of the approaching vehicle.

3.2 Signalling functions

Daytime Running Lights
The DRL function was introduced as a safety feature and as such has value in itself. On top of that the industry developed it into a tool for brand signature by diversified LED applications. With the increasing pressure on CO_2 reduction by penalties (DRL is active in the test cycle) in some CO_2-critical cases carmakers may decide to go for simple, energy efficient, less differentiating solutions. But as a general trend we expect that the DRL function will remain a major lever for styling and brand signature in the future, and its value in this direction may still increase if the main illumination functions become smaller and less pronounced.

Turn signals
The direction-indicator function will remain as one of the most important signalling functions as long as human-driven and semi-autonomous vehicles are on the road (i.e., for the foreseeable future). There will be an evolutionary development by adding animation features like the sequential or progressive turn signal, which we expect to become implemented globally in the mid term. Another regionally important safety, styling, and application aspect is the trend, however halting and fitful, toward amber (rather than red) rear turn signals in North America where both colours are legally permissible. This trend toward amber is driven by the suggested introduction of credits for amber rear signals in vehicle safety evaluations.

Adaptive rear lights
Adaptive rear light systems (ARS) that tune their lighting to brake application force or prevailing conditions like day/night, fog, or bad weather are known; they have been applied for some time now. The ARS concept will show significant growth in the next decade, enabled by the strong cost reduction efforts put into LED systems for rear lighting.

3.3 New communication functions for safety

Car to driver

Construction guidance lighting

This function, which projects vehicle-width lines ahead of the car, can help the driver in the decision of whether to pass another vehicle in road areas with limited space. In the event of passing, it supports the driver to best keep his lane—all without disturbing other drivers. We consider this function useful and likely to expand in application.

Obstacle avoidance lighting

This is an early warning about obstacles on the road detected by sensors on the vehicle or even coming from GPS. The projected light stripes warn the driver and guide them around the obstacles. Initial investigations show that more than 75% of drivers would follow the stripes. No disturbance of other road users is evident. This function useful and likely to proliferate.

Optical lane assist lighting

Unclear road markings are illuminated or missing road marks are projected on the road to give guidance to the driver. This system is driven by cameras and/or GPS. Disturbance or confusion of other road users is an open discussion. If disturbance is nil or negligible, we consider this function to be useful and likely to proliferate.

Warning Functions

Studies have shown that stripes projected on the road in front of the vehicle cause most drivers to intuitively slow down. If cameras or other sensors detect traffic irregularities, such stripes can be effectively used to warn and slow down the driver. In future, an addition of symbols or pictograms will strengthen and focus the message.

If a driver applies the brakes urgently and severely, the vehicle can project symbols to the rear. In case of traffic with medium distance between cars this function seems logical. In case of more crowded traffic, animated rear signalling like ARS seems to be more effective. Other options under consideration are pictograms to indicate warnings about traffic jams, accidents, road construction work, etc. Since such warnings do not need immediate action from the driver, it seems more logical to integrate such functionalities in HUD or holograms or LED arrays at the rear of the vehicle rather than projections on the road.

V2V, V2VRU (vehicle to vehicle/vulnerable road user)

Pedestrian crossing

If a vehicle or driver detects a pedestrian positioned as though to cross the road, a crosswalk is projected on the road surface. This can be useful at night, because no face-to-face communication by eye contact is possible after dark.

Turn signal projection

Projecting the signals of the turn indicator on the road/walkway can give additional warning to VRUs, thereby improving their safety. The level of disturbance seems limited. We consider this function useful and likely to proliferate.

Door opening light

By this function VRUs (especially bicyclists) are warned that a vehicle door will be opened. This will serve safety of VRUs, but also contributes to safety of passengers who want to leave the vehicle. We consider this function as useful, especially under crowded traffic conditions.

3.4 New functions for convenience communication

Navigation symbol projection

Projection of turn direction, lane selection, and other navigation symbols on the road is intended to support the driver to find his way. This can help also other road users to identify the intended movement of a vehicle, but direction indicators serve this same function. Similarly it is more logical to use the HUD to communicate to the driver. Additionally a uniform symbol language has to be developed, because other not only the driver, but also other traffic participants are affected. In crowded traffic this function could lead to disturbing and unclear situations, but on rural roads with low traffic density this application may be useful. Overall, we are not in favour of this function.

Find-your-car lights

In big parking garages or with crowded rental car areas it is often difficult and time consuming to find a parked vehicle. This situation will also occur more and more with growing car sharing fleets. Therefore an indication of your car by symbol projection on the road will be helpful. This can be applied to front and rear.

Welcome/exit/departure lights

This type of luxury convenience function will grow in line with the trend of vehicle buyers spending extra money for impressive gadgets. These functions will develop further by adding animations to the portfolio. Furthermore, with growing digitalisation of lighting, a trend to offer personally programmable editions of such functions can be foreseen, including the potential for new business models. Presently, regulations forbid such functions while vehicles are moving, but there is growing pressure to approve them at least at lower speeds.

