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WHITE PAPER AUTOMOTIVE

Nano- and digital technologies in automotive

A full view on the road ahead

General Introduction

The car of the future will be a marvel of technological achievement. Not only because of the technologies it contains, but also because of the way it seamlessly communicates (and works together) with other vehicles as well as the roadside infrastructure. All with one important purpose: to keep us safe.

This white paper offers you a panoramic view on the future of automotive technology. It's not a catalogue of technologies, but **three compelling stories** about how ingenious combinations of hardware and software innovations define the car of the future.

The first part of this white paper series you a thorough overview of the current and future state of **ADAS technologies**. You'll find answers to questions such as:

- What are the benefits and weaknesses of **sensor technologies** such as cameras, radar and lidar systems?
- Which form of **sensor fusion** is most suited for mapping a car's surroundings?
- Which **AI developments** will make cars truly 'smart'?

The second part looks into technologies that guarantee a secure, comfortable and reliable **driving experience**. You'll get a detailed answer to questions such as:

- Which wireless technology is most suited for **unhackable keyless entry** systems?
- How can we accurately and unobtrusively **monitor a driver's alertness and health**?
- How do we support the **connectivity** of a car's electronics without giving in on **security**?

Finally, the third part unravels the various candidate technologies for supporting the **connected car**. It offers you answers to questions such as:

- Is **5G** really indispensable for enabling connected cars?
- How do **cellular and Wi-Fi-based** technologies compare when it comes to enabling cooperative intelligent transport systems (C-ITS)?
- How can OEMs and Tier 1 suppliers anticipate developments towards the **smart highway**?

Our goal is to offer you an objective and up-to-date overview of several key nano- and digital technologies for the automotive sector. Of course, this is a fast-moving world, where new technological advances are continually made. We therefore urge you to **check the latest developments** by visiting www.imec-int.com/press and filter for 'automotive'.

If you want more information about our technologies, or if you are interested in working with us, feel free to contact Philip Pieters, business development director at philip.pieters@imec.be and he will soon be in touch.

Who should read this white paper?

Imec's automotive white paper is aimed at technical and business professionals from: original equipment manufacturers (OEM), car system developers (Tier 1), car component manufacturers (Tier 2), hardware and software companies with an interest in entering the automotive market

It offers them **state-of-the-art and objective insights** into the pathways and roadblocks that automotive companies are facing today. And allows them to take informed technological and business decisions.

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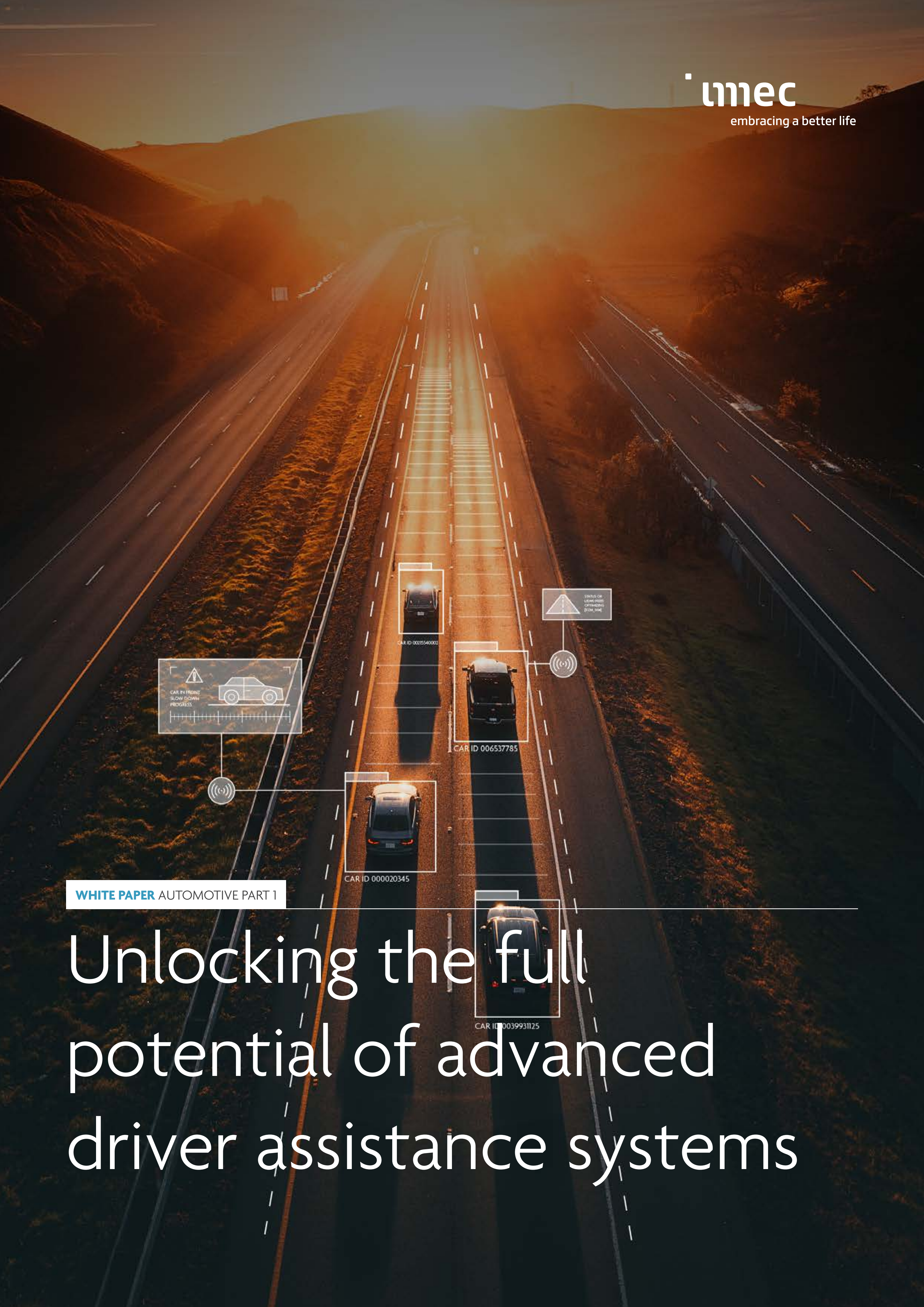

WHITE PAPER AUTOMOTIVE PART 1

Unlocking the full potential of advanced driver assistance systems

Contents

Introduction

No one can say when autonomous driving will become a reality. One thing is certain: when it does, it will not be come from of one game-changing breakthrough.

The autonomous car will result from of a **series of improvements in advanced driver-assistance systems (ADAS)** that mitigate or prevent human driving errors.

This first section of imec's automotive white paper gives you a thorough overview of the **current and future state of core ADAS technologies**. You'll find answers to questions such as:

- What are the benefits and weaknesses of **sensor technologies** such as cameras, radar and lidar systems?
- Which form of **sensor fusion** is most suited for mapping a car's surroundings?
- Which **AI developments** will make cars truly 'smart'?

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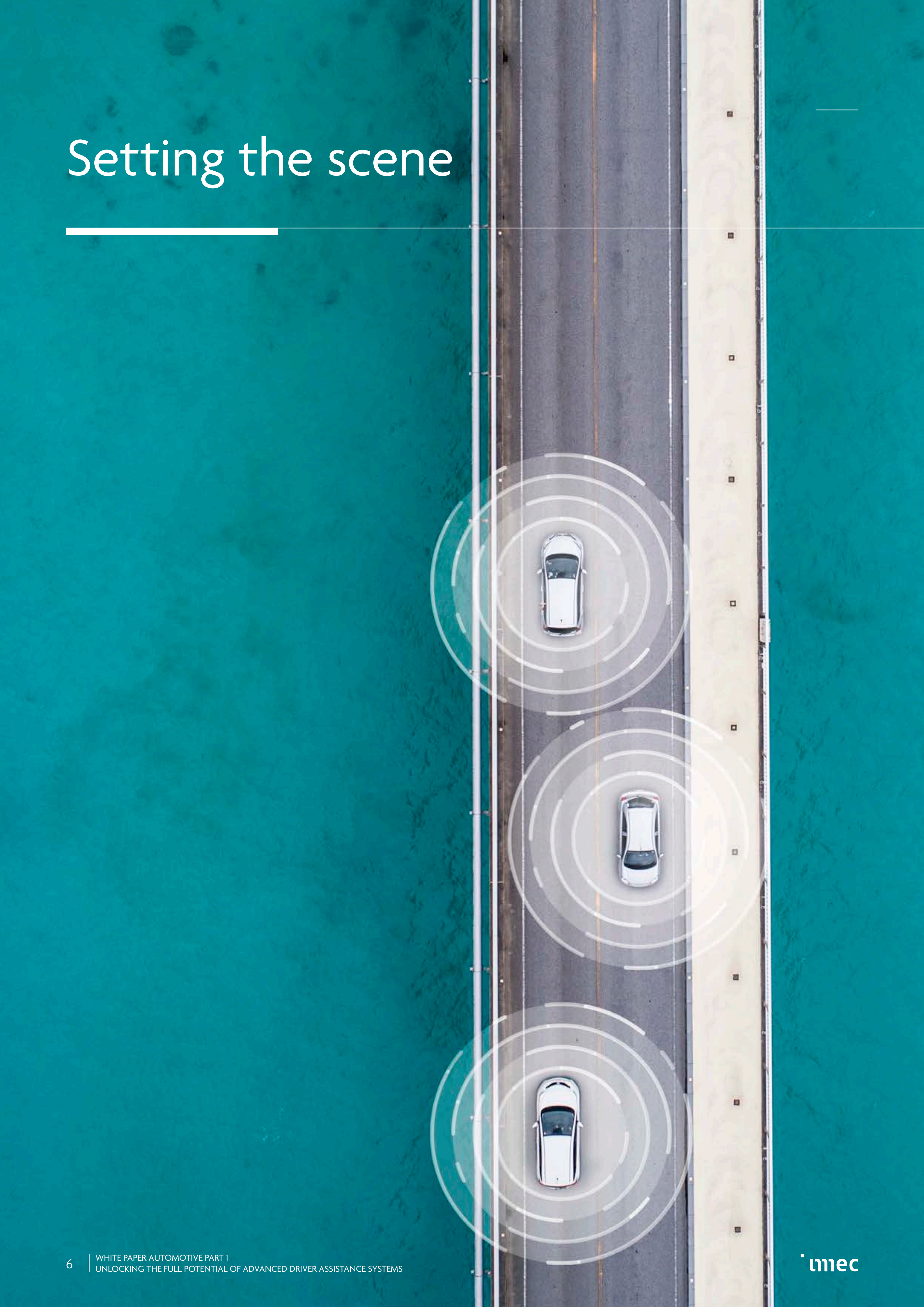
Setting the scene



According to the World Health Organization, road traffic injuries caused an estimated 1.35 million deaths worldwide in the year 2016[1]. That is, one person dying in traffic every 25 seconds.

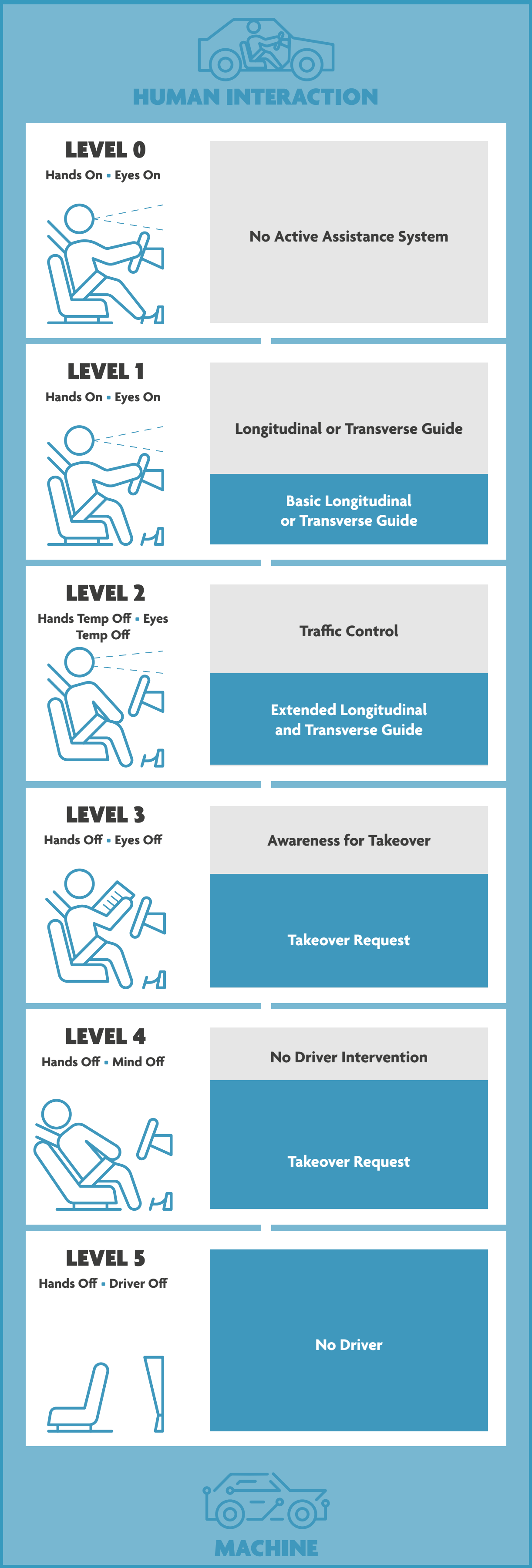
In response, a number of regions have started to make road safety a strategic priority. This, in turn, has allowed them to initiate a steady decrease in the number of casualties. In the EU, for instance, the European Transport Safety Council (ETSC) counted approximately 25,000 road casualties in 2018 – down from 55,000 in the year 2001[2].

It is clear, however, that road safety continues to be a problem child – with the latest figures seeming to indicate that some of our roads are becoming less safe again[3 4].

Hence, policymakers around the world have started to present even more ambitious road safety programs. The European Union's '**Vision Zero Initiative**', for example, aims at achieving a near zero fatality rate on EU roads by 2050[5].

Meanwhile, studies from the American National Highway Traffic Safety Administration (NHTSA) show that human error (e.g. speeding, fatigue and drunk or distracted driving) is at the basis of 94 to 96 percent of all motor vehicle accidents[6]. As a result – in order to meet their ambitious (zero fatality) road safety targets – governments, insurance companies, the medical community and other interest groups are eagerly awaiting the introduction of solutions that minimize or prevent the chance of human (driving) errors. Case in point: **autonomous vehicles**.

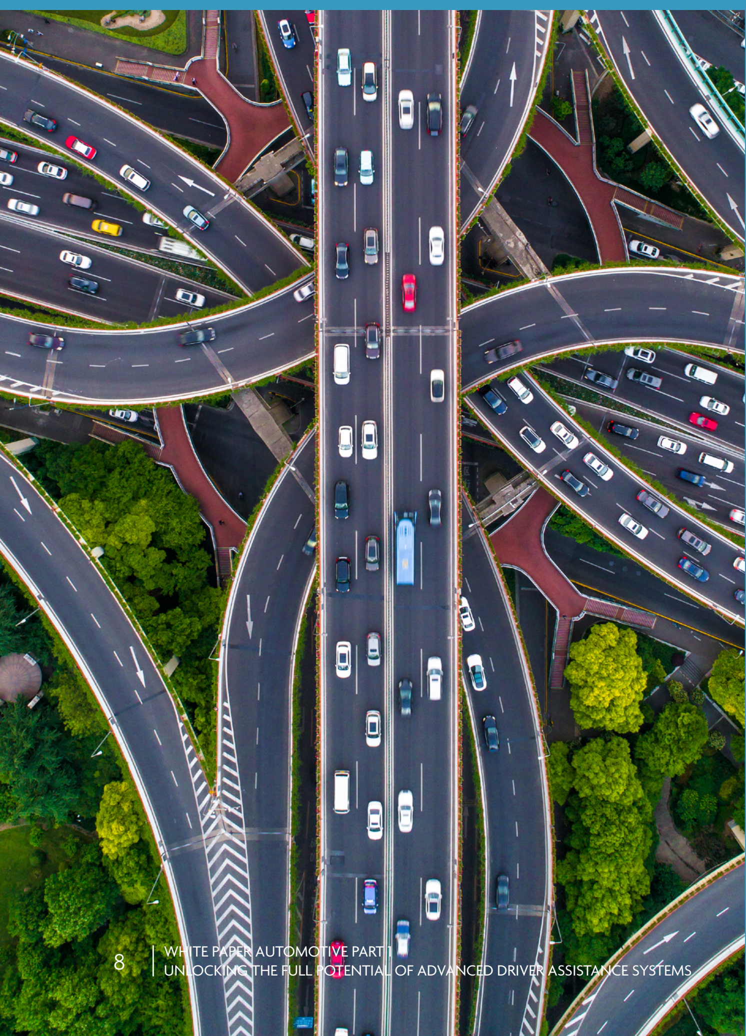
Yet, it might take a while before fully autonomous vehicles become an integral part of everyday life/traffic: they still require years of development and thorough testing. As a stepping-stone, though, car manufacturers have started to equip their cars



with the first generation(s) of **advanced driver assistance systems (ADAS)**.

