

A man is seated in the driver's seat of a car, looking out the window. Overlaid on the image is a blue digital grid of points and lines, representing a sensor fusion or facial recognition system. The grid points are located on the man's face, neck, and torso, and lines connect them. Additionally, lines extend from the grid towards the car's interior, suggesting sensor coverage or data flow.

# Pioneering In-Cabin Monitoring

**Unmasking the Power of 2D and 3D Cameras  
through Sensor Fusion**



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# About Fraunhofer IOSB

As part of the largest organization for application-oriented research in Europe, the Fraunhofer Institute of Optronics, System Technologies, and Image Exploitation IOSB, with headquarters in Karlsruhe, is one of the leading scientific institutes in the fields of Artificial Intelligence (AI), Computer Vision and Optics in Germany and Europe. Approximately 850 employees research and support companies in optimizing products, services and processes and in developing new digital business models. Fraunhofer IOSB is shaping the digital transformation of our working and living environments: with innovative AI applications for industry, health and sustainability, with forward-looking computer vision technologies and extensive optical sensor know how.

In the department “Human-AI Interaction”, innovative interaction methods and assistance systems are developed to support people in their tasks. With the development of camera-based perception and adaptive user interfaces, the focus is particularly on the detection of humans and the evaluation of their activities for multimodal human-machine interactions in intelligent and proactive environments. For more than 10 years we have been focussing on vehicle cabins.

Numerous publications resulted from the research on occupant monitoring:

- Martin, M., Lerch, D., & Voit, M. (2023, June). Viewpoint Invariant 3D Driver Body Pose-Based Activity Recognition. In 2023 IEEE Intelligent Vehicles Symposium (IV) (pp. 1–6). IEEE.
- Martin, M., Voit, M. & Stiefelwagen, R. (2021). An Evaluation of Different Methods for 3D-Driver-Body-Pose Estimation. IEEE. <https://doi.org/10.1109/itsc48978.2021.9564676>
- Martin, M., Voit, M. & Stiefelwagen, R. (2020). Dynamic Interaction Graphs for Driver Activity Recognition. 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC). <https://doi.org/10.1109/itsc45102.2020.9294520>
- Martin, M., Roitberg, A., Haurilet, M., Horne, M., Reib, S., Voit, M. & Stiefelwagen, R. (2019). Drive & Act: A Multi-Modal Dataset for Fine-Grained Driver Behavior Recognition in Autonomous Vehicles. Proceedings of the IEEE International Conference on Computer Vision. <https://doi.org/10.1109/iccv.2019.00289>
- Roitberg, A., Pollert, T., Haurilet, M., Martin, M. & Stiefelwagen, R. (2019). Analysis of Deep Fusion Strategies for Multi-Modal Gesture Recognition. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops. <https://doi.org/10.1109/cvprw.2019.00029>
- Ludwig, J., Martin, M., Horne, M., Flad, M., Voit, M.,

Stiefelwagen, R. & Hohmann, S. (2018). Driver observation and shared vehicle control: supporting the driver on the way back into the control loop. *Automatisierungstechnik*, 66(2), 146–159. <https://doi.org/10.1515/auto-2017-0103>

- Martin, M., Popp, J., Anneken, M., Voit, M. & Stiefelwagen, R. (2018). Body Pose and Context Information for Driver Secondary Task Detection. IEEE. <https://doi.org/10.1109/ivs.2018.8500523>
- Lerch, David J., et al. “Unsupervised 3D skeleton-based action recognition using cross-attention with conditioned generation capabilities.” Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision. 2024.
- Lerch, D. J., El Bachiri, Y., Martin, M., Diederichs, F., & Stiefelwagen, R. (2024). 3D Skeleton-Based Driver Activity Recognition Using Self-Supervised Learning. In 2024 IEEE 27th International Conference on Intelligent Transportation Systems (ITSC) (pp. 798-805). IEEE.

The Advanced Occupant Monitoring System from Fraunhofer IOSB uses optical sensors inside the vehicle. It captures the cabin, the driver and all occupants, recognizes the 3D body pose of all individuals, analyses their movement behaviour, and classifies the activity of each detected person. With this, it is not only possible to recognize critical situations, such as a driver falling asleep, but also to distinguish between various activities and the associated attention levels. This supports both safety systems and comfort functions inside the vehicle.

Fraunhofer IOSB technology has been developed in joint projects with leading industry partners and funding from German Government. In the BMBF projects InCarIn and PAKoS, the Fraunhofer IOSB developed machine learning-based methods to capture the body pose and interactions of all vehicle occupants. With these methods, functions in the vehicle were adjusted and personalized. In the BMWK project INITIATIVE ([www.initiative-projekt.de](http://www.initiative-projekt.de)), the detection was expanded to pedestrians in traffic and applied to the interaction of pedestrians with automated vehicles. In the BMWK funded project KARLI ([www.karli-projekt.de](http://www.karli-projekt.de)) [36], these skills are currently being transferred to new AI methods of unsupervised learning. In the BMWK funded project KARLI ([www.karli-projekt.de](http://www.karli-projekt.de)), those skills were transferred to new AI methods of unsupervised learning. The BMWK funded project SALSA ([www.projekt-salsa.de](http://www.projekt-salsa.de)) builds on it expanding to level 3 and 4 use cases relaxation and sleep as well as investigating generative UI.

<https://www.iosb.fraunhofer.de/de/kompetenzen/bildauswertung/interaktive-analyse-diagnose/automotive.html>

[www.iosb.fraunhofer.de](http://www.iosb.fraunhofer.de)

# 1. Why In-Cabin Monitoring?



Figure 1: Overview legislation regarding in-cabin monitoring

According to the World Health Organization, approximately 1.19 million people die each year in road traffic accidents [1]. National and international studies indicate that driver distraction and inattention are significant factors in traffic accidents [2]. In 2022, 3308 people were killed, and an estimated additional 289,310 people were injured in motor vehicle traffic crashes involving distracted drivers [3]. Automation of driving tasks stimulates further distraction, sleepiness and vehicles operation under reduced driving ability.

Regulatory authorities in the automotive industry in Europe, America and Asia are paving the way for safety technologies.

In-cabin monitoring and driver monitoring are considered major contributors to improving traffic safety in the future. This expectation has led to the enactment of new and expanded laws compelling automotive manufacturers to integrate in-cabin monitoring into vehicles.

Improving traffic safety is the primary driver for the introduction of in-cabin monitoring and driver monitoring. Worldwide legislation defines the causes of traffic accidents and injuries that should be mitigated with in-cabin monitoring.

Consumer test associations design and publish vehicle assessments in parallel with the ambitious demands from legislation.

These assessments define how in-cabin monitoring is tested and which key performance indicators need to be achieved.

Hence, technology providers have increased their efforts to offer sensors, algorithms and systems to comply to legislation and assessments. A large variety of options is currently under development.

Beyond safety applications, in-cabin monitoring can and will be used for comfort and entertainment and will also play a fundamental role in creating personalized digital services for car users. In parallel to services on smartphones, AR headsets and in smart home environments, the vehicle interior may become one of the most digitalized and personalized environments for humans to be – thanks to in-cabin monitoring.

Hence, the development of in-cabin monitoring is currently driven by five major forces:

1. Legislation and multilateral agreements from governments
2. Vehicle assessment programs and consumer tests
3. Technology advancements
4. Consumer electronics
5. User requirements

## 1.1 Legislation and Multilateral Agreements

Due to the impact of human error in traffic safety, governments around the world have identified interior monitoring and driver monitoring as key technologies to improve safety. Furthermore, advancements in automated driving require humans as operators and fallback actors for automated systems. Ensuring human availability and reliable performance is hence a safety relevant factor. Many legislations for the introduction of automated driving require monitoring systems to ensure the human fallback layer. Many countries have already passed or updated such regulations.

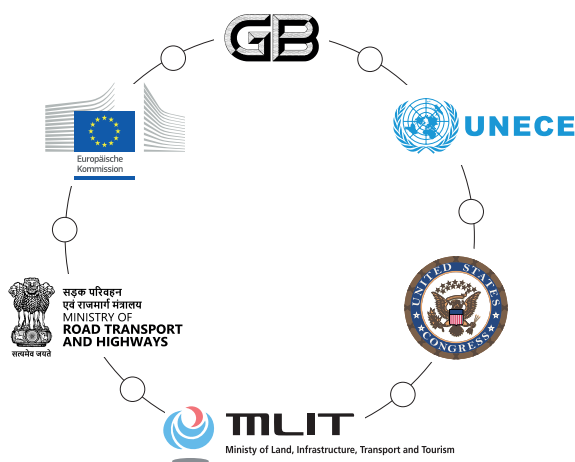


Figure 2: Overview automotive safety institutions

### Europe

Due to the persistently high number of road accidents and injuries across Europe, the EU introduced the General Safety Regulation (GSR) in November 2019 [4]. This new set of measures is projected to save more than 25,000 lives and prevent at least 140,000 serious injuries by 2038 [5]. Among other provisions the GSR specifically addresses requirements for **Driver Drowsiness and Attention Warning, DDAW** ([EU] 2021/1341) [6], for **Driver Availability Monitoring, DAMS** ([EU] 2019/2144) [4] and **Advanced Driver Distraction Warning, ADDW** ([EU] 2023/2590) [7]. These technologies have major potential to reduce the number of casualties substantially.

#### Driver Drowsiness and Attention Warning (DDAW)

This system defines a system that assesses the driver's alertness, by detecting signs of fatigue or drowsiness. Based on vehicle system analysis, it warns the driver with visual and acoustic warning if needed, to encourage them to rest or refocus on the road. The trigger behavior may cascade and intensify until acknowledgement thereof by the driver. It automatically activates at speeds over 70 km/h, typically encountered on highways where drowsiness-related accidents are more likely. The DDAW system

may issue a warning to the driver when their drowsiness reaches a level equivalent to 7 on the Karolinska Sleepiness Scale (KSS). Data collected must remain confidential, never shared with third parties, and be deleted immediately after processing.

The implementation is being introduced step by step:

- **July 6, 2022:** DDAW systems became mandatory for all newly introduced vehicle types or models within the EU.
- **July 7, 2024:** This system is legally mandated for all new vehicles sold in the EU, including older models.

Learn more about the specific test procedures and technical requirements for the type-approval of motor vehicles regarding their fatigue and alertness warning systems in documents EU 2021/1341/C(2021) 2639, supplementing Regulation EU 2019/2144.

#### Advanced Driver Distraction Warning (ADDW)

This system monitors the driver's eye movements and head position to detect signs of distraction, such as looking away from the road. When a distraction is identified, it issues a warning to alert the driver.

The implementation is being introduced step by step:

- **July 7, 2024:** ADDW is required for all newly registered vehicle types.
- **July 7, 2026:** ADDW systems will be mandatory in all new vehicles sold on the European market, including older models.

#### Specific requirements in GSR 2023/2590

The publication specifies necessary technical requirements and test procedures for ADDW systems to monitor the direction of the driver's gaze. Warning signals are activated when the driver's gaze deviates from the specified areas within a predetermined time, thus being defined as "distracted".

#### Defined distraction zones

- Area 1
  - Roof
  - Left side (-55°)
  - Right side (+55°)
- Area 2
  - Area of the windshield and windows 10° around the area of the windshield and windows, measured from the eye reference point
- Area 3:
  - Any surface below a plane extending 30° downward from the driver's eye reference point
- **Operating and ambient conditions**
  - ADDW system must be automatically activated at speeds above 20 km/h
  - Measurement and calibration of the system permitted with a cumulative travel time of up to 1 minute of driving at speeds  $\geq 20$  km/h



- System must operate under both daytime and nighttime conditions

#### ■ Performance indicators

- For speeds between 20 km/h and 50 km/h the ADDWS system must provide a warning if the driver's gaze remains within the defined "distracted" vision for more than 6 seconds.
- Remains the driver's gaze within the specified areas of distraction for more than 3.5 seconds and a speed above 50 km/h, the ADDW system must give a warning.

#### ■ Warnings

- When driver distraction is detected, the ADDW system must provide a warning strategy.
- Driver must be informed by visual warning, plus an acoustic and/or direct/indirect haptic warning.
- Intensification and escalation of warnings until the driver distraction ceases

#### ■ System failure

- Issuance of an error warning signal upon detection of a temporary non-electrical fault condition as well as permanent failures.

#### ■ Roadworthiness testing provisions

- For the purpose of regular technical monitoring of vehicles, the regulation specifies the features of the ADDW for verification.

### Driver Availability Monitoring Systems (DAMS)

A system designed to assess whether the driver can appropriately take over control from an automated vehicle in specific situations. Technical specifications for Driver Availability Monitoring Systems do apply to automated vehicles. The European Union's GSR 2019/2144 regulation mandates driver monitoring systems in new vehicles, further accelerating the adoption of DAMS. An initial

technical study was conducted to identify a comprehensive set of DAMS system requirements and to finalize a preliminary list of items for inclusion in future requirements and tests within the DAMS technical annex (Annex 1).

The implementation is being introduced step by step:

- **July 6, 2022:** Date for refusal to grant EU type-approval without DAMS.
- **July 7, 2024:** Date for the prohibition of the registration of vehicles, as well as placing on the market and entry into service of components and separate technical units without DAMS.

### DAMS system requirements [8]

- **Continuous Monitoring:** DAMS must continuously and directly monitor the driver to ensure they are ready and capable of safely taking over control from the automated driving mode.
- **Driver State Detection:** The system must assess key driver states. If any of those exceed set thresholds or the driver fails to respond, the system must initiate appropriate action.
  1. Driver Presence
  2. Wakefulness
  3. Attentiveness
  4. Engagement in secondary tasks
  5. Sudden sickness
- **Transition Phase:** A minimum of 10-second transition period is required for handing control back to the driver. If the driver is performing a handheld secondary task, the transition time must be at least 15 seconds.
- **Post-Transition Support:** After the transition, DAMS must continue monitoring and assisting the driver until they have fully regained situational awareness and full control (both longitudinal and lateral) of the vehicles.

## EU – General Safety Regulation

Driver Monitoring System	Regulation	M1	M2	M3	N1	N2	N3
Driver Drowsiness and Attention Warning (DDAW)	EU 2021/1341	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022
		NT 7/2024	NT 7/2024	NT 7/2024	NT 7/2024	NT 7/2024	NT 7/2024
Advanced Driver Distraction Warning (ADDW)	EU 2023/2590	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022
		NR 7/2026	NR 7/2026	NR 7/2026	NR 7/2026	NR 7/2026	NR 7/2026
Driver Availability Monitoring System (DAMS)	EU 2019/2144	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022	NT 7/2022
		NR 7/2024	NR 7/2024	NR 7/2024	NR 7/2024	NR 7/2024	NR 7/2024

Table 1: EU legislation and binding dates of system integration (based on: SafetyWissen [9])

NT = New Vehicle Types. Date for refusal to grant EU type-approval of vehicles that do not meet the requirements.

NR = New Regulations. Date for the prohibition of the registration of vehicles that do not meet the requirements. Vehicles as well as the commissioning of components and autonomous technical units that do not meet the requirements are excluded from approval.

Some of the new measures will be expanded to cover different kinds of road vehicles until 2029. Regulations and testing procedures for vehicle and system approvals will be developed and harmonized at Union level.

## United States

The United States have introduced several regulations for Driver Monitoring Systems (DMS).

### Hot Cars Act of 2021

The Helping Overcome Trauma for Children Alone in Rear Seats, HOT Cars Act of 2021 [10] was introduced in 2021. The bill aims to make child safety alert systems mandatory in all new passenger vehicles to reduce death and injury resulting from heatstroke in vehicles. Within two years after the date of enactment of this section, a final rule shall be published requiring all new passenger vehicles to be equipped with a system to detect children that are left in a parked car. The Act was referred to the Subcommittee on Consumer Protection and Commerce and remains on status Introduced (Accessed on July 17th, 2025).

### Safe Act of 2021

The Stay Aware for Everyone Act of 2021 (SAFE Act of 2021) mandates the use of driver monitoring systems to minimize or eliminate:

- **driver distraction**
- **driver disengagement**
- **automation complacency by drivers**
- **foreseeable misuse of advanced driver-assist systems**

A final rule establishing performance standards and the installation of driver monitoring systems is due within four years of the date at the latest. Further, automakers are instructed to comply within two model years of the effective date of the final rule. As of right now, the Act remains in Committee on Commerce, Science, and Transportation on status Introduced (Accessed on July 17th, 2025) [11].

### IIJA of 2021

The Infrastructure Investment and Jobs Act (IIJA) from 2021 calls in section B for the use of Driver Monitoring Systems to be investigated and for a corresponding DMS regulation to be issued once the research has been successfully completed. The Act became Public Law by November 15, 2021 [12].

Specifically, the act demands:

- **Reduction of driver distraction  
(HR 3684; Section 24209/P. 1045)**

The Safe Act was included in the IIJA with its requirements for research into driver monitoring systems for use against driver distraction. By November 15, 2024, the Secretary must conduct research on the installation and use of DMS in motor vehicles to minimize or eliminate:

1. Driver distraction
2. Driver disengagement

3. Driver complacency with automation

4. predictable misuse of advanced driver assistance systems.

NHTSA published an Advance Notice of Proposed Rulemaking, ANPRM (89 FR830) on January 5, 2024, under RIN 2127-AM50 with section B. Distracted Driving [13].

- **Advanced Impaired Driving Prevention Technology  
(HR 3684; Section 24220/P. 1066)**

Within three years of the entry into force of this Act, a standard shall be issued that requires all new passenger motor vehicles to be equipped with advanced drunk and impaired driving prevention technology as standard.