Advertisement and messaging

This function may become a big hit especially in Asia. It can be the basis for new business models for financing the major investments in such new lighting technologies. Such functions will not be governed by vehicle approval regulations, but will have to follow different national and local laws as well as landowner decisions. Owners of parkades would allow or forbid this type of usage. We regard such functions as non-essential and not beneficial to safety, and we could lament (in advance) the spread of advertising's mental pollution to yet another space, but it could be nice for advertisers.

Autonomous driving status indication

To communicate vehicle status, indication lights can be installed on the vehicle. By this means it may be easy for authorities to discern when vehicles are allowed to enter defined zones, while other road users can distinguish whether intuitive communication with the driver is possible. The ideas about this topic show a big diversity, with no clear trend visible. We consider lights as indication for authority control purposes to be a cost effective solution. Communication with other road users is a matter under discussion; it may be helpful but also misleading depending on interpretation, and it may even be counterproductive (if human drivers will decide to "bully" autonomous vehicles). Therefore we do not hold a clear opinion about such functions yet. Nevertheless, in autonomous mode, a signal function indicating to pedestrians that the vehicle sees them could be useful.

Others

Automatic adaptation of exterior lighting intensities depending on ambient lighting levels will become a strong trend. Safety, energy savings and avoidance of glare and light pollution are the main drivers. Broader beam shapes to support cameras in their lateral detection range are another development direction. Today's difficulty in attaining and maintaining good headlamp aim will be solved when competent, reliable digital automatic beam control will become common.

3.5 How will mega trends impact styling and vision for future cars?

Clearly the trends towards autonomous driving and electrification trigger new directions in car design. Most obvious are studies to redesign the interior of the car for when the driving task is no longer centrally important (autonomous cars). In this vision the car interior is considered as a cocoon in which people can relax, work, sleep, etc. Next to autonomous driving, also electrification will have some impact on future car design: the flat-pack battery location at the bottom of the car will create additional styling possibilities compared to cars with a combustion engine. Based on our discussions with industry experts we can conclude that we do not see a dedicated styling direction for exterior lighting on AVs and EVs. At the same time it is clear to all stakeholders that styling will remain a strong driver in the next decade for new exterior lighting applications. It is also clear that automakers will continuously seek new, different, and attractive styling to spur a desire in car buyers for new models. In exterior lighting design, four overarching trends can be expected:

• **The design of light becomes more and more decoupled from its primary safety functions**, to become in effect a new design material. Originally the shape of lighting was purely functional (generally round). Form followed function. But during the last 100 years designers got increasing freedom to diversify the shape of light, thanks to new technologies.
Now the DRL function is getting more and more important to define the exterior styling and brand identity of the car, because the DRL function is always switched on and has more design freedom than high and low beam headlamps. Lights have become one of the major design éléments to express visual identity. Especially for emerging brands not constrained to shapes with ancient origins; they focus very strongly on the styling aspects of lighting as an expression of progress and to position the new brand. But in the future this can go much further. Not only a decoupling of shape and function due to miniaturisation, but really starting to use light as a new design material. This will offer new styling directions to make a stronger brand identity not only during the day (DRL) but also at night. We'll start to use light just like we have used chrome.

• **Vehicles are becoming more and more intelligent**
This leads to an increasing need for communication and interaction. Styling will also serve the need to express what content is available in the vehicle. In this respect lighting is a very logical and strong styling tool; it's a great communicator for the growingly intelligent content of a car. Furthermore, lighting is dynamic. In terms of light styling, the next additional parameter will be dynamic lighting, to enhance the interaction with the vehicle. The first application was made by Audi with their dynamic turn indicator. But eventually dynamic lighting will require new competencies in design—from working with shapes to working with movement and interaction. In the long run, the rear lighting application can evolve more and more into a kind of display. Of course these functions can also be linked with the trend toward car sharing, to use lighting information to recognise and announce or react to scenarios.

• **Interaction of the vehicle with its environment**
As cars become aware of where they are through GPS and onboard maps, lighting will automatically adapt to the need of its environment. A dark country road has different needs than a crowded city centre. And full-colour light projectors can play a big role in this. Future lighting has the potential to generate a more positive presence of the car in its environment. For instance by advertising that the car is driving in a zero-emission mode, supporting other road users (e.g., pedestrians or cyclists) by providing them extra lighting even when the car is not in use, and in augmenting street lighting, car lighting can contribute to real and perceived safety.