ADAS have the potential to avoid or mitigate the severity of car crashes – through features such as **adaptive cruise control**, **lane keeping assistance**, **blind spot warning** and **pedestrian detection**.

ADAS (level 2) technology – such as lane keeping or semi-automated parking assistance – is becoming increasingly prevalent on new vehicles. In fact, according to data from the American Automobile Association (AAA), at least one ADAS feature is present in 92.7% of new car models available in the US as of May 2018 . And that is just a start: over the next decade, the demand for ADAS is expected to increase exponentially – not in the least since (as of 2020) both the EU and the US require all new vehicles to be equipped with safety features such as automatic emergency braking and forward collision warning.



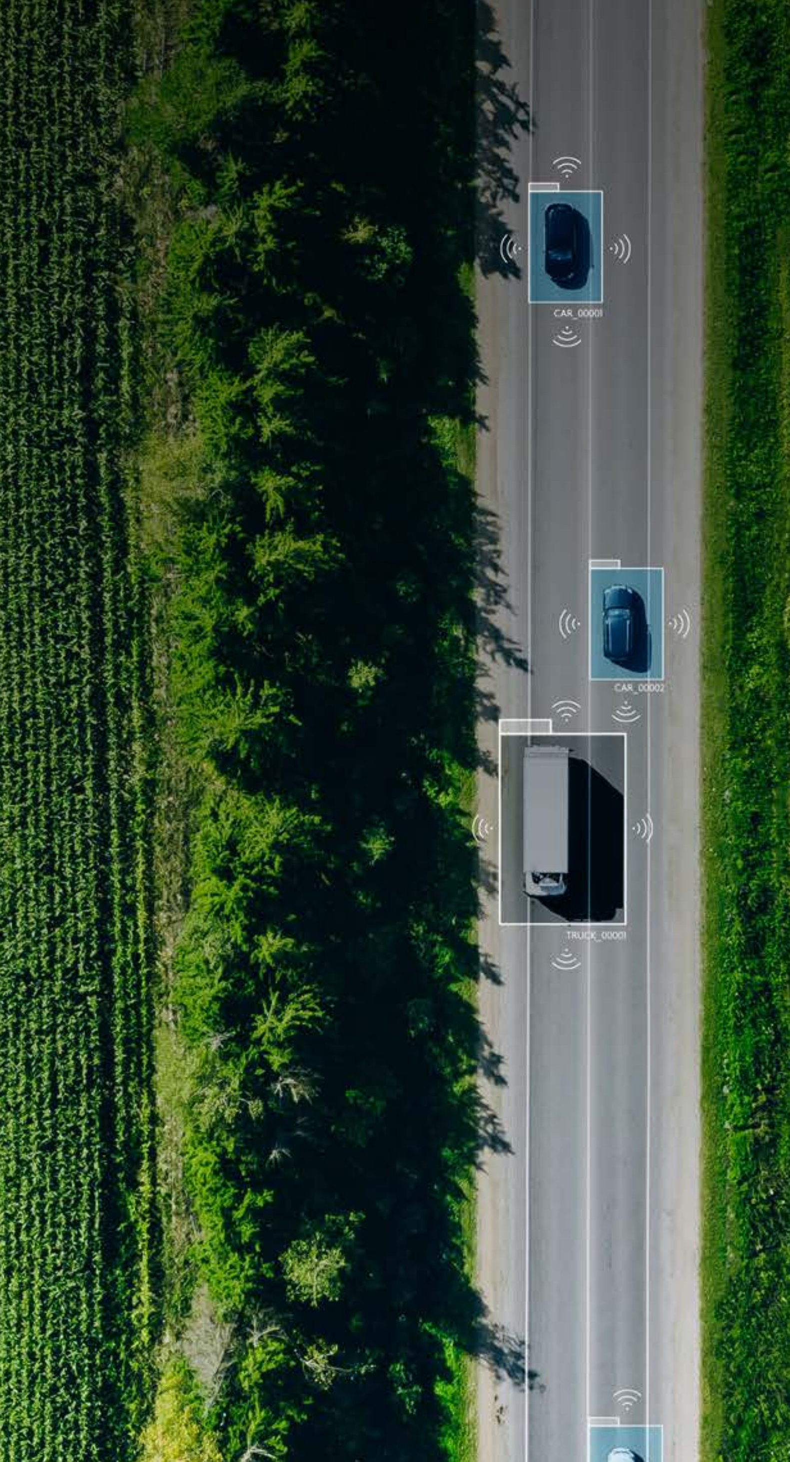
In pursuit of the next level of car automation

While a number of basic building blocks are in place already, today's driving assistance technology continues to suffer from some important shortcomings – both from a hardware and a software perspective. For one, current automotive sensors lack accuracy (especially at longer distances). Secondly, sensors work in silos and have no real 'understanding' of a vehicle's surroundings. Finally, today's ADAS merely provide input: any action is still to be taken by a human driver.

In this first section of imec's automotive white paper– which highlights how the next generation(s) of ADAS can be brought within reach of the automotive industry – key advances in three intertwined ADAS-enabling technology domains will be discussed: **sensor systems**, **sensor fusion** and **artificial intelligence (AI)**. More specifically, this section describes how:

- Anti-collision sensor technology – from cameras to radar and lidar systems – can support higher resolutions and longer-range detection;
- A 3D mapping of a car's environment will be crucial to accommodate autonomous vehicles;
- Autonomous systems can be equipped with new forms of artificial intelligence to assess – and adequately react to – the intentions of other road users.

Next-generation (anti-collision) sensor technology: making the invisible visible

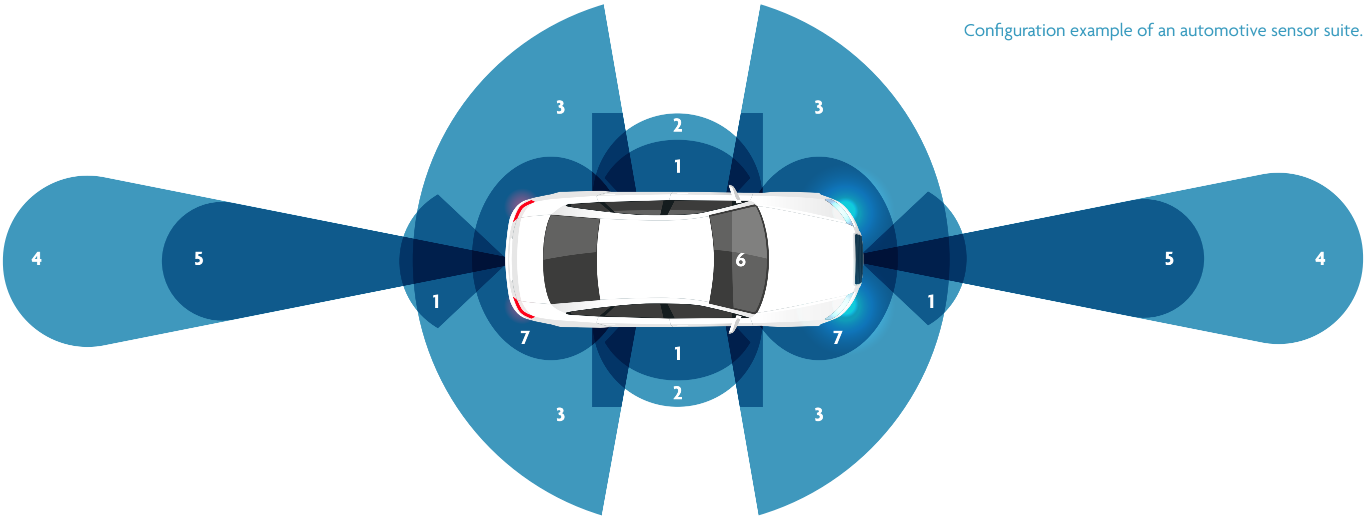


To do their magic, advanced driver assistance systems heavily rely on a combination of technologies – from processors and image processing algorithms to actuators. But everything starts at the level of a vehicle's built-in **sensors**, gathering information on road signs, pedestrians, cyclists, oncoming cars, etc.

Choosing the right sensor technology

In pursuit of ever more powerful and increasingly differentiating ADAS features, original-equipment manufacturers (OEMs) and tier-1 suppliers can opt for multiple sensor technologies and sensor suite configurations. Technologies range from camera / vision systems to ultrasound, radar and lidar – each supplying unique information on a vehicle's surroundings, yet each coming with its pros and cons.

Configuration example of an automotive sensor suite.



1 **CAMERAS** 2 **RADARS UP TO 30 M** 3 **RADARS UP TO 50 M** 4 **RADARS UP TO 250 M** 5 **LIDAR** 6 **GPS** 7 **ULTRASOUND**

1 CAMERA SYSTEMS

Using visual input to monitor a vehicle's surroundings; supporting ADAS features such as lane departure warning, surround view and (semi- or fully-) automated parking assistance.

Making use of the visible light spectrum (wavelengths from 380 to 740 nm).

- (+) Proven, reliable and widespread technology
- (+) Comes with mature (pixel-based) image processing algorithms

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- (−) Suffering from poor lighting/ weather conditions (heavy rain, fog, twilight, facing the sun)
- (−) 3D imaging requires use of multiple cameras, in combination with simultaneous localization & mapping (SLAM) algorithms

2 - 3 - 4 RADAR SYSTEMS

Detecting and calculating the range, velocity and position of approaching objects; supporting ADAS features such as blind spot warning and adaptive cruise control.

Using the radio spectrum around a vehicle for object detection; typically operating in the 76 GHz to 81 GHz bands.

- (+) Robust (indifferent to lighting, only mildly affected by weather conditions)
- (+) Becoming cost-efficient (available as a silicon-based chip technology)
- (+) Working across all lighting (and most weather) conditions
- (+) Long range (up to 300 m)
- (+) Instant measurement of target speed and direction
- (+) Radar antennae can be integrated in prescribed car shapes
- (+) (Planned) support for 3D imaging

- (−) Limited angular resolution

5 LIDAR SYSTEMS

Using a laser scanner to generate a 3D image of a car's environment and to provide the exact location of objects in its vicinity; accommodating ADAS features such as dynamic driving assistance.

- (+) Excellent range (up to 150 m)
- (+) Excellent resolution
- (+) Best technology option to create detailed 3D maps of the environment

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- (−) Expensive
- (−) Difficult to calibrate
- (−) Bulky, requiring external mounting
- (−) Limited performance in case of bad weather conditions (rain, snow, fog, dust)
- (−) Large amount of data to be processed
- (−) Full silicon-based solution not yet available

With so many options to choose from, it is impossible to decisively say whether the automotive industry will continue to rely on each of these sensor technologies (for safety/redundancy reasons, for instance), or whether some sort of consolidation/cost-optimization will ultimately take place. That being said, some clear trends can be discerned already:

- No one system covers all needs, scenarios and conditions. As a result, the power of next-generation ADAS will likely stem from a combination of sensor technologies and the inherent need for **sensor fusion** (using the input from two or more sensor systems – and overlaying that info for every scene).
- Within this ecosystem, camera systems will continue to play an important role – thanks to their versatility and proven accuracy in good weather conditions.
- Radar technology is not likely to disappear either, since it is commonly used in automotive already (to enable features such as automatic emergency braking, blind spot warning, adaptive cruise control, etc.).
- Main question for now is whether the automotive industry will resort to cost-optimized lidar technology to offset some of radar's current limitations (by moving to all-silicon lidar, for instance). Or will next-generation (silicon-based, on-chip) radar systems be able to cover all future automotive requirements and approach lidar angular resolution in both azimuth and elevation of less than 1 degree?

As of today, no consensus has been reached on this topic. As a result, different technology options – and mitigation scenarios – continue to be explored.

"The power of next-generation ADAS will likely stem from a combination of sensor technologies."

Sensor fusion

Sensor fusion - the process of merging and analyzing data from multiple sensors – will be crucial for developing next-generation ADAS. A sensor fusion engine uses the images and point clouds – a set of data points in space, generated by a car's sensors – to create a perceptive (3D) model of the world surrounding that car. Based on that info – and leveraging **deep learning** approaches – detected objects are classified into categories (e.g. cars, pedestrians, cyclists, buildings, sidewalks). Based on that 'knowledge', intelligent (driving and anti-collision) decisions can be taken.

Sensor fusion goes hand in hand with increasingly stringent hardware requirements. For one, sensors need to be made more **energy-efficient** – a key requirement for integrating larger quantities of them into moving vehicles. In fact, this is one of the hot topics being addressed by the semiconductor industry. Leveraging advances in silicon technology and complementary metal-oxide-semiconductor (CMOS) fabrication processes, on-chip sensors can be created that feature a small form factor, physical robustness and resistance to electrostatic discharge – while being energy and cost-efficient (to mass-produce).

From an 'intelligence' perspective, sensors will need to be equipped with local **(edge) computing power** as to avoid that each piece of data needs to be sent to the cloud (and back) for processing and analysis before any action can be taken. In other words: embedding computing power on an (on-chip) sensor will allow tomorrow's smart vehicles to react to dangerous situations much more quickly. In this domain as well, the semiconductor industry – and more specifically the work that is ongoing in the domain of memory chips – is bound to play an important role. Today, experiments are already ongoing with various form factors, from graphical processing units (GPUs) and field-programmable gate arrays (FPGAs) to application-specific integrated circuits (ASICs).

The economics: new technologies come with a new business case

Equipping a vehicle with next-generation ADAS comes with a considerable price tag. Will consumers actually be prepared to spend several thousands of dollars/euros on the latest safety features? Possibly, the next generation of ADAS – and autonomous vehicles in the longer run – will be linked to a whole new business case, i.e. **mobility-as-a-service**.

Today, cars are standing idle on people's driveways for approximately 95% of their lifetime[8]. As a result, any investment in better equipped (and thus more expensive) vehicles will have to be compensated for by an increased utilization rate. Enters **car sharing**.

One possible scenario is that – in the future – people will no longer acquire their own (autonomous) vehicles but will rather opt for a (subscription-based) mobility-as-a-service package, with the right type of (self-driving) car picking them up whenever they need one. In such a scenario, the cost equation of building and maintaining cars will change completely: the investment will be spread over a large number of subscribers, meaning that the cost of innovation might no longer be a prohibitive factor.

Where today's sensors fall short

Camera, radar or lidar systems alike, each sensor technology comes with its limitations; limitations that need to be addressed in pursuit of the next level(s) of car automation.

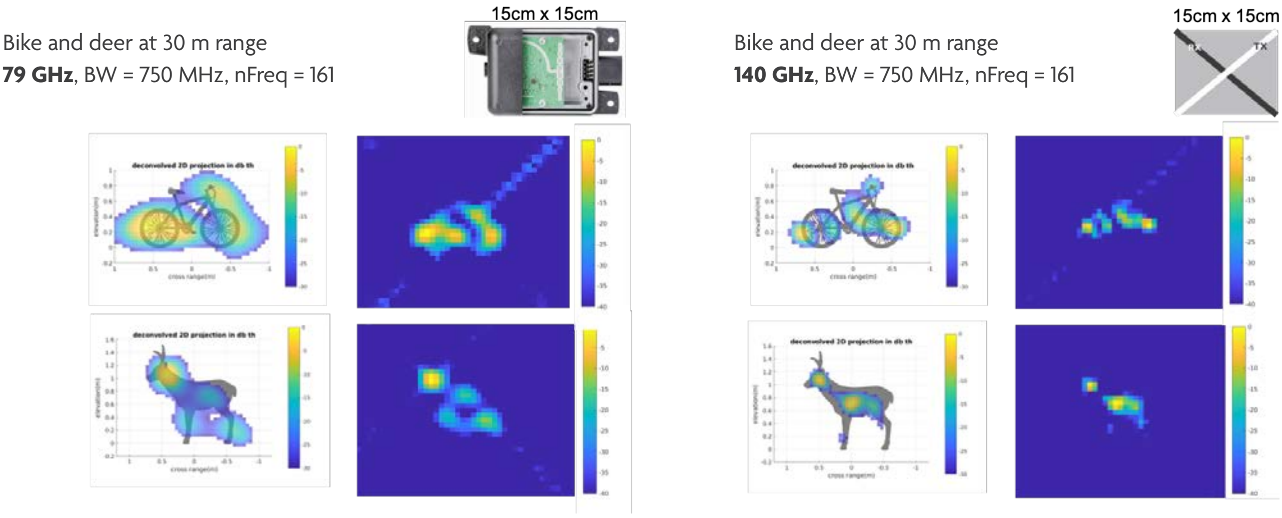
As illustrated by means of the following examples, sensors' basic functionalities as well as their robustness need further refinement.