The issuance of the final rule is governed by subsection (e), "Timing", which allows for an extension of up to three years if the Secretary determines that the FMVSS cannot comply with the requirements of 49 U.S.C. 30111(a) and (b). Hence, the legislation directs NHTSA to adopt a new safety mandate by November 15, 2024, and begin enforcing it by September 2027 (at the latest) if this is feasible. The NHTSA is developing technology to detect alcohol impairment in drivers, as required by IIJA § 24220.

Research has advanced, but the technology isn't yet at a stage of maturity that would allow the agency to effectively implement such a mandate [14]. NHTSA published an Advance Notice of Proposed Rulemaking, ANPRM (89 FR 830) on January 5, 2024, under RIN 2127-AM50.

- **Awareness of children in motor vehicles  
HR 32304; Section 32304B/P. 1077)**

Directs the secretary to conduct a study on the possible retrofitting of existing passenger vehicles with one or more technologies that reduce the risk of children being left in the rear seats after a motor vehicle is disabled. Section contains parts of the HOT Cars Act. NHTSA has an ongoing rulemaking, titled, "Rear Designated Seating Position Alert" (RIN 2127- AM49), to implement the requirements of 49 U.S.C. 32304B (enacted as IIJA § 24222). Staus July 2025 they continue to conduct extensive research and analysis on technologies designed to detect unattended occupants as they become available. Due to the lack of fully effective technology, rulemaking has been delayed. Research and testing continue, and NHTSA plans to propose a rule (NPRM) in 2025 once technology has matured [14].

### Alliance of Automobile Manufacturers

Participating car manufacturers in the Alliance of Automobile Manufacturers have made an independent and voluntary commitment to integrate rear seat reminder systems as standard equipment in passenger cars by model year 2025 at the latest. This measure serves to protect and minimize cases in which children are left alone in the vehicle. The industry is making strong progress toward its voluntary goals. Adoption

has increased by 22% since 2023 and has grown fivefold since 2019. According to the Alliance for Automotive Innovation Press Release of November 4, 2024, rear seat technology is already available in more than 263 new vehicle models (standard and optional) [15]. The rear seat reminder system uses radar to monitor and detect movement at the rear seats and alert the driver through various acoustic or visual options.

## China

In 2018, Jiangsu became the first Chinese province to require the use of driver monitoring systems in long-haul trucks and vehicles transporting dangerous goods. At the present time, the China-GB/T does not set any binding requirements but rather makes an official recommendation on performance requirements for DMS to ensure that hardware and algorithms used in DMS are not only functional but also consistent across OEMs and suppliers.

This recommended national standard (GB/T 41797-2022) entitled Driver Attention Monitoring System (DAMS) sets out test procedures and test methods that were implemented in May, 2023 [16]. The 5 types of distracting behavior are outlined, along their associated warning conditions.

The criteria can be summarized as follows [32]:

- **Eye-closing**
  - Eyes completely closed for a duration of  $\geq 2$  s
- **Abnormal head pose**
  - Head deflection angle left or right  $\geq 45^\circ$  for a duration of  $\geq 3$  s
  - Head up or down  $\geq 30^\circ$  for a duration of  $\geq 3$  s
- **Answering hand-held phone**
  - Distance between any point of the hand-held phone and the face  $< 5$  cm for a duration of  $\geq 3$  s
- **Yawning**
  - Mouth opening height-width ratio (the ratio of the minimum vertical height of the inner edge of the upper and lower lips to the horizontal width of corners of the mouth)  $> 0.6$  for a duration of  $\geq 3$  s
- **Smoking**
  - The minimum distance between the hand-held cigarette and the lips shall not be greater than 2 cm, for a duration of  $\geq 2$  s

## Japan

### Safety regulations for automated operation devices

In March 2020, safety regulations for automated operation devices were formulated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) within the Road Transport Vehicle Act (enacted in May 2019, took effect in April 2020) [17]. These safety regulations establish driver monitoring technology as equipment for vehicles that monitor the driver's condition and ensure whether they are ready to take over. In the following, main requirements are specified:

### Performance requirements

1. Safe operation shall be continued until the driver takes over, and the vehicle shall be stopped safely if he or she does not take over. An alarm to alert the driver before taking over operation shall be made before leaving the standard operating environment.
2. The vehicle shall be equipped with driver monitoring to monitor the driver's condition.
3. Measures shall be taken to ensure cyber security to prevent unauthorized access.

### Operation status recording equipment

- ON/OFF time of the automated operation device:
- Time when the alarm was triggered to take over driving
- Time when the driver became unable to respond, must be able to be recorded for 6 months (or 2,500 times).

## India

Currently, India has no specific laws requiring DMS in vehicles. The Ministry of Road Transport and Highways (MoRTH) has instructed the Automotive Industry Standard Committee (AISC) with a final draft (Draft AIS-184/DF) in 2022 [18], to initiate a new Automotive Industry Standard (AIS) with the topic of Driver Drowsiness and Attention Warning Systems (DDAW) that shall meet the European requirements like EU 2021/1341. The draft sets requirements for DDAW systems in transport vehicles (M2, M3, N2, N3 categories), with some exemptions for certain vehicle types (N1), and outlines requirements for DDAW systems in transport vehicles of categories M, N2, and N3, with certain exemptions for specific vehicle types, such as N1.

### General requirements

- The DDAW system shall issue a warning to the driver when the drowsiness level is 7 and 8 or higher, according to the Karolinska Sleepiness Scale (KSS).
- The functionality of the DDAW system shall be without biometric information or facial recognition of the vehicle occupants. Any processing of personal data shall be carried out in accordance with the data protection law.

- Manufacturers must carry out validation tests to ensure that DDAW systems are capable of monitoring driver fatigue accurately, robustly and scientifically.

While the draft calls for the indirect nature of the measurements and requirements to be considered, they should also be technology-neutral to encourage the development of newer technologies.

## UNECE

UNECE has adopted a framework document in automated/auUNECE has adopted a framework document in automated/ autonomous vehicles by the World Forum on Harmonization of Vehicle Regulation (WP.29) at its 178th session [19]. The document presents the identification of key principles for ensuring consistent safety of Level 3 and higher automated/autonomous vehicles, with the aim of harmonizing vehicle regulations.

### New UN Regulation draft

On February 1, 2024, the UNECE Special Working Party on Automated/Autonomous and Connected Vehicles (GRVA) adopted a new draft regulation laying down provisions for the approval of vehicles with Driver Control Assistance Systems (DCAS) and minimum safety requirements for vehicles equipped with advanced driver assistance systems (ADAS) [20]. Building on UN-Regulation No. 79 published in 2018, the new draft regulation includes an expansion of the technologies to be introduced in new models.

According to the regulation, DCAS, as a subgroup of Advanced Driver Assistance Systems, must guarantee and ensure through its design that the driver fulfills his driving task.

- The driver's vision (visual interaction between the driver and the road) must be monitored,
- and the driver's hands must remain on the steering wheel.
- An alarm must be triggered after 5 seconds if it detects that this is no longer the case. The purpose of this is to prevent the driver from relying too much on such systems and overestimating them (Mode Awareness).

### Framework document on automated/autonomous vehicles

During the 178th session of the UN WP. 29 (World Forum for Harmonization of Vehicle Regulations) in February 2022, a Framework Document on Automated/Autonomous Vehicles (FDVA) of levels 3 and higher was published [19]. This document was prepared at the interstate level by representatives from China, the European Union, Japan, and the United States of America. The aim of the framework is to harmonize worldwide requirements and guidelines for automated driving and to create space for the development of innovations. Updated tables show HMI (internal and external) and driver monitoring as functional requirements for automated/autonomous vehicles.

New assessment and test methods demand for in-use monitoring.

## 1.2 Vehicle Assessment Programs and Consumer Tests

In addition to legal regulations, vehicle assessment programs e.g. from NCAP define how Interior Monitoring and Driver Monitoring Systems are tested and assessed. Such assessment programs define the priorities for the new car market in the next decade. Although they are not legally binding, high safety ratings are important arguments for customer trust, homologation and legal disputes. Consumer tests in Europe (Euro NCAP), America (IIHTS-HLDI), Asia (e.g. ASEAN NCAP and C-NCAP) and Australia (ANCAP) have adapted and updated their criteria during the technological turnaround in the past years.

## EU-NCAP

The European New Car Assessment Program (Euro NCAP) is a European voluntary car safety performance assessment program. Since January 2023, Driver Monitoring Systems (DMS) and Child Presence Detection (CPD) are a requirement for any new car launched on the European market and considered in the test protocols [21]. Euro NCAP in 2025 announced its new provisional 2026 protocols, to set higher standards for vehicle safety. These changes will introduce updated requirements for Advanced Driver Assistance Systems, driver monitoring, crash avoidance, and post-crash safety.

### Euro NCAP 2026 protocol updates summary

Starting in 2026, Euro NCAP will significantly tighten the requirements for driver monitoring: instead of a maximum of 2 points, up to 25 points can now be awarded. Indirect systems like steering behavior detection will no longer be sufficient – direct monitoring technologies such as real-time tracking of eye and head movements will be required. This will lead to significantly increased development, validation, and testing efforts for manufacturers and suppliers. Starting in January 2026, the following updates will be implemented:

#### 1. Expansion of Driver States [22]

Fatigue detection must reliably identify drowsiness and assess it using recognized sleepiness scales. Distraction detection requirements will be more precise: it will no longer be sufficient to simply detect if the driver's gaze is off the road. Systems must also recognize frequent, brief glances away from the road – known as visual attention time sharing. The systems should also be able to detect mobile phone use – not just general distraction, but specifically whether the driver is looking at, holding, or interacting with a phone. In addition to fatigue and distraction, non-fatigue-related impairments (e.g. due to

alcohol or drugs) will also be considered for the first time.

Euro NCAP will distinguish between **transient** (temporary) and **non-transient** (persistent) impairment states:

- **Transient Driver States:** Long distraction, Short distraction (VATS), Phone Use
- **Non-Transient Driver States:** Impairment, Microsleep, Sleep, Unresponsiveness.

To comply with the new standards, Driver Monitoring Systems must detect signs of impairment within the first 10 minutes of driving at speeds of 50 km/h or more. Instead of using generic thresholds, systems should analyze a driver's current behavior in comparison to their usual patterns to identify anomalies. If the driver becomes unresponsive, the system must escalate warnings and, if needed, intervene – such as by increasing safety assist features or initiating an emergency stop.

## 2. On-road assessment of DSM for identifying false positives [23]

DSM systems will be tested on public roads in the future to assess the number of false alarms (false positives) and the clarity of warnings. Objective: Increase user acceptance through realistic evaluation scenarios. Manufacturers are expected to validate their systems in this fashion in advance.

## 3. Active DSM as a Prerequisite for Assisted Driving [24]

Starting in 2026, an active DSM system will be mandatory for assisted driving (SAE Level 2). Only vehicles that actively monitor driver attention, steering wheel use, and disengagement will receive full evaluation points. Systems that block functions after repeated driver inactivity will be rewarded additionally. Misleading system names suggesting a higher level of automation will result in point deductions.

### Child Presence Detection (CPD)

Leaving a child unattended in a parked car can quickly lead to fatal heatstroke due to rapid temperature rise and a child's vulnerability. To prevent these avoidable deaths, Euro NCAP has recognized Child Presence Detection (CPD) systems as a standard safety feature since 2023 [25].

From 2025, vehicles equipped with indirect sensing or limited to only an alert or initial warning will no longer be eligible for points. CPD technology aims to address both intentional and unintentional cases. Vehicles must use direct methods that detect movement, breathing, or heartbeat to confirm a child's presence inside the car. This system must be default ON at the start of every trip and start the detection within 15 seconds after the car is locked, or within 10 minutes if the doors remain unlocked.

CPD Systems are expected to detect children up to and including six years old in two key scenarios:

- A child left behind in a locked vehicle

- A child who enters an unlocked vehicle and becomes trapped

Cover all seating positions (including optional/removable seats), footwells, and the driver's seat – excluding the luggage area.

The system must issue an initial visual or audible alert that can be noticed from outside of the vehicle. If no response follows, the system must escalate the alerts – repeating them every minute for at least 20 minutes. Escalations can include notifications to the vehicle key, mobile app alerts, or connected emergency services. To achieve the maximum score, the system must go beyond detection and warnings by actively intervening – for example, by turning on climate control, unlocking the doors, or sending notifications directly to caregivers.

### Seatbelt and Posture Monitoring

While seatbelt reminders are standard in vehicles, Euro NCAP is introducing stricter requirements. From 2026, cars must detect not only if seatbelts are fastened but also if they're being worn properly. Failure to do so will result in lower safety ratings, addressing the widespread issue of seatbelt misuse [26].

- **Seatbelt misuse detection:** The system must identify when a seatbelt is fastened but not worn properly. Three misused cases are illustrated as (1) seatbelt buckle only, (2) seatbelt completely behind the back and (3) lap belt only. Additional misuse cases and driver's seating positions may be added in 2029.
- **Rear seat position with occupant detection:** Any rear seat equipped with occupant detection and a seatbelt reminder that meets the criteria – triggering a warning when an adult is present but not wearing a seatbelt – will earn points.

### Passenger Airbag status

Euro NCAP's 2026 protocols drive the adoption of intelligent restraint systems that adapt to the occupant's size, position, and seating posture. For automakers, this signals a shift toward standardizing more advanced occupant classification technologies. Vehicles must feature intelligent restraint systems that automatically deactivate the passenger airbag for rear-facing child seats, adjust airbag deployment based on occupant size, and detect unsafe seating positions – like leaning too close to the dashboard – to issue appropriate warnings. To meet these requirements, more vehicles will incorporate cabin-facing cameras, 3D depth sensors, weight sensors, or integrated combinations of these technologies [26].

## Australia NCAP

### The Australian New Car Assessment Program (ANCAP) [31]

aligns with Euro NCAP standards, focusing on safe driving, crash avoidance, crash protection and post-crash safety, including in-cabin monitoring.



Like Euro NCAP, ANCAP structures its initiatives around:

- **Driver monitoring**
- **Occupant monitoring and classification**
- **Child presence detection**

## US IIHS-HDLI

According to new US regulations, semi-automated vehicles must have safety features that support the driver's concentration on the road. To address these requirements for driver monitoring and attention reminders, the Insurance Institute for Highway Safety (IIHS) has developed a new test program to evaluate safety features in semi-automated systems [27]. The IIHS test protocols and safety ratings will be included in Consumer Reports' scoring of semi-automated driving systems as they become available. The ratings of safety features as good, acceptable, marginal or poor are intended to support technologies and their functional aspects that reduce intentional and unintentional misuse. Systems monitor the driver's gaze, head position or hand position to ensure an active and conscious driving state. Ratings are based on the output and type of warnings that remind the driver to look back at the road or put their hands on the steering wheel in the event of inattention. Possible warning signals include bell tones, vibrations, pulsating brakes or pulling on the seatbelt, which are emitted via several channels and are intended to escalate as urgency increases and time passes. If the driver fails to respond, the system slows the vehicle to a stop and should initiate notification of emergency services if necessary. This escalation level allows the driver to be locked out of the system for the remainder of the drive.

### Summarized requirements for a good partial automation safeguard:

- Monitors both the driver's gaze and hand position
- Uses multiple types of rapidly escalating alerts to get driver's attention
- Fail-safe procedure slows vehicle, notifies manufacturer and keeps automation off limits for remainder of drive.

## China NCAP

A new C-NCAP Management Regulation has been published in January 2024 by the China Automotive Technology and Research Center Co., Ltd. (CATARC) [33]. Since its introduction in 2006, C-NCAP has undergone six revisions, with updates occurring regularly every three years. While the rating system has traditionally assessed both passive and active safety, the 2024 revision of the C-NCAP protocol, effective from July 1, 2024, places greater emphasis on active safety (3.3) [28]. It introduces new tests for Autonomous Emergency Braking (AEB), Driver Monitoring Systems (DMS), road feature recognition (RFR), and protection for Vulnerable Road Users (VRU). For the first

time, DMS is factored into the overall safety rating by testing **Driver Attention Monitoring (DAM)** and **Driver Fitness Monitoring (DFM)**. 2 Bonus points can be awarded for the function of **Child Presence Detection (CPD)**. Collected driver data must adhere to China's Personal Information Protection Law (PIPL), ensuring biometric information is anonymized and data transmissions are securely protected.

### Driver Fitness Monitoring (DFM)

- Evaluates a driver's physical and cognitive ability to drive safely, focusing on medical incapacities, fatigue, or substance impairment and trigger warnings once specified threshold is reached.
- The Test measure factors like driver's height, eyelid gap, head pose, and other parameters. It includes a fatigue assessment to determine the driver's fitness to drive.
- Long-term ability to drive safely

### Driver Attention Monitoring (DAM)

- Concentrates on the monitoring of driver's immediate alertness and focus. Monitors gaze direction and driver distraction, triggering escalating alerts if the driver's eyes are off the road for more than 3–5 seconds.
- Relies on sensors and cameras to monitor indicators like eye movements and head position, aiming to detect real-time signs of distraction or drowsiness.
- This system prioritizes short-term vigilance rather than long-term driving capability.

### Test scenarios (Appendix L.6.4)

Requires at least 90 % detection accuracy for full points and assesses how well interior and exterior systems (e.g., DMS, AEB, VRU) work together.

### DFM

- Driver Behavior: Eye closure (completely 3 s)
- Driver facial accessories: Naked eye, wear sunglasses.

### DAM

- Driver distracted behavior: Prolonged distraction (Head moving)
  - Driver side rear-view mirror (3 s)
  - Interior rear-view mirror (3 s)
  - Car entertainment system central control screen
- Prolonged distraction
  - Instrument panel speed display area (3 s)
  - Driver's right leg knee (3 s)

### Child Presence Detection (CPD)

- For direct sensing systems, vehicle manufacturers must submit relevant materials, which are reviewed to determine if the full 2 bonus points are awarded.
- If criteria are met, 2 points are awarded; if not, 0 points are given.

