PHOTONICS21

Photonics21 Strategic Research and Innovation Agenda (SRIA) –

1. Executive Summary

2. Introduction

(background, reflecting the changes in the geopolitical, industrial, ecological, and societal landscape since the last SRIA, and the resulting new challenges for the EU to achieve targets relating to the Green Deal, Technological Sovereignty and Digital Transformation)

3. Photonics in the coming decade

(focus on the importance of photonics over the coming decade to address all the above challenges, and also support the five EU Missions, the recent Chips Act and the ambitions of the current Council and the Commission)

WG4 (Mobility) input:

- Automated vehicles as economy booster through added value
  - Less accidents
  - Increase of technology levels and thus market value of technologies.
  - Europe well positioned technologically. Challenge in marketability? Let’s use our tech developments.
- Should be net-zero compatible according to international initiatives proposed
  - Time 2 market in an IA are 5 years, but R&D cycle in automotive >6 yrs: Research, pre-development, serial development (longer for new technology)
  - Net-zero implementation to be defined (input).
- Transition to higher energy efficiency levels and novel sources of energy (towards net 0)
  - 1W extra power consumption cost €1-2/vehicle due to cost of increased battery capacity needed
- Transition to the Automated Vehicles
  - More sensors & computation increase power consumption (while overall reduction needed)
  - Better sensors, algorithmics, and AI implementations strategies moving towards “zero false alarms while full reliability” (no false positives) in all relevant environmental conditions-

- Resilient supply of technologies and goods
    - Chip shortages halt production regardless of chip type
    - Massive economic impact:
        - Automotive Europe's biggest manufacturing industry (by far)
        - Estimated that the semiconductor shortage will cost Europe's automotive sector about EUR100bn during 2021-2022[1]
- Safety aspects
    - using vehicles as long-range detectors for other vehicles
    - street lighting as active safety system
    - projection systems of cars to give security information to other participants
    - AR/VR to present critical information in an efficient way to the driver
    - Infrastructure need be involved and needs further developments in different ways (improved markings, signs, …)
    - V2I communications strategies to be defiend/tested/set based on efficient strategies.

WG4 (Energy) input:

- Transition to energy-efficient lighting can save 671 million tons of CO2 per year in 2025[2]
- Car2X communication and cooperative lighting will play a crucial role for autonomous driving
- Sustainability in the production requires research on sustainable electronics, packaging, components (for example the lighting systems as a whole to be optimized for energy saving and sustainability)
- Advanced energy concepts: energy optimization of the full lighting system requires research on DC-grids (reduce conversion inefficiencies), renewable energy generation (solar,…), more efficient energy storage solutions.

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[1] Allianz Trade: https://www.allianz-trade.com/en_global/news-insights/economic-insights/european-automotive-semiconductor-shortage.html

[2] Spectaris Report „Light as the key to global environment sustainability", page 21

4. Photonics Research and Innovation Challenges

4.1 Digital Infrastructure

4.2 Manufacturing

4.3 Health

4.4 Mobility

Photonics plays a role in the targets of Decarbonisation towards Zero Emission Road Transport, Clean Energy Transition, the Industrial Battery Value Chain, energy saving by Smart Lighting.

Main socio-economic challenges addressed

Resilient supply of technologies and goods

In today's global economy with a relationship between regional economies and their ecosystems of suppliers, a key success factor for Europe's photonics industry is to maintain and strengthen critical parts of the value chain regionally - from raw materials, hardware, software, energy consumption to production - and its domestic market access. A new focus should be placed on supply and services being close to customers.

Further integration of photonic components and devices into objects or structures (for example the displays or solar panels in windscreens) provides the opportunity to the European industry for novel, value-added products.

The European lighting industry is still the leading global player with companies like Philips/Signify, Osram or Zumtobel Group, and can therefore significantly influence the global energy-saving and climate impact. The global smart home market is estimated[21] to grow from $24.1B in 2016 to $53.4B by 2022. Acting as the 'intelligent backbone', lighting is in a strong position to contribute to this growth, connecting the increasing number of IoT devices via short transmission distances to the next lighting node, regional anonymized data collection to improve energy-efficient usage of devices, while minimising the necessary transmission power. Battery lifetimes of IoT devices, therefore, rise and electromagnetic interferences decline.

The importance of the automotive industry for the EU's economy is crucial. The EU is one of the largest exporters of vehicles and vehicle components in the world. The automotive sector generated a trade surplus of €90.3B, which far exceeds the trade surplus of goods for EU-28 - €22.9B in total in 2017 - while the trade surplus for services was €133B in 2016[22]. Automobile taxation is a vital source of government revenue with €413B in fiscal income from motor vehicles in EU15 alone, compared with the total EU budget of €172B.

Furthermore, transport is critical to the EU economy: with a total of 13.3m jobs (6.1% of all EU jobs) automotive manufacturing directly employs 2.5 million people (8.3% of EU employment in manufacturing) and another 900,000 in indirect manufacturing jobs. Most of the developments required for automotive autonomy and energy savings are easily expanded to other transportation modes (railway, maritime…), improving impact and creating jobs and value in parallel in all involved sectors.