• **"Zero threshold" use**
Car users increasingly expect operation to be easy and intuitive, and won't spend a lot of time on a learning curve. For lighting this can mean full automation with no on/off or mode switches, including adaption to adverse weather conditions; fully-automated beam control (ADB); use of the B-pillar to display additional lighting symbols and communication to seamlessly understand your connection to the car, and active and personalised lighting functions integrated in door handles. Zero threshold operation will also reduce driver stress and increase safety by dint of better operation and reduced fatigue.

4. Vehicle lighting regulation

The regulatory rules and regulatory bodies form one of the important pillars of traffic safety. These rules differ according to the regions of the world and even from country to country or state to state.

Regulatory Systems influencing Vehicle Lighting

Overall vehicle lighting is influenced by various types of regulations, i.e. Construction of Vehicles, The Vienna Convention on cross-border traffic, Use Requirements and Circulation Requirements.

Construction of Vehicles

Five ways of regulating the technical specifications concerning the construction of vehicles and their approval /certification exist:

1. **The United Nations ECE "1958 agreement"** creates "UN Regulations" based upon the principle of reciprocal adoption of type approvals granted by the Contracting Parties and regular check of the "Conformity of Production (CoP)"
2. **The United Nations ECE "1958 agreement"** creates Globally harmonised Technical Regulations (GTR's) that are then incorporated into the national laws of the Contracting Parties.
3. **The EU Framework Directive** is a system based on "Whole Vehicle Type Approval" and now makes direct reference to the UN regulations.
4. **The USA "Federal Motor Vehicle Safety Standard (FMVSS108)"** describes the requirements with some references to SAE recommended standards. Manufacturers self-certify that their products comply with the requirements of FMVSS 108. Enforcement is controlled by the "National Highway and Traffic Safety Administration (NHTSA)"
5. **The Chinese mandatory GB standards and certification by CCC**. "GB" is the abbreviation of the Chinese expression "GuoBiao" which means National Standard. Currently, for automotive lighting equipment, 10 GB standards apply. They are the basis for testing and type approval according to the "China Compulsory Certification (CCC)" system. This approval includes a very strict "Conformity of Production (CoP) control.

The Vienna Convention (The UNECE "Working Party No. WP.1) This agreement determines the legal requirements under which vehicles crossing the national borders are allowed in public traffic.

Use Requirements

Use requirements prescribe under which conditions lighting functions shall be used / may be used / may not be used AND which functions may not be used together. Such requirements are national or even state law. In the US there is a big diversity of use requirements between the different states which makes it hard for OEMs to design and test their lighting systems accordingly. Also in the EU there exist differing national laws e.g. on the use of low beam or fog lights.

Regional Regulations

Regulations define what lighting equipment is required and allowed on vehicles, the configurations and specifications of the system and its devices, and how compliance is enforced. These regulations are regional; the main structures are:

- The UN (formally "UNECE") system, which originated in Europe in the late 1950s and is now broadly influential throughout much of the world.
- The US system, exclusively effective on the North American "regulatory island", mainly the USA and Canada, with pockets of acceptance sprinkled around the world (usually co-equal with the UN system).
- The Chinese system which has similarities with Europe. Both regions rely on governmental approval and CoP control. Therefore, the chance of success is higher, though still alignment in different areas has to be done. During this alignment process it is important that the different parties have in mind that China can base its position on a more than 25% world market share, and still growing.
- Other regions (Japan, Korea, ASEAN, SA) where the legal systems are diversified, some of them following US as well as UNECE philosophy in parallel. In general, the UNECE system of type approval prevails.

Regulatory approaches:

Self-certification:

The manufacturer or importer is responsible for determining and asserting that their vehicles or regulated items—including lights—comply with all applicable safety standards. There is no pre-approval by any government or other agency. Self-certification is used in the USA, Canada, Australia, and Korea, for example. Because the maker must certify that each item complies, lamps, for example, are designed and built well enough within the regulatory boundaries that they are more than just barely compliant. This guards against inadvertently non-compliant items resulting from the production tolerances.

Type approval:

The manufacturer submits each type of vehicle or regulated equipment to a test laboratory owned or accredited by the government. The most notable system of type approval is the UN system, that is the UNECE "1958 Agreement", with some 61 signatories including all European countries and many others besides. The UN Regulations appended to that 1958 Agreement cover numerous aspects of the design, construction, and performance of vehicles and their equipment, including lighting. If the item passes tests, a type approval (homologation) is granted, then that type of vehicle or equipment may legally enter the market-and every signatory country must honour homologations granted by any other signatory country (Reciprocal Recognition).

Speed of Amendment of Regulations

A common and well-known complaint in the automotive lighting community is that the speed of innovation is faster than the introduction timing of the respective amendments to the regulations.