## C-IASI

Inspired by the U.S. IIHS, China has introduced the **China Insurance Automotive Safety Index (C-IASI)**. This system complements the existing C-NCAP and evaluates vehicles not only through standard insurance tests but also with advanced crash tests and pedestrian protection assessments. To carry out these tests, the China Insurance Research Institute of Automobile Technology (CIRI) has set up a new crash test facility. The Driver State Monitoring System Protocol 2023 is part of the Vehicle Assistant Safety Index [29]. It evaluates vehicles equipped with a driver state monitoring system. This document applies to M1 and N1 vehicles that use image recognition technology for their driver state monitoring systems. It may also serve as a reference for other systems with similar functions.

### Driver Identification Ability Rating

- Basic monitoring items include detecting eye closure, abnormal head position, and the use of hand-held phones (both answering and making calls). These items must meet the performance standards for driver identification in the driver attention monitoring system to address distraction, fatigue and unresponsiveness.
- Yawning and smoking are also detected; however these behaviors are not included in the system's rating.
- Each individual test item must achieve a pass rate of at least 95 % across all tests conducted by any given tester.

### Test scenarios and Function Rating

The test is considered **passed** if a warning is issued **within 1.5 seconds** after the prompt conditions are met. If not, the test **fails**.

- **Wearing conditions:** Naked Eyes, sunglasses, glasses
- **Basic Monitoring Items (Score Rating 3 points)**
  - **Closing eyes:** Prompt message after complete closure of eyelids  $\geq 3$  s
  - **Abnormal head pose:** Prompt message after the head deflects to the specified position  $\geq 3$  s
  - **Answering / making hand-held phone calls:** Prompt message after the distance between the hand-held phone and the drivers face is within 5 cm  $\geq 3$  s
- **Monitoring items**
  - **Yawning:** Prompt message after the mouth aspect ratio is greater than 0.6  $\geq 3$  s
  - **Smoking:** Prompt message after the distance between the hand-held cigarette and the driver's mouth is within 2 cm  $\geq 2$  s

## IVISTA

The IVISTA China Intelligent Vehicle Index, established in 2017, is a comprehensive evaluation system for intelligent connected vehicles, focusing on safety, interaction, and driving assistance features. The independent third-party testing and rating system operates under the guidance of the China Association of Automobile Manufacturers and the China Society of Automotive Engineering Research Institute (CAERI) and is based on the National Intelligent Vehicle Integration Test Area. The current implementation of IVISTA Index Rate and Testing Protocol is the 2023 edition, which came into effect in March 2024, includes ratings for intelligent safety, intelligent driving, intelligent interaction, intelligent parking, and intelligent energy efficiency. The document specifies the rating methods of the Intelligent Interaction Index on Occupant Status Monitoring System.

The total score of the Occupant Status Monitoring (OSM) in IVISTA Protocol 2024 [30] is 16 points, including

- Driver distraction monitoring (14)
- Driver fatigue monitoring (2)
- Child presence detection (extra score) (4)



Figure 3: Overview consumer test organizations

### 1.3 User Requirements

In 2023 we conducted a brain-writing focus group in order to understand user requirements and to collect user ideas for applications of in-cabin monitoring. The use of cameras in vehicles is stimulated by user's expectations of in-cabin monitoring. Users benefit and acceptance is key to successful applications. By involving users in our research and development processes, these expectations and wishes to future functions and applications can be made visible and taken into account.

#### Method

In total 11 test person of different ages (19 to 48 years), genders (4 male/7 female), educational backgrounds and professions took part and were guided through discussion by two experts for

in-cabin sensing systems. With the combination of brain-writing, headstand method, focus group and online collaboration tools, a methodologically established approach was chosen for generating and categorizing ideas.

The complexity of the technology as well as the heterogeneity of the participants required, prior to idea generation, the establishment of a common starting point and working basis. Thus, the technology and the potential applications of occupant state recognition via optical sensors were described with the metaphor of the butler, who observes situations and offers appropriate assistance when needed. This step ensures that all participants have a common understanding of the technology's capabilities as well as the study objective, validating the final quality of the results.



Figure 4: Metaphor for in-cabin monitoring systems as a butler

### Results and conclusions

Clustered and prioritized by two technology experts, a total of 29 applications from the areas of active safety, passive safety, entertainment and comfort were obtained (see figure 5).

Apparently, users have a lot of ideas for applications and functions that can be implemented with cameras in the vehicle.

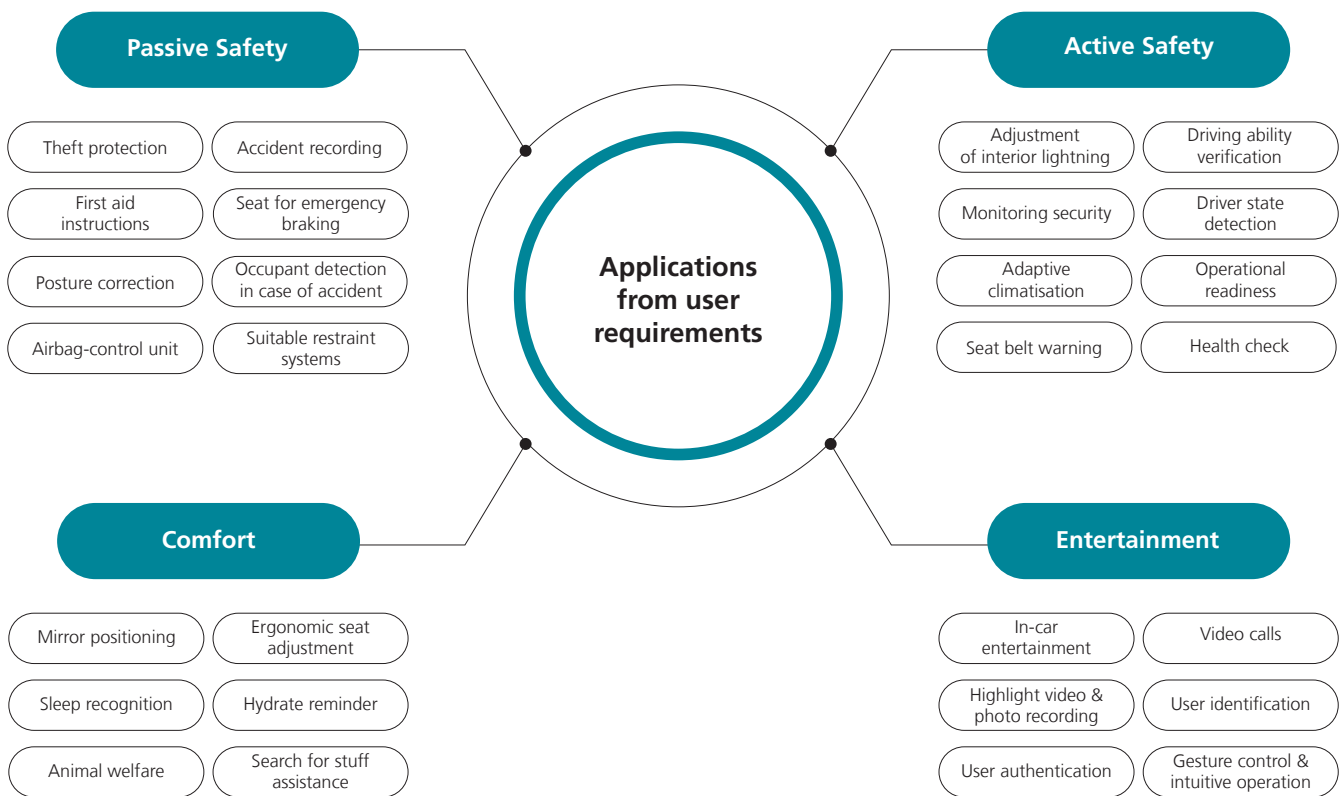


Figure 5: Overview of applications from user requirements study

## 1.4 Technology providers

Interior Monitoring solutions have gained significant traction in the automotive supply chain. It supports vehicle safety, user personalization, and passenger comfort. With rising expectations around driver attention, occupant behavior, and regulatory compliance, companies are integrating advanced in-cabin sensing into their product portfolios. This development goes beyond OEMs – it is reflected in the automotive value chain. Technology providers play a crucial role in enabling this transformation. From hardware developers to AI algorithm specialists and integration partners: Infineon e. g. supplies essential chipsets, enabling energy-efficient and powerful sensor processing. SIMI delivers motion tracking algorithms, used in driver state monitoring. ZF provides system-level solutions, contributing to scalable in-cabin sensing platforms. And OEMs are integrating the technology, e.g. in the Mercedes EQS which is already used at Fraunhofer IOSB as a technology demonstrator. Fraunhofer institutes in general act as key innovation drivers in this ecosystem. They support the development process through early-stage feasibility studies, Proof-of-Concept prototypes, and validation tools. As independent research partners, they also offer benchmarking services and support regulatory alignment through advanced testing frameworks. Thus, the Interior Monitoring value chain spans from founda-

tional silicon to high-level human-machine interaction. Figure 6 outlines current market-leaders. The companies shown exemplify the collaboration between hardware, software, research, and integration partners required to bring these systems into production vehicles.



Figure 6: Selection of companies working on DMS



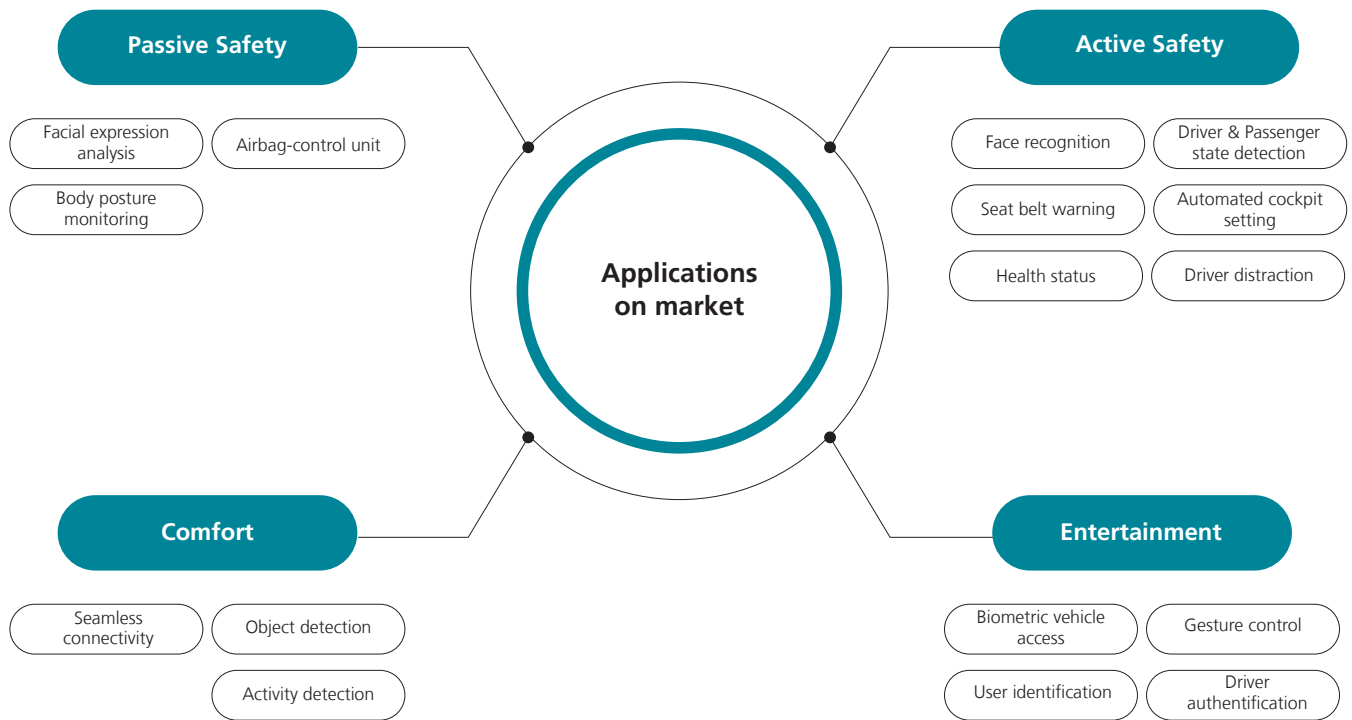


Figure 7: Overview applications on market

## 1.5 Realizing DMS and OMS Applications with a ToF sensor

Technology providers have been demonstrating high quality and advanced in-cabin monitoring applications with different sensors. In a joint project of Melexis and Emotion3D, both companies demonstrated a combined Driver Monitoring System (DMS) and Occupant Monitoring System (OMS), based on a single camera with ToF technology. The combined system is called Driver and Occupant Monitoring System (DOMS).

The project results were demonstrated at CES 2024 in Las Vegas.

The Melexis ToF sensor provides a full VGA resolution of 640 x 480 pixels for the depth image as well as for the NIR image. At full resolution this allows for a readout rate of up to 120 fps which is required for detecting fast movements.

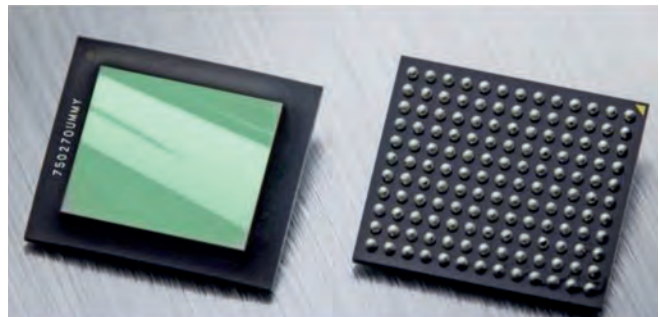


Figure 8: Melexis ToF sensor specifications

- Full VGA 640 x 480 pixel resolution
- Full resolution readout up to 120 fps
- Simultaneous depth and NIR image caption
- Support up to ASIL B system integration
- Industry high quantum efficiency
- Flexible parameter set, incl. modulation frequency (up to 100 MHz) and exposure time
- 11 x 9.5 mm IBGA package





**By combining depth and NIR images, EuroNCAP compliant DMS in combination with OMS applications are achieved with a single ToF sensor from Melexis. "**

Kristof Lieben, Product Manager at Melexis

The realization of the DOMS with only one VGA ToF sensor was achieved by combining the depth image and the NIR image of the Melexis ToF sensor.

- DMS functions are realized with the NIR image. The algorithms from Emotion3D required only little retraining to adapt to the inherent NIR image.
- OMS and passive safety functions are realized based on the 3D body pose which is extracted from a combination of the sensor's depth and NIR image.

The aim of the project was to realize a single camera system not only capable of doing EuroNCAP compliant DMS applications, but also OMS and passive safety.

At CES 2024, visitors could experience the ambient light robust DMS applications, as required by EuroNCAP, based on the sensor inherent NIR image with VGA resolution. that are required by EuroNCAP, specifically:

- Distraction/Drowsiness/Attention classification based on
  - Eye-gaze
  - Eye-openness/blinking
  - Head position

Additionally DMS relevant feature detections were demonstrated for applications that use DMS:

- Calling on the hand-held phone
- Smoking
- Yawning
- Spoofing authentication
- Wearing glasses or a mask

Some of those activities are considered to be distracting and to be related to higher risks of accidents.

For the realization of OMS and passive safety applications, the Melexis ToF depth image was used in combination with the NIR image. Within a 110° x 85° field of view of the camera, following features could be detected, which are the foundation for restraint control systems and dynamic airbag control, as well as for comfort applications for the vehicle passengers.

- Sitting height
- Occupant classification
- Out of position detection
- High speed body pose tracking for safety applications.

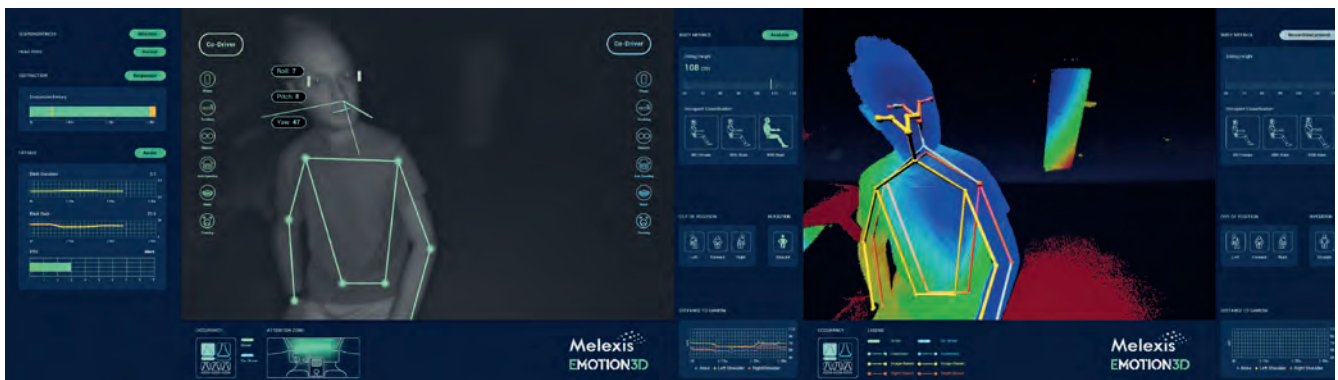


Figure 9: OMS detection features from combination of NIR and depth image



Figure 10: DMS detection features with Melexis ToF and its NIR image sensor

## 1.6 Consumer Electronics

Smart home and smart phone camera-based applications are not only stimulating but transformative for in-cabin monitoring. In-cabin monitoring enhances the user experience by elevating personalized comfort and entertainment for occupants. Inspiration for camera-based applications stems from the functionalities found in smart home and smart phone applications. Features like user authentication, face pay, memoji-based virtual chatting, and other smart home and smart phone applications can be migrated into camera equipped vehicles.