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[21] https://globenewswire.com/news-release/2018/08/03/1547019/0/en/Market-Size-of-Global-Smart-Home-Industry-Predicted-to-Reach-USD-53-45-Billion-by-2022.html

[22] The EU in the world - international trade, Eurostat. https://ec.europa.eu/eurostat/statistics-explained/index.php/The_EU_in_the_world_-_international_trade#Balance_of_payments_.E2.80.94_share_of_world_trade.

EU automotive investment in R&D has increased to an annual spend of €53.8B, making the automotive sector the European Union's number one investor in R&D, and responsible for 27% of total EU spending on innovation. The EU is, therefore, the world's largest investor in automotive R&D[23]. The majority of the annual €54B spent on innovation comes from private sources. In comparison, the total budget for Horizon 2020 (FP8) during its lifetime period 2014-2020 was €74.8B, of which Smart, green and integrated transport received 8.23% (€6.3B)[24].. Although we cannot necessarily assume that a full leverage of a factor 50 exist between EU funded research and private sources, it is however clear that EU-funded research is essential to promote private innovation spending to ensure the European automotive industry, and its suppliers, maintain and strengthen its market position.

Spending on innovation for the automotive industry grew by 7.4%, which is substantially higher than both the growth rate of the EU economy and the EU automotive vehicle production volume. The level of spending on innovation is helping to lay the foundation for future higher value-added products with significant contributions from industry which need be supported by the EU to keep European competitiveness. The automotive industry is, therefore, a key sector for safeguarding existing jobs and for generating new, high value-added jobs, growth and, by extension, wellbeing in Europe.

Driverless, connected vehicles and electrification are technological changes to address the societal challenges of traffic-related injuries and fatalities, pollution, and congestion. Driverless and connected vehicles also have the potential to promote social inclusion with mobility to all efficiently[25]. Connectivity is a crucial factor in the development of driverless vehicles and electrification but will not be enough: vehicle-based sensors remain the chief enabler for this future mode of transport.

Sufficiently performing photonics sensors are one of the main roadblocks that prevent Europe from deploying fully automated and connected vehicles at scale and are a stronghold of the capabilities of EU. Even though radar technologies continue to evolve, with improvements made in radar technologies with multiple emitters and receivers (MIMO), improving resolution and higher frequencies, there are physical limits that prevent radar from achieving the same resolution as a photonic sensor.

Human drivers will continue to play a vital role in the foreseeable future at automation levels 1-4. The best possible visibility to the driver and an improved infrastructure will be essential for improving safety: smart illumination in darkness and inclement weather conditions will allow better lighting of the road ahead while minimising glare. A pre-requisite will be an improved (bidirectional) dialogue between vehicle and infrastructure. Efficient information exchange is also necessary to promote safety and fight driver distraction. Europe, therefore, needs to be prepared for this major transformation of mobility.

The following objectives will therefore be considered in this context.

Main societal objectives driving the challenges

Main societal objectives involving photonics technologies that are driving current societal challenges may be listed as:

1. *Cleaner mobility* in all aspects, such as electric vehicles or other forms of low emission vehicles, will be essential. Each generation has grown in mobility needs, requiring more cars per person,

[23] Key Figures, ACEA, the European Automobile Manufacturers' Association. https://www.acea.auto/fact/facts-about-the-automobile-industry/

[24] Factsheet: Horizon 2020 budget, European Commission, Research and Innovation. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en.

[25] On the road to automated mobility: An EU strategy for mobility of the future, European Commission, COM (2018) 283 final. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0283&from=EN.

and with each person driving greater distances. While increases in mobility provide social benefits, they have severe impacts on sustainability and create more greenhouse emissions. Both the transport and the automotive sectors, in general, need to reduce their environmental footprints and CO_2 emissions, both in production and use[26].

2. *Reduced energy consumption* of lighting in general and mobility in particular. Better control of lights for where it is needed, e.g., street lighting with ambient sensing and communication with other road users.

3. *Better quality of life with adaptable light* when future lighting systems will adapt to the user and provide the lighting when and where needed and therefore save energy and provide additional features (i.e. special spectra for enhance vitamin D production or increasing the performance) supporting the health of the users. Better quality of life for the ageing society with Human Centric Lighting to improve the circadian synchronisation, giving daytime structure to the elderly when living largely indoor or otherwise low sunlight exposure. An easy to use interface adapted to elderly will be critical for success adoption.

4. *Autonomous vehicles and improved road safety* will transform the automotive and transport sector, both from the vehicle and the infrastructure points of view. Their development could take several different forms: autonomous vehicles could take over the driving process entirely in all conditions; in other automation levels they could take over some or all of the driving in selected circumstances, and in other areas, the systems will only supervise human driving, preparing to intervene or aid whenever specific risky situations arise. EU statistics show that 19,800 road users died in 2021[27]. Consolidated progress towards accident-free road transport, therefore, has substantial societal benefits.

5. *Improved safety of other transports,* for example monitoring of railway access control and safety monitoring such as overheating of braking systems or automated detection of infrastructure signals, monitoring of other infrastructure such as airports, seaports, crossroads and bridges, as well as urban zones with mixed use of pedestrians, cyclists and motorised vehicles.