UN Regulations

Statements from stakeholders involved in the UN regulation process on this topic are threefold in the direction of industry:

- Start the regulation process at an early stage and show enough engagement during the process
- Align interests with peers in the industry in a flexible way
- There are possibilities to go through other channels like UN, EU or national exemptions

Sometimes for secrecy reasons, industry stakeholders opt to go for regulation when all Intellectual Property (IP) etc. is covered. A heavier point is the engagement of industry in the process. In recent years, regulation has not been high on the agenda of top automotive lighting executives from the different companies. A sign for change is coming from the recent foundation of the Working Group "Strategy" within GTB.

With respect to alignment of interests the current regulatory system can result in a minority of parties causing a delay in the process amendment and this can cause stakeholders to seek by-passes. Consequently, some automotive lighting innovations in the last 25 years have been introduced to the market as exemptions. On the other hand, a pre-requisite was mostly that the time frame for enforcement of the respective UN regulations was visible. One by-pass can be through the Article 20 of the UN framework directive (whole vehicle type approval). A best- case estimation of the processing time amounts to 15-18 months.

USA FMVSS

Basically, industry parties can self-certify their products. On the other hand, for innovations it may well happen that the FMVSS is not clear enough about the requirements and wrong self-certification can lead to heavy legal and financial implications for the company. In this case, it is common use to ask NHTSA about clarification of the situation. This clarification process can take quite some time, durations of 1-2 years are not unusual. A striking example is the introduction of ADB. Since one company asked for clarification to NHTSA, all other players wait for the answer because in case they start before the answer their risk is out of control. Again, in this case minorities can delay against majorities.

Chinese GB and CCC system

This Chinese testing and approval system for automotive lighting is largely based on the technical requirements of the UN regulations, but deviations by additional requirements and more strict rules about implementation exist. In case of innovations which are important for the Chinese market, there may be the tendency to go for quick national regulation process instead of waiting for the international community. It could be lighting functions for Mega-Cities helping to reduce traffic accidents between vehicles and pedestrians, cyclists etc. In view of the size of the Chinese automotive market this could become a successful endeavour.

Around the world

The UN and US systems are primary, but they are not the world's only vehicle regulatory systems. Consider China: it's the world's largest auto market, but it has its feet only partly in the UN system. Vehicles in China must meet Chinese "GB" regulations, which are previous-version UN Regulations with additional rules on top-the "CCC" China Compulsory Certificate requirements and very strict conformity of production control, for example.

UNECE: Actions launched

To simplify the UN lighting regulations, GRE is working through a two-stage plan. The first stage, now completed, was to draft three new device regulations to replace 31 of the existing regulations. This was an editorial activity that did not change the existing technical requirements.

The three new regulations (UN Regulation No. 149 -Road Illuminating Devices, UN Regulation No.148 -Light-Signalling Devices and UN Regulation No. 150 -Retro-reflective Devices) will enter into force in November 2019.

Stage 2 of the GRE Simplification plan consists of two steps that will

(a) re-write the technical requirements of the three new regulations to be technology neutral and performance based to avoid blocking the innovations. It is expected that this will be completed and enter into force by November 2020.
(b) Re-write the installation Regulations. This is expected to be completed and enter into force by November 2022.

5. Vehicle lighting market trends

The main drivers for growth will be increased penetration of LED-based headlighting systems, more advanced technologies and applications in safety, convenience and styling both in front and rear lighting, additional new lighting functions, and additional growth in car production.

5.1 Function-based market trends

ADB (Adaptive Driving Beam) systems
ADB will grow from 1% in 2016 to 15% by 2025. This growth projection is still in line with DVN's earlier forecast on ADB published in November 2013. ADB offers great benefits in safety and convenience for many driving conditions, but additional work has to be done to identify and create additional user benefits for use in mega-cities. Success in that effort will likely increase ADB demand and prevalence. ADB functions will need to be approved in global regulations. In the coming years cameras will continue to drop in cost and improve in acuity, and will become a standard component for every new car. This will support the growth of ADB systems.

Communication functions
A new category of functions is entering the scene of exterior lighting which is moving from the basic see-and-be-seen functions to the level of being a major safety communication tool under future conditions of a traffic mix containing human-driven, semi-autonomous, and autonomous vehicles. New safety-unrelated convenience communication will become an area of interest and revenues. Advanced projection functions is a key area of growth. For safety communication these include guidance and warning functions projected on the road under difficult traffic conditions. Another important element is road projections for communication with other road users like pedestrians and cyclists especially in dense traffic. Convenience communication makes drivers' lives easier and exploits new business angles for personalisation. Especially the personalised communication incorporates elements to create considerable new business opportunities.

Dynamic signal lights
The signal functions have long been orientated to style novelty and distinctiveness. LED adoption first brought a dotted appearance, then light guide or surface guides, and more recently 3D effects or massive structural homogeneous designs. To go further, the main current trend is to introduce more "live", animated, attractive evolutionary light in motion. The basis for this idea is that the human visual perception system is especially sensitive to motion both in central and peripheral vision. To attract the attention of road users for safety, dynamic lighted signals are much more efficient than fixed lights.