Through user status detection and identification, these applications can seamlessly enhance the in-car environment, providing a more connected and personalized experience in the vehicle interior. This integration opens possibilities for advanced customization, convenience, and entertainment options within the automotive space. The following camera-based applications are based on the possibilities of Smart Home and Smart Phone cameras.

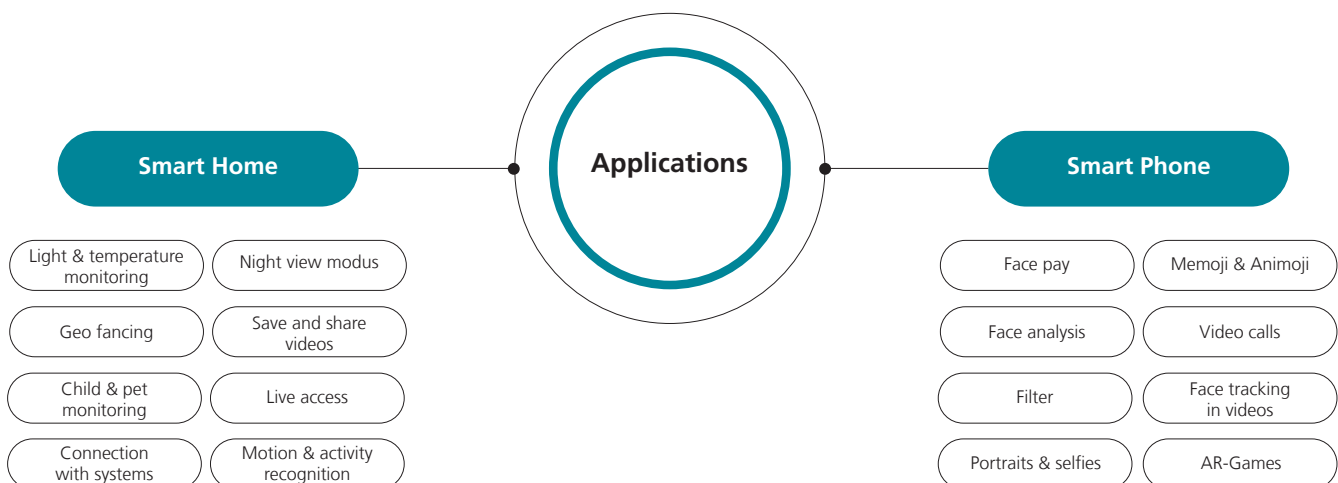


Figure11: Overview applications from consumer electronics

### 1.7 Interview with Quirin Anker from Daimler Truck (FUSO) about DMS for Trucks

Quirin Anker has been involved in the development of driver monitoring systems for Daimler Truck and for features for the Japanese market in vehicles of the brand FUSO. He studied Automotive Engineering in Munich with a focus on powertrain, driving assistance and acoustics. His master thesis treated the evaluation of a driver's fatigue detection system. Since 2020 he is ADAS Engineer with a focus on driver monitoring systems. He has been involved in the development of local DMS solutions at FUSO for the Japanese market and in the development of global system solutions for Daimler Truck.



Figure 12: Quirin Anker from Daimler Truck (FUSO)

**Japan is a leading country in introducing driver monitoring systems with camera technology first introducing such technology in the early years of 2000 and since then leading the market in passenger cars and commercial vehicles. What are the pull factors in Japan?**

Several heavy accidents in Japan pulled the public and political attention to driver distraction and drowsiness. As a result, manufacturers pushed for a higher penetration rate in passenger cars and commercial vehicles and found a market willing to accept and pay for it. Due to the high acceptance rate in Japan, currently no legislative initiative is needed to push driver monitoring systems into the market. Contrarily, governments and authorities in other markets have been – rather recently – releasing regulatory frameworks to enforce a comprehensive introduction of driver monitoring systems, such as in the European Union or in the People's Republic of China. Camera-based driver monitoring systems are legally bound in the EU and People's Republic of China from 2024 onwards, whereas FUSO has been introducing its first generation in 2017 in Japan, called the Active Attention Assist. This feature is fusing driving behaviour-based parameters with an interior NIR camera.

**What do your customers expect from driver monitoring systems (DMS) in trucks?**

Our customers are mainly fleet owners and less private customers or end-users. Their buying decisions are driven by economic factors, such as fuel-efficiency, durability, longevity and of course safety. As a matter of fact, the human factors are still the dominant root cause of road accidents. Hence an effective, low-cost driver monitoring is what our clients ask for. Additional to this, the truck drivers care about having effective and highly accurate systems, which are not annoying and have a user-friendly interface. With the introduction of cameras in driver monitoring systems, accuracy and the number of applications could be improved significantly.



**With the introduction of cameras in driver monitoring systems, the number of use cases and the accuracy and graduation of the warnings could be improved significantly.”** Quirin Anker

### What benefit provide DMS today?

DMS can be utilized in many ways, but for a commercial vehicle manufacturer the safety aspect is the most important. DMS can help the driver to stay more focused while driving, by warning and reminding the driver. Those use-cases can be related to monitoring over a longer period (driver drowsiness) or detecting imminent critical situations (micro-sleep or distraction). For example, DMS recommend taking a break when high drowsiness levels are detected or when a driver is distracted. With such use-cases the risk of safety critical driving situations and ultimately accidents can be reduced and mitigated.

Furthermore, DMS provide an indirect benefit for improving safe driving. Having DMS available and sharing warning occurrences with fleet owners could also help to create transparency and awareness of the working conditions as well as the driver's individual condition. In some cases this might have an impact on improving the working conditions and bring health benefits to the driver (e.g. better sleep quality due to better shift management).

### Which camera technology is used to realize the desired functions?

The adequate camera technology depends on the target function. In most cases an active infrared illumination is required for stable image quality in all, but especially in low light conditions. A reliable 3D depth image can only be measured with Time of Flight or stereo cameras. This is needed in high precision, e.g. when measuring the drivers longitudinal head or body movements. Mono cameras may be good enough in lateral position however.

Camera position is an important criterion, especially if only one camera is used. An ideal camera position provides a non-occluded field of view without obstruction objects and at a suitable angle.

The field of view is also an important factor to consider, since algorithms, such as eye-tracking, require a resolution with sufficient number of pixels on facial features. Narrow field of view cameras are more cost effective for this use case. Other functions, such as video calls and cabin monitoring require a wide field of view.

### Which functions do you see in the future and how would you cluster them?

Safety is the major focus on functions in commercial vehicles. This is reflected in regulations worldwide.

Effective systems also hold a high potential for improving Advanced Driver Assistance Systems and driving functions. From my point of view this is of very high priority after fulfilling the legal regulations.

Video recording for liability cases, theft protection and training are additional functions.

Comfort functions however have a rather low-priority still for

commercial vehicle manufacturers. Gesture control features, video-calling etc. might be of interest, but only if it brings a clear benefit for drivers or fleet owners. E.g. reduced distraction or increased fitness to drive.

For fleet owners, generally every feature, that reduces cost or stand-still time, increases efficiency, reliability and safety is of high interest. I would cluster the functions as followings:

- Driver condition and health monitoring
- Driver distraction monitoring, with visual distraction and with distracting activities
- Interior monitoring and sensing
- Co-driver and passenger monitoring
- Infotainment and comfort functions

### How do you see the future of in-cabin monitoring?

State of the art driver monitoring is a bridging technology for classic and assisted driving and will continue having its relevance in the market for the next decade to come, especially since it is tied to regulations (e.g. GSR DDAW & ADDW) and its revisions. The technology will contribute effectively to assisted vehicle control, e.g. by considering attention level, eye gaze and driver intentions in assisted and automated driving functions.

Developing active intervention concepts, countermeasure strategies and further use-cases based on the driver condition monitoring is the next step after fulfilling regulatory requirements and current market demands.

In commercial vehicles, factors such as reliability, efficiency, safety and practicability are among the most relevant factors for customers to choose a vehicle. Putting this into the context of driver monitoring, safety features and practicable features are the focus area for a CMV manufacturer.

Towards increased automated driving time, health monitoring, presence detection and comfort use-cases with in-cabin monitoring supported HMI might become more useful, since drivers would be less required for the actual vehicle control.

For example, the industry is already displaying first concepts of radar-based heartbeat monitoring, which could ultimately be used together with camera systems to monitor the health conditions of a driver. Such information could be used in the future for more precise health monitoring and initiating active steps in health critical situations (e.g. automatic safety stops and placing emergency calls. However, I currently do not see the radar-based technology to be ready soon.

**Thank you, Quirin for this inspiring interview.**

April 2024

## 1.8 Marco Willems from CARIAD about Digital Twins

At the AutoSense InCabin Conference 2023 in Brussels on June 22nd Marco Willems, Head of Development Vehicle Occupant Monitoring at CARIAD presented a vision of creating digital twins of all cabin occupants.

### Who needs the digital twin?

Marco Willems pointed out that in the generation of Software Defined Cars and Human Centred Cars, this digital twin representation is a core component to enable the next evolution of comfort and safety features for today's and tomorrow's consumers.

The best representation of a digital twin will enable brands and service providers to differentiate from competitors and enable the best and most personalized user experience on the market.

Hence the ultimate goal is a rich digital representation of all cabin occupants, with traits and states, that other agents in the car can use as a source of data.

### What is the digital twin?

Marco Willems envisions a holistic representation of the occupants in a digital twin. He states that CARIAD will use a fusion of sensors for the in-cabin monitoring. As it is done today for exterior monitoring. He states that relying on only one sensor, leaves too many blind spots. Sensor fusion is the key. It is also most cost efficient.

According to Marco Willems, the digital twin appears to be an open-ended feature list of the occupant's traits and states and other data. He named some examples:

- Traits:
  - Weight
  - Height
- Constructs of cognitive states:
  - Mood
  - Workload
  - Cognitive focus
  - Drowsiness
- Physical state:
  - Body Pose
- Physiological data:
  - Heart rate

### Who wants the digital twin?

According to Marco Willems, occupant monitoring is not a function for itself, but an enabler for many other functions and services in the car.

Today a car is designed in a "one size fits all" approach. In the future of digital cars, this will change.



**CARIAD Mission:  
We try to create a  
holistic interior scene  
understanding, and to  
give this information  
to all features and  
assistants in the car."**

Marco Willems



**From cars optimized  
for a standard person,  
towards highly  
individual user  
experience in the car."**

Marco Willems



**You have to know  
about the humans  
in the car."**

Marco Willems



According to Marco Willems we see three stakeholders with requirements towards highly personalized and universal digital twins derived from occupant monitoring.

Legislation will not accept discrimination against ethnic groups by treating them differently. The representation has to work for everybody.

Society will expect safely driven vehicles and same value for money for everyone, fostering diversity and personalization. Some customers will not accept being monitored all day. And others want to see the technology which takes care for them very present.

The contradicting customer expectations appear to be related to camera integration, but may also play a role how obvious assistants use information from the digital twin.

### Who uses the digital twin?

According to Marco Willems, occupant monitoring is not a function for itself, but an enabler for many other functions and services in the car.

Occupant monitoring is an enabler for many functions that customers buy:

He points out five categories of functions that can be enhanced with digital twins:

1. Assisted and automated driving
  - a. Is the driver attended to the road?
  - b. Is the driver ready to take over control?
  - c. Do the occupants behave in the way they have to behave?
2. Active safety systems
  - a. Attention
  - b. Occupant pose

- c. Identification
- d. Workload
- e. Cognitive state
- f. Side activities

3. Passive safety systems, especially in open, non-traditional interior settings
  - a. Position
  - b. Identification
  - c. Child detection
  - d. Object detection
4. UI/UX and entertainment, incl. new digital business models
  - a. Gaming
  - b. Gesture control
  - c. Identification
  - d. Mood
5. Health and well-being
  - a. Tele-medicine in the car
  - b. Health data collection

### What are the challenges of an OEM?

While an OEM can buy occupant monitoring or entire systems that deliver a digital twin, it still has to solve challenges with regards to integration, good enough quality, legal compliance and business models. Marco Willems presented the pyramid of challenges where CARAID is aiming for the best sweet spot.

The four corners of the pyramid are composed of:

1. Lean Design
2. Best Function
3. Security
4. Costs

In Summary, Marco Willems emphasizes the need of occupant monitoring system for future cars.

July 2023



**Advanced Occupant Monitoring enables future car concepts, innovative features and unlocks a huge data source for digital business models in the future."**

Marco Willems

Following chapter 1, a comprehensive overview of the identified applications sourced from user requirements (chapter 1.2), technology providers (chapter 1.3 and 1.4),

and consumer electronics (chapter 1.5) is provided. The applications are categorized by their source and function-categories.

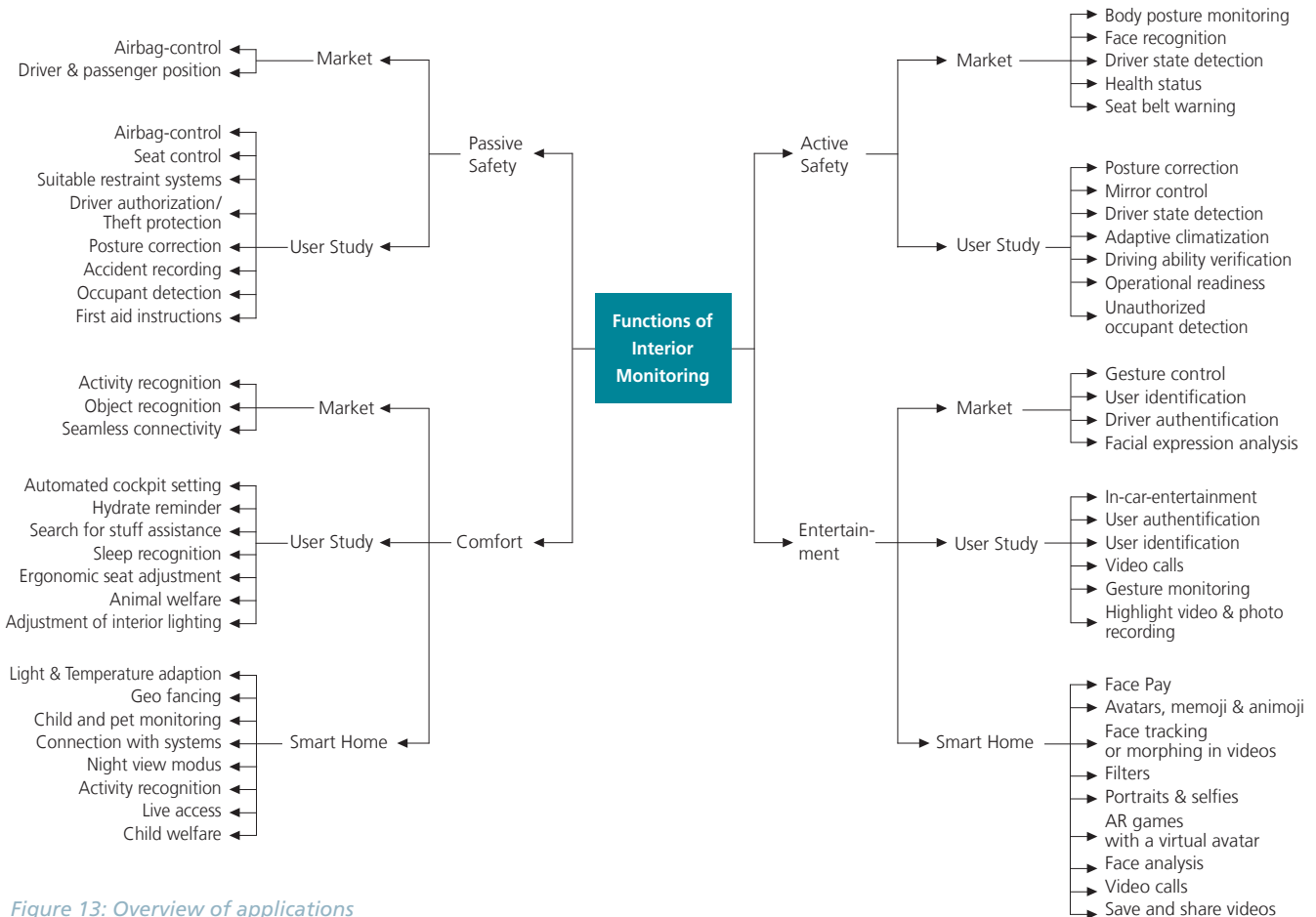


Figure 13: Overview of applications

## 2. Applications for In-Cabin Monitoring

Chapter 1 collected applications for interior monitoring from different sources, such as

- Legislation
- Consumer test programs
- Technology providers
- User requirements
- Other domains such as smart home and smart phone

Chapter 2 summarizes and specifies the applications.

Further we categorize the applications into the areas of:

- Active Safety
- Passive Safety
- Entertainment
- Comfort
- AI personal assistants

In the subsequent chapters, the detection functions are individually introduced and defined based on our experience and knowledge.

## 2.1 Active Safety

Under the chapter **Active Safety**, all applications of assisted and automated driving are compiled with the aim of improving safety and preventing accidents.

Active safety refers to assisted and automated driving that recognizes and warns about potential dangers for occupants. It may also steer or brake in order to reduce accident risks. With the aim of improving safety and preventing accidents, corrective measures are taken, such as controlling the vehicle in the event of inattentive drivers.