Camera systems

Challenge	Example	Mitigation scenario(s)
Easily affected by poor lighting and weather conditions	Camera systems based on visible light cannot be used at night and in harsh weather conditions (heavy rain, snow, etc.)	Start using **high-definition (HD) cameras** Investigate the use of short-wave infrared (SWIR) frequency bands that support longer-distance monitoring, and that can see through smoke or rain (e.g. the 1450 nm and 1550 nm bands) Develop more powerful image processing algorithms to extract more information from the available imagery Complement with radar systems

Radar systems

Challenge	Example	Mitigation scenario(s)
Suffering from low angular resolution and limited precision	Radar systems only have a basic idea of a vehicle's surroundings: they have been programmed to focus on the limited number of moving objects on a road, and to ignore stationary ones on the roadside Adaptive cruise control systems, for instance, will typically ignore stationary objects – such as a lamp post accidently lying on the road; this makes for potentially dangerous situations	Complement the use of 77/79 GHz radar with radar systems operating in higher frequency bands (e.g. 140 GHz or 300 GHz radar) to increase radar's angular resolution and/or form factor Investigate the use of imaging radar to increase resolution Develop new radar algorithms that are able to process doppler info (instead of the pixels generated by camera systems)



Comparing the resolution of 79 GHz and 140 GHz radar at a 30 m range (with a radar aperture of 15 cm x 15 cm). Source: imec

Lidar systems

Challenge	Example	Mitigation scenario(s)
Cost	The number of high-quality components that go into a lidar system makes these devices bulky, fragile and expensive	Integrate lidar technology into a silicon platform (i.e. solid-state lidar)

A closer look at three promising research tracks

Lots of research is currently ongoing in an effort to mitigate the limitations of today's sensor systems. As it is impossible to focus on all that is happening, let us have a look at three promising research tracks that are particularly relevant to the automotive industry: **SWIR camera systems**, **imaging radar** and **solid-state lidar**.

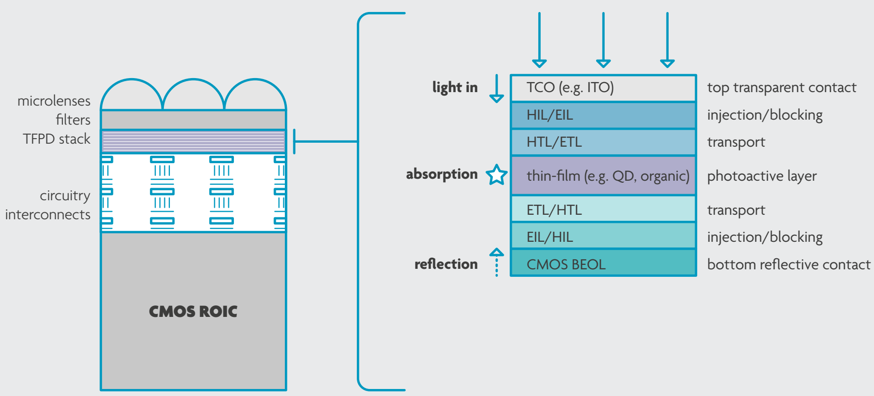
Short-wave infrared (SWIR) camera systems

Cameras making use of the short-wave infrared (SWIR) spectrum could offset some of the limitations of today's camera systems. Cameras operating in the 1450 nm band, for instance, support longer-range scanning while cameras operating in the 1550 nm band can see through mist, smoke and water vapor.

So far, however, these wavelengths have been transparent to silicon-based, on-chip imagers (a must-have when equipping vehicles with larger quantities of sensor systems) – since silicon photodiodes cannot detect light with wavelengths above one micrometer. Approaches that use III-V materials can overcome this detection barrier but are not available for consumer devices at an acceptable price point.

Today – thanks to the combined efforts of experts in material sciences, semiconductor process engineering and system-level design – some important breakthroughs are laying the foundation of silicon-based SWIR sensors that come at the price level of conventional CMOS imagers. Key enabler to achieve this are thin-film photodetectors (TFPDs): multilayer stacks with an overall thickness of a few hundred nanometers, with one of those layers being sensitive to the short-wave infrared spectrum. By post-processing these onto a Si-CMOS read-out circuit, the best of both worlds is combined: infrared detection via a CMOS-compatible process flow.

In the automotive domain, specifically, researchers are investigating the use of monolithically integrated TFPD stacks into the RGB pixel composition on the CMOS imager. In such a design, pixel-level multispectral sensors in the near-infrared and SWIR ranges can be added to the conventional red, green and blue photodiodes. This means a separate sensor for IR detection would not be required, reducing the system's price, footprint and power consumption.



By processing a thin-film multilayer stack with photoactive layer that is sensitive in the infrared range (right), on top of a silicon readout circuitry (ROIC), an IR-sensitive CMOS imager (left) is created that is suited for mass-production.

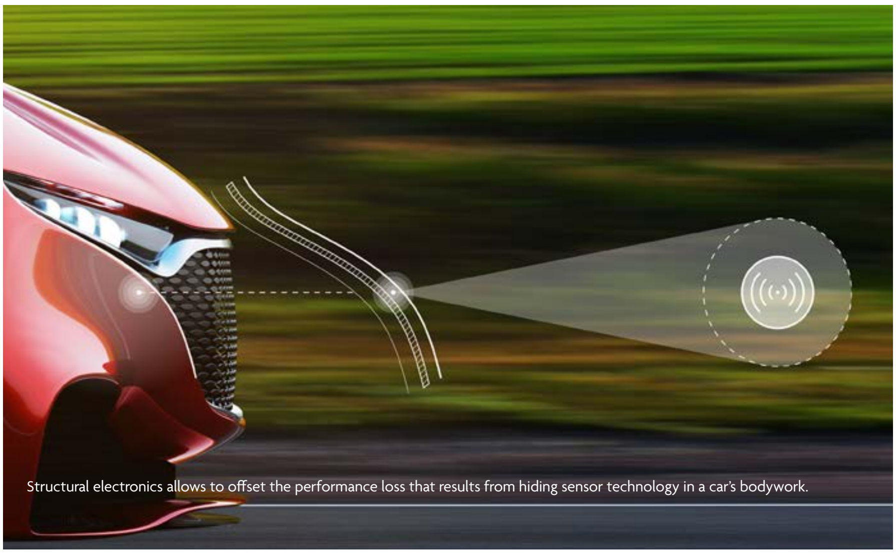
Imaging radar

Imaging radar can be used to create a high-resolution 4D image of a vehicle's surroundings – at a higher angular resolution than what can be achieved by current automotive radar systems. As such, it can detect roadside obstacles as well as smaller targets (e.g. a person or a bike), even if these are partially hidden by a larger object.

Imaging radar holds great potential, not in the least since many questions remain on the economic feasibility of using (costly) lidar systems in automotive. That being said, imaging radar still comes with its share of challenges as well.

One such challenge relates to the use of the right beamforming approach – a technique to focus the radar's transmitter and receiver in a particular direction. Over the years, the industry has moved from analog to digital beamforming techniques. Imaging radar for automotive applications, however, might rather benefit from a **hybrid beamforming architecture**, combining the best of both worlds.

A second challenge (and opportunity) relates to the size of imaging radars, which can become large and difficult to integrate behind vehicle bumpers and fascia. A possible solution makes use of **structural electronics**, i.e. integrating electronic functions – such as radar antennae – into molded plastic structures (e.g. a car's bodywork). After all, design and aesthetics remain one of the primary concerns for car manufacturers: they require any (sensing) technology to be hidden. Within a highly tiered supply (and thus design) chain, new technologies and close collaborations are needed to come up with cost-effective and aesthetically satisfying solutions, such as the structural integration of (imaging) radar systems into a car's fascia or other subsystems, e.g. the headlights.



Structural electronics allows to offset the performance loss that results from hiding sensor technology in a car's bodywork.

“The lidar market remains very fragmented. This makes it difficult to objectively evaluate the performance of lidar systems and to make the right technology choices.”

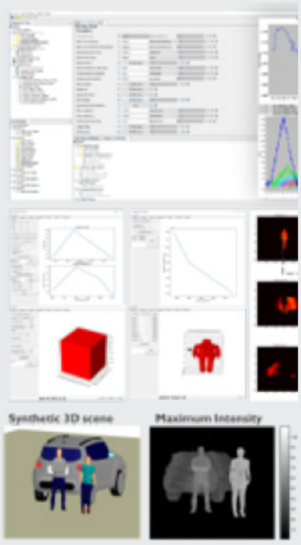
Solid-state lidar

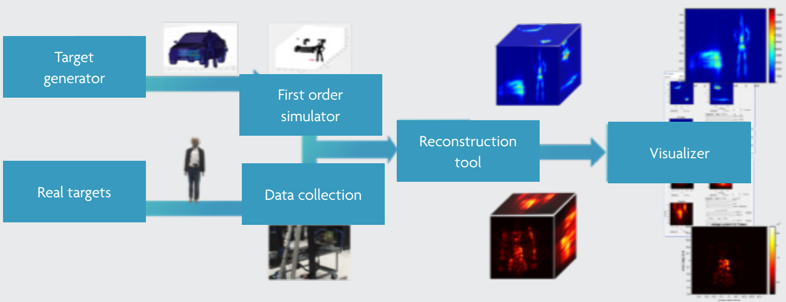
Using laser-based lidar technology, very detailed 3D maps of a car’s environment can be created. A major drawback, however, is that lidar technology builds on some very bulky and expensive pieces of equipment (costing several tens of thousands of dollars). On top, its moving parts make for a complex calibration exercise – with a laser scanner moving the (laser) light around and a detector capturing the light that bounces back.

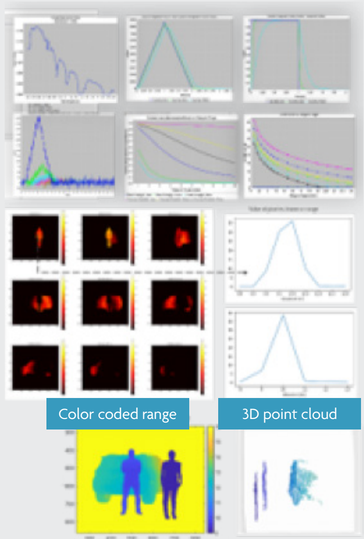
Enters solid-state lidar: a lidar system built entirely on a silicon chip. No moving parts are involved, which makes the system more robust and allows it to be made smaller and cheaper (with predictions that the price could eventually fall below $200 per unit).

Research into solid-state lidar is well underway. Initial focus has been on the integration of the lasers and on the related optical beamforming approaches. In the next phase, the integration of the detectors needs to be tackled, while more focused work on the lidar chip’s output power will be required as well.

Yet, in the meantime, the lidar market remains very fragmented. Each vendor typically focuses on improving the performance of one specific component (source, MEMS detector, scanner, etc.). This, in turn, makes it difficult for OEMs and lidar systems suppliers to objectively evaluate the performance of lidar systems and to make the right technology choices.







Modelling and simulation tools help automotive players evaluate a lidar system’s optical components (and their performance) and allow them to translate device-level requirements to a system and application level; this, in turn, enables them to decide objectively which system best fits their needs.

Imec covers the entire sensor systems research chain – from material science, photonics and electronics to chip and systems design, sensor fusion and machine learning.

Via imec, (automotive) companies can access the latest sensor technologies, put these to the test, check whether they comply with their specific requirements and use them to develop their own sensors for specific applications.

Imec can help companies explore and evaluate all technology options – based on objective evaluation criteria – and works with its industry partners to verify the potential of a given use-case. If this is of interest, companies can license the underlying imec technologies and building blocks afterwards.

Imec has pioneered the development of the digital radar sensor chip.

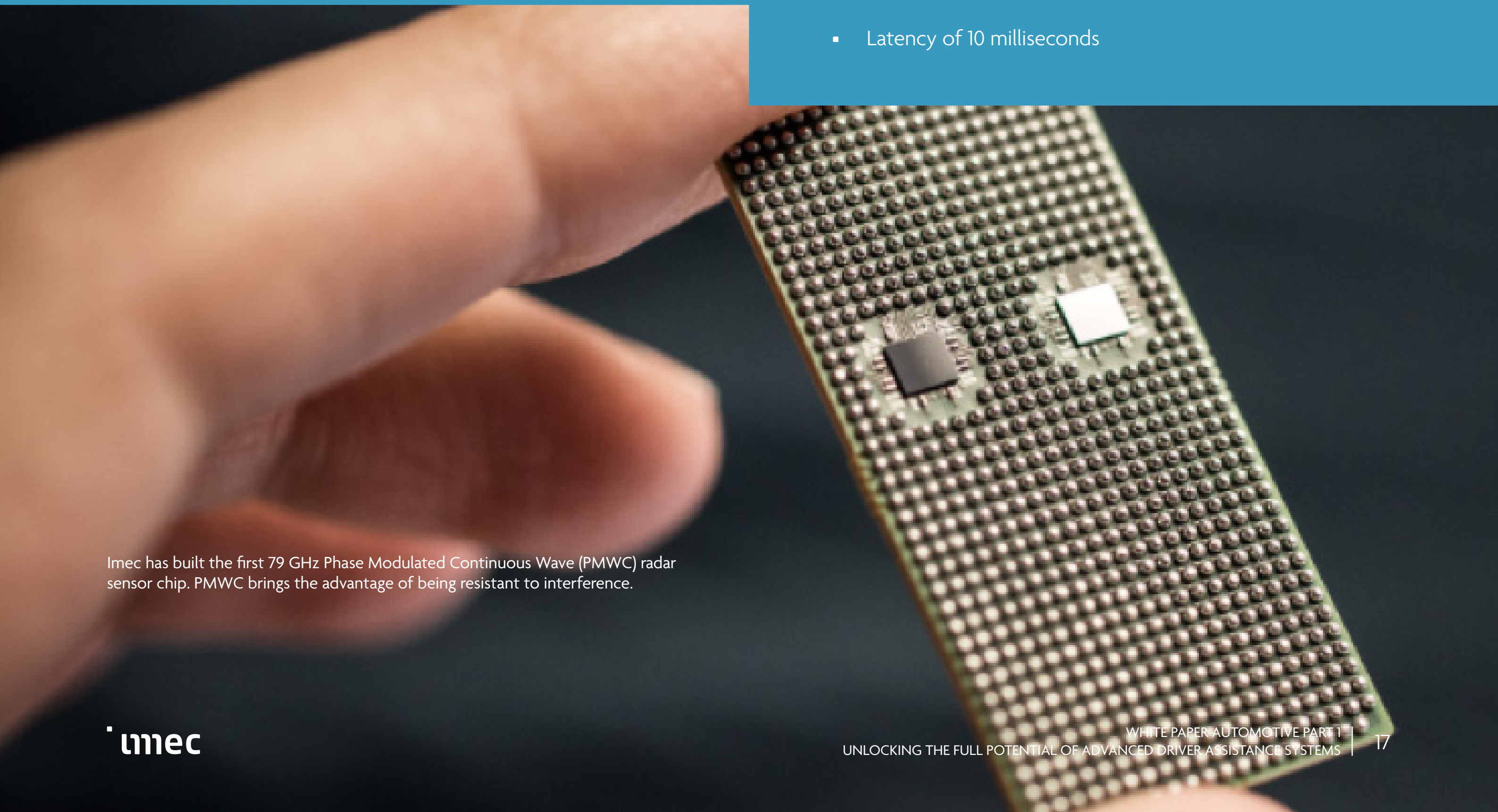
While most of today's wireless communication products use digital modulation to deal with interference and provide higher data rate, radar products still use analog modulation. The imec 79 GHz radar was the first prototype to support phase modulation and other digital wave forms. That opened many new dimensions to increase radar resolution and improve robustness to interference. Moreover, it can be implemented in standard CMOS technology, whereas radar products – so far – rely on more expensive specialty processes.

CMOS-based radar chips are:

- Compact
- Low-power
- Low-cost
- Supporting high resolutions

As a next step, imec researchers are aiming to develop a radar sensing solution that focuses on pedestrian detection – featuring a:

- 120° field-of-view
- Range of 30 meters
- Range resolution of 7.5 cm
- Maximum velocity of 50 km/h
- Velocity resolution of 1 km/h
- Angular resolution of 10 degrees
- Latency of 10 milliseconds



Imec has built the first 79 GHz Phase Modulated Continuous Wave (PMWC) radar sensor chip. PMWC brings the advantage of being resistant to interference.

Imec's solid-state lidar research aims to reduce the size of lidar systems by a factor of 20.

Imec's solid-state lidar research focuses on the efficient integration of semiconductor materials and devices into a silicon chip, without reducing the technology's efficiency or accuracy. Concretely, imec aims to reduce the size of conventional lidar systems by a factor of 20 (or more) and to reduce its cost from tens of thousands of dollars to less than 200 dollars.

Imec is developing on-chip optical beamforming technology that is up to three orders of magnitude more powerful than the milliwatt beams of existing solutions.

As the automotive industry has started to look into the potential of solid-state lidar for detection and ranging, optical beamforming technologies are needed that enable the modulation of the beam emitted by the on-chip antennae to form one precise, steerable beam.