6. *Reduced transport congestion (including Urban Freight Transport - UFT)* that optimises available road infrastructure is coinciding with a growing need for cleaner mobility and with it a critical improvement in the quality of life for citizens and goods. Cities and urban areas are becoming more and more concentrated, with enormous implications for citizens' mobility. The cost of road congestion in Europe is estimated to be over €110B a year, equivalent to 1% of GDP[28]. Novel mobility involves novel public transport modalities adapted to state-of-the-art technology

7. *The digitisation of the mobility industry and (real-time) availability of in-vehicle data*, with a variety of services to road users (such as finding available parking in an area), is expected to be closely linked to economic growth and jobs for a mature, traditional sector of transport. Novel connectivity will develop services and modes of transportation by using V2X - communication (vehicle-to-vehicle, vehicle-to-infrastructure, or vehicle-to-other road users like pedestrians or cyclists). This connectivity provides new services for drivers and passengers which, in turn, create a wealth of jobs and economic opportunities. *Mobility-based apps* and novel functions

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[26] Reducing CO2 emissions from passenger cars, European Commission Climate Action. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en.

[27] 2021 road safety statistics: what is behind the figures? European Commission. https://transport.ec.europa.eu/2021-road-safety-statistics-what-behind-figures_en.

[28] Measuring road congestion. European Commission, Joint Research Centre. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC69961/congestion%20report%20final.pdf.

which can be added to a better-connected vehicle have enormous economic and societal implications and enable the more efficient cars of the future.

Significant photonic research and innovation challenges

The trends presented could be achieved due to the convergence of a group of disruptive game-changers currently appearing in the market. Such developments involve advances in the hardware, the software, and even the business models that were commonplace in 2018. The disruptive technology changes will shape the mobility industry for the future, where a vital European industry will have to face the emerging global competition to keep and grow its present industrial weight.

One of the most critical game-changers is expected to be the development of autonomous (or self-driving and connected) vehicles of various types. Automated railways or metro-lines are increasingly used for public transport in larger cities, but other transportation modes (for example, cars, shuttles, buses, tramways, small and large ships) will likely follow the automation trend. The most disruptive autonomous vehicles - socially and economically - are however expected to be in the automotive field.

First vehicles with levels of automation that allow a driver to take their eyes off the road, at defined operational design domains and take over readiness[29] have been introduced. This trend is progressing and noteworthy is the recent amendment to ECE regulation[30] allowing automated driving under certain circumstances up to 130 km/h.

The vehicle complexities and costs are expected to increase with rising levels of automation on roads. As a consequence, our concept of mobility and ownership of vehicles is expected to change substantially. Such a change is generally referred to as Mobility as a Service (MaaS). In contrast with the current situation with mainly individual ownership of cars, mobility will be turned into a service where the use of sensors, connectivity, and IT advances, enabling point to point fast mobility with service providers holding the vehicle ownership, may become the new normal.

Furthermore, self-driving vehicles are expected to be moving 80% of their time and will be easily shareable, while a private car is parked, on average, 95% of the time[31]. Correctly managed, this will lead to less congestion and fewer emissions with safer roads for everyone. Central urban areas will be reallocated to other uses when the need for large parking spaces in the city centre will diminish. The autonomous vehicle has the potential to bring a real social and economic revolution.

Such a development will require novel concepts of vehicle capabilities in all transport modes related to connectivity. Such a paradigm shift requires the development and deployment of connected mobility systems (V2X) which enable vehicle to vehicle communication, vehicle to infrastructure and the communication of the vehicle with other road users, especially with vulnerable road users like pedestrians and cyclists.

Photonics is an important sensing mode that allows the necessary high-resolution 3D imaging, providing the relevant environmental perception and detection. Furthermore, future communications between other vehicles, road users and infrastructure could be enabled by photonics, as well as improved and dedicated sensing needs.

Moreover, photonic sensors can be used for the integration of sensors into the vehicle's subsystems, leveraging on their robustness and ability to be embedded in materials and structural parts, to generate

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[29] Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE SURFACE VEHICLE RECOMMENDED PRACTICE J3016_202104, April 2021. https://www.sae.org/standards/content/j3016_202104/.

[30] Amendments to UN Regulation No. 157 (Automated Lane Keeping Systems). Economic Commission for Europe, ECE/TRANS/WP.29/2022/59/Rev.1. https://unece.org/sites/default/files/2022-05/ECE-TRANS-WP.29-2022-59r1e.pdf.

[31] Today's Cars Are Parked 95% of the Time. Yahoo finance. https://finance.yahoo.com/news/today-cars-parked-95-time-210616765.html?guccounter=1.

the data necessary to enable advanced functions like automated driving, predictive health monitoring as well as predictive system and equipment. As for IoT products, vehicle components have to become smart components, with multi-physical sensors (like temperature, pressure, force, strain) used for their monitoring and control functions.