In the next decade, the pressure of communication and safety needs will boost light in motion to new applications for signal lamps more creative and distinctive than today's, if regulations will change to allow it. The technologies for such future applications exist already, at least at concept levels and at high costs-for instance pico projectors, LCD screens, and holograms to reinforce the strength of the perceived messages.

5.2 Light source technologies

Overall it's clear that LEDs will carry on eating away at the filament bulb's market share, and HID technology will disappear. However, we see regional differences and external drivers that may accelerate this transition.
First off, a summary of the technologies involved:

Incandescent
Incandescent bulbs were introduced for car applications early in the 20th Century. Today they are used only for signalling lights around the perimeter of the vehicle (front, side, rear). Currently at least 50% of all signals are realised in incandescent technology, with a steadily decreasing trend due to replacement by mid-power LEDs.

Halogen
Halogen technology boosts the efficacy (lumens per watt) of incandescent bulbs. It was introduced for vehicle headlamps in 1962 in Europe and 1979 in USA. It remains the predominant headlamp light source technology

worldwide due to its extremely low cost as a mature technology. Large emerging markets like India and South America will still have significant halogen shares in the next decade. The leading markets to supplant halogen with LED will be Japan and Europe, followed by North America, China, and Korea. In the leading markets, premium brands have no halogen applications any more in their base headlighting function for new designs.

Halogen, cont'd

Generalist automakers are starting to follow the premium brands for part of their range, excluding halogen from new vehicle designs even for basic equipment. In the USA it's expected halogen lights will retain substantial market share for a number of years, especially in cost-sensitive segments, but third-party rating systems like IIHS can very strongly accelerate the shift from halogen to LED in cases of low-scoring halogen systems and high-scoring LED systems on a given vehicle model.

HID

High-intensity discharge technology, first used in car headlamps in 1991, brought a giant increase in available light flux (3× that of halogen). But it is costly, and quickly being rendered irrelevant by high-performing LED systems. The clear consensus is that HID is a technology of the past. Most automakers stopped going for HID headlamps in new designs several years ago. New HID designs will be mainly based on the low-power 25W execution rather than the high-performance 35W version.

LED

LED headlamps first appeared in 2007, and proliferation has been very rapid. Clear consensus is that LED will be the light source for the coming years. Since the migration from HID to LED has already happened, the adoption speed of LED will be determined by how fast halogen will be dropped. Cost is going down through the whole supply chain at the BOM level for all parts, and at the same time we see trends that generalist automakers are actively getting involved in the supply chain to push for scale and modularisation as a next step to drive down the overall cost for LED headlighting systems. In Europe and North America, automakers can claim credits at the fleet level for CO_2 emissions and fuel consumption by using LED headlighting solutions. The financial impact can be large in case an automaker is facing penalties (in Europe 1 g/km CO_2 above the agreed norm will be penalised at €150, but by using LED headlighting as an eco innovation 1 g/km CO_2 credit can be achieved). In the longer run, however, it's not expected that environmental drivers will exert strong influence; electrification of the fleet (zero emission) swamp out the relatively minor effect of LED rather than halogen lights, and LED will soon become standard—hence no longer subsidised as an eco innovation. All new advanced headlighting systems are LED based (and potentially laser in the later future). This will stimulate the growth of LED matrix- and pixel-based applications.

Laser

Laser diode technology is an outgrowth and extension of LED technology. It offers clear advantages in luminance, but at this point we do not foresee a clear consensus that laser-based headlamps will take significant market share in the near or mid term. Most generalist automakers are not actively developing laser headlamps, so they will not use laser as a marketing tool or lever, but will look for customer benefits. And most likely they will wait until it will be possible to make a full high and/or low beam based on laser light. Premium automakers do use laser to differentiate themselves by creating dynamic lighting spots, light projection systems & variable beams, miniaturisation of headlighting systems. But we do not see laser being strongly applied soon for high beam boosters beyond niche vehicles, or to advance towards the goal of very small headlamps. In the coming 10 years, laser will be used as an add-on, hence not as an LED replacement for a full low or high beam. It is possible that in the long run laser could have more potential than LED. Laser is expected to grow in the next five to 10 years and will also get a fixed position. At the recent Shanghai DVN Workshop, Nichia announced a new concept for a laser.

OLED

We find consensus that OLED is not perceived as an established light source for the near future; opinions differ when it comes to the long future. Cost, availability, durability, and reliability are perceived as challenges. OLED will only be used when it can create an outstanding styling differentiator compared to LED solutions (e.g., 3D shapes). In combination with outstanding styling, OLED lighting for selected rear and/or front functions can be a powerful marketing tool for premium brand positioning.