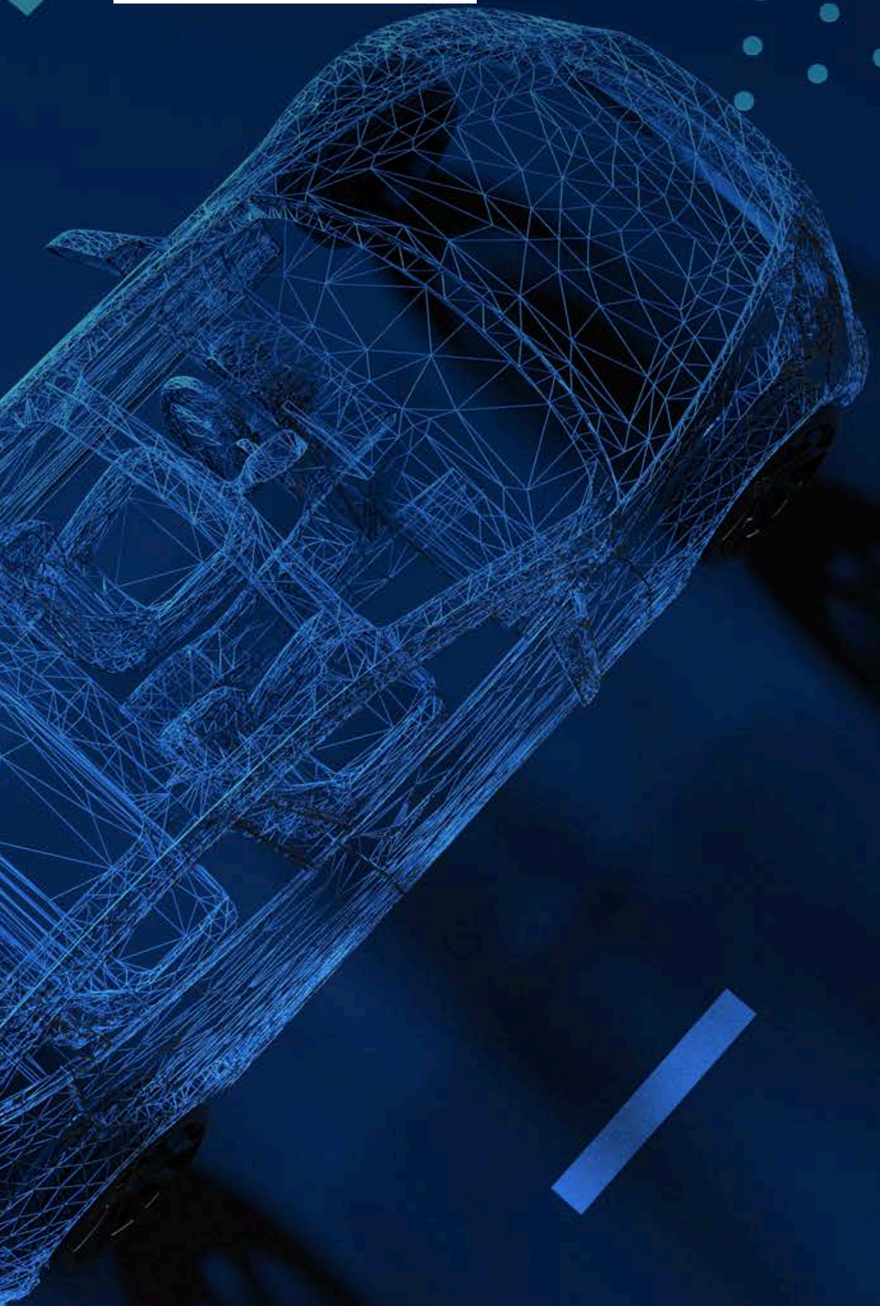
Imec's optical beamforming program investigates the use of on-chip waveguides and phased antennae to manipulate the laser inputs and outputs – meaning that only a tiny integrated circuit is needed.

One of the key requirements to make this work, is for the (small) chip to emit a sufficiently powerful beam. While this is a problem for conventional silicon photonics systems, imec researchers are leveraging new materials and advanced patterning techniques that enable the formation of beams that are up to three orders of magnitude more powerful than the milliwatt beams of existing solutions (without any trade-off in resolution).

Advantages of imec's optical beamforming technology include:

- It is a full photonics solid-state solution, lacking any mechanical parts; as a result, it is much easier to assemble – while featuring a higher reliability;
- It supports a high optical power (30 W) with low beam divergence (<1°), suitable for long-range measurements;
- As it builds on semiconductor technologies, the system can be fully integrated with all electronics into a system-on-chip and/or a system-in-a-package;
- Leveraging semiconductor technology, its cost is drastically reduced;
- Imec can manufacture beamformers tailored to a company's specific needs.

Sensor fusion and AI: making a vehicle 'understand' what its surroundings look like



Accurate detection and tracking of road users and obstacles is essential to the introduction of driverless cars and many other smart mobility applications. As no single sensor can provide the required accuracy and robustness to cover all circumstances and scenarios, the output from several sensors will need to be combined. Enters **sensor fusion**.

When driving in poor lighting conditions, for instance, a vehicle's regular cameras only see what is being illuminated by the car's headlights. In such circumstances, it would be great to have the camera switch to the infrared (IR) or near-infrared (NIR) bands to improve its sensing capabilities.

Another advantage brought by sensor fusion is a much higher level of **redundancy**. As long as a human driver is still in control of the car, a false-positive (pedestrian) warning is not so much a problem; but that changes when self-driving vehicles appear on our roads. In such a scenario, sensor fusion allows the validation of various sensors' data to achieve the right level of **precision** and **confidence**.

Actually, the concept of sensor fusion is no longer a groundbreaking idea: virtually every automotive OEM has started to investigate its potential. But sensor fusion comes in various flavors – and the industry might very well be betting on the wrong one...

The inextricable link between sensors, sensor fusion and AI

Sensors, sensor fusion and artificial intelligence (AI) are inextricably linked. It is a combination of technologies that can help us overcome people's physical and cognitive limitations. While we suffer from limited night vision capabilities, for instance, an AI engine that gets its input from a combined camera and radar sensor system can analyze and interpret its surroundings in much greater detail – no matter if it is day or night. In a next step, leveraging those sensor data, the AI engine should be able to adequately respond to whatever it observes.

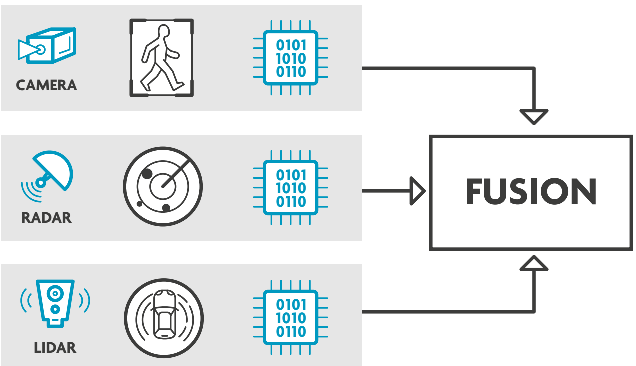
Actually, the concepts of sensor fusion and AI are no longer groundbreaking ideas: virtually every automotive OEM has started to investigate their potential. But sensor fusion and AI come in various flavors. That, by itself, warrants some further discussion.

Early fusion vs. late fusion: neither approach suits the automotive case

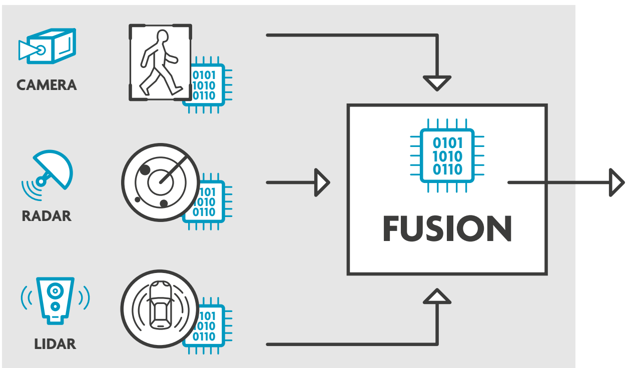
Today's most popular type of sensor fusion is called late fusion (as opposed to early sensor fusion).

Late fusion implies that sensor data are fused after each individual sensor has performed object detection and has taken its own 'decisions' (based on its own, limited collection of sensor data). Late fusion comes with the main drawback that each sensor throws away all the data it deems irrelevant. As such, a lot of sensor fusion potential is lost. In practice, this might cause a self-driving car to run into an object that has remained under the sensors' detection threshold.

Early fusion (or **low-level data fusion**) builds on all low-level data from every sensor – and combines those in one intelligent system that sees everything. Academically speaking, early sensor fusion makes for a very popular research path because it works with each and every bit of info that is available Yet, in practice, it requires high amounts of computing power and massive bandwidths – featuring high-bandwidth links from every sensor to the system's central processing platform. Moreover, practically speaking, it typically requires all equipment to be procured with one and the same vendor (causing vendor lock-in). So, in the end, early fusion does not really suit the automotive use-case either.



Late fusion: sensor data are fused after each individual sensor has performed object detection and has drawn its own 'conclusions'. Source: imec.



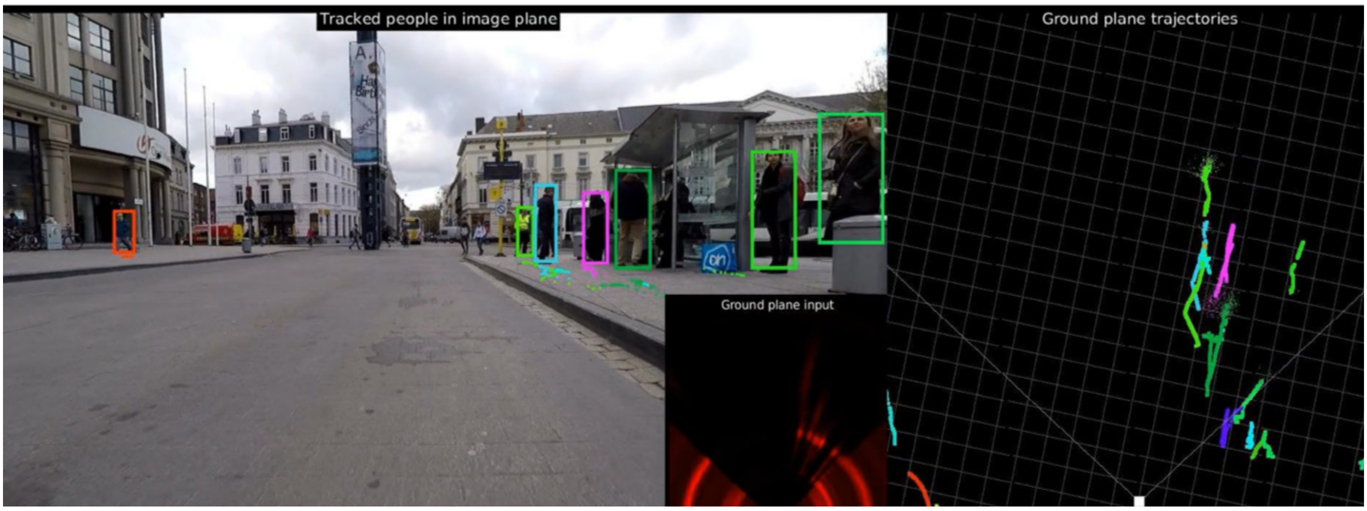
Early fusion builds on all low-level data from every sensor – and combines those in one intelligent system that sees everything. Source: imec.

Cooperative sensor fusion: the new kid on the block

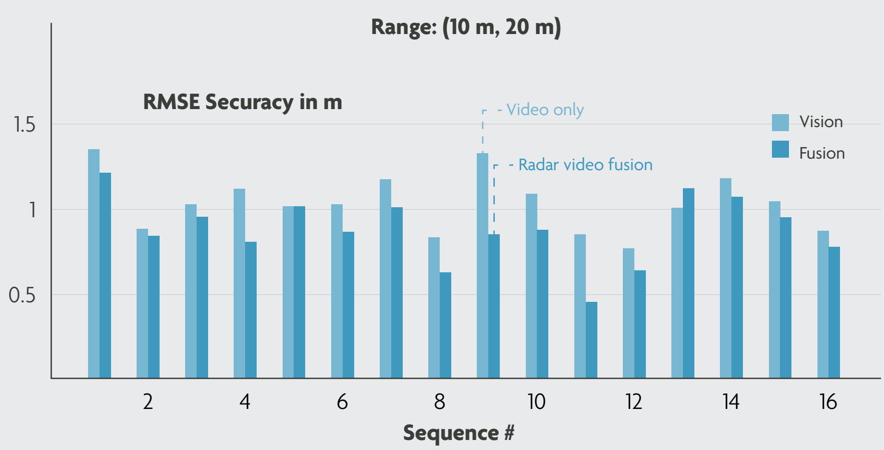
In response to the shortcomings of traditional sensor fusion approaches, researchers have developed the concept of **cooperative sensor fusion**. It features an extra feedback loop, with different sensors exchanging low-level or middle-level information to influence each other's detection processing. If a car's radar system suddenly experiences a higher degree of reflection, for instance, the threshold of the on-board cameras will automatically be adjusted to compensate for this – thus improving overall tracking performance.

First results show that this method is much more powerful than the late fusion approach that is commonly used today. Moreover, it is easier to implement than early fusion since it does not come with the same bandwidth issues and practical implementation limitations.

Cooperative sensor fusion closely couples the detector and tracker. This allows to exploit the benefits of early fusion of the rich sensor data without the need for high-throughput data links to the fusion center.



Field tests in the City of Ghent (Belgium), 2019 – featuring cooperative (radar and video) sensor fusion. Source: imec.



Demonstrating cooperative sensor fusion's accuracy, researchers captured a dataset consisting of various complex traffic scenarios in a European city center. For multiple targets up to 10 meters in front of the vehicle, they measured accuracy improvements of 20% over a camera-only system, with only a fractional load to the network compared to low-level fusion. Source: imec.

Video and radar make for a good sensor fusion match

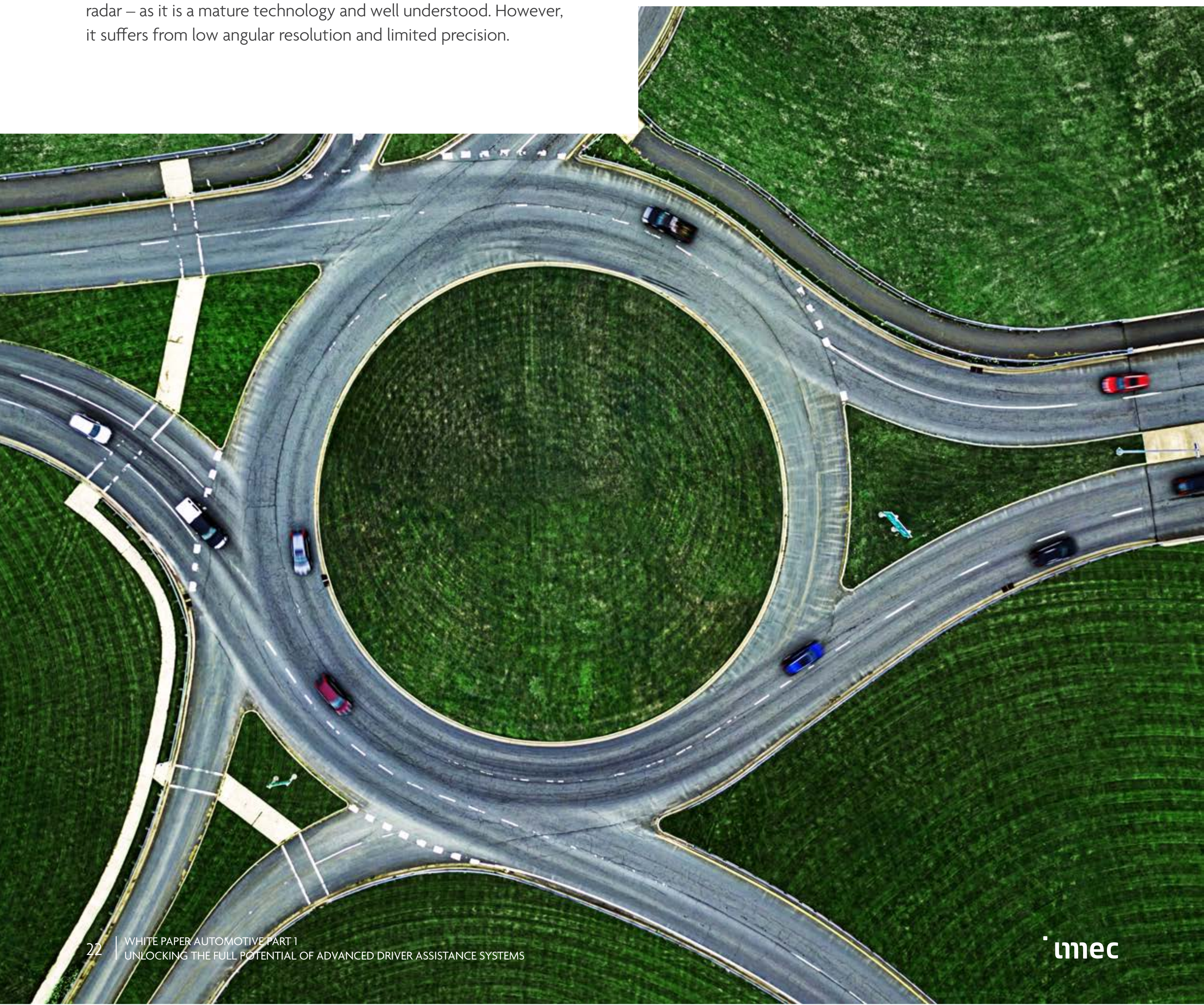
As discussed above, every sensor technology comes with its pros and cons. For instance, cameras don't work well at night or in dazzling sunlight. And radar can get confused by reflective metal objects. But combining the two technologies makes for a good match, because their strengths and weaknesses complement one another.