**Driving ability verification** | Verification of the driver's condition to ensure fitness to drive. To intervene in cases of inadequate states such as alcohol-impaired driving, fatigue or illness. Also ensuring fitness to drive with respect to constant traits such as legal age, driver's license, etc.

Source: Market

**Unauthorized occupant detection** | Detection of attempted break-ins or unauthorized vehicle access. Logging and transmission of the recordings to the owner and relevant authorities, e.g. police, insurance company.

Source: Market

**Driver state detection** | The interior cameras record and monitor the current state and activity of the driver while driving. In this way, risky situations such as tiredness, distraction or emotional states can be detected.

Source: Market

**Adaptive climatization** | Adjustment to personalized and preferred climate settings. The aim is to optimize driving comfort for each passenger, minimize energy consumption and generate a pleasant environment in the vehicle.

Source: User Workshop

**Mirror control** | Head- and eye-position tracking allows an automated and situation-specific adjustments of rearview mirrors. Digital mirrors can respond to the viewing angle and increase the field of view according to head movements.

Source: User Study

**Operational readiness** | Detection and ensuring that the vehicle and the interior configuration is ready for use and able to perform its intended tasks safely and effectively.

Source: Market

**Seat belt warning** | Recognizing and warning of improper or non-use of the seat belt. Warning system for the correct use of belts.

Source: Market

**Health status** | Recognize signs of illness leading to immediate loss of fitness to drive such as a stroke or in the event of an accident, scan the injuries and issue instructions for action.

Source: Market/User Workshop

**Posture correction** | Automatically adjusting the driver's seat and controls to ensure optimal ergonomic positioning, reducing fatigue and the risk of musculoskeletal issues.

Source: User Study

## 2.2 Passive Safety

**Passive Safety** refers to functions that protect occupants from injuries during accidents. Passive safety typically aims for protecting the human body.

**Driver & passenger position** | Recognition, counting and location of all occupants positions in the vehicle. This can help passive safety systems to protect passengers in all seats.

Source: User study, Market

**Airbag control** | Detection of seat occupation, estimation of body pose and safe seating position, location of body parts and objects and estimation of occupants' weight.

Source: Market | User Study

**Seat control** | A specially designed car seat that adjusts the occupant's position during sudden braking and before crashes to reduce the risk of injury.

Source: User Study

**Accident recording** | Utilizing onboard cameras and sensors to record data and footage before, during and after a collision, providing crucial information for insurance and legal purposes.

Source: User Study

**Occupant detection** | In case of an accident the system detects the presence and position of passengers in the vehicle to inform emergency response in the event of an accident.

Source: User Study

**First aid instructions** | Providing automated, voice-guided first aid instructions through the vehicle's infotainment system in the event of an accident or medical emergency.

Source: User Study

**Driver authorization/theft protection** | The permission to drive the vehicle and to be responsible for moving it, can be controlled by driver authentication. Theft and misuse can be hindered.

Source: User Study

## 2.3 Entertainment

The Entertainment chapter brings together functions for entertaining occupants and improving the human machine interface (HMI). Entertainment functions typically aim for increasing user experience for the car occupants.

**Facial expression analyses** | Interpretation of human facial expressions, often for the purpose of understanding emotions or reactions. Human Machine Interaction, entertainment and content can be adapted to facial expressions.

Source: Market

**Gesture control** | A human machine interface allowing humans to operate certain vehicle functions such as adjusting the stereo or climate control through specific hand movements.

Source: Market/User Study

**User identification** | Recognizing a user and distinguishing the user from other users in the car, e.g. distinguishing between driver and co-driver, to adjust vehicle HMI, settings and permissions.

Source: Market/User Study

**Driver authentication** | Ensuring that the person operating the vehicle is authorized to do so, or authorize payments.

Source: Market

**Video calls** | The ability for real-time video communication between passengers or drivers in the vehicle and external contacts. Typically, the camera capturing users inside the vehicle is combined with a display to see the external person.

Source: User Study/Smartphone

**Portraits and selfies** | The ability of the vehicle's infotainment system to take and save high-quality photos or self-portraits of passengers, often enhanced by lighting or background adjustments.

Source: Smartphone

**Filters** | Visual or acoustic effects applied in real time to video calls, photos or recordings within the vehicle system, often for entertainment or privacy purposes.

Source: Smartphone

**Highlight video and photo recording** | An automated function that captures and records important moments, memories or scenery while driving, using the vehicle's on-board cameras.

Source: User Study

**Avatars, Memoji & Animoji** | Customizable, animated characters or emojis in a vehicle's infotainment system that can

mimic the facial expressions of the driver or passenger and are often used for messaging or entertainment.

Source: Smartphone

**Face tracking or morphing in videos** | A feature that recognizes and tracks faces in real time during video conversations or recordings, ensuring consistent framing and focus. Also morphing the face towards the camera is helpful in the car, to create the perception that the passenger is looking directly into the camera, even though he or she may look on the road.

Source: Smartphone

**AR games with a virtual avatar** | Augmented reality games integrated into vehicle systems that provide interactive, immersive experiences and can incorporate the in-cabin situation and passenger movements into an avatar in the virtual world.

Source: Smartphone

## 2.4. Comfort

**Comfort** functions enhance the well-being of occupants or ease their achievement of goals. Some comfort functions can also improve users' health and fitness.

**Automated cockpit setting** | Automatic and personalized adjustment of the driving seat position, steering wheel position and air conditioning to the driver's preferences when the occupant gets in. Radio stations, music, navigation and connectivity options can also be customized.

Source: Market

**Adjustment of interior lighting** | Changing the interior lighting to support passenger activities such as driving, searching, reading or sleeping or adapt the interior lighting to moods or circadian rhythm.

Source: Market

**Health check** | Monitor health over a longer period. Collect a baseline of health status and detect abnormalities. Perform early disease screenings.

Source: Market/User Workshop

**Activity recognition and prediction** | Many comfort functions can be realized or supported by activity recognition and prediction. A system that knows the current or future activities of car occupants can adjust automated driving performance, morph interior settings, tailor speech dialogues and proactively support passengers. It can contribute noticeably to the user experience and personalization.

Source: Market/Smart Home

**Object recognition** | Recognizing objects in the vehicle interior can support many comfort functions. A system that knows which objects are in the car, can help searching for it, provide an inventory of (forgotten) objects and adapt for the context when such systems are used.

Source: Market

**Hydrate reminder** | A system within the vehicle that reminds occupants to drink water at regular intervals, promoting hydration and overall health during long drives.

Source: User Study

**Sleep recognition** | Detecting sleep of passengers can improve comfort by adapting driving dynamics, noise cancellation, temperature control, and light control. Wakeup scenarios can be trigger with personalized snooze time.

Source: User Study

**Ergonomic seat adjustment** | Automated adjustment of the vehicle's seats according to the occupant's body shape and size for optimal comfort and posture, reducing fatigue and pressure points.

Source: User Study

**Animal welfare** | Reminding owners of pets to care for them, e.g. not forgetting them alone, providing water and assuring safe and comfortable transportation.

Source: User Study

**Light & temperature adaptation** | A system that automatically adjusts the vehicle's interior lighting and climate based on occupant preferences for optimal comfort and visibility.

Source: Smart Home

**Child presence detection/Child welfare** | Reminding parents to care for children, e.g. not forgetting them alone, assuring safe and comfortable transportation, improving interaction between parents in the front and the child in the back.

Source: Smart Home/Market User Study

## 2.5 AI Personal Assistants

In-cabin monitoring with camera can contribute to the personalization and contextual adaptation of AI assistants in vehicles. This field is relatively new and holds a huge potential for many applications.

Adaptation of speech dialogues to visible information about past and current context, user state and about user activities will make speech dialogues much more intuitive, relevant and personalized. Information becomes more trustful if it is tailored to the current situation. Context awareness of AI assistants can also support explainable AI methods and dialogues.

Applications for AI assistants with OMS features are:

**Pro-active intervention** | Pro-active intervention at the right moment is possible when considering the passenger activities. Context sensitive pro-active support or approaching users' in-between activities can increase acceptance and flow.

**Inventories** | Inventories of objects seen in the car will allow to ask the car for support to find stuff (e.g. I saw an umbrella in the car yesterday, maybe it is still there?)



### 3. Roadmap for In-Cabin Monitoring Applications

The stakeholders pushing the introducing of in-cabin monitoring functions are in accordance to chapter 1:

- Legislation
- Test protocols
- User expectations
- Technology providers
- Users

With respect to the timing of introduction, the legislation provides ambitious deadlines for safety functions that require in-cabin monitoring. In accordance to legislation, also test protocols call for effective safety functions.

In the slipstream of safety functions, users and technology providers propose an armada of entertainment and comfort functions which become reachable with cameras in the interior. Also multimodal interaction with vehicle functions, e.g. by gestures will spread more and more. Large Visual Models that interpret visible scenes will significantly improve individualized interaction. Health functions are on the horizon with an enormous promise for user benefit and monetarization possibilities.

We foresee three waves of in-cabin monitoring integration:

1. Legislation drives the safety functions and is currently dominating development resources. Legislation does not require a special technology for the requested functions and 2D and 3D sensors have been used by technology providers to demonstrate the requested functions. Test protocols benchmark functions and will disclose which technology enables the best function performance. Driver fatigue and distraction monitoring has mostly been demonstrated with 2D cameras, but also ToF sensors have been demonstrated.

Legislation may benefit certain technologies, e.g. detection of children left alone in the car requires sensors that cover all parts of a car, including footwell on the backseat. Radar sensors are proposed for this use case, because seats, clothes and other objects in the car do not block the radar waves and hence do not occlude hidden places in a car. Smart airbags that adapt to the occupants' distance and body pose require depth information with a certain functional safety level. This is best provided by ToF cameras.

2. Followed by the safety functions, users request a variety of entertainment and comfort functions, that they know

and use in smart phones and smart homes. In those domains, high resolution RGB cameras are dominating and are used for photos, videos and video calls. ToF cameras are used in high-end smartphones for precise depth measurements, which is used for face authentication, depth effects in photos and AR visualizations. All those functions are meaningful in the car interior as well and user will ask for it. If it is not well integrated, they will use smartphones and after marked devices – with a burden of uncontrolled distraction and consequently safety impact. In parallel to the before mentioned functions, an intuitive and distraction free interaction with the vehicle is an important driver for in-cabin monitoring. Gesture recognition, activity recognition, body pose detection and occupancy provide a high benefit for context sensitive human machine interfaces. AI Assistants that are able to reflect complex user inputs, not only by text, but also by body language and facial expressions are likely to become more context sensitive, distraction free and more personalized by integrating input from in-cabin monitoring systems. The technology for this is not yet defined, but most likely a fusion of different optical sensors will provide the most complete digital representation of the human. Hence 2D, 3D and thermal optical sensors can provide this.

3. Health functions based on optical sensors are still under research and may be the latest wave for introduction in the car. A strong push from legislation, to detect intoxication and sudden incapacity is pushing such functions. Most research in this field is done with thermal cameras. Also precise 3D body pose and body movement measurements are useful for health monitoring.

## 4. Cameras for In-Cabin Monitoring

Many applications for interior monitoring are realized with some kind of optical sensor. Different optical sensors have been used, investigated, or proposed. Each optical sensor has specific characteristics and is more or less capable for one or the other application.

The challenge for automotive OEM is to find the best mixture of relevant applications and suitable sensors to achieve a high or good enough quality of the application.

### 4.1 What kind of camera sensors are suitable?

Cameras are small and cheap, non-invasive sensors. Different kinds of camera allow for different information extraction and a multi-view camera system can perform as a unit with broad perception possibilities.

Cameras provide information about

- depth
- surface reflectance and
- temperature.

Depth cameras like ToF, stereo systems, or multi-camera systems with triangulation provide the 3D shape or geometry of the scene.

2D methods with or without active illumination like RGB or NIR enable deductions about the scene's surface reflectance.

Thermal imaging sensors like FIR measure surface temperatures.

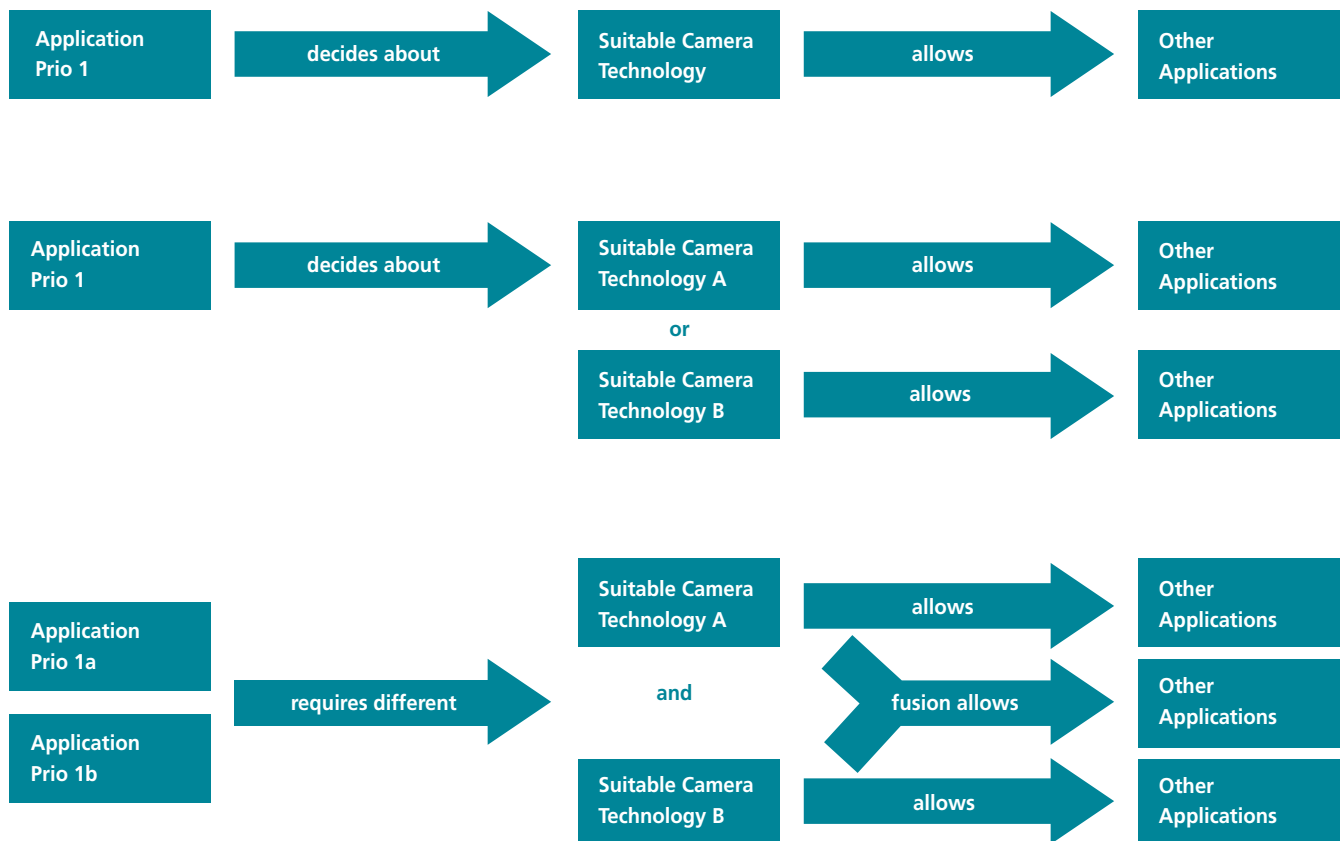


Figure 14: Start with the prio 1 application to decide on the camera technology which will enable further applications.

Each camera technology has its own advantages and disadvantages. There is no technology that is universally suitable for all applications. It is therefore important to select the most suitable camera technology for the prio 1 application. This camera technology will then enable further applications. Many times, more than one camera technology will be good enough to realize the prio 1 application. In this case, the other possible applications may drive the decision for the camera technology. And some times, different prio 1 applications will require different camera technologies. The fusion of different camera technologies opens the stage for the largest variety of applications. The combination of several camera technologies and even other sensors may significantly improve functionality and range of possible applications. By combining different technologies, gaps in the capabilities of one technology can be compensated by another technology. On the other hand, the usage of a single camera restricts the number of realizable functions.

#### Key differences of the sensors

- **Applications:** Each type of sensor is suited to different applications based on their ability to capture different types of information (color, temperature, light intensity, etc.).
- **Spectral sensitivity:** RGB captures visible light, NIR captures near-infrared, FIR captures thermal radiation, and monochrome captures light intensity without color.
- **Image content:** RGB produces color images, FIR produces thermal images, NIR can produce images based on infrared illumination (usually monochromatic), and monochrome produces grayscale images.

**Radar:** A radar system uses radio waves to detect the distance, speed, and direction of objects in the environment. Radar can work in a wider range of light conditions and passes objects in the car, such as seats and other passengers. It does not suffer from occlusions as most other cameras. It is not effective at detecting fine details such as facial expressions. Radar image quality also suffers from vibrations in moving cars. It is better suited for use in parking cars.

**Time of Flight (ToF) Camera:** Time-of-flight technology is based on measuring the time it takes for a light signal to travel from a light source to an object and from there back to the sensor surface.

A light pulse, usually in the infrared range, is generated by a light source, often a laser. This pulse is emitted in the direction of the object to be measured. The emitted light hits the target object and is reflected by its surface. The time it takes for the light to complete this round trip depends on the distance between the sensor and the object. A sensor catches the reflected light. The sensor measures the time it takes for the light to return. This is known as the time of flight.

By measuring the time, it takes the light to travel back and forth, the sensor can accurately calculate the distance between itself and the target object. The advantages of time-of-flight

sensors lie in their accuracy and fast detection of distances. They are well suited for applications such as distance measurement, gesture recognition and three-dimensional environment mapping.