Key developments required to address identified photonic challenges

The identified technological needs involve the following key developments:

Photonic sensing

The development of innovative sensing solutions will be required to increase the safety of future non-Autonomous and Autonomous vehicles, contributing to the "Vision Zero[12]" and "Triple Zero Goal[13]" objectives defined by the European Commission with zero emissions, zero congestion and zero accidents. Improvement of traffic safety, with a mandatory dramatic decrease of the number of deaths and severe injuries occurring on roads are among the main objectives to be addressed. For this, new, or improved, robust sensing capabilities at affordable costs are required. The necessary sensor systems must be further developed for the realization of automated driving. Photonic systems are of particular importance in this context. Integrated systems with a high range of functions and robustness against environmental influences are important for the detection of the environment. The development of infrared based sensing solutions can be considered as a viable complimentary solution for improving detection of pedestrians, obstacles, especially under lowlight and/or bad weather conditions. The sensor technology must be efficient and cost-effective to manufacture and integrate, so as not to create market barriers. At the same time, energy consumption should be minimized by intelligent system technology and supported, when possible, by artificial intelligence developments. Particularly from connected systems, significant safety increases and energy savings can be expected. Fully performant 3D sensors will need the required spatial resolution and range that allow motorway to travel at normal traffic flow[30]. An example of 3D sensor output is shown in Figure 1.

Although appropriate sensing systems are required for the necessary comprehensive detection and classification of the environment, the final sensing requirements will be highly influenced by the proper processing of said sensing systems. Besides the information sourced by on-board sensors, other information will be transferred to the vehicle in networked scenarios (V2X). The increasing data transfer places ever higher demands on real-time processing and thus also on edge computing. Such edge computing strategies in the vehicle will have high demands on processing power, but also in cost efficiency and in lowered power consumption.

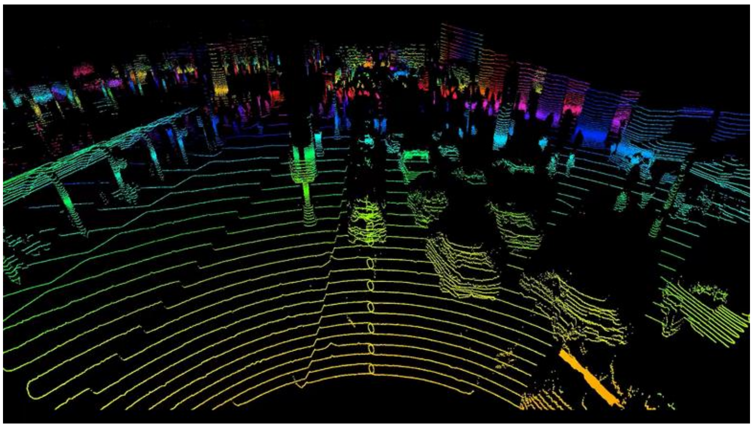

Figure 1 Example of point cloud data generated by a lidar. Courtesy LUMINAR TECHNOLOGIES/NYT

Specific requirements:

- The vehicle sensing systems use cameras – both in visual and infrared wavelengths - lidar, radar, or a combination of all three to detect an impending crash in the road ahead. These systems have been demonstrated as sufficient performant while driving under daylight and fair-weather conditions. However, the performances of such systems have to be improved, especially at falling day/night and/or under bad weather conditions. The developed sensing systems should be fully performant under established test cases such as EuroNCAP under different real-world environmental conditions that a vehicle faces, which include different ambient light conditions as well as weather conditions including rain, snow, fog, dust, water spray (from preceding traffic). The sensing systems shall also have a high immunity to interference from various sources.

- These sensors are key enablers in the future self-driving vehicle market but also essential for many other applications. The proposed technological advancements for increased performance include areas of beam steering, light-emitting, and light receiving devices. All those components must be finally integrated efficiently in novel platforms.
- For light-driven chemical processes, it is of vital importance to have the right reaction conditions: temperature, pressure, light intensity, chemical composition, etc. Such in-operando monitoring requires advanced sensing systems. The sunlight-powered production processes usually demand high-temperature and high-pressure condition, and the chemical composition in the reactor may lead to degradation of sensors. Optical fiber sensors could provide a solution to those harsh conditions and meet the stringent requirements. Additionally, integrated photonics sensor might provide advantages accompanying optical fiber systems to realize a fully inert and highly integrated full sensing system for the processes.
- The sensory data are most useful when integrated in the control loop for the chemical feed through or flow control and also for optimal lighting control. The system integration of the sensor system with the reactor and lighting requires development in opto-electronic devices, system engineering and special lighting module design and packaging.
- To facilitate those, advanced next generation reactors need to be developed. Upscaling practice already set trend to advanced flow reactor design for many light-driven chemical processes. Light management structure or elements can be added to the transparent flow reactor front and back surface to improve the light utilization efficiency of the system.
- As the systems relies on more and more sensors, tools to evaluate its condition will be required. A reliable evaluation of system state and performance, and the use of redundant systems to allow for the fault-tolerant and resilient operation needed for the sensor-set used. Graceful degradation of sensor performance, for example, when exposed to adverse weather conditions, will also be essential. Complementarity of sensing modes will become a cornerstone of future sensing strategies.
- Improved sensing capabilities are also necessary for improving safety of other transports for example monitoring of railway access control and safety monitoring of braking systems or automated detection of infrastructure signals, monitoring of other infrastructure such as airports, seaports, crossroads and bridges, as well as mixed-use urban zones with pedestrians, cyclists and motorised vehicles.
- Finally, the efficient combination of various sensing modes for complementarity and redundancy is expected to be critical (multimodality). Photonic-related developments of sensing are expected to be further driven by sensor fusion. The complementary inputs from several sensors in an integrated sensing platform contribute to increased overall performance and improved robustness of the system and the reduction of false alarms. Sensor fusion may affect individual sensor requirements. Such sensors systems will be developed according to functional safety, considering sensing redundancy and system development according to relevant standards, such as ISO 26262[32] for automotive.