It is expected that the use of camera systems as a sensor technology will remain fundamental. Ideally, however, they should evolve to a single box that features high dynamic range (HDR) capabilities (supporting a wider range of contrasts) as well as a night vision component (IR or NIR – which is less expensive than its IR counterpart). Those technologies could then be fused on a low level to end up with a single image.

Secondly, camera technology will need to be combined with a distance/depth perception system. Today, the only technology for depth sensing that is widely accepted for automotive use cases is radar – as it is a mature technology and well understood. However, it suffers from low angular resolution and limited precision.

As a result, efforts are ongoing to either squeeze more out of today's (relatively cheap) radar systems – or to accommodate new capabilities using different frequency bands (think of pedestrian detection). Apart from innovations from a hardware perspective, this goes hand in hand with the development of **machine learning technology** that does a better job at distinguishing objects from one another (e.g. pedestrians from road signs or other metallic objects with a lot of reflection).

In parallel, powerful lidar systems for distance/depth detection are getting cheaper. Research indicates that **flash lidar,** for instance, makes for a more cost-effective and robust alternative to present-day lidar. Flash lidar replaces rotating lasers with an array of light emitting diodes and uses beam steering approaches to scan a vehicle's environment.



Launching a call for integrated solutions

Current sensor fusion implementations greatly suffer from a lack of integration. Each tier-1 supplier, for instance, offers its own traffic sign recognition package featuring a combination of dedicated software and hardware.

This forces automotive OEMs to buy a camera box from one supplier and a radar box from another supplier; boxes that are typically not talking to one another. This makes sensor fusion a difficult feat to achieve.

In such a siloed market, OEMs could benefit from launching a call for integrated solutions (such as an integrated radar-video sensor) that build on general recognition structures, in the same way our brain works. That could be an important first step to start investigating the potential of concepts such as cooperative sensor fusion.

An important challenge remains: improving accuracy

Clearly, sensor fusion is a topic that is still fully developing. One of the main challenges that remains to be addressed, relates to achieving the **detection accuracy** that is required to accommodate truly autonomous vehicles.

To give a concrete example: today, the best technology option for detecting vulnerable road users (i.e. camera technology) achieves a 90% accuracy rate. In an assisted driving scenario, with a human driver who is ultimately in control, that is fine. Still, it makes truly autonomous driving in a non-mapped and challenging urban environment a distant dream.

Perceptive systems need to become much better at detecting specific contexts – so that they can anticipate situations just like humans do. A human driver, for instance, will spontaneously assess the risk of someone suddenly appearing from behind a parked vehicle – based on context and experience. An autonomous vehicle, however, does not have this context and simply resorts to rule-based decisions. In other words: to make autonomous driving a reality, perceptive systems need to have a much better 'understanding' of their surroundings. And that is where artificial intelligence (AI) comes in.

AI: mimicking human intelligence to adequately react to the intentions of other road users

The introduction of artificial intelligence (AI) is just another example of how human limitations are being offset by means of technology. In the automotive domain, this process started off with the advent of the motor car in the 1880s – substituting people's physical power with a much better alternative: the combustion engine. As a next step, thanks to AI, 'smart' cars will also optimize our cognitive (driving) skills.

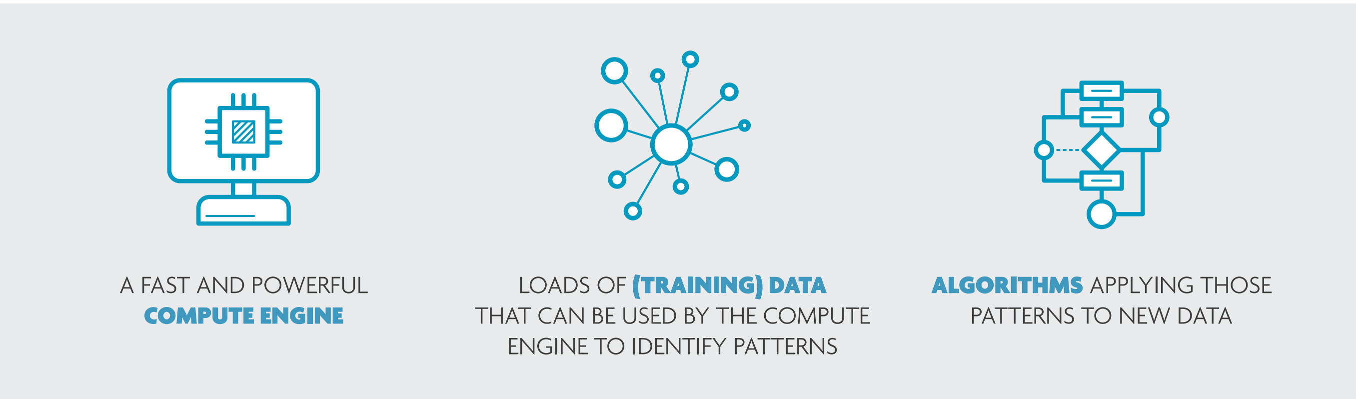
As previously discussed, building smart cars that can assess – and adequately react to – the intentions of other road users will require a clever combination of increasingly powerful and versatile sensors. But that is not sufficient: they will need to be complemented with an AI engine that is capable of learning and – ultimately – reasoning.

Demystifying AI: how do smart cars learn?

AI stands or falls with its ability to learn. But how does this **(machine) learning** process actually work?

Just like humans acquiring knowledge, AI needs to be trained using lots of **training data** (e.g. thousands of pictures of road signs, pedestrians, traffic lights, etc.). In a second step, algorithms are used to derive patterns from those training data. The ultimate objective: making the AI engine recognize objects in totally new settings. When it sees a picture of a road sign it has not yet encountered, for instance, it should be able to confirm with x% probability that this is a picture of a road sign.

To accommodate this process, (lots of) **computing capacity** is needed to train larger and more complex models – using structured and unstructured data.



Artificial intelligence builds on the combination of computing capacity, (training) data and algorithms. Source: EDUbox AI

Machine learning comes in various flavors. One of its latest additions includes **deep learning** – a technique that enables smart systems to 'think' in multiple layers, just like humans do. Deep learning is particularly relevant when dealing with very complex situations such as driving, which involves lots of action and interaction (monitoring one's surroundings, accelerating, changing gears, braking, anticipating the intentions of other road users, etc.). In other words: deep learning is perfectly tuned to the learning needs of smart vehicles.

The concept of deep learning goes hand in hand with the use of (artificial) **neural networks:** networks that mimic the human brain. While the human brain is made up of connected networks of neurons, neural networks aim at acting like interconnected brain cells, so that they can learn and make decisions in a more humanlike manner.

Automotive Intelligence

Artificial intelligence can be defined as the ability of a technical solution to mimic human intelligence – characterized by behavior such as sensing, learning, understanding, decision-making and acting.

In an automotive context, AI is typically described as "the technology enabling a vehicle to learn and operate independently – and to ultimately make its own decisions – based on past experiences (in the form of data)".

Tiny AI

In order to realize this vision of intelligent vehicles, multiple extreme edge devices will need to cooperate locally and share with one another partially processed information and partial decisions. They will need to involve the next hierarchical level – the edge – when acceptable (e.g. with respect to latency, privacy, etc.) or when needed (with respect to available compute power, storage or energy capabilities). In turn, edge devices will mutually share data and decisions as well, involving local or global cloud servers when acceptable or needed.

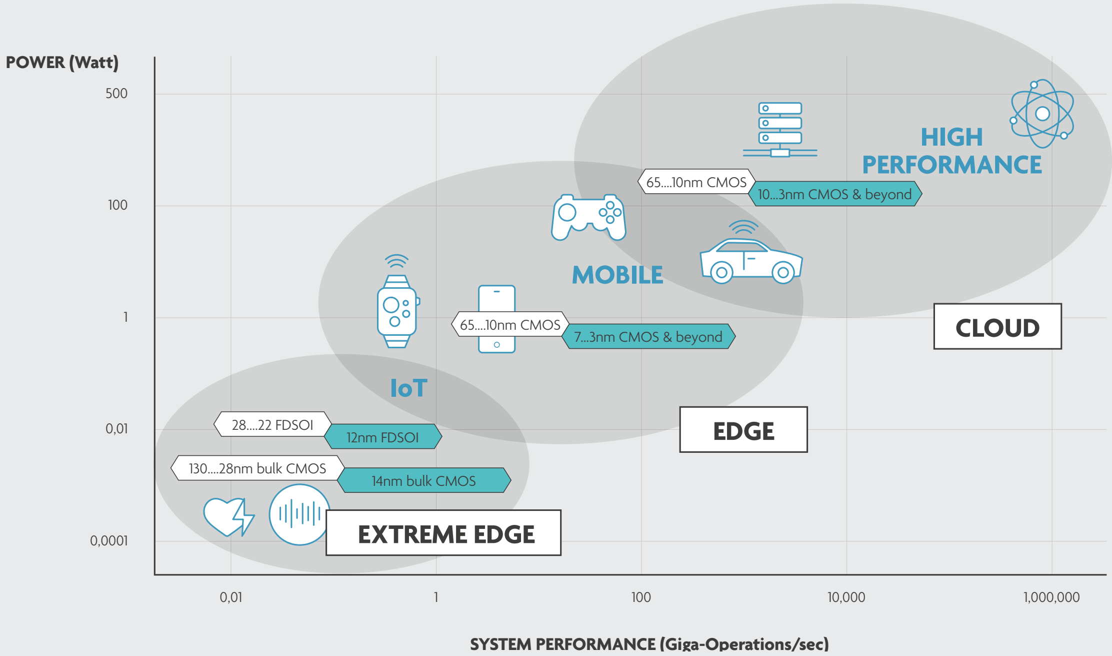
To support such vision of connectivity at the edge, intra-device and inter-device algorithms will be needed. At imec, that approach is called **tiny AI**.

From Cloud AI to (Extreme) Edge AI

Today, lots of (machine) intelligence resides in the cloud – where virtually unlimited computing power is available. That being said, the emergence of applications such as next-generation ADAS and autonomous driving will put an end to **cloud AI**'s dominant position; A concept such as cooperative sensor fusion requires AI solutions to function autonomously – in a distributed way and running at the **(extreme) edge**.

After all, the next generation(s) of smart vehicles will simply not have the luxury of being able to rely on enormous amounts of data sets to make (real-time) decisions. The computing power, nor the latency, nor the required energy will be available to do so. Moving in the direction of (extreme) edge AI, an architecture can be built that uses very small, highly energy-efficient chip sets to process limited data sets in a cleverer way.

Edge AI is characterized by local processing, using a microprocessor that has been decoupled from the sensing hardware. Extreme edge AI features local processing as well – yet makes use of a microprocessor that has been embedded on the sensing device. Source: imec.



Advantages of such an approach are plenty:

- **Real-time decision-making**: (extreme) edge applications generate results that are stored locally on the device or sensor. They can process data and make independent (real-time) decisions.
- **Low-bandwidth communication**: since less data needs to be transmitted to the cloud and back, (extreme) edge solutions can do with low-bandwidth (and low-cost) communication.
- **Enhanced power-efficiency**: (extreme) edge devices are characterized by a reduced power consumption (thus improving battery life).
- **Improved data security**: by processing data locally, lots of vulnerability and privacy concerns – which are typical of IoT solutions – are solved.

From narrow AI to broad AI for better decision taking

So far, research in the AI domain has largely been focusing on narrow AI – with AI techniques being developed to solve specific problems. For instance, the first generation of smart cars that is being tested today still contains dozens of narrow AI (sub)systems: there are systems that analyze images from the on-board cameras, other systems aim at identifying road junctions and traffic signs, others are looking into navigation, etc.

To accommodate more complex technologies (such as autonomous vehicles), however, we will need to resort to broad AI approaches. Broad AI aims at developing AI solutions that can tackle problems in much the same way that humans can.

Broad AI has:

- The ability to take knowledge from one area and apply it somewhere else;
- The ability to make plans for the future based on past knowledge and experiences;
- The ability to reason;
- The ability to adapt to the environment as changes occur.

Longer-term perspective: getting smart vehicles to interact with one another

As highlighted in this section, quite some new insights have recently been introduced to make smart(er) cars a near-future reality. Yet, if there is one more challenge that merits to be called out, it is the (lack of) interaction between smart vehicles.

YouTube movies of (semi-)autonomous cars interacting with one another are pretty impressive and get huge amounts of views. However, when taking a closer look, one will see that they are typically cars from the same manufacturer and that they can only do their magic in a pre-mapped or highly predictable environment.

The underlying issue is that, today, AI agents are not yet contextually adaptive in a flexible way. What's more, they have no knowledge of the state-of-mind of other objects crossing their path: they cannot anticipate how other objects (robots/cars) – let alone vulnerable road users – will react in a given situation. In that domain, particularly, more research is required – featuring promising research tracks such as online action detection and the use of long short-term memory (LSTM) architectures.

Hybrid AI: adding reasoning to the mix using cognitive systems

The following scenarios illustrate where AI currently falls short:

- Imagine an AI-enabled car driving through a street and 'spotting' the statue of a person riding a horse. Today, that car might perform an emergency stop in the middle of the road as it thinks it is being confronted with a real horse; simply because it is not familiar with the concept of a statue.

- A similar thing might occur in a shopping street, where each mannequin in each shopwindow might be regarded as a real, living person.

- And how will AI-enabled cars react to pedestrians not using the sidewalk?

AI's current inability to deal with the above scenarios results from limitations in its training stage: if an AI system has been trained using data from a location where no statues or mannequins can be found, it has no way of knowing what a statue or a mannequin is. And the same goes when it encounters rare or unexpected traffic scenarios (such as pedestrians not using the sidewalk).

In order to take driver assistance technology to the next level and pave the way for self-driving vehicles, we will need to equip AI with the ability to 'reason' – just like humans do. And that means replacing today's (mainly data-driven) AI approaches with hybrid AI.

The topic of hybrid AI makes for a rather recent research track. It starts from the observation that data-driven AI is very fragile: it requires enormous amounts of data, it does not provide explanations or justifications, it is susceptible to biased datasets, and it can only be used for prediction (not for models that can be understood and interpreted by humans). At the other end of the spectrum, knowledge-based AI faces significant limitations as well, since manually encoding all required knowledge is simply impossible; some of it should be learned instead.

So that is where hybrid AI comes in. It integrates learning and reasoning – using a combination of data and knowledge – to get to better cognitive systems. Cognitive systems are AI systems that perform human-like tasks in natural environments. Importantly, cognitive systems are not only able to make predictions; they can explain their predictions as well. The latter is essential for AI systems that should adhere to certain standards regarding ethics, safety, or even just legal regulations.

The importance of bringing reasoning into the equation can be illustrated by means of the following example. When a person is hiking through South-Africa and comes across a lion, he or she instinctively knows it is time to run. But when that person sees the same lion in a zoo, he or she will feel totally at ease: human reasoning tells us that – this time – there is a glass wall in-between ourselves and the lion (a wall one can look through, but it is definitely there). Tomorrow's smart cars will need to possess similar AI reasoning principles in order to adequately deal with unexpected or unknown situations.

imec expertise

Researchers at imec - Ghent University (Belgium) excel at tracking pedestrians and cyclists in the most challenging scenarios (i.e. urban centers).

Researchers from the Image Processing and Interpretation (IPI) research group (an imec research group at Ghent University, Belgium) have been leading the way in the development of cooperative sensor fusion. They have defined the underlying architecture and have built an initial proof-of-concept.

Leveraging cooperative sensor fusion, the IPI research group has a proven track record of locating pedestrians and cyclists in urban centers more accurately than anyone else. While these are incremental improvements, being able to locate vulnerable road users with cm accuracy allows (self-driving) vehicles to anticipate dangerous situations much more quickly. The team's most recent test results indicate, for instance, that their first moment of detection outperforms competitive approaches with a quarter of a second.

Conclusion

Current ADAS systems suffer from substantial shortcomings: their sensors lack accuracy, they work in silos instead of in concert, and they only provide input, leaving it to the driver to take action.

This first section of imec's automotive white paper focused on **two domains for improvement**:

1. **anti-collision sensor technology** – Although nano- and digital technology can make camera, radar and lidar systems more efficient, probably no single technology option covers all ADAS requirements.

2. **sensor fusion and AI** – Delivering a full perceptive (3D) model and acting upon it will be the job of smart algorithms that increasingly run on energy-efficient computing devices on the (extreme) network edge.

Unlocking the full power of ADAS therefore requires you to **leverage several hardware and software capabilities**, and to look for partners within and outside the traditional automotive value chain.