**Far-infrared (FIR) Camera:** FIR (Far-Infrared) cameras are designed to detect and analyse infrared radiation, which is a type of electromagnetic radiation, invisible to the human eye but can be sensed as heat by humans. FIR cameras detect the infrared radiation emitted by objects and body parts. Every object emits some form of infrared radiation, and the amount varies with temperature. The human body, if warmer than the surrounding environment inside a car, emits infrared radiation detectable by FIR cameras. Occupant detection and changes in body temperature due to emotions or illness are applications for FIR cameras.

Since the system works on infrared, it can operate in low-light conditions or even complete darkness, making it effective at night or in tunnels.

**Near Infrared (NIR) Camera:** The NIR sensor emits invisible light pulses in the near infrared spectrum. These light pulses are invisible to the human eye. The material properties influence the reflection and absorption of the NIR light. The NIR sensor detects the reflected light that comes back from the surfaces of the objects. The reflected intensity and the spectrum of the light provide information about the material properties of the surfaces.

NIR sensors are often used for interior monitoring. They can monitor drivers' facial expressions and detect the direction of gaze. In addition, NIR sensors can be used in combination with other sensors for occupant monitoring and access control. The advantages of NIR sensors lie in their ability to provide information about surface conditions in the invisible NIR range. These sensors are able to detect subtle nuances in the reflection of light and are therefore well suited for applications that require precise and non-contact sensing in light and dark conditions.

**RGB:** RGB stands for red, green, and blue, which are the primary colors of light. An RGB sensor captures light in these three color channels. In an RGB camera, each pixel on the sensor is covered by a red, green, or blue filter. This setup allows the sensor to capture the intensity of each colour at every pixel, which can then be combined to produce a full-colour image. Downsides of RGB cameras are that they provide images only with visible light spectrum and hence cannot be combined with invisible infrared illumination. They do not work at night.

Table 2 maps the sensor functionality and operating principle with typical detectable functions with this sensor and typical applications for in-cabin monitoring.

Sensor	Functionality	Operating principle	Detectable features	Unique selling point/ Unique application area/optimal for applications, such as
<b>Radar</b>	uses microwave or radio waves	measures time delay and Doppler shift	<ul style="list-style-type: none"> <li>Object detection</li> <li>Object localization</li> <li>Distance measurement</li> <li>Movements</li> </ul>	<ul style="list-style-type: none"> <li>Measures breath and heart rate</li> <li>Child presence detection</li> </ul>
<b>Time of Flight</b>	uses modulated near-infrared light	measures the time it takes for light to travel from the source to the target and back	<ul style="list-style-type: none"> <li>Object detection</li> <li>Object localization</li> <li>2D Body pose detection</li> <li>3D Body pose detection</li> <li>3D scene reconstruction</li> <li>Movements e.g. steering wheel rotation</li> <li>Distance measurement</li> <li>Face recognition*</li> <li>Eyetracking*</li> </ul>	<ul style="list-style-type: none"> <li>3D sensing for passive safety</li> <li>3D Position of hands, head, hips</li> <li>Smart airbag</li> </ul>
<b>FIR</b>	detects thermal radiation	measures the intensity of light in the thermal wave length	<ul style="list-style-type: none"> <li>Body temperature</li> </ul>	<ul style="list-style-type: none"> <li>Occupant detection</li> <li>Body temperature changes</li> </ul>
<b>NIR</b>	detects near-infrared light, especially reflections from own active illumination	measures the intensity of light in the 850–940 nm wave length, typically combined with active illumination for night use	<ul style="list-style-type: none"> <li>Object detection</li> <li>2D Body pose detection</li> <li>Movements e.g. steering wheel rotation</li> <li>Face recognition</li> <li>Eyetracking</li> <li>Visual focus of attention</li> </ul>	<ul style="list-style-type: none"> <li>Eyetracking</li> <li>Visual focus of attention/distracted</li> </ul>

\*at DMS position

Table 2: Comparison of sensors

#### 4.2 Interview with Elena Zhelondz from A2MAC1 about In-Cabin Sensors in Series Production Vehicles



Figure 15: Elena Zhelondz, A2MAC1

Elena has a solid background in Electrical and Information Technology acquired through dual studies at the prestigious Technical University of Munich and CentraleSupélec, and she possesses a deep enthusiasm for technological advancements. Elena started her career at A2MAC1 in 2020, where she continues to apply her expertise as a Senior Cost Engineer in the dynamic field of electronics and autonomous driving.

With offices and teardown centers all over the world, A2MAC1 Automotive Benchmarking is a global reverse engineering firm directly serving every major automotive OEM, as well as 120+ members of the global automotive supply chain. A2MAC1 deploys its database in pursuit of identifying best practices and cost and design optimizations. Relying on this extensive database, A2MAC1 engineers are able to calculate costs of all electronic and mechanic components of a vehicle, as well as provide valuable technology insights and benchmarks.

**Thank you Elena for the insight into the A2MAC1 database. A2MAC1 has torn down – not only for us – all modern car models worldwide to analyse the in-cabin monitoring cameras in modern vehicles.**

#### What kinds of camera sensors do we find in today's cars?

In our database, the first cars with interior cameras started appearing in 2018. Over the years and with more safety norms being introduced, the share of vehicles with interior cameras has increased.

In general, we see Chinese OEMs setting the trends for in-cabin monitoring. Driver monitoring cameras are seen more often in Chinese vehicles, and only in cars made by Chinese OEMs do we see two interior cameras – one for driver monitoring and one for interior surveillance. In American and European cars, the introduction of occupant monitoring sensors is pioneered by upper-class vehicles.

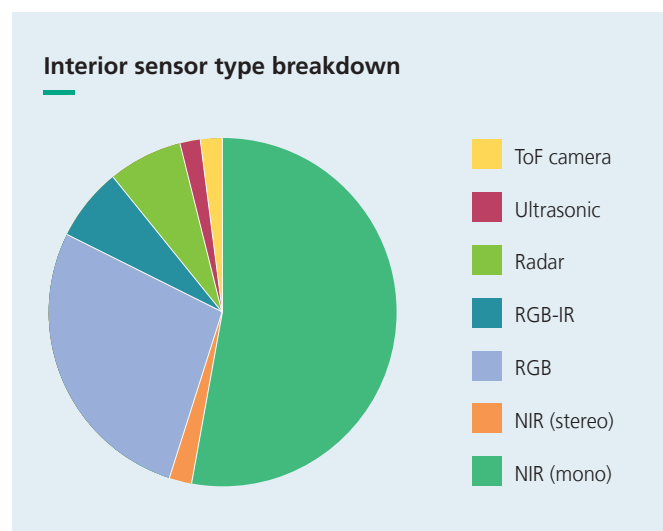


Figure 16: Sensors used for in-cabin monitoring



**2D sensors are prevalent among in-cabin monitoring modules. While a 3D video feed provides more information, the additional hardware requirements imply a higher cost."**

Elena Zhelondz A2MAC1



As we can see on Figure 14, more than half of the in-car sensors are near-infrared (NIR) illuminated monochrome cameras. This means that several infrared LEDs are included in or next to the camera to illuminate the driver's face. Facial expressions and eye movements thus become visible even at night or with the driver wearing sunglasses. The use case for these is to issue alerts in case of driver fatigue or distraction.

The second largest share are regular RGB cameras that are usually mounted in the middle of the vehicle and oversee the whole cabin. These cameras have no illumination of their own and therefore cannot function well in the dark. The main use case is currently for infotainment, like taking photos or videos of the vehicle's passengers.

RGB-IR cameras take a step towards safety-relevant cabin monitoring by introducing a NIR component to an RGB camera while keeping color fidelity. On the hardware side, this means adding IR illumination to the camera. Similarly, to RGB sensors, RGB-IR cameras usually oversee the whole cabin.

Recently, non-camera-based sensors for passenger monitoring have been introduced, with either radar or ultrasonic signals as the enabling technology. These sensors lose the infotainment component of recording video material but can still reliably detect passengers and are very cost-efficient.

### What are the main locations?

Driver monitoring cameras (DMCs) are used to notice if the driver is tired or distracted. They use active infrared illumination to ensure driver visibility in every setting and are focused on the driver. As seen on figure 17, the most popular location is on the steering column or around the cluster (about 60 % of DMCs), followed by the A-pillar (25 %) and the rear-view mirror (7 %).



Figure 17: Most popular locations of DMCs

Interior surveillance sensors are usually positioned in the centre of the vehicle and as high as possible to enable optimal visibility of all occupants. RGB cameras without active illumination are usually mounted close to the front roof module to capture both driver and passenger (over 75 %), while modules that

serve to warn the driver about rear seat occupants are installed directly above the second row. Rear-row monitoring sensors are mostly radar- or ultrasonic-based.

Gesture control cameras are usually located on the dashboard or roof module between the two front seats to enable access by both driver and passenger. Face recognition cameras, similarly to DMCs, are installed so they focus on the driver's face. Some OEMs use the same camera for both driver monitoring and face recognition.

### Which part play 3D sensors for in-cabin monitoring?

For now, 2D sensors are prevalent among in-cabin monitoring modules. While a 3D video feed provides more information, the additional hardware requirements imply a higher cost (see figure 16), and it seems that for most OEMs, 2D data is sufficient for all use cases of occupant monitoring, especially for non-safety-related features.

There are currently two ways to create a 3D video feed that we have seen in vehicles on the market: using a standard stereo camera, or using a time of flight (ToF) camera. In our breakdown of interior sensors in figure 16, 3D cameras have a share of 4 %: 2 % of ToF cameras and 2 % of stereo NIR cameras.

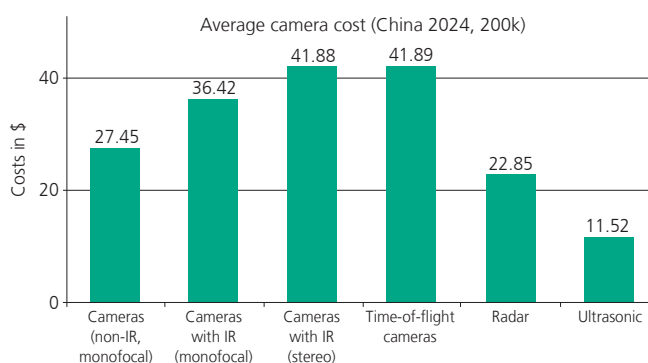


Figure 18: Average cost of interior camera modules with different optical sensors

The main argument against the usage of 3D sensors is, without a doubt, their costs. As seen in Figure 18, ToF cameras are on average the most expensive modules. For stereo NIR cameras, the costs are on average 15 % higher than for a regular NIR camera, which places it in the same price range as a mono ToF camera.

To sum it up, the trend of 3D data is still a very new one among automotive OEMs. Only one OEM uses stereo driver monitoring cameras, and only two vehicles in our database have ToF cameras – one for gesture recognition and one for driver monitoring.

We are curious to see whether 3D sensors will become more widespread in the coming years, similar to the emergence of Lidar sensors in the last few years.

**Thank you, Elena for this analysis of A2MAC1 database!**

### 4.3 Comparison of sensors

The following tables were rated by Fraunhofer IOSB experts on a 3-point scale as highly (green), average (orange) or little (red) suitable sensor performance for the feature detection. In particular, the quality that a sensor can achieve was assessed. Tables 3, 4 and 5 compare the RGB (red, green, blue), NIR (Near infra-

red), FIR (far infrared) and ToF (Time of Fly) sensors. The experts have assessed the quality that a sensor can achieve within its principle boundaries. This means that for example daylight is assumed for RGB and visibility of all relevant objects is assumed – which depends on the camera position. The evaluation is based on the best possible placement, with little or no occlusion, in order to achieve the best possible sensor quality.

Table 3 shows how good the sensor can detect the features.

Detected features	RGB	NIR	FIR	ToF
Object detection	Green	Green	Red	Green
Object localization	Yellow	Yellow	Red	Green
2D Body pose detection	Green	Green	Red	Green
3D Body pose detection	Yellow	Yellow	Red	Green
Body weight detection	Red	Red	Red	Yellow
3D scene reconstruction	Red	Red	Red	Green
Movements e.g. steering wheel rotation	Green	Green	Red	Green
Distance measurement	Red	Red	Red	Green
Face recognition	Green	Green	Red	*
Eyetracking	Yellow	Green	Red	*
Heart rate	Yellow	Red	Yellow	Red
Breath rate	Red	Red	Yellow	Yellow
Body temperature	Red	Red	Green	Red
Visual focus of attention	Green	Green	Red	Yellow

\*at DMS position

Table 3: Detected features of sensors

Table 4 shows how good the technical suitability of the sensors are.

Technical suitability	RGB	NIR	FIR	ToF
Dealing with concealment	Red	Red	Red	Red
Function in low light conditions	Red	Green	Green	Green
Function in changing light conditions	Yellow	Yellow	Green	Green
Resolution	Green	Green	Red	Yellow
Temporal resolution	Green	Green	Red	Yellow
Assembly space	Green	Green	Yellow	Yellow
Cost efficiency	Green	Green	Red	Yellow

Table 4: Technical suitability of sensors

Table 5 shows how suitable the sensors are for the different applications.

	RGB	NIR	FIR	ToF
Child Presence Detection				
Seat belt warning				
AirBag control				
Driver state detection				
Accident recording				
Theft protection				
Posture corrections				
Sleep recognition				
Video calls				
Gesture control				
Activity recognition				

Table 5: Applications and suitable sensors

The rating for RGB assumes daylight conditions and good visibility.

The rating for NIR assumes good visibility.

The rating for FIR assumes parked car and interior temperature not equal to body temperature.

The rating for ToF assumes good visibility and high resolution of the drivers face or ToF with a wide field of view. ToF includes a NIR image, which was assumed to be used as well.

#### 4.4 Interview with Prof. Dr. Rainer Stiefelhagen

Prof. Dr. Rainer Stiefelhagen holds the professorship “Computer Science Systems for Visually Impaired Students” at the Faculty of Computer Science at the Karlsruhe Institute of Technology (KIT). He heads the research area “Machine Vision for Human-Machine Interaction” at the Institute of Anthropomatics and Robotics, as well as the KIT’s Center for Digital Accessibility and Assistive Technology – ACCESS@KIT. He received his doctorate in computer science from the University of Karlsruhe (TH) in 2002 and habilitated in 2009.

His research interests include image and video understanding, multimodal interfaces, applications in medical image analysis, assistive technology for seeing impaired users, driver assistance, robotics and surveillance.



Figure 19: Prof. Dr. Rainer Stiefelhagen

### What kinds of applications for in-cabin cameras have you been working on?

I have been working together with PhD students on different use cases for in-cabin monitoring. A main focus was activity recognition of all passengers, including the driver. Knowing the historical and current activities allows human machine interactions that respect the context of the user. Automated cars also promise important mobility improvements for blind passengers. Blind persons can be guided to find objects, doors, seatbelts and can be informed about the general situation by camera-based assistance systems – also in cars.

### Which cameras are used in these applications?

We have been working a lot with 3D information for activity recognition and also for assistance of blind persons. A 3D representation of the scene provides independence from changing camera positions. It also measures distance and hence provides a more accurate positioning of body parts and objects. 2D information can only guess distances which means extra efforts. However, it is very good to classify surface types and objects.

We used Time-of-Flight cameras and multi-view cameras in a setup of 3 or more mono cameras. Time-of-Flight cameras require less installation and calibration efforts, while multi-camera setups cover larger areas and suffer less from occlusions. I think the detection area inside the jagged car interior is of very high relevance to get a complete understanding of the situation. E.g. children or objects in the footwell cannot be seen from a camera in the windshield. Of course, it depends on the use case – but my guess is that 3D information and a large coverage is a main feature for in-cabin monitoring. This can be achieved by multi-view systems. Furthermore, they provide additional RGB or FIR signals.

### What trends do you see from your research for in-cabin monitoring systems?

Current developments of generative artificial intelligence with powerful foundation models open a large space for new approaches.

Models should be able to handle different but modular sensor input for a holistic representation. Sensors should learn from each other. For this reason, we started a new PhD to investigate multimodal representation learning for in-cabin semantic situation analysis.

### Thank you, Prof. Stiefelhagen for your insights!

May 2024

## 4.5 Interview with Prof. Dr. Beyerer

Jürgen Beyerer is a professor at the Faculty of Computer Science at the Karlsruhe Institute of Technology. He is also the managing director of the Fraunhofer Institute for Optronics, System Technologies, and Image Exploitation IOSB. He teaches and publishes in the field of computer vision and received his PhD in Engineering with a topic in image processing habilitated in measurement technology. His research interest covers automated visual inspection and image processing and advanced signal processing, environment modeling for intelligent technical systems and human machine interaction. Prof. Dr. Beyerer supervises research in the field of visual perceptual user interfaces and driver assistant systems and consults academic and industry scientist on computer vision measurement technology, environment representation and sensor fusion.



Figure 20: Prof. Dr. Jürgen Beyerer

### What is the benefit of using optical sensors in the vehicle interior?

Optical Sensors for different wavelengths provide information about depth, surface reflectance and temperature. This information is unique and not available in cars without cameras. 3D methods like ToF, stereo systems, or multi-camera systems with triangulation provide the shape or geometry of the scene. 2D methods, with or without active illumination like RGB, NIR, enable deductions about the scene's surface reflectance. And thermal imaging sensors like FIR measure surface temperatures. Such information can be helpful for a large variety of safety and comfort functions in future vehicles of private, public and commercial use.