6. Impact on industry and value chain

The market will show a strong growth, and the next question is who will benefit from this growth. The stakeholders anticipate shifts in their value chain within the coming years. Two areas are expected to play an important role in the value chain for the future: tTechnology developments and migration from halogen to LED lighting, at the lowest cost. Innovation in exterior lighting technology is influenced by major trends in sustainability, autonomous driving, car sharing, and electrification. And in parallel, technology developments in more advanced light sources, new materials, miniaturisation, and digitalisation act as an enabler for new exterior lighting applications and business models.

6.1 Impact from technology development

Skills

• New skills in electronics, software, optics, semi-conductors need to be mastered
• Lighting systems will need to be integrated with sensors and actuators in the car
• Lighting will become digital and software-controlled
• Further miniaturisation is required to create space for integration new additional components

Resource availability

• More resources will be needed to make new technologies and applications available on the road. It looks like no single company will have sufficient resources to follow all the new emerging opportunities.
• It will also be required to develop and use new more advanced software for design and simulation in all sectors (mechanics, optics, electronics, thermal, condensation) of new complex lighting systems. This will decrease throughput time and to some extent also reduce the number of FTEs needed to design and release new lighting systems.
• Rapid prototyping technologies and simulation tools with increased precision and increasingly accurate representations of reality also are addressing the workload increase.

New entrants

• Specialist companies in components including electronics required for autonomous driving, e.g., cameras, other sensors, ECUs and CPUs, will be part of the future lighting value chain.
• Lighting applications will go beyond see-and-be-seen, this will be realised by integrating lighting fully within the board electronics and software of the car. Current lighting tier-1s may lack the resources and scale to take full system ownership.

Shift in cost, added value

Future advanced lighting systems will have a different cost breakdown than today's. (Currently, ~1/3 by tier-1 and 2/3 external materiel). With the use of more electronics, advanced micro optical systems, lasers, the share of external materiel will increase. At the same time current tier-1s will need to spend more on R&D compared to what they spend today. So tension between automakers and tier-1s, and between tier-1s and tier-2s, can occur on the added value.

6.2 Migration from halogen to LED headlighting systems, at the lowest cost

How can LED headlighting systems be significantly reduced in cost, to allow generalist automakers to migrate faster from halogen?
• Standardisation and modularisation: Use standard modules for LED headlighting systems, which will be used across car line: same internal architecture, and at the same time allow freedom in exterior styling (for instance Koito Bi-Beam LED high/low beam projector used in Toyota Corolla, Prius, Lexus, and Renault with 2 standard modules in all their new models).
• Integration of parts will lead to a shorter value chain, lower cost, and improved quality. Additional integration will also support miniaturisation.
• Scale: the use of standard (and more integrated) modules will automatically create more scale, hence lower overhead cost per module-also driven by the fact that fewer release activities have to be done.

Despite the clear trend toward LEDs replacing halogen light systems, our market projection still sees relevant volumes for basic halogen headlighting systems for the coming years. It must be noted that new halogen bulb types (H17, H18, H19) have been approved and commercialised as recently as 2016. Specialist companies with a strong focus on cost leadership may focus on this business space, leveraging it to extend the life of halogen headlighting system as long as possible at the expense of the established tier-1s.

6.3 Stakeholder impact and scenarios

Changes in the value chain are an opportunity for all stakeholders. Here are some plausible scenarios, from the perspective of automakers, tier-1, tier-2, and new entrants.

Potential scenarios and impact for automakers
Technology
• Automakers will need to invest heavily in new technologies, and will have to make choices where to invest. Especially premium car makers will need to make decisions on how to maintain their leadership in the right technology.
• Automakers may drive the process to bring in new parties in the value chain, to ensure that new skills and amount of resources will be available. Those new parties can be somewhat disruptive in the case automakers will decide to take more ownership of direct sourcing.
• In case the automakers' requirements will exceed the capacities of current lighting tier-1s, automakers could bring in "super integrator tier 1s" (sometimes called "tier-0.5"), to take system ownership of fully integrated lighting solutions, or play a larger role themselves.

Cost
• Generalist automakers can take ownership for the process to define standardised modules for LED headlamps. These modules will be used across car lines within that specific automaker's model family.
• Generalist automakers will coöperate with key tier-1s (and tier-2+) to design the modules, and define level of integration, to meet the automakers' requirements as well as possible.
• In production, multiple tier-1s and tier-2(+)s will be invited to supply the modules for each individual generalist automaker.
• As to cost, within this supply chain model can be expected: Lower overhead cost due to reduction in types and validation Higher scale, lower BOM.