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End notes

1 https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death (May 24th, 2018)

2 https://www.euronews.com/2019/08/20/road-fatalities-which-eu-countries-are-the-most-dangerous (August 21st, 2019)

3 https://etsc.eu/more-enforcement-needed-to-reverse-decline-in-dutch-motorway-safety/ (October 15th, 2019)

4 https://www.vrt.be/vrtnws/en/2020/03/12/number-of-road-deaths-in-belgium-on-the-rise-again-after-3-year/ (March 12th, 2020)

5 https://trimis.ec.europa.eu/?q=project/vision-zero-initiative#tab-outline

6 https://www.digitaltrends.com/cars/2016-nhtsa-fatality-report/

7 Based on ADAS fitment data published by research firm SBD Automotive – www.sbdautomotive.com

8 https://fortune.com/2016/03/13/cars-parked-95-percent-of-time/

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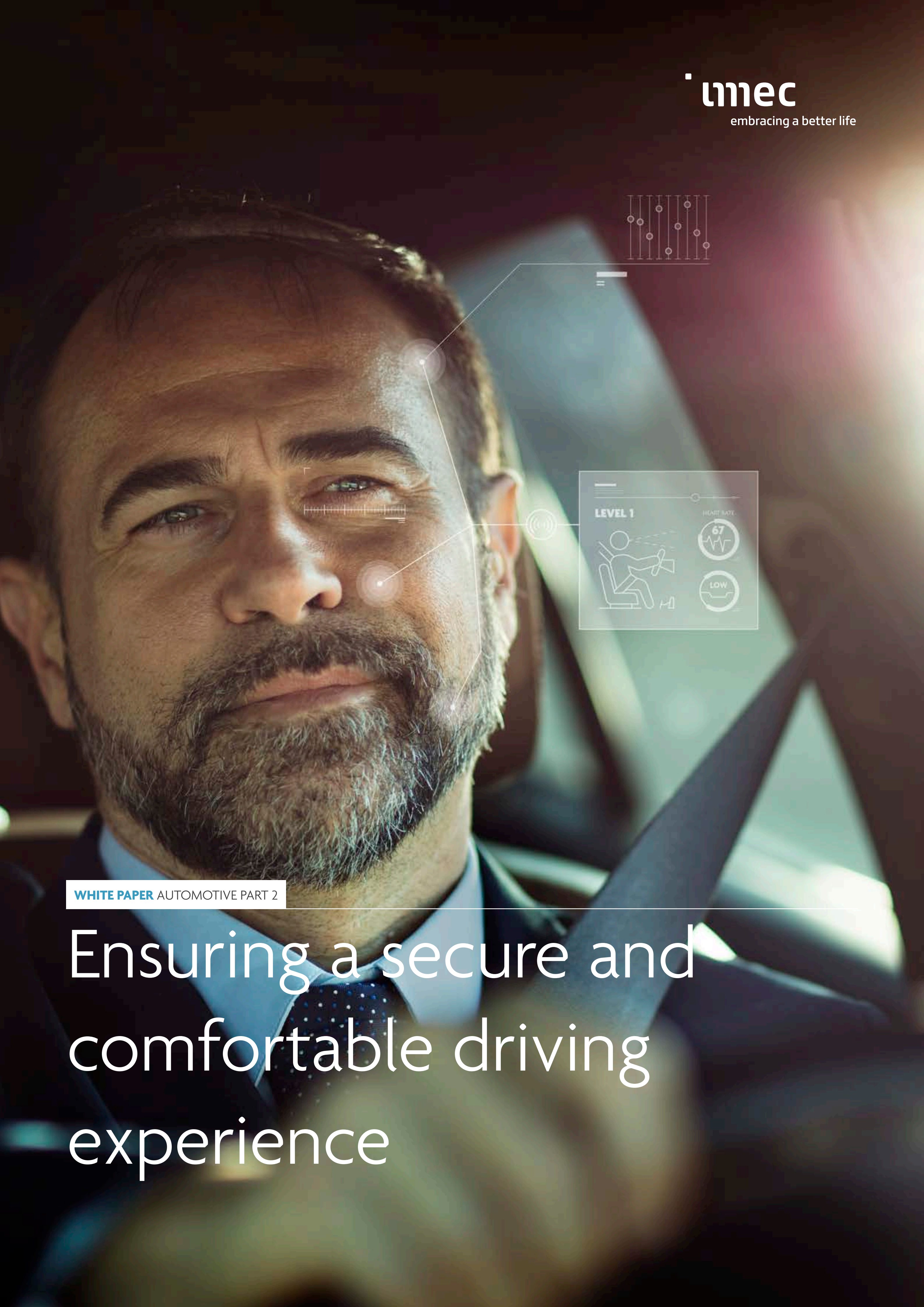

WHITE PAPER AUTOMOTIVE PART 2

Ensuring a secure and comfortable driving experience

Contents

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Introduction

Now that ADAS technologies are gradually releasing the driver from some of his duties, and car sharing is evolving from niche to norm, car manufacturers need to focus on the driver's experience to differentiate themselves from their competitors.

This second section of imec's automotive white paper looks into technologies that guarantee a safe, comfortable and reliable ride. You'll get a detailed answer to questions such as:

- Which wireless technology is most suited for unhackable keyless entry systems?
- How can we accurately and unobtrusively monitor a driver's alertness and health?
- How do we support the connectivity of a car's electronics without giving in on security?

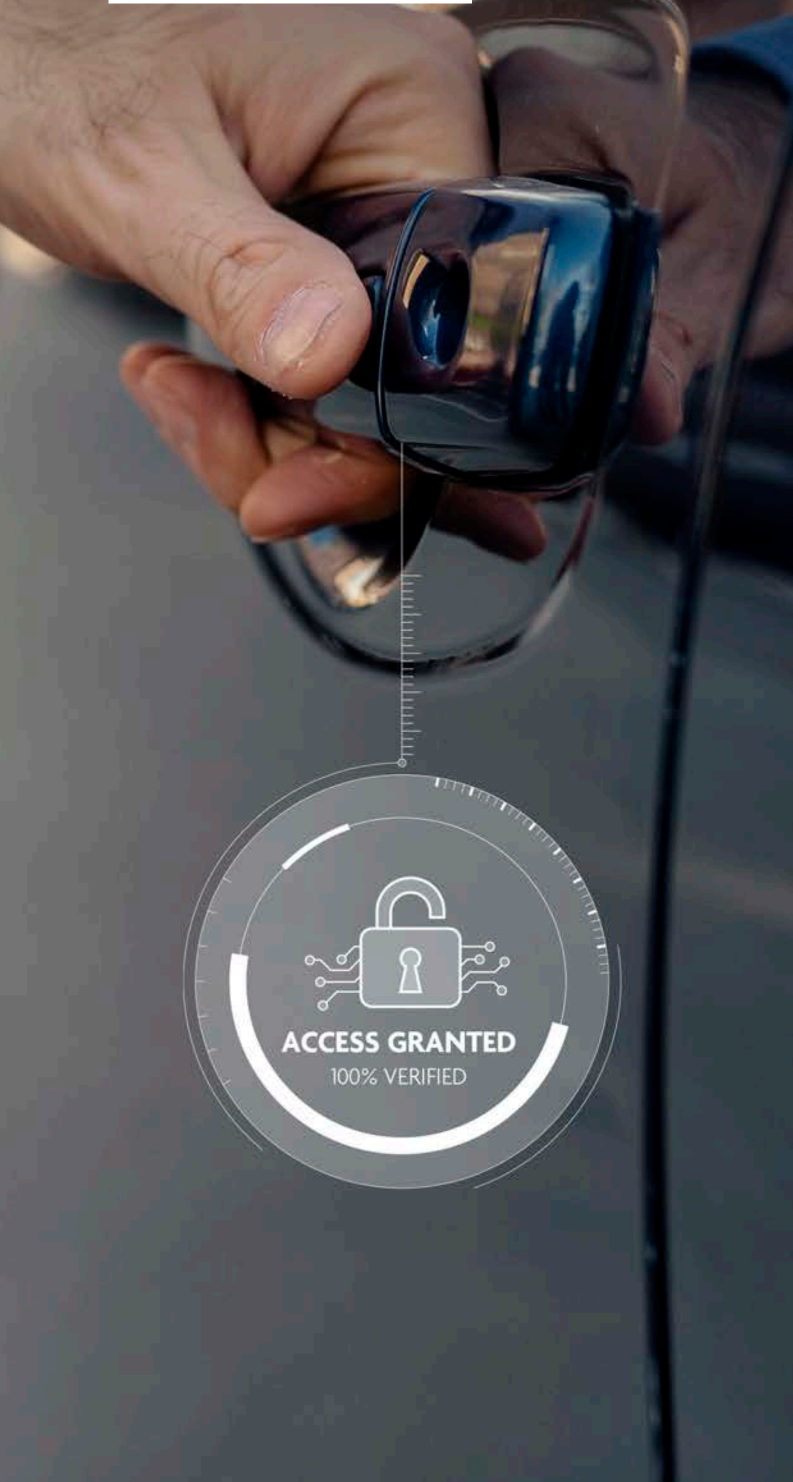
Setting the scene

The first section of this white paper ('Unlocking the full potential of advanced driver assistance systems') explored some state-of-the-art ADAS-enabling technologies; technologies that enable ADAS to optimize people's driving experience, increase overall road safety (through features such as adaptive cruise control, pedestrian detection, etc.) and pave the way towards autonomous driving.

As discussed, car manufacturers are investing a great deal of effort in making their vehicles increasingly safe. At the same time, however, they are looking to capitalize on new technologies to enhance the **in-vehicle experience** as well – for drivers and passengers alike.

In the following chapter, we will have a look at three touchpoints that will define the in-car experience going forward – from **vehicle entry** and next-generation **driver monitoring systems** to **securing a car's underlying electronics**.

Equipping vehicles with passive keyless entry systems that are highly accurate and secure



A growing number of car manufacturers make use of passive keyless entry systems (also known as 'smart lock' solutions) that automatically unlock a car's doors as its owner approaches, while locking the car when the owner moves away.

For this to work properly, the underlying (radio) technology must comply with quite a few requirements:

- It should be accurate and secure – able to withstand relay and other electronic attacks;
- It should be low-power and come at a low cost;
- It should ideally be supported by an ecosystem of smart device manufacturers (ensuring compatibility with today's smartphones, smartwatches, etc.).

The current state of affairs: solutions that are bulky, expensive and easy to compromise

Today's smart lock solutions (including those used in automotive) come with a number of drawbacks:

- They rely on dual low-frequency / subGHz radio chips – which adds to the cost;
- Their antennas are large and difficult to install;
- The technology can easily be compromised;
- One still needs a key, card or other device that comes with the car (no integration with people's smartphones or other smart devices has been foreseen).

In response to these shortcomings, the automotive industry has been exploring several other (radio) technologies to build passive electronic keys. Yet, no alternative seems to really suit the automotive use-case:

- GPS technology, for instance, cannot be used indoors;
- RSSI-based Bluetooth localization lacks accuracy and, as an access technology, is susceptible to relay attacks;
- NFC technology is not passive.

The issue of relay attacks is anything but theoretical. According to a recent BBC News article[1], smart lock solutions from several leading car brands performed poorly in anti-theft tests: all tested cars proved vulnerable to relay attacks (which can be successfully performed in less than a minute).

Importantly, what is typical of relay attacks is that they do not require any knowledge of the actual data that are being transmitted. As such they cannot be prevented using cryptographic countermeasures. What is needed to effectively mitigate these attacks, is the implementation of secure distance bounding (SDB) protocols – allowing a device to authenticate another device and to securely determine its physical proximity.

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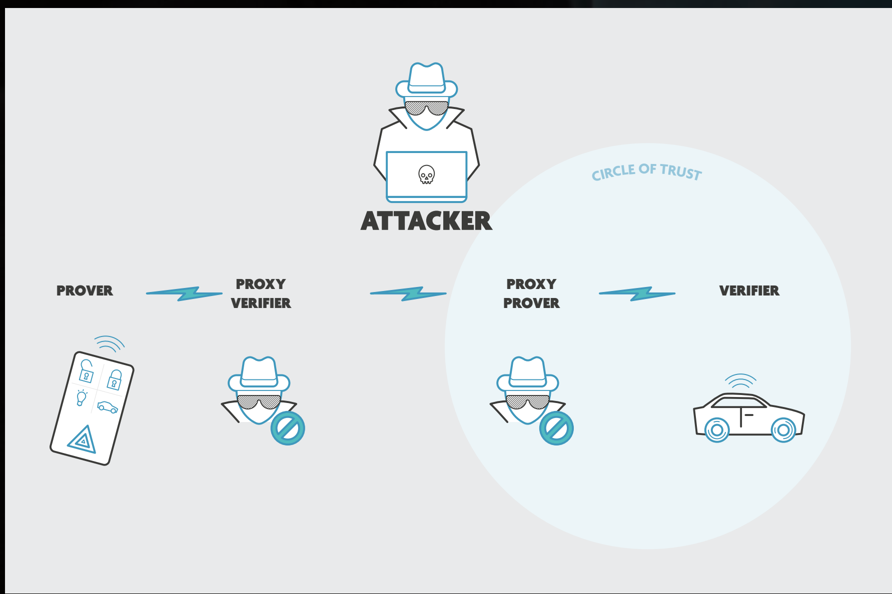
Beware of relay attacks

Passive keyless entry systems use a wireless technology to establish a (secure proximity) link between the 'key' – a smartphone, smartwatch or other smart device – and the device we want to access (the electronic lock).

For security purposes, such a system involves two entities: a 'verifier' and a 'prover'. The verifier controls access to the car's lock, while the prover tries to gain access to it. By default, however, such systems are highly vulnerable to relay attacks.

In a relay attack, an adversary attempts to make a legitimate verifier believe that the legitimate prover entity is close – while in fact it is far away. The adversary does so by putting a proxy device close to the legitimate prover, and another proxy device close to the legitimate verifier. It then relays the communication between these illegitimate entities.

Example: suppose your car is locked and parked in front of your house, with the car keys (safely) inside the house. By using relay boxes that capture wireless signals through walls, windows and doors, the signal from your car to your car keys can easily be relayed – and back. Result: the attacker can unlock your car, start the engine and drive away.



How relay attacks work. Source: imec

Technologies to the rescue: Bluetooth Low-Energy (BLE) and ultra-wideband (UWB)

In pursuit of radio technologies that meet the accuracy and security specs required for passive electronic keys, two good candidates include next-generation **Bluetooth Low-Energy (BLE)** and **ultra-wideband (UWB)**.

BLE High Accuracy and Secure Ranging

Bluetooth Low Energy (BLE) is a highly energy- and cost-efficient technology (using low-cost and low-power chipsets). It is readily available in all of today's mobile phones (and other smart devices), and it is backed by a broad and healthy industrial ecosystem.

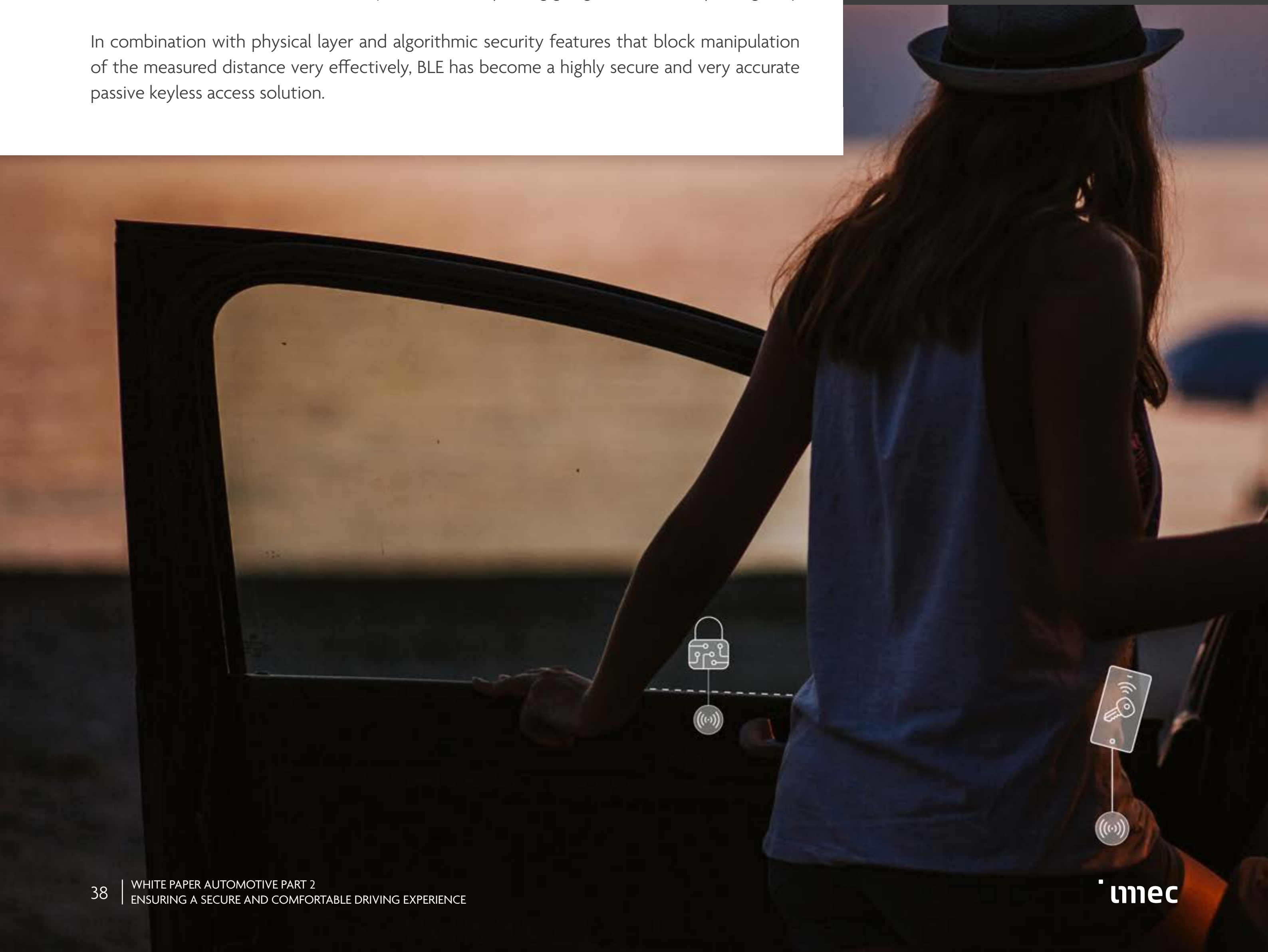
Until recently, Bluetooth had an aura of poor accuracy and weak security. But thanks to recent technological advances[2], Bluetooth can actually be made highly accurate and secure – making it an alternative to ultra-wideband technology (which has so far been regarded as the only suitable standard for automotive keyless access).