### **How do you assess the estimation of depth data by monocular cameras?**

Cameras in stereo and multi-camera systems can measure depth data accurately and reliably based on triangulation, which is a geometric principle. Stereo systems, similar to human binocular vision, perform a passive triangulation to create a depth map of the scene. With more cameras the principle of triangulation achieves even higher 3D depth accuracy and robustness to occlusion.

Time-of-Flight cameras are based on measuring the travel time of light to an object and back to the sensor. Knowing the speed of light, distances to the object can be calculated. Due to the very short time differences the spatial measurement uncertainty is greater than that of triangulation-based measurements, but is still small enough for vehicle interior surveillance tasks.

Both principles, triangulation as well as time-of-flight, measure depths almost directly.

However, pure 2D images from a single monocular camera can't measure depth directly. However, there are methods to derive depth information from a single 2D image. These are indirect estimations which require extra computing capacity. They are relying on cues similar to how humans estimate depth with one eye – relatively accurate but prone to errors. Known object sizes in the vehicle interior allow for dimension embodiment techniques, and stereo from motion, combining stereoscopy and motion analysis principles. Moreover, end-to-end neural networks and hybrid approaches estimate depth from 2D images. All these methods involve indirect derivations and estimations, with associated error susceptibility, and their adequacy depends on the applications, the required measurement quality and the available computing capacity.

For reliable depth measures, an adequate 3D sensing setup, based on triangulation or time-of-flight, is in most cases the first choice.

### **What role will camera arrays play in the future?**

Camera arrays will become increasingly important. They can, depending on the setup, increase the field of view coverage area compared to single cameras. And if they cover the same area, they can create 3D data via triangulation, crucial for applications needing object distance or absolute 3D position information. Camera arrays can comprise different sensor types (e.g. NIR + ToF, NIR + Thermal) combining their strengths and alleviating their weaknesses, also merge information from various sources for a more accurate reality representation. Combining different optical sensor advantages is a key focus.

### **What is the future of visual representation in vehicle interiors?**

An optimal representation of vehicle interiors and occupants

should describe all relevant aspects and their relationships. An object-oriented world model of the vehicle interior, with abstract representations of humans can achieve this requirement. Such a model has inevitable gaps due to sensor limitations and abstraction. Necessary features, their temporal and spatial resolution, and capture quality must be specified. Scientific institutions like Fraunhofer can contribute models and architectures to this endeavour. Such models also enable simulation and prediction of interior changes, critical for applications like airbags, predicting body movements during crashes. The goal is to develop a cyber-physical model for vehicle interiors to respond to inquiries about past, present, and future states.

Fraunhofer IOSB researchers are also working with the latest neural network-based methods to answer these questions. Large Visual Foundation Models are pivotal, and current AI models are being tested and tuned for interior applications at Fraunhofer IOSB, combining current measuring methods with generative, transformer-driven AI capabilities.

### **What contribution offers Fraunhofer IOSB to the supply chain of interior monitoring systems?**

As an institution for applied research, Fraunhofer IOSB focuses on systems that can reach production readiness in vehicles within 3–5 years. We focus on technologies that are ready for application – or close before. Our contribution includes testing methods, developing methods, implementing proof-of-concepts, and sharing knowledge through publications, consulting and development with clients.

Our research has a long-term foundation and we are a reliable partner for our clients. Long term research projects enable us to dive deep into technologies. Our excellent laboratories are always up to date. A Level 3 automated Mercedes EQS data collection vehicle for public roads, a driving simulator with a mid-sized Audi A3 chassis, and a portable interior monitoring environment are equipped with a variety of cameras and sensors. This comes with a still growing data-base of in-cabin monitoring data, sufficient computing power and the Fraunhofer IOSB Advanced Occupant Monitoring System for research and demonstration.

**Thank you, Prof. Beyerer for this insightful interview!**

May 2024



## 4.6 2D vs. 3D sensing

2D images and 3D images are two different types of visual representations that are used in different contexts and for different purposes.

2D images represent the world as on the human retina and can be interpreted by passengers. Algorithms also interpret this image. 2D images lack depth perception, meaning that they only provide a flat, two-dimensional view of a scene or object. In contrast, 3D images provide depth perception, allowing to see the object or scene in three dimensions, with height, width, and depth, incl. the distance of each pixel from any defined other pixel or view-point, however this 3D image is not interpretable by the passengers.

Most applications in in-vehicles sensing use 2D sensors. Common are NIR and RGB sensors or a combination of both. Also, 3D sensors are used in some vehicles. Stereo vision with two mono-cameras in a defined distance from each other can be used, as well as multi-camera setups with defined positions. More common for car interior monitoring are ToF sensors, that measure the distance between a sensor and an object, based on the phase shift between the emission of a signal and its return to the sensor, after being reflected by an object. This 3D image provides 3D coordinates of each point in the scene.

	2D (e.g. NIR, RGB)	3D (e.g. ToF)
<b>Pro</b>	<ul style="list-style-type: none"> <li>■ High resolution allows a wide field of view with sufficient resolution</li> <li>■ High resolution at low cost</li> <li>■ Better availability of training data</li> <li>■ Algorithms are more mature and integrated in production cars</li> <li>■ Provides an image that humans can interpret (monochrome or RGB)</li> </ul>	<ul style="list-style-type: none"> <li>■ Measures depth information (instead of estimating it)</li> <li>■ Provides two image modalities (depth and NIR)</li> <li>■ Allows to reason in space, e.g. distance between objects, distance between passengers and interior</li> <li>■ Easier segmentation of objects and passengers</li> <li>■ ToF data is less influenced by the environment and by the texture of objects, which can reduce training data and improve generalization</li> </ul>
<b>Contra</b>	<ul style="list-style-type: none"> <li>■ Lacks depth information and distances between camera and object and between pixels</li> <li>■ 3D information can only be estimated using machine learning</li> <li>■ Segmentation of objects and passengers only by estimation with machine learning</li> </ul>	<ul style="list-style-type: none"> <li>■ Lower resolution of the NIR image, compared to dedicated 2D</li> <li>■ Higher cost compared to conventional 2D</li> <li>■ Algorithms for in-cabin sensing have been demonstrated but are less common in production cars</li> </ul>

Table 6: Pros and Cons of 2D and 3D interior monitoring sensors

## 4.7 The dependency of camera position, lens opening angle and resolution

All optical sensors are combined with optical lenses. The lens' opening angle defines the field of view for the sensor. The wider the field of view, the larger the covered area but the lower the pixel resolution per covered inch. The larger the distance from the lens, the smaller the pixel resolution and hence there are less pixels to identify objects and passengers in the back row when the camera is mounted at the windshield. In consequence, the position of the camera in the vehicle is of paramount importance for a given application. It defines the distance to the object of interest and, hence defines, in dependence of the lens' opening angle and the sensor native

resolution, the available pixel resolution for the application. The position also defines the viewing angle of the object of interest, e.g. if the driver's face is visible from front, side or not visible at all.

The position further defines which parts of the cabin interior are occluded by the vehicle's geometry or by passengers or by hands, arms or objects moving around in the cabin. This is often the case when a hand is placed on the steering wheel right in-between a camera positioned behind the wheel and the driver's eyes. In this moment the camera cannot see the eyes and cannot detect sleepiness or distraction. Because of this paramount importance of camera position for field of view and available pixel resolution, we have exemplarily

conducted a proof-of-concept study with an automotive ToF sensor provided by Infineon, mounted in a camera with a 120° lens. The results reveal suitability of the sensor for passenger monitoring and in-cabin monitoring, with sufficient resolution for the front row and limiting resolution for the back row. Driver monitoring applications like distraction detection or face authentication would require a different lens opening angle and different position in the car. Also, a different position, e.g. in the roof above the back row, allows to cover the back row with a higher resolution and less occlusion by the front seats.

Because of these dependencies and relevance of the camera position, a principal differentiation is, if the camera needs to cover as much of the cabin interior as possible (wide angle lens, high resolution sensor, positions with little occlusions, fusion of different cameras) or if the camera shall monitor a very specific field, e.g. the drivers face (narrow angle lens, position without occlusions).

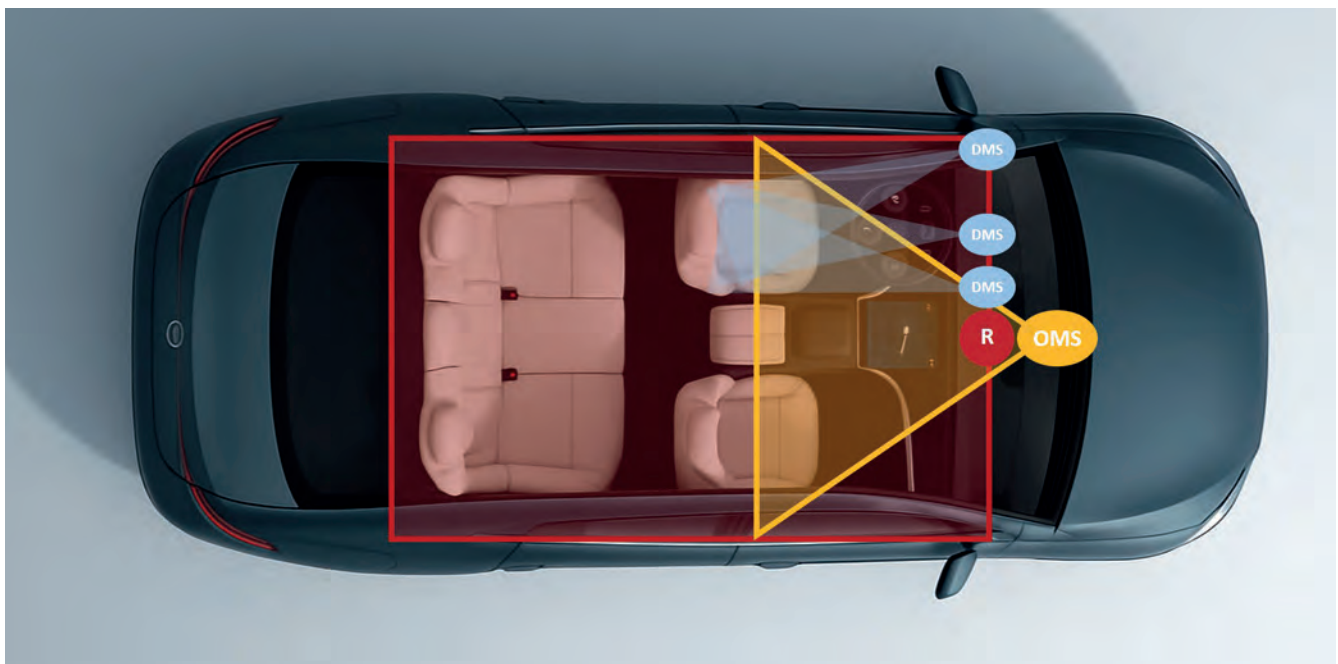


Figure 21: Typical camera positions with different lens opening angles

*R: Radar Sensor*

*DMS: Driver Monitoring Systems (2D or 3D), 40–65°, Driver Focus, e.g. with ToF*

*OMS: Occupant Monitoring System (2D or 3D), 100–120°, e.g. with ToF*

#### 4.8 Evaluation of ToF for in-cabin monitoring

Time-of-Flight (ToF) sensors in the vehicle interior hold significant potential for monitoring purposes due to their robustness against environmental factors. This chapter provides a comprehensive overview of the results obtained from an evaluation project examining the application of Infineon's ToF sensors for vehicle in-cabin monitoring. It delves into both the technical specifications of the Infineon ToF sensors and their practical implementation and assessment within the project.

An interview with Martin Lass, Senior Manager of Product Marketing at Infineon Technologies AG, offers valuable insights into the importance of depth measurements for vehicle monitoring and the necessary specifications for safety applications. The summary of the project results and the interview presents an in-depth analytical examination and interpretation of the performance of ToF sensors in the vehicle interior, along with their potential applications and challenges.

### Project Results/Summary

Fraunhofer IOSB test of Infineon ToF:

The **position of the camera** in the car is most important for the coverage and hence for the supported applications.

Additionally, the opening angle of the lens defines the coverage area and resolution of focus areas. A  $\sim 120^\circ$  horizontal angle provides the best compromise of large coverage area and good enough resolution. Typical detection functions of ToF are possible with VGA resolution and  $120^\circ$  lens:

- Body pose and limbs distance measuring
- Object detection and distance
- Position of adjustable elements (seat, steering wheel etc.)

This allows reliable applications such as:

- Passenger count and position
- Passenger body pose and activities
- Objects recognition and position

Narrow lenses increase resolution of relevant areas such as driver's face and supports:

- Person authentication
- Eye lid opening and gaze area segmentation

### Infineon Sensor Specs

- REAL3™ ToF imager IRS2877A(S)
- VGA system resolution (640 x 480 pixels)
- 4 mm image circle enabling small lens sizes
- Optimized for 940 nm IR light with up to 100 MHz modulation frequency
- Flexible imager operation after each frame: adaptation of frame rate, exposure time or modulation frequency
- Suppression of Background Illumination (SBI) in every pixel for best dynamic range
- Optical PG-LFBGA-65 package, 9 x 9 mm
- ISO 26262 (ASIL-B) compliant

### Martin Lass

Senior Manager Product Marketing  
3D Time-of-Flight Imager  
Infineon Technologies AG



Figure 22: Martin Lass, Infineon

### Interview

#### Why is depth measurement relevant for in-cabin monitoring?

"The real distance measurement of a ToF-sensor in combination with the simultaneous available grey scale image is the most powerful data of the environment. This enables unique use-cases like spoofing robust face authentication and innovative HMI interaction where seamless user-experience is key. A direct, in real time measured 3D body model is also essential for reliable occupant classification and smart restraint and airbag systems."

#### What specification is required for safety use cases?

"A VGA depth resolution meets the sweet spot between required pixels for the requested detections, calculation efficiency, cost and size. Furthermore, an ISO 26262 compliant imager incorporating on-chip safety mechanisms is mandatory for any safety design."

Time of flight (ToF) sensors hold high potential for in-cabin monitoring. The advantage of ToF sensors is their robustness towards environmental influences like lighting conditions and shadows. In addition, they provide two different image modalities in the form of a Near Infrared (NIR) image as well as a depth image. One drawback specific to ToF is the limited resolution compared to 2D cameras. Disadvantages they share with all cameras relate to the coverage area and possible occlusions depending on the position and interior landscape. In an evaluation project of an Infineon REAL3™ ToF Sensor,

we estimated possible coverage and detection capabilities for relevant interior features with a  $120^\circ \times 90^\circ$  lens. A  $\sim 120^\circ$  lens covers most of the interior, depending on the camera position. A narrow lens should be used to increase resolution in specific areas of interest, such as the driver's face.

For the project, we simulated the Infineon ToF sensor in the Fraunhofer IOSB Audi A3 driving simulator cabin in different mounting positions. To evaluate these in the context of in-cabin monitoring, we simulated data according to a ToF-camera

specification provided by Infineon. This camera has a field of view of 120° x 90° and VGA system resolution (640 x 480 pixels).

The data for the evaluation was simulated in the 3D animation tool Blender using a to scale model of an Audi A3. On the front seats we placed two people of different genders at the borders of the statistics for body height. The small female driver was rendered in two different poses either holding a smart-phone to her ear, like calling someone, or holding the smart-phone in front of her for texting. The co-driver is a large male. He is rendered in a bent over position to interact with the infotainment system.

This lets us evaluate a typical driver’s position doing common secondary tasks as well as an out-of-position scenario of the co-driver that causes additional occlusions, depending on the camera viewpoint.

We rendered this scene from five different camera locations from both A-columns at the top and bottom end, as well as above the interior mirror. All these camera locations are viable for in-cabin monitoring, but they pose different challenges. The following discussion of the rendered images focusses on the viability of the introduced ToF sensor at the respective position including an expert opinion on the overall field of view and occlusions, body pose estimation, smartphone detection, head tracking and eye tracking.

The basis of this evaluation were manual measurements of different attributes of the passengers, like their overall bounding box, face bounding box, eye corner distance and bounding box around a smartphone (see figure 23).



Figure 23: Overview of the measured features for the evaluation

In the following, the five different camera mounting positions (see Figure 24) are discussed in detail and the corresponding feature measurements (in pixels) are summarized in table 7.



Figure 24: Simulated sensor data for five different camera positions and two different secondary activities of the driver

frame	driver bbox	Co-driver bbox	driver face bbox	Co-driver face bbox	driver right eye corner distance	driver left eye corner distance	smartphone lap bbox	smartphone car bbox	lap eye right	lap eye left
Co-driver low	120 x 136	283 x 300	18 x 21	32 x 48	4	2	9 x 10	24 x 20	2	–
Co-driver high	256 x 160	608 x 376	30 x 30	80 x 88	3	–	11 x 33	36 x 33	2	–
Central Mirror	240 x 410	317 x 480	46 x 46	109 x 96	9	7	56 x 18	32 x 48	6	5
driver low	176 x 272	53 x 120	34 x 37	–	6	8	–	8 x 22	5	7
driver high	640 x 264	259 x 198	120 x 92	33 x 50	15	21	54 x 51	57 x 22	12	16

Table 7: Comparison of different features of the driver and co-driver for different camera positions with Infineon VGA resolution and 120° x 90° lens

All measurements are in pixels, either a line of pixels or bounding box (bbox) square.

Green indicates good suitability. Orange indicates limited suitability because of resolution or occlusion. Red indicates unsuitable.

**Co-driver low A-column position:** Compared to the driver side this position on the co-driver side is much more usable because there is no steering wheel to block the view. However, the driver's resolution in the image is still low, and occlusions by the co-driver and the challenging side view of the driver make this position difficult for monitoring the driver.