Potential scenarios and impact for tier-1s
Technology
• Tier-1s will need to invest and acquire new skills to integrate, digitalise, and miniaturise lighting systems. With these skills a forward integration in the lighting system will be possible. At the same time new (large) companies might consider to acquire a lighting tier-1 company and integrate lighting in their architecture to create seamless functionality and communication with other functions in the vehicle and external environment.
• Tier-1s will also need to form new partnerships to keep leveraging their unique expertise experience in lighting systems, by analysing merger and acquisition prospects, actively looking at startups, and working with other automakers or tier-1 super integrators.
New partnerships, in whatever form, can also gain a strong impact in regional market access, along with the technology impact it can have, and we also see lighting tier-1s investing in a backward integration, especially in high precision high quality PWB (printed wiring board) components assembly. By mastering this technology, tier-1s can create value by a modular integration and miniaturisation and control the full optical and thermal tolerance chain.

Cost
• In case generalist automakers will play a much stronger role in the specification and devisement of LED headlamp modules, it will imply some changes in the current relationships between automakers and tier-1s.
• Tier-1s can take the lead to form partnerships with some automakers to co-design modules for those automakers' needs (and not starting from the tier-1 perspective). It will also need to be addressed how the tier-1 will be compensated in case another tier-1 will produce the same module or subassembly. Tier-1s leading the design in specifying and defining modules will have some head start when it comes to production of those modules in large scale.

Potential scenarios and impact for tier-2s and new entrants

Technology

Tier-2s may not necessary move in the chain, but can create a strong position by providing leading-edge technology in micro optics, light sources, sensors/ cameras, CPUs, and new materials.

Cost

Tier-2s can create additional value by using their competencies to further integrate and miniaturise subassemblies of LED headlighting systems. Tier-2s could consider as part of their integration to offer modules instead of components.

7. Conclusion

Disruption, revolution and evolution
Although substantial change will surely happen, the vehicle exterior lighting industry will not face a disruptive change within the next 10 to 20 years. The need for exterior lighting will not disappear in the next two decades; lighting will remain at least as significant a vehicle system as it is now. And we see no indications that newcomers will come in to take over the exterior lighting business from established market shareholders. Perception of a given change will differ based on perspective afforded by the observer's position within the value chain. Phasing out a light source technology has more impact for the light source tier-2 supplier than for the automaker.

Societal and industry trends
Social and industrial trends will alter the vehicle (and vehicle lighting) industry with an increasing rate of change. We have identified the following crucial trends in urbanisation & mega cities , ADAS, zero-crash/zero-fatality goals of industry and regulators, the sharing economy including car- and ride-sharing, environmental protection and sustainability, personalisation, global ageing population, EVs and AVs, digitalisation and communication, and artificial intelligence.

Ignoring or fighting the trends is a high-risk strategy. By embracing the trends, and engaging with them with innovative approaches to exterior lighting business drivers such as safety, convenience, styling, and sustainability, automakers, tier-1s, tier-2s (including new parties) can have a bright future.

Technologies
Technologies enabling near/mid/far field projection with high or ultrahigh resolution, for illumination and communication purposes, will flourish. The main near-field technology will be based on micro-lens arrays. For mid- and far-field projection the technologies can be divided into subtractive (DMD, LCD, LCoS) and additive concepts (matrix, micro-matrix, scanning laser). In our view the subtractive systems will be first to market around 2020, but longer term (2025+) the additive systems should take over the majority of the market due to their higher efficiency and simpler system architecture. Animation and styling technologies for rear lighting will likewise see strong growth. Mid-power LEDs will be the main source to create animated functions for ARS, sequential turn signals, and similar functions. Holograms will enter the market in next years for styling and communication purposes; they allow to create real 3D impressions. Holograms can also comprise a (limited) number of different images, and switching among these images can create semi-dynamic effects. OLED will only be used in high-end, high-content systems with cutting-edge styling.

We'll see a lot of miniaturisation, integration, and modularisation for cost and quality improvement. There is a clear trend that front and rear lamps will become loaded with more functions needing space for more subsystems and components, while overall packaging constraints will shrink or, at best, will not enlarge. Therefore, miniaturisation by simplification and integration is a must and will become a key technology driver. System design based on (industry) standard modules is a key tool for cost reduction and to keep development resources under control. This will be a key enabler for halogen to LED migration. A typical example would be regulated LED light sources.

Software design, release, and quality control will become key success factors for future development of sophisticated lamp systems. For instance, code reduction in hardware by software programming of output characteristics (e.g., left/right hand traffic, UN/US beam patterns). High-speed data transfer amongst ECUs and lamps across the board net will become a key challenge. A consequence will be that the power control units must be close to the light source leading to a change in headlamp topology compared to today. High-level simulation during design phases and the use of artificial intelligence during road testing will become
key tools to manage the workload for the development and release of systems with ever-increasing complexity.

Applications
Lighting for Illumination will remain an important safety feature. More lighting functions than today may be needed in future, at least during the long period of mixed human-driven, semi-autonomous, and autonomous road traffic. In this timeframe an additional challenge will be that lighting has to serve the needs of the human eye, but also requirements of sensors with respect to illumination as well as glare. Safety augmentation will grow as a trend by added functionalities for rear lighting through animation like ARS and dynamic turn signals. Additionally, the use of pictograms will evolve in the future.

Communication among vehicles, drivers, and other road users by road projections during the driving state will become a key factor to improve road safety at night. Such projections will be used not only in front and rear direction, but all around the car. Under current regulations this type of communication is not allowed; it will be a core issue to push for revisions to allow it. Communication for convenience and personalisation of vehicles will become another growing area. Functions like welcome lights will develop in the direction to become not only animated, but also individually programmable. Projection of messages and advertisements is another application area not yet exploited. This topic will show strong growth in the future, especially in Asia, and may even lead to new business models. Communication from vehicle to vehicle for information exchange by digital high-frequency modulated lighting signals is not foreseen as a strong trend.

Aim of headlamps must be improved. This comprises not only initial aiming, but aim maintenance throughout the life of the vehicle. Camera-controlled lighting should be able to solve most of the problems.

From an application point of view there will be few special developments for lighting on electrical or autonomous vehicles. Status indicator lights might be added to AVs (to replace pedestrian/driver communication by glance and hand signal).

Regulations

The speed of lighting innovation is not synchronised with the speed of approval by regulatory bodies. Worldwide OEMs and Tier1s expressed their severe concern about the speed of movement of regulation versus their investments necessary in innovations. Some regions explicitedly expressed their intention to go by themselves It seems attractive and efficient for the industry to have a globally harmonised regulation system. The main hurdle will be to overcome differences in legal systems, which is what drove various countries to select self-certification or type-approval regimes years ago. At the same time it may well be possible that some major regional markets will not wait for others and go with local based regulations. The new Strategy Working Group launched by GTB in April 2017 to define where support is needed has to take the necessary actions to ensure that the support is forthcoming. This support will be the key to success!

Market trends

• ADB will show the most growth: from 1% in 2017 to 15% by 2025. Defining new user benefits for driving in mega cities is required to achieve a higher ADB penetration.
• A new category of functions will be developed in the field of communication for convenience and safety by road projections.
• Light-in-motion effects will surely find new applications for more creative and distinctive signal lamps, pending regulatory allowance.
• LED will be the dominant light source technology
• HID will finish being phased out in the next few years
• In the next decade laser will be mainly used for supplemental beams in niche applications. After that, depending on technical progress, laser has the potential to compete directly with high-brightness LEDs.
• OLED will continue to evolve as a high-end, niche-application technology, but overall OLED is promising but not yet confirmed as a light source of choice for rear lighting.

Value chain

• The gap will grow between future requirements by automakers and currently available capabilities and resources at tier-1s. As a consequence, tier-1s will evolve either to super integrators ("tier-0.5") for advanced lighting systems-on their own or in partnerships and acquisitions or they will become a kind of specialist subsystem supplier "tier-1.5" for advanced lighting modules. It is likely from the perspective of tier-1s, that this transition will be rather more revolutionary than evolutionary.
• New specialist and component suppliers will enter the arena to support autonomous driving with system integration of sensors and electronics, hardware, and software, and to support digitalisation of light with e.g., LCOS, MOEMS, LCD, electronics, and software.
• Current component suppliers will have opportunities to further integrate and miniaturise lighting systems to allow more space for other components needed for autonomous driving and digitalisation of light as well as cost reduction to support the transition from halogen to LED.

List of DVN Gold Members

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Aston Martin, UK
Audi, Germany
Bentley, UK
BMW, Germany
Changan Design Center, Italy
FCA, USA
Daimler, Germany
Ford, Germany
GM, USA
Great Wall, China
Harley-Davidson, USA
Honda, Japan, USA
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Nuremberg university, Germany
Pacific Insight, USA
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Rensselaer university, USA
SLD Laser—formerly SoraaLaser
UMTRI, USA
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Set Makers and Tier 1s

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Elba, Romania
Farba, Turkey
FIEM Industries, India
Flex'N'gate, USA
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Harbin Good Time, China
Hascovision, China
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Magna, USA, Austria
Microlight Auto Parts, Taiwan
Mind Optoelectronics, China
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NAL, USA
Neolite ZKW, India
Nordic Lights, Finland
Odelo, Germany
Olsa, Italy
Plastic Omnium, France
Peterson, USA
Rebo Lighting, China, Germany
SL Corporation, Korea
Stanley, Japan
Tianchong, China
Truck-Lite, USA
Valeo, France, Spain, China
Varroc, Germany, Czech R.
Wipac, UK
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Light Source Suppliers

Anrui Opto, China
Diodes Dynamics, USA
Dominant Opto Tech., Malaysia
Everlight Electronic, Taiwan, Germ.
Excellence Opto Inc., USA, Taiwan
LG Innotek, South Korea
Lumileds, Nederlands
Nichia, Japan
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Samsung Electronics, Korea
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