Measuring the distance between the smart lock and the car owner's mobile authentication device, today's BLE radio technology – employing next-generation high-accuracy multi-path resistant algorithms – can achieve an accuracy better than 30 centimeters, even in harsh environments with a lot of reflection (such as indoor parking garages or crowded parking lots).

In combination with physical layer and algorithmic security features that block manipulation of the measured distance very effectively, BLE has become a highly secure and very accurate passive keyless access solution.

Looking for more details on this specific topic?

Download imec's white paper on "Secure and Accurate Distance Bounding for Bluetooth Secure Access" at **www.imec-int.com/sdb**



Next-generation high-precision and low-power UWB

Intrinsically, UWB technology offers an even higher (i.e. single digit cm) accuracy for ranging and localization than BLE. Yet, its lack of ecosystem support, high power consumption and potential relay attack susceptibility have been major showstoppers for the technology's commercial adoption in the secure access domain. Today, however, the new UWB IEEE 802.15.4z standard addresses secure ranging requirements and enables the creation of next-generation low-power UWB radio transceivers, aiming at a 10-fold decrease in power consumption.

Wider industry support is another reason for UWB's growing momentum – following the announcement from Apple in 4Q 2019 that it has started to incorporate the technology in its iPhones. Today, it is not yet clear if other phone manufacturers will start to support UWB as well – but an important first step has been taken nonetheless.

Certainly, to enable passive keyless entry, the <30 cm accuracy that is offered by BLE High Accuracy and Secure Ranging is sufficient. UWB, however, may accommodate many new and differentiating features – such as in-car person (e.g. infant) detection, using the UWB anchor nodes in a radar mode to passively detect a person and even monitor their life signs.

Other BLE & UWB use-cases in the automotive domain

BLE and UWB are technologies the automotive industry is pretty familiar with already. Bluetooth, for instance, is commonly used to connect all kinds of on-board sensors, accommodating applications such as tire pressure monitoring. For more robust localization (as required by smart trunk openers, for example) the industry has typically been resorting to UWB.

What's more – going forward – BLE and UWB could also enable a whole new range of other, hyper-personalized automotive applications – such as in-vehicle comfort and entertainment services (think of automatically adjusting one's seat position, air conditioning settings, or audio/media preferences.)

Imec has been pioneering research in BLE and UWB technologies.

Imec is convinced that BLE and UWB will co-exist – accommodating distinctive automotive use-cases and both conquering part of the market. For many use-cases, they might even get deployed as combo-solutions.

In the BLE domain, imec

- Has been first to develop a BLE high-accuracy and secure ranging technology demonstrator. The demonstrator features a commercial off-the-shelf Bluetooth Low Energy device, coupled with imec's high-accuracy ranging algorithms on BLE and extended with imec's physical layer security features. Enabling an accurate and secure distance measurement between two Bluetooth communication devices, imec's technology achieves <30 cm accuracy – which is 10 times better than today's state-of-the-art;

- Has demonstrated the strength of its BLE high-accuracy and secure ranging technology even in heavily crowded and reflective environments that are loaded with radio interference from Wi-Fi operating in the same frequency band;

- Is enabling industrial partners across the value chain to join its 'Secure Proximity' research program for secure and very high-accuracy ranging technology development.

In the UWB domain, imec

- Has a proven track record of conducting more than 15 years of research, pioneering low-power UWB impulse radio (IR) transceiver implementations;

- Is focusing on the development of next-generation low-power UWB technology (IEEE 802.15.4z) – accommodating single-digit cm accuracy through new software, algorithms and silicon IP (and aiming at a 10-fold decrease in power consumption);

- Continues to pursue the development of advanced machine learning and sensor fusion algorithms for UWB localization with improved multi-path and non-line-of-sight resilience, aiming to improve UWB's performance in difficult (industrial) environments.

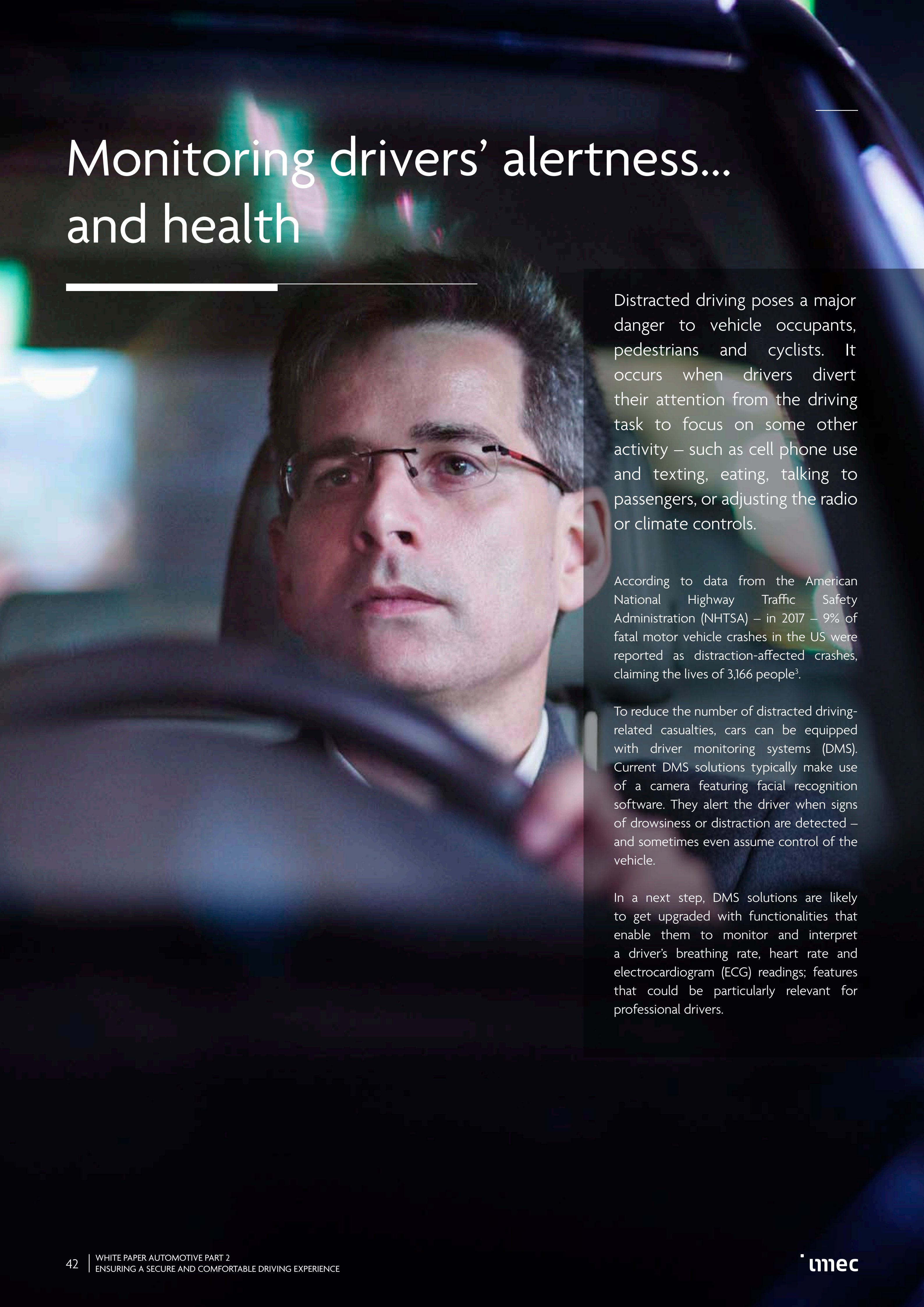
imec expertise

Imec has ample credentials in the domain of secure and low-power wireless communication.

- Imec has been pioneering research into wireless communication technologies for more than two decades – featuring e.g. 60+ ISSCC publications and 100+ patents;

- Imec actively participates in high-impact standardization bodies such as the Bluetooth Special Interest Group (SIG), IEEE, Car Connectivity Consortium (CCC) and others;

- COSIC – an imec research group at KU Leuven, and one of the key contributors to imec's BLE High Accuracy and Secure Ranging implementation – is one of Europe's main powerhouses when it comes to the protection of digital information. COSIC develops advanced cybersecurity solutions to protect data in the cloud and in the Internet of Things (IoT), and to protect the privacy of users. During the last 15 years, COSIC obtained more than 1200 international reviewed publications in journals and conferences, 13 edited books, 10 patents and has graduated over 60 PhD students.



Monitoring drivers' alertness... and health

Distracted driving poses a major danger to vehicle occupants, pedestrians and cyclists. It occurs when drivers divert their attention from the driving task to focus on some other activity – such as cell phone use and texting, eating, talking to passengers, or adjusting the radio or climate controls.

According to data from the American National Highway Traffic Safety Administration (NHTSA) – in 2017 – 9% of fatal motor vehicle crashes in the US were reported as distraction-affected crashes, claiming the lives of 3,166 people[3].

To reduce the number of distracted driving-related casualties, cars can be equipped with driver monitoring systems (DMS). Current DMS solutions typically make use of a camera featuring facial recognition software. They alert the driver when signs of drowsiness or distraction are detected – and sometimes even assume control of the vehicle.

In a next step, DMS solutions are likely to get upgraded with functionalities that enable them to monitor and interpret a driver's breathing rate, heart rate and electrocardiogram (ECG) readings; features that could be particularly relevant for professional drivers.

The (market) potential of driver monitoring systems

Reports from market intelligence company Report & Data indicate that the global DMS market was valued at USD 987 million in 2018 and is projected to witness a growth of 12.3% of CAGR during the forecast period in 2026[4].

Today, (camera-based) driver monitoring systems are mainly adopted by luxury car owners. Europe accounts for the highest share of the DMS market and is expected to continue its dominance in this domain – due to government initiatives such as the New Car Assistant Program (NCAP), listing driver monitoring as a primary automotive safety system.

What's more, the relevance of driver monitoring systems will only increase as they start to include more functionalities. Think of sensors that are built into a car driver's seat, steering wheel and dashboard to measure respiration rate, blood pressure, heart rate and cardiac activity on a continuous basis.

Doing so, accidents could be prevented – by detecting fatigue, stress or heart problems before they become an issue for the driver. But also in cases where an accident cannot be avoided, the DMS sensors could be used to check (and communicate) the condition of the driver and passengers to the emergency services. In a next step, car seats could even carry out daily health checks and provide regular reports with all the facts and figures recorded.

Carrying out daily health checks in cars using capacitive, optical and radar sensing technology

Complementing today's camera systems, three technologies will play an important role in accommodating the next generation of DMS solutions: **capacitive, radar** and **hyperspectral sensing technologies**.

Capacitive sensors

Capacitive sensing is a technology that can detect and measure anything that is conductive or has a dielectric different from air. Many types of sensors use capacitive sensing – including sensors to detect and measure proximity, pressure, position and displacement, force, humidity, fluid level and acceleration.

Capacitive sensors can be integrated into a variety of objects – from office chairs to car seats – to carry out ECG readings or detect respiration rates through clothing. That being said, so far, the technology has not yet been used in practical (automotive) applications: the quality of the readings tends to deteriorate if a person moves about in his/her seat, or when driving on bumpy roads.

The solution to this challenge lays in the use of smart algorithms. First of all, algorithms can compensate for variations when movements and artifacts are detected. This makes the readings more reliable. Secondly, algorithms can make the system adaptive. This means for instance that, in good conditions, an (ECG) signal of medical grade quality can be recorded. When conditions are not so good, however, the sensors might switch to 'robust' mode and take more general readings – implying that although the heart rate could still be recorded, obtaining an accurate ECG graph might (temporarily) not be possible.

Capacitive sensors can be incorporated into armchairs, office chairs, car seats, etc. Imec has developed a system that can support up to 64 sensors. Source: imec

Radar sensing

While a 79 GHz radar module particularly lends itself to detecting (road) objects[5] , other radar flavors can be used to measure heart and respiration rates.

Some radar devices are capable already of measuring these parameters in one person standing still. And more recently, researchers have succeeded in using an 8 GHz radar to measure the heart and breathing rates of two different people, 2 meters away from the radar – with smart algorithms being used to tackle the issue of variable reliability.

For the time being, however, the radar device used in this type of experiments is still fairly large and serves mainly to demonstrate the working principle. Ultimately, a much smaller radar module is needed that can be integrated (virtually invisibly) into suitable surfaces such as a car's dashboard or the car seats. From a cost perspective as well, further steps remain to be taken – with the semiconductor industry resorting to CMOS technology[6] to enable the production of more cost-efficient radar modules. An additional benefit of using CMOS technology is that it makes for an easier integration with post-processing systems.

In parallel, radar solutions are being developed that operate at 140 GHz. A **140 GHz radar** unit is very compact because the antennas are very small and the whole system has been integrated onto a single chip. As such, the footprint required to measure both the distance and direction of a person in relation to the radar becomes a lot smaller.

Hyperspectral optical sensors

Using ordinary RGB cameras, it is possible – under certain conditions – to measure someone's heart or respiration rate. With **hyperspectral cameras**, which detect the reflected light of objects in very fine wavelength bands, you can do the same – be it with much greater accuracy.

When it comes to expanding the capabilities of DMS solutions, hyperspectral optical sensors could prove highly useful. While today's cars might be equipped with an ordinary camera, in the future – and for just a few dollars/euros more – this could very well become a hyperspectral camera.

> "Smart algorithms can enhance the quality of sensor readings by compensating for variations and increasing the adaptivity of the system."

Ultra-sensitive and low-power 60 GHz on-chip radar can detect very small movements

A new kid on the block, 60 GHz on-chip radar can detect very small movements while consuming little power. This makes the sensor easy to integrate into wearables, small devices, a car's dashboard, etc.

A radar operating at a lower frequency usually consumes less power – but is also less sensitive. A 24 GHz radar, for example, is expected to combine low power consumption with moderate resolution, but the radar would be relatively large. If you want to detect micro-movements with very high accuracy, a radar operating at 140 GHz seems better suited: at 140 GHz, a very small sensor achieves a much better resolution – but, then again, this comes at the cost of an increased power consumption.

Between these two extremes lies 60 GHz radar, combining the best of both worlds. Contrary to the 79 GHz band, which has been reserved for automotive applications, the frequency band around 60 GHz has the advantage of being a license-free ISM band that can be used for all kinds of new IoT applications. Think of detecting people, recognizing gestures, or vital life signs monitoring (in vehicles).

Challenges and opportunities

A car is a moving platform that continuously vibrates due to road, vehicle and driver conditions. Hence, if two challenges need to be called out, those are the robustness of DMS solutions – as well as their ability to extract useful information out of multiple sensors.

Today's technology indeed enables us to monitor people's heart rate through their clothes. But what is really needed, is for those measurements to be medical grade. To predict, for instance, whether a driver risks getting a stroke in the next 30 minutes, much better and continuous measurements are required.

For this, we might need to use a combination of sensors – resorting to sensor fusion approaches and powerful algorithms to filter out the noise.

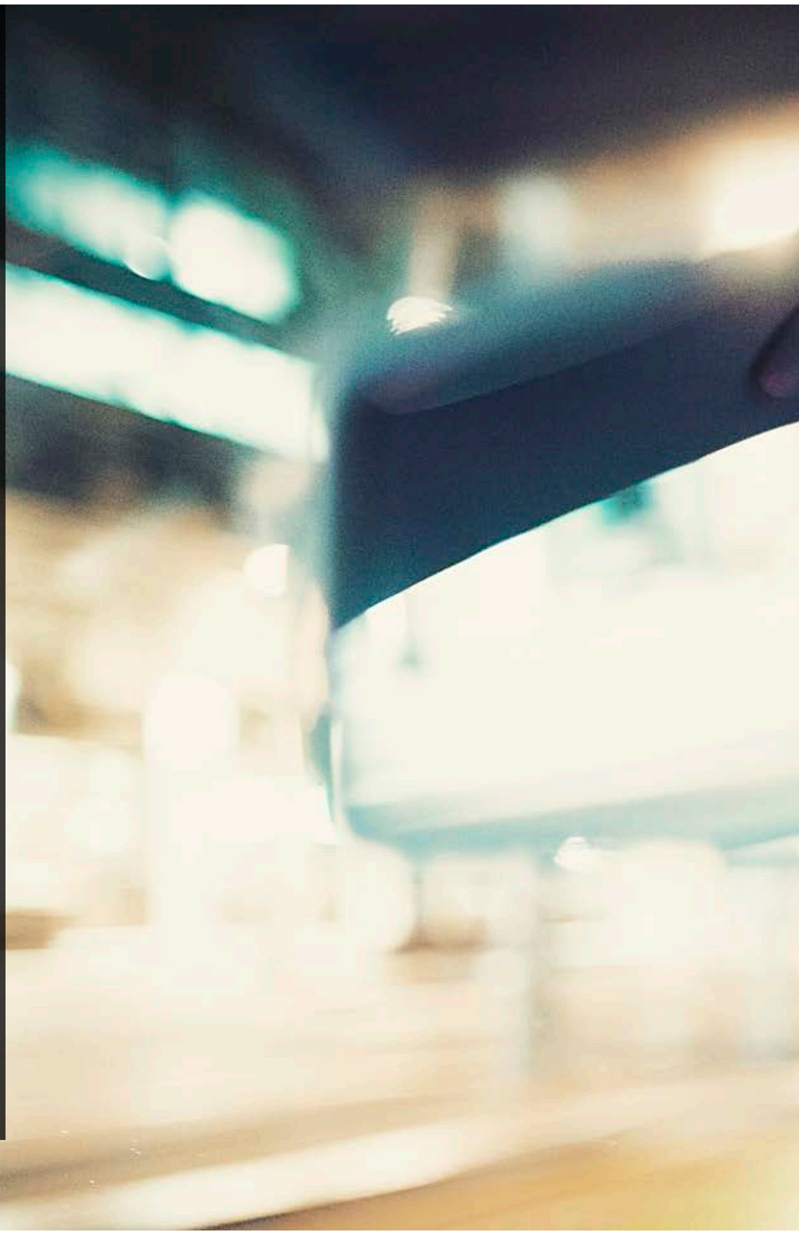
As a sidenote, DMS-enabling technologies not only bring increased safety and health monitoring opportunities. Other interesting in-vehicle applications include detecting whether a child has been left onboard, or automatically adapting airbags to a person's height.

How about ethics and privacy?

Monitoring people – and their life signs – inevitably comes with ethical and privacy concerns. Who owns those data? What happens with them? Where are they stored – and for how long? Who can access them (for instance, could they be shared with people's insurance companies)? And what steps to take when the technology does identify an imminent health hazard?

These are all valid questions. Yet, the ethical and privacy concerns that come with this type of applications are much more far-reaching than just the automotive use-case. Hence, they should be part of a wider societal debate on the use of new (sensing) technologies.

So, while this is a very important topic that warrants further research and discussion, ethical and privacy aspects are not dealt with in the framework of this white paper.



imec expertise

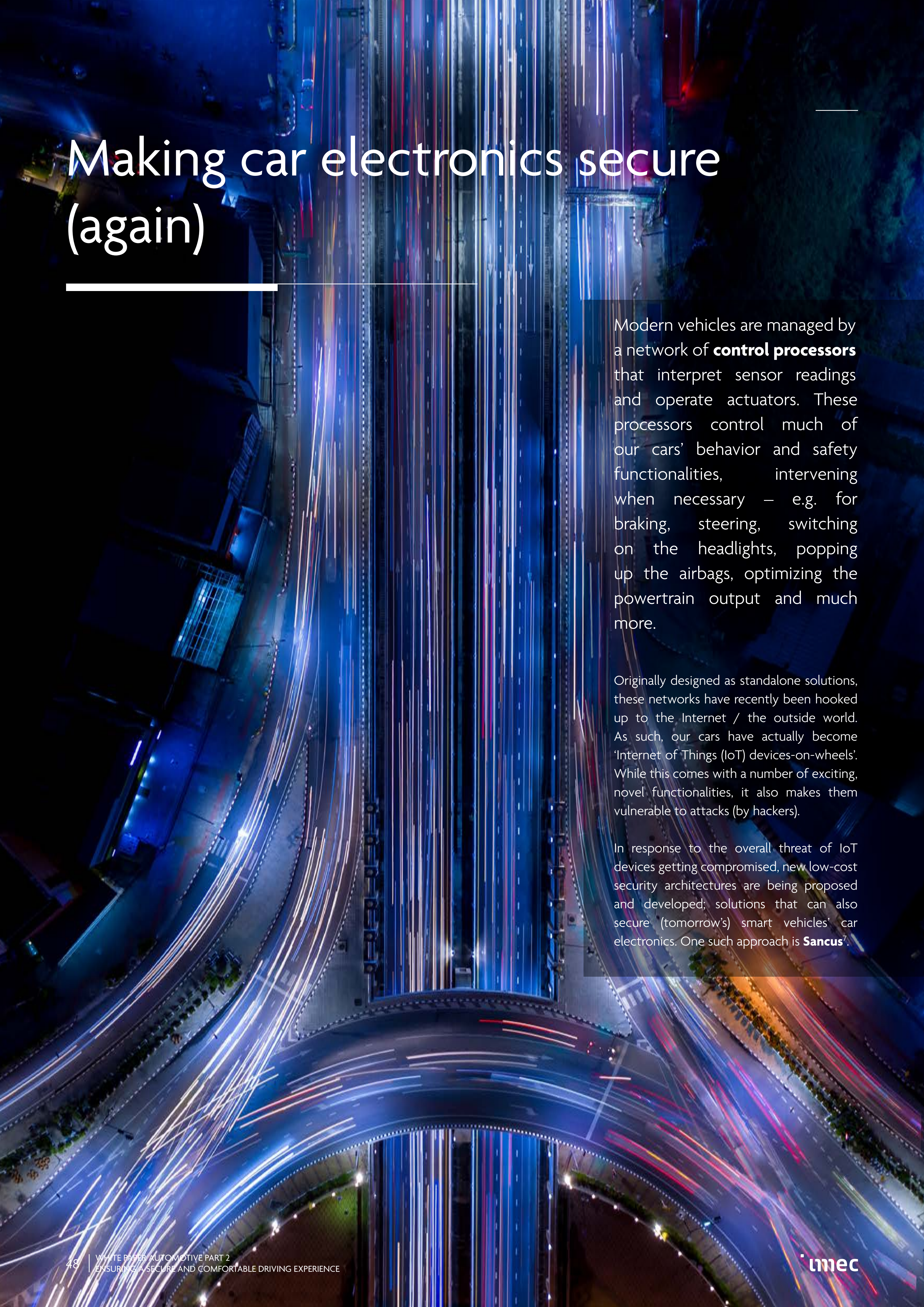
Imec's 140 GHz radar technology measures vital signs with very high precision.

Thanks to the high radio frequency that is being used, 140 GHz radar technology enables highly precise (in-car) vital signs measurements.

Key differentiators of imec's 140 GHz radar-on-chip prototype system are its small size and high radar performance – in terms of resolution and motion sensitivity. The radar operates up to a 10 meter range, with a 15 millimeter range resolution and 10 GHz of RF bandwidth.

Imec is developing a 60 GHz on-chip radar operating in the license-free ISM band.

Thanks to a new transceiver architecture, the power consumption of imec's 60 GHz on-chip radar has been decreased significantly – compared to state-of-the-art 60 GHz radars. Featuring a power consumption of 62 mW (including a power consumption of 12 mW for its new low-power phase-locked loop), this is a phenomenal reduction in power compared to other designs.



Making car electronics secure (again)

Modern vehicles are managed by a network of **control processors** that interpret sensor readings and operate actuators. These processors control much of our cars' behavior and safety functionalities, intervening when necessary – e.g. for braking, steering, switching on the headlights, popping up the airbags, optimizing the powertrain output and much more.

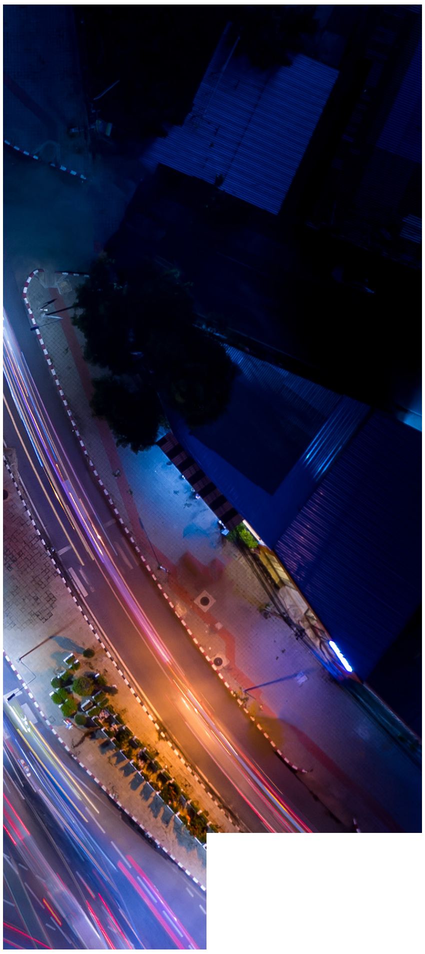
Originally designed as standalone solutions, these networks have recently been hooked up to the Internet / the outside world. As such, our cars have actually become 'Internet of Things (IoT) devices-on-wheels'. While this comes with a number of exciting, novel functionalities, it also makes them vulnerable to attacks (by hackers).

In response to the overall threat of IoT devices getting compromised, new low-cost security architectures are being proposed and developed; solutions that can also secure (tomorrow's) smart vehicles' car electronics. One such approach is **Sancus**[7].

Smart cars: islands of smart electronics

Smart cars are monitored and steered by networks of electronics – including sensors, actuators and control processors that continuously exchange messages. All of this interaction is organized around the so-called **CAN (Controller Area Network)** bus, which has been designed as a closed, wired network; an island with no obvious access points for (external) intruders.

The specification of this CAN bus, and thus of networked sensing and computing in vehicles, is about 30 years old. Essentially, it enables the growing number of heterogeneous car sensors and control processors to send and receive reliable and timely messages without any sort of central computer. It connects e.g. the rotation sensors in the wheels with the anti-lock braking system (ABS) and with the drivetrain. Modern cars' infotainment and navigation systems are hooked up to the CAN network. Using information from the CAN network, it is possible – for instance – to automatically turn up the music volume when starting to drive faster.



Opening up to the world (comes with a safety hazard)

Recently, CAN networks have started to talk to the outside world – e.g. allowing the infotainment system to communicate with the driver's mobile phone or headset, or to receive software updates. And the introduction of autonomous vehicles is bound to take this level of connectivity another a step further – as they will need to communicate with each other and with the roadside infrastructure to achieve optimal road safety.

As such, a car's CAN network becomes a potential entry point for intruders. CAN, for example, features no real authentication or authorization. If a syntactically correct CAN message arrives at the car's braking system, the brakes just assume that the message is legitimate and comes from a trusted source, not from somewhere else.

While relevant **cryptographic security specifications** have been part of the AUTOSAR standards since 2015, efficient and cost-effective implementations do not yet exist. Moreover, important parts of the automotive attack surface, e.g., low-level software security and cryptographic key management, remain unspecified.

One of the underlying issues is that the processors used in automotive are designed to be very small, good enough for their task, inexpensive and consuming as little power as possible. They may run tiny operating systems and a communication and control application. But in contrast to laptop or smartphone processors, they do not have memory protection or an isolated sandbox to run processes in.

In other words: hackers could very well control a car remotely – by hacking its Wi-Fi or Bluetooth gateway.

This is not to say that such attacks are easy: they require a high level of sophistication, ingenuity and patience. But because of the sheer number of electronically identical cars, an attacker that manages to find a way into one system, poses a real threat to the security of many such systems.

Creating isolated, safe harbors for processing

As discussed, contrary to higher-end processors in laptops and smartphones, cars' controller chips are small and resource-constrained. They lack the security features that have become a standard in other processors, such as privilege levels and memory segmentation.

Replacing these resource-constrained (IoT) processors with high-end systems is not an option for the automotive industry – as they come with increased cost and complexity, as well as a higher power consumption.

That is where initiatives such as Sancus come in, focusing on the design of a secure – yet low-cost and noncomplex – architecture that is built from the ground up; an architecture that can secure low-end embedded systems, such as CAN networks in cars.

The Sancus research project took a lightweight microcontroller as its basis. Its design was complemented with secure memory management and a crypto unit optimized for low-power consumption. The result is a processor that is not much larger than the original one and does not consume much more energy (about 6 percent). Yet, it can isolate the critical software, creating a kind of 'safe harbor' for that software to run in. Because of this isolation, the software cannot be compromised. Its trusted computing base is restricted to the hardware on which it runs. Barring vulnerabilities in a protected application itself, no software (be it applications, operating system components running on the same processor, or outside processes) can override the security checks and read or overwrite the protected runtime state.

> "High-end (IoT) processors are not an option for the automotive industry – as they come with increased cost, complexity and power consumption."

Knowing whom to trust

Nonetheless, even if the processor that controls a car's brakes can no longer be hacked, it will still obey a braking command that comes from an illegitimate source. To prevent that from happening, an approach has been defined that limits the trusted sources of messages to those that can authenticate as legitimate. Thus, a braking command should only come from a trusted processor, which itself cannot be hacked, and from an authenticated software component. That way, a car's CAN network is made up of small unbreakable applications that mutually authenticate and trust each other.

Sancus

The Sancus-based solutions for vehicular trust management are not restricted to securing CAN communication. Sancus relies on lightweight trusted computing primitives that can be used to implement strong security mechanisms – independent of communication media and the scale of communications. As such, Sancus can also be integrated into, e.g., automotive Ethernet or vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communication scenarios.

Looking for more details on this specific topic?

Download the research paper "Sancus 2.0: A Low-Cost Security Architecture for IoT Devices" at https://distrinet.cs.kuleuven.be/software/sancus/publications/tops17.pdf [10].

A major leap forward: automated testing of electronic control units' vulnerability

Modern vehicles are governed by a network of electronic control units (ECUs). ECUs are programmed to sense inputs from the driver and the environment, to process those inputs, and to control actuators that, e.g., regulate the engine or control the steering system.

ECUs within a vehicle communicate via automotive bus systems such as the Controller Area Network (CAN), and beyond the vehicle's boundaries through (upcoming) vehicle-to-vehicle and vehicle-to-infrastructure channels.

As more and more low-level vulnerabilities in these communication systems are being revealed, the need for advanced testing methodologies is acknowledged; it provides a basis to guide the reverse-engineering and penetration testing of vehicular communications and control systems. A testing approach that promises a particularly high level of automation is fuzzing.

Fuzz testing is a well-established methodology to expose software and systems to unexpected conditions, for example by providing random input streams that may crash the target. Yet, the approach does not easily apply to embedded software. What's more, few approaches have been looking into fuzzing embedded control systems – or automotive ECUs in particular.

Recent research, however, has contributed to –

- Defining fuzzers, fuzzing configurations and oracle functions for testing automotive ECUs through their CAN interface;
- Developing a sensor harness to automatically evaluate fuzzing oracles for ECUs with physical outputs;
- Evaluating this approach, taking commercial automotive instrument clusters and an experimental setup for testing AUTOSAR-compliant message authentication as case studies.

Sancus software freely available on GitHub

In summary, cars' embedded systems will increasingly be contacted from the outside. Think of software providers that need to install updates, or information provided by the roadside infrastructure. To this end, secure communication and remote attestation protocols need to be implemented. They allow an outside party to send messages to – and receive messages from – a specific software module on a specific node, while making sure that it is the correct module (authenticity), that it has not been changed (integrity), and that its status is correct (freshness).

Sancus – a security architecture for resource-constrained, extensible networked embedded systems – can provide remote attestation as well as strong integrity and authenticity guarantees with a minimal trusted computing base. It consists of an extended microprocessor, the dedicated software to run in the safe harbors and a C compiler that generates Sancus-secured code.

To ensure that the Sancus results can be verified and reproduced, the hardware design and software of the Sancus prototype have been made publicly available. The hardware designs, all source files, as well as binary packages and documentation are actively maintained on GitHub[8 9].

The Sancus project involved researchers from COSIC and DistriNet (imec research groups at KU Leuven).

The DistriNet research group focuses on the development of open, distributed object support platforms for advanced applications. Its research is always application-driven and is often conducted in close collaboration with industry.

Founded in 1984, DistriNet works on a wide range of problems – involving computer networks, middleware, distributed systems, embedded