[32] https://www.iso.org/standard/68383.html

Battery health monitoring

Technology for measuring the battery state of charge, state of health, and inside temperature should be safe in case of vehicle collisions or other damages to the battery pack. A beneficial approach appears to be based on fibre optics which are not electrically conducting. Such battery health monitoring may bring additional benefits:

- A sensor that provides a 'battery life history' and the ability to measure the capacity more precisely will improve the safe utilisation while extending the useful life of the battery in first and second life applications.
- The current uncertainty relating to battery temperature and health forces manufacturers to use safety margins built into today's battery monitoring systems, that prevent the complete battery capacity to be utilised efficiently, slower charging, increased safety risks, and lack of information of remaining battery life. The current lack of battery health monitoring makes it hard to set a resale price of batteries. It is also difficult for the seller to provide a warranty or establish a malfunction cause.

Photonic Integration for Sensors

More and more systems act autonomously and enable energy-efficient use through intelligent control of the systems. Intelligent photonic monitoring systems are needed to monitor and self-diagnose the systems. The development and testing of these monitoring systems enables safe operation and the use of the systems for additional innovative added value in networked infrastructures.

Key aspects to enable extensive industrialisation are the technologies' scalability, cost, packaging, and integration. Photonic sensors are widely used in industrial fields, effectively used both as stand-alone systems and as embedded sensing elements in mechanical and structural parts. However, for a larger uptake, they require suitable interrogation systems not currently available, in terms of compactness, weight, power consumption, cost and robustness to harsh temperature and vibration environments. Photonic integration is a key enabler to overcome these and to create embedded sensing systems suitable for compact, robust and cost-effective multi-physical sensing. The silicon on insulator (SOI) and hybrid III-V materials on SOI platforms, combined with mass manufacturing packaging and assembling technologies, can leverage decades of experience from the microelectronics industry, successfully addressing large volume market requirements.

Affordable photonic sensors can be used for the Internet of things (IoT) of various systems, leveraging on the robustness and the ability to embed safely electrical non-conductive connection in various materials and structural parts, to generate the necessary data to enable advanced functions like automated driving, predictive health, or maintenance monitoring. These IoT products will enable a stepwise improvement in efficiency through digitisation and integration of smart components with multi-physical sensing capability (like temperature, humidity, pressure, force, or strain).

Research and Innovation challenges:

- Low cost, high-performance photonic integrated circuit (PIC) based on Silicon Photonics, III-V and hybrid III-V – SOI platforms
- Advanced mass manufacturing packaging and assembling technologies
- Multimodal sensing and its application using artificial intelligence algorithms in all-weather conditions.
- Cost-effective technologies to allow compact PIC systems operating at high temperatures (>100°) with low power consumption (< 1 W), including reliable packaging and assembling for mass production

Affordable and efficient Adaptive Driving Beam (ADB) for mainstream vehicles

Headlights are no longer the passive unit we have become accustomed to and have instead turned into an active device that reacts to contextual and ambient conditions. Headlamps and taillights are expected to actively extend their functionalities in future vehicles with adaptive headlight beam shapes that extend the illuminated range while remaining glare-free for approaching cars and other road users. These systems use visual or IR cameras near the visual wavelength to detect and adapt driving beam systems in the road ahead.

First generations of the adaptive driving beam are already on the market, and future generations may move further into an always-on matrix headlight with a precise selection of the areas which need to be obscured to avoid glare and blinding of other road users. An example of glare-free illumination is illustrated in Figure 2. Lights have also become “the new chrome” and are an essential part of vehicle styling and brand identity. Unfortunately, both the new functions and the styling of light sources have increased the power consumption when we need a reduction. Besides the environmental aspect, there is also a significant cost implication of the increased power consumption, stemming from the increased size of battery needed to compensate for the power consumption of the lights. Thus, focused research is needed to achieve light sources with up to 1M controllable light elements and attractive styling opportunities while decreasing the overall system power consumption.
Such systems have been demonstrated as “performant enough” while driving under sunlight and/or good weather conditions but further improves are needed at falling day or at night conditions.
Infrared sensing can be considered as a valuable complement to improve the performances of ADB systems under low daylight conditions and different road use-cases. These systems need robust and affordable integration into vehicles. Such developments need to be conducted with the whole value chain involved, from the Device Manufacturers via the Tier 1 suppliers to the automotive OEMs.

Traditional illumination		
Glare-free illumination		

Figure 2 Example of glare-free headlights. Courtesy Mercedes-Benz AG

- Current ADB technologies, already with a high TRL[33] level will enable the development of cooperative lighting schemes, where optimal use of cameras, exterior illumination, headlamps, and infrastructure information have the potential to significantly increase visibility in darkness or adverse weather conditions, especially for vulnerable road users like pedestrians often not carrying their own light source for visibility.

- Novel high-resolution headlamp systems offer the potential to adapt their light distribution to the surroundings to increase road safety and to reduce the energy consumption of vehicles. In inner-city areas in particular by means of situationally adapted illumination of the traffic area. To this

[33] Technology Readiness Levels (TRL) is a measurement of estimating technology maturity

end, the state of the art of lighting systems must be advanced significantly in terms of better detection of the traffic area, sensor systems, lighting systems, and appropriate data processing. Cooperative lighting, in which streetlights and headlights of the vehicle are coordinated in suitable scenarios, reduces light pollution and increases energy efficiency. Furthermore, there will be a safety increase, due to the fact that today the parallel lighting of streetlights and headlights leads to some negative effects concerning camera-based object detection, since some object detection is impaired in "double lighting" scenarios. Therefore, this research topic is important for enabling connected and cooperative automated mobility for night drives.

- V2X and IoT are key enabling technologies for cooperative lighting
- Integration and fusion of novel sensors (radar, cameras, lidar) in other vehicle components such as headlights, where cost-effective integration can help address system and maintenance costs. A careful balance of the integration benefits versus the cost of repair and warranty costs of replacing complete modules containing expensive sensing function will be needed to benefit consumers.

Information Projection

New pixelated headlights allow efficient communication with the driver as well as other road users by projecting selected symbols and additional relevant information on the road. Such information may be in different forms, for example, warning symbols and driving path guidance (Figure 3 illustrates example cases). Therefore, advanced lighting functionality will also be required in the most automated vehicles.

Figure 3 Example of a driver interface through projected symbols. Courtesy Mercedes-Benz AG.

- High-resolution matrix-beam headlights can project a variety of information onto the area in front of the vehicle, with the expected benefit to the driver and surrounding road users. Functional requirements for such information projection, and Human Factors aspects such as distraction potential, need to be carefully investigated. Other elements such as how an automated vehicle should communicate its intentions to other road users will require thorough investigations.
- Light in VR/AR. Development of high-efficient, lower cost micro-LEDs and MEMS-based projection systems as micro projection tools.
- Advanced and miniaturized 3D photonics sensing of the environment for VR/AR equipment.
- Advanced and miniaturized communication for VR/AR equipment.
- Integration and testing of VR/AR systems, such as performance validation.

Communication with Light (V2X)

The development of low-cost, reliable, and small components for light-based communication (LiFi[34]), together with the implementation of Vehicle-to-everything (V2X), such as Vehicle-to-Vehicle (V2V) and Vehicles to Infrastructure (V2I) communications will enable new capabilities of interaction between various IT devices, machines, vehicles, other road users, and the infrastructure through high-speed, short-range communication.

- Automotive lights enable transparent components which allow the sending and receiving of optical energy for data sensing (e.g., embedded sensors in headlamps) or data emission. Such capability provides for integrating additional capabilities into the lighting systems. These novel designs should improve capacity, shape, and maintainability.

- Cooperative driving and various levels of automated driving in urban areas will take place in mixed traffic situations. Automated vehicles will encounter non-automated road users such as pedestrians and cyclists, but also other non-automated vehicles. For unclear traffic situations, communication between both groups is essential in order to resolve critical scenarios. The vehicle must therefore be able to communicate with the environment. Communication must be safe and unambiguous. The current state of research and the respective databases are not yet sufficient to establish any norms for light-based V2X communication, which are especially critical and relevant for cooperative driving. Hence, further research is needed on communication via lighting for different scenarios in mixed-traffic situations and different ambient light.

New internal and external Human Machine Interface (HMI) for automated vehicles and Occupant Monitoring

The involvement of photonics technologies in new tasks like communication and passenger entertainment is expected to be significant. Higher levels of automation and new ways for in-vehicle sensing are expected to bring substantial changes in the way humans interact with the vehicle, not only from the driver and passengers' point of view but also with other road users that may interact with the vehicle. An example of possible future vehicle driver interface is illustrated in Figure 4.

Figure 4 Example of possible future vehicle driver interface. Courtesy Fotolia photos.

[34] Li-Fi is a technology for wireless communication between devices using light to transmit data

Improved, advanced HMIs are required to cope with the increased amount of information available through digitalisation, enabling safe control of the car. At the same time, vehicle occupants should be informed about driving manoeuvres when higher levels of vehicle automation are in use to increase acceptance of automated driving functions and to prevent occupants from interfering with communication without being asked. Successful implementation will require cooperation between the photonics industry and Human Factors specialists[35].
This also requires occupant monitoring since the behaviour of the occupants is of central importance for communication between the vehicle and the occupant. Due to the fact that several, partly strongly varying interactions with the driver will be required for automated driving scenarios, further research and development is required in this field. A major challenge in this regard is to capture the many individual behaviours of drivers and occupants. Both external and internal HMI are key to enabling various automated driving levels.

- The automated vehicle is expected to modify the patterns of vehicle use, enabling eyes off-the-road, from short-duration tasks such as email or web interaction to longer duration tasks such as movies, reading, or gaming. Regulations allowing such systems are now in place[30]. Detailed analysis of the physiological effects of lighting under the new forms of vehicle use, which combine different levels of visual performance, together with aesthetics and comfort, will be needed. Means of monitoring occupants will be required to sense the driver's readiness to resume control of driving when required.

- A more immersive system interaction experience is expected to be a future trend in next-generation vehicles. Such interaction involves various modalities, including novel displays which involve larger conformal, congruent, frameless displays, enabling multiple levels of three-dimensional engagement such as holographic displays.

- Interactions with the extended information content should be combined with the priority of safer roads, thus requiring less driver attention with better and faster access to relevant information in semiautonomous modes. Novel communication with the driver and other users would be required, involving possible different levels of augmented reality, head-up display (HUD), display projection, and multimodal interaction strategies (for example, eye-tracking). The autonomous vehicle cockpit is yet to be defined, and several alternatives are possible, requiring cooperation with display expertise, human factors, and end-users.

- Such new devices and systems need to be well-integrated, reliable, and low-cost, with reduced system unit volume and power consumption. These new devices should be able to be utilised efficiently depending on the task at hand for the vehicle occupants. Such a trend is envisioned by reducing the gap currently existing between the automotive and the consumer market of photonics and electronic devices. As automotive applications will increasingly use more enabling technologies based on photonics from consumer electronics, the costs should decrease, and the integration level should increase.

Micro Displays

Information will become personal and ubiquitous – always and everywhere. Such aspects hold in all aspects of life, both in personal as well as in business environments.
Micro-Displays in glasses and contact lenses will offer personalised information via augmented reality to make complex work easier and life more comfortable. Classical navigation and information systems will be replaced by information that can consider the preferences and habits of every individual.

Research on optical materials

In combination of the photonic device development, the chemical photocatalyst material development is crucial and necessary. Classical bulk material is not the optimal for the light-matter interaction.

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[35] Automotive HMI: Present Uses and Future Needs. D. Barat et al., Society for automotive displays. Future of Automotive Displays and HMI. https://onlinelibrary.wiley.com/doi/abs/10.1002/sdtp.11633.

Micron sized or nano sized particle materials are more suitable to achieve maximum light absorption, which will lead to higher production efficiency.

Energy savings through increased productivity

To increase productivity by 10% means the required energy consumption (and therefore the related CO_2 emissions) could be reduced by 10%. To increase productivity by 10%, the first challenge will be for lighting to become a fully and seamlessly integrated system in buildings, objects, and within the structures that surround us. This challenge presents new research problems: material development ('how can lighting be integrated into different materials without reducing its performance or lifetime?'), system architecture ('how can the lighting system communicate with other systems such as the building management, car control, security systems'), or component development.

Besides the technical aspect of productivity, light also influences the wellbeing of every individual. New scientific findings show that reaction of the human body to certain spectral light distributions is complex and depends, among other things, on the age, gender, cultural environment, geographical location, mood, and health of the individual. Continuous and intensive research will enlighten our understanding of the interaction of light with humans, animals, and plants.

Long Wave Infrared (LWIR) sensing technologies can also play an important role for energy saving purposes.

Climate

The development of innovative sensing solutions is required for an improved monitoring of earth pollution. Such developments are in direct relation with the European Green Deal objectives, regarding a better monitoring and an adaptation of human activities versus climate change. The development of new free space optical sensing solutions to monitor earth pollution from space are among such new solutions. Solutions avoiding atmospheric obscurance include cooled infrared Focal Plane Arrays based upon III-V or II-VI semiconductor technologies, detecting in the Short Wave to the Very Long Wave bands. Increased resolution (i.e., with larger detector formats), and improved performances (e.g., through very low dark currents) based on new manufacturing technologies are required. Remote sensing and monitoring of pollutants to evaluate emissions needs further development for improved accuracy. Targeted applications are improved weather observation and prediction, better quantification of greenhouse gas and pollutant within the atmosphere - including pollutant coming from human activities (such as anthropogenic CO_2 emissions), better monitoring of natural resources, and better anticipation and resilience of the EU society versus extreme climate events. Such developments (all of them directly related to photonics technologies) will likely be achieved throughout collaborations between Research Institutes, Integrated Device Manufacturers and End-Users of the Space industrial sector.

Photonics as a flagship science for innovation

An emerging opportunity for Europe where automotive, transportation and aerospace industries are strong is tied with photonics, combining traditional microelectronics, flexible, printed & hybrid electronics, and mechanical structures together.

This process enables the integration of photonics functionalities (displays or lighting, large-area sensors, user interfaces) inside traditional structures like cars, aeroplanes, trains, trams, elevators, escalators, providing displays inside a laminated glass, switches, and user interfaces on the surfaces or within injection-moulded parts.

The technology provides the design freedom, weight and space reduction, functional conformability, durable integration of electronics and mechanics, lean assembly and novel innovative solutions and services.

To keep these markets in Europe evolutionary and revolutionary further action will be essential. An example of next-generation demands is on material and device development for broadband and narrow wavelength emitter and detection systems, for the frequency band from 1µm to 12µm, that are compatible with the existing semiconductor and optoelectronic technology. Such devices can be used as sensors for medical, environmental and transportation systems, but also in Human Centric Lighting (HCL).

Cooperation needs with other disciplines or fields

A human-centric design approach should be beneficial, where the changes introduced by the novel concepts will require intense cooperation of technologists (experts in systems and platforms) and other specialists, to properly integrate the different types of sensors and information to ensure the acceptance of end-users to the novel concepts being introduced.

While lighting becomes more and more connected, the collaboration with other Photonics21 workgroups will become increasingly important. Machine Learning (ML) and Artificial Intelligence (AI) will play a crucial role in lighting to learn user preferences and behaviour to improve the performance of the systems by interpreting the sensor data more accurately and to allow for 'noisier' data.

Finally, high volume, cost-driven, industries (such as automotive lighting) require efficient integration of the components, systems, and platforms at large manufacturing scales. Such demands require strict quality assurance and cost control for the successful introduction in the market at the pace required by the current technological change.

Proposed roadmap for 2025 – 2028

Identified Technologies with Milestones, challenges, and cooperation needs

Mobility

	2025/2026	**2027/2028**
Overview Technology Challenges	• **Energy efficient Adaptive Driving Beam** • **Projection of information** • **Photonic Integration for Sensors** • **Efficient sensing technology for autonomous vehicle**	• **Battery health monitoring** • **Communication with Light (Lifi)** • **Immersive Interaction with displays having new properties** • **Micro Displays** • **Mixed use zone surveillance technology**
Critical milestones to move from Science to Market	• **Daylight vs night-time information projection requirements.** • **Adaptive Driving Beam adverse weather performance** • **Optimization and cost reduction of sensing technology for autonomous vehicle**	• **LiFi Range, bandwidth and immunity requirements** •
Photonics Research (R) & Innovation (I) Challenges	• **High energy efficiency lights** • **All weather sensing technology**	• **Wavelength selection** • **Communication protocols and interference handling** • **Virtual displays** • **Augmented reality** • **Congruent displays**
Joint actions required with other disciplines (e.g., Artificial Intelligence) or fields (e.g., robotics)	**Human factors, such as physiological effects of lighting and human information projection without causing a distraction.**	**V2X community**

Climate

	2025/2026	**2027/2028**
Overview Technology Challenges		• Photonic-driven chemical conversion of the unwanted greenhouse gas CO2 and green H2 to carbon containing fuels (e.g., CH4, CH3OH) or other high value chemical product (e.g., syngas) • Photonics sensing of pollutant gas concentrations
Critical milestones to move from Science to Market		**Tailored energy efficient LED light engines to compensated for the fluctuating sunlight intensity to ensure a stable and high-quality, continuous chemical process production.**
Photonics Research (R) & Innovation (I) Challenges		**Tailored energy efficient light engines. Optical components to concentrate and couple natural sunlight and artificial light.**
Joint actions required with other disciplines (e.g., Artificial Intelligence) or fields (e.g., robotics)		**Climate, lighting.**

Lighting & organic photovoltaics

	2024/2025	2026/2027
Overview Technology Challenges	• Extended 2D materials + integration in optoelectronic devices to save resources • Integration of energy generation • Automotive lighting (LED, OLED, laser,…) • LiFi, e.g. in transportation • Photonic computer simulation models (aligned with experiment) • Lighting for IoT • DC grids for lighting	• New materials (for more energy-efficient light emitters and detectors, …) • Smart GaN for HF/VHF • In-vivo sensors coupled with AI • Photoelectrochemical devices for water splitting • LIDAR for wind turbines • High-efficiency optical transceivers
Critical milestones to move from Science to Market	• Cost-effective integration of passives with usable performance. • Single-chip-solution/topology for Lifi receivers • Fast phosphors for LiFi • Energy efficient LED drivers	• High-speed detectors • Low voltage photonic detectors • Long lifetime lighting systems
Photonics Research (R) & Innovation (I) Challenges	• Single-chip-solution/topology for light-source: GaN transistor on LED • Phosphor with high time-constant and high efficacy for low light-ripple.	• Energy-Harvesting concepts based on light (IR, visible-light), temperature and radio. • New materials for compacter and more energy efficient drivers • Energy optimization on system level (especially for matrix lighting etc.)
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	• CCAM/automotive industry • IoT • Photonics21 WGs • Energy monitoring systems • Energy-efficient Building •	• CCAM/automotive industry • IoT • Artificial Intelligence • Big Data • Photonics21 WGs • Energy monitoring systems • Energy-efficient Building •

4.5 Safety

4.6 Agriculture & Food

4.7 Core Photonic Technologies