**Co-driver high A-column position:** This camera position produces a mirror image compared to the driver side. All advantages discussed for that view apply to the co-driver instead of the driver. However, monitoring the co-driver in greater detail than the driver is usually not advantageous. In addition, depending on the posture, the co-driver occludes the driver severely.

**Central mirror position:** This is the camera position favored by many for in-cabin monitoring. It provides an equal view of the driver and the co-driver. Depending on the slope of the front screen and the dimensions of the vehicle interior, the field of view of the lens limits what can be captured. By angling the camera slightly towards the driver, it is possible to monitor this seat more closely. Overall, all features are well visible but for detailed eye tracking the resolution is too low. However, it should be possible to determine if the passengers look left or right. In general, this view limits occlusions and interference between the passengers. The smartphone is also well visible for both body postures of the driver.

**Driver low A-column position:** In this view the steering wheel blocks the view severely. This position only works for

monitoring the driver's head. Such a driver monitoring use case, a lens with a narrow field of view should be used.

**Driver high A-column position:** This camera position is well suited to monitor the driver with higher detail than the co-driver. It offers the best resolution for the driver's face and eyes. Although depending on the driver's position the driver's face is only visible from the left side obscuring the right eye. While monitoring the driver from above works well to detect the smartphone when texting, it restricts the use of eye tracking because eyelashes and deep-seated eyes can obscure the pupil of the eye.

### Applications

With a 120° lens, most of the interior can be covered with only one camera. The best position for most applications appears to be close to the rearview mirror in the windshield. This position provides good enough resolution for most applications and even covers some parts of the backseat and front passengers. It enables 3D.

- Body pose and limbs distance measuring
- Object detection and distance
- Position of adjustable elements (seat, steering wheel etc.)

This allows reliable applications such as:

- Passenger count
- Passenger position
- Passenger body pose and activities
- Hands close to wheel detection
- Objects recognition and position



For driver monitoring applications a narrow field of view lens of about 50° is recommendable for the ToF. This increases the 3D pixel (voxel) resolution of the driver's face and upper body which allows applications similar to those known from smartphones with ToF sensors:

- Secure Person authentication
- Eye lid opening angle for sleepiness detection
- Robust eye gaze and head tracking for driver distraction measurements and interaction by eye-tracking

Usually, the high resolution requirement for wide field of view cameras are regarding the 2D information and not on the depth resolution. As such, a ToF camera can also be combined with other cameras, such as RGB or RGB-NIR.

### Summary

Overall, this study shows that the simulated ToF camera can work well for driver and passenger monitoring in 3D. ToF provides measured depth information together with a 2D NIR image. The evaluated camera setting provides a good overview when positioned at the central mirror. Depending on the model of the car the field of view may be a bit larger or narrower. The camera positions on the driver side improve the resolution

for monitoring the driver while still allowing to detect rough features of the co-driver. 3D Body pose estimation is possible from all camera positions with this setup. Occlusions are a challenge for certain camera positions. Head tracking is possible with this camera setting from most positions. Side views are more challenging for this task. For precise eye tracking the resolution is too low in general. For some camera positions it should be possible to roughly determine if the passengers' eyes are looking straight, left or right. Regarding the detection of objects, it is advantageous if the camera is viewing the interior from above because there are less occlusions. Object detection capability appears to be good with the given resolution for objects of the size of a smartphone or larger for the front seats. For person authentication and for measuring the eyelid opening angle, we recommend a narrower field of view, of e.g. 50°. The 3D information allows measuring the position in the interior and a better size estimation. 3D information is also very helpful for positioning body parts, tracking the body pose and doing accurate size and weight estimate of the occupants. This is particularly useful for airbag and seat adjustments and activity recognition.

April 2024

## 5. State-of-the-art in Sensors, Sensor Fusion, Training Data and Algorithms

### 5.1 State-of-the-art

The state of the art in in-cabin monitoring with cameras is rapidly advancing, driven by technological innovation, user expectations and an increasing demand for safety. Some of the key developments in the field are:

- **Automotive-grade camera technology:** The latest camera technology includes automotive-grade high-resolution sensors, depth sensors and temperature sensors with advanced architectures and a well-balanced cost-benefit ratio. This allows OEM now to specify and select from various suppliers the adequate hardware. Single-sensor as well as multi-sensor setups can be realized from the hardware side.
- **Advanced image processing:** Software for image processing and computer vision is advancing rapidly. Limitations are reasonable computing power and energy consumption, data traffic – for higher level computer vision, training data. This implies that significant efforts are still required for implementation of sensors for a specific application in a specific vehicle. However, many demonstrations have shown proof-of-concepts and some singular applications are already implemented in series product-

ion vehicles. However most applications cannot yet be bought from the shelf and require thorough sensor selection, specification and image processing development efforts. Even applications offered from shelf still require quality testing and may fail in meeting the requirements. Most DMS safety applications in series production still do not meet safety and user experience requirements. In a 2024 test, the Insurance Institute for Highway Safety (IIHS) rated none of the DMS with the label "good" (see IIHS safeguard ratings for partial automation) [27].

- **Sensor fusion:** Sensor fusion is likely to propel the quality and quantity of in-cabin monitoring to a new and finally really useful level. Sensor fusion in in-cabin sensing is however not very advanced yet. Most activities are in-between research and development. Fraunhofer IOSB and other research organizations conduct PhD thesis and develop prototypes for certain applications. Successful demonstrations have been seen in fusing NIR and depth images from ToF sensors. The most promising target appears to be a combination of ToF sensors incl. NIR and depth images with high resolution RGB cameras. However, recently, Infineon reported on 2D+3D fusion in the form of an "RGB-D" camera (see chapter 5.2).

- **Applications and training data:** One of the main outcomes of this paper is the conclusion, that the number of possible applications for in-cabin monitoring is enormous and there are possibly even more applications to be discovered in the future. Today state-of-the art in algorithms require training for each application, and finetuning for each vehicle. The number of possible applications for series production is mainly limited due to the limitation of available training data and the effort to finetune models for each application. There are several limiting factors for the availability of training data:
- Training data collection, data processing and annotation requires a lot of effort. Only few data sets from universities are available [34] [35]. Most datasets from companies are closed and not shared.
- Most applications require processing of personal data in the training. Or training data needs to be anonymized which increases efforts and costs. Legislations such as GDPR protect users, but they also increase the cost for model development. Many applications (alone) do not promise a respective return of invest.
- **Multi-modal visual foundation models:** Very new advancements in large vision models (similar to large language models), promise a revolution of image processing, based on large image foundation models. Even 2024 models already interpret situations for in-cabin monitoring (see figure 25). However, accuracy and relevance are still under investigation in research projects, such as "KARLI" and "SALSA" Projects by Fraunhofer IOSB [24].

Overall, the state of the art in in-cabin monitoring with cameras is characterized by advanced camera technology, the need to finetune AI and ML algorithms to the applications, and significant advancements in foundation models for computer vision. These developments are driving the increase of in-cabin monitoring systems.

**Prompt:** You are a personalized driver monitoring system based on a multi modal model. You see the image. Is the driver ready to take over from level 3 to manual driving?

**ChatGPT response:** Based on the image, the driver (person on the left, assuming left-hand drive) **does not appear ready to take over control from Level 3 to manual driving.** Here's why:

- **Posture:** He is turned slightly toward the passenger and appears relaxed, not oriented toward the road or controls.
- **Hand position:** His hands are not on or near the steering wheel.
- **Gaze:** He is not looking at the road; his attention seems directed toward the camera or passenger.

In a takeover situation, a driver should ideally:

- Face forward with attention on the driving environment.
- Have hands near or on the steering wheel.
- Show readiness in posture (upright, alert).

**Conclusion:** Takeover readiness is low in this moment. A warning or transition buffer would likely be needed before handing over control.

(Source: ChatGPT 4o, July 2025)



Figure 25: ChatGPT4 in April, 2024, alerting car drivers based on an in-cabin image

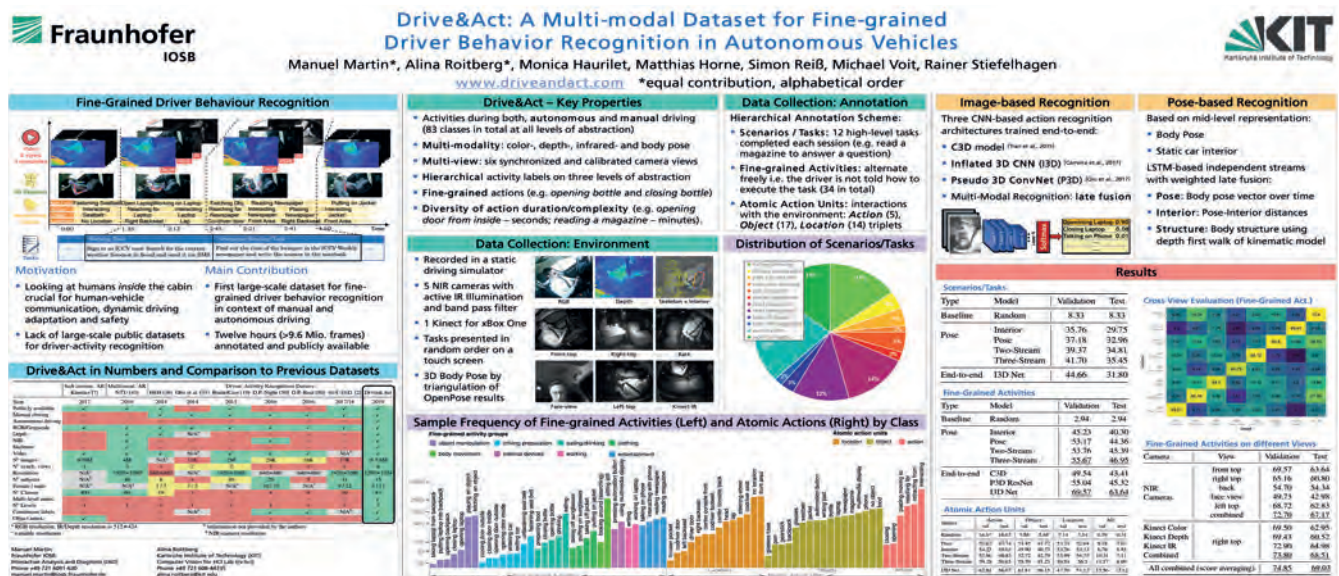


Figure 26: Drive & Act dataset for driver activity recognition training

## 5.2 Future prospects of sensor fusion

Regulations demanded by the European Union as well as Euro-NCAP require future vehicles to be capable of detecting occupant states to enhance passenger safety. In June 2025, we asked Martin Lass from Infineon questions on ongoing sensor as well as sensor fusion development solving this issue. It appears that the combination of 2D images, 3D Time-of-flight (ToF) point cloud and radar sensors are the best sensor setup for the most relevant applications.

### Which complex situations do you expect to be addressed with sensor fusion soon? Which features need to be detected?

One application is the smart airbag. Companies are striving to provide the best timing and deployment force for all kinds of passengers. Adaptive airbags require the estimation of an occupant's size, their weight, position in front of the airbag, and motion. Another application considers the situation of driver impairment which requires detection of vital signs. If we want to monitor not only the driver but all passengers, we need sensors with a wide view. In certain situations, we must deal with occlusions, for example, for child presence detection where we must include detecting children covered by blankets or sun blinds. Finally, the situation of post-crash assessment benefits from the detection of chest movement as this is related to heart rate.

### What sensors can deliver the required information?

In general, we observe a trend to one central camera combining DMS with OMS. To deliver the best possible user experience while meeting challenging requirements, the result is a so-called RGB-D camera, which utilizes 2D + 3D fusion (see Figure 27). Hereby, RGB-D is a simplified expression. The 2D sensor can be an RGB sensor, an IR sensor or an RGB-IR sensor, depending on the requi-



Figure 27: Sensor fusion, schematically

red use-case and the “D” stands for the depth data from a ToF sensor. 2D provides high resolution for pupil tracking or visualization features, 3D provides depth for 3D body model, best size and weight estimates as well as real-time body and hand tracking. Moreover, depth can be utilized for verification and robustness of 2D AI algorithms, for security applications like anti-spoofing, and for functional safety. As 2D and 3D ToF complement each other, their fusion allows handling of complex applications like smart airbags and the increasing requirements towards SAE Level 3. In situations with no-line-of-site limitation, radar sensors can make the invisible visible. This can leverage functionality like child presence detection, seat occupancy detection, and vital signs sensing.

### What sensors provide Infineon for future cars?

Infineon offers a unique in-cabin sensing portfolio including 3D ToF, 60 GHz Radar, silicon microphones and gas sensors. The REAL3™ ToF product family provides highly integrated, single-chip ToF image sensors that are sunlight-robust and highly optimized in terms of cost and size. Notably, it comprises the only ISO26262 ASIL-B compliant ToF imager on the market, which is crucial for functional safety-related applications, such as smart airbags. In addition, Infineon's ToF solution for automotive includes a new automotive-grade VCSEL driver IC, which simplifies the ToF camera module design. This market proven bundle of imager and VCSEL driver is already highly optimized, and we anticipate major upcoming innovations to occur at the system level rather than the product level, such as 2D+3D fusion and AI algorithms. As such, we collaborate closely with partners to integrate our ToF sensor into RGB-D cameras. For example, the RGB-D camera from Ofilm integrates the REAL3™ VGA ToF imager IRS2877A and a 2.3 Mpxl RGB-IR imager and provides 2D+3D fusion with 1 ToF and 6 RGB pixel upscaling with a FOV of 110 x 80° and a dimension of 120 x 36mm. This RGB-D camera is already used in mass production for back row monitoring and rear-seat entertainment. In collaboration with pmdtechnologies, a reference camera has been developed, integrating a REAL3™ HQVGA ToF imager with a 5 Mpxl RGB imager, featuring a 105 x 85° FOV. By leveraging powerful AI processing, the resulting fusion data is impressive, and this camera provides a versatile tool to explore the potential of RGB-D fusion.



Figure 28: Smart airbag application: Unsafe seat position



## 6. Conclusion

Camera based in-cabin monitoring systems are getting increasingly popular and important. Human error (e.g. distraction, sleepiness, impairment) is one of the major contributors to accidents. With automation of the driving task new requirements emerge for driver attention (e.g., hypovigilance, sleep, out-of-position).

Legislation addresses these risks with international initiatives to implement driver monitoring systems. The potential of driver monitoring systems is enormous, due to the high rate of human error. It may be comparable to the introduction of seatbelts and airbags with regards to the safety impacts.

In the slipstream of safety functions, a huge number of applications for camera based in-cabin monitoring is waiting to be developed. Technology providers have demonstrated several applications, user studies reveal a high quantity of possible applications and smart phone and smart home technologies deliver an increasing bunch of applications.

We see the first introduction of in-cabin monitoring applications in the area of safety, followed by entertainment and comfort features. On the horizon, health monitoring applications are emerging, which will require intensive sensor fusion.

Our impression is, that it is difficult to identify “the one killer application” for in-cabin monitoring. It is rather the sheer number of possible applications that underline the importance for OEM to increase efforts for implementation and to demonstrate the courage to implement the relevant hardware.

The largest potential for in-cabin monitoring is only imaginable right now and many more applications will be imagined in the future. Even third-party developers and after market solutions should be considered, which leverage a huge amount of creativity and development forces.

The main advancements are expected in software development and can be implemented “over-the-air” if the respective hardware is on-board.

We foresee at least two more technology leaps (that follow the current application of machine learning). Sensor fusion of camera arrays or even other sensors will significantly increase the accuracy of the detectable features and also the number of reasonable applications.

Large multi-modal visual foundation models are the next technological leap. Their potential was barely becoming visible in 2024. In 2025 multi modal models are omnipresent in AI solutions. They suffer from reliability challenges still, but show overwhelming improvement in accuracy and flexibility. Considering the fast development of AI, we highly recommend implementing sufficient calculation and energy hardware in new vehicles.

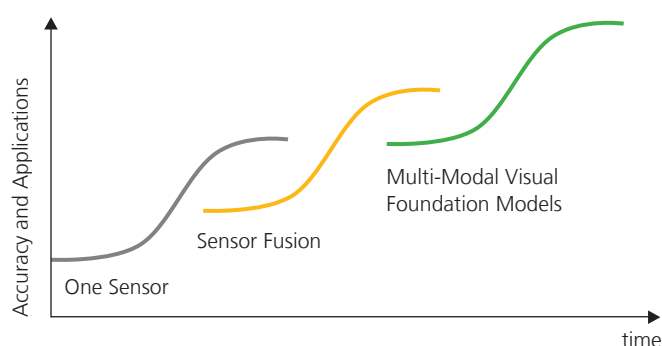


Figure 29: Expected technology leaps in in-cabin monitoring software

Along this technological progress, applications of in-cabin monitoring systems extend beyond safety functions to encompass a wide range of user-centric interactions and assistance mechanisms. From activity recognition to aiding blind passengers, these systems are poised to revolutionize the in-vehicle experience by providing personalized and context-aware services.

The choice of cameras plays a pivotal role in determining the effectiveness and coverage of in-cabin monitoring systems. While RGB cameras offer a high resolution and an image that can be used for video calls and photos, 3D sensors like time-of-flight cameras offer robust depth information. Multi-view camera arrays provide broader coverage and reduced occlusions. The fusion of different sensor modalities, such as RGB with time-of-flight enhances the capabilities of these systems.

As automotive manufacturers strive to integrate in-cabin monitoring systems into production vehicles within a relatively short timeframe, the role of research institutions like Fraunhofer IOSB becomes increasingly crucial in bridging the gap between cutting-edge research and practical implementation.

By leveraging these technologies effectively, automotive manufacturers can create safer, more intuitive, and personalized driving experiences for occupants and thereby shaping the future of mobility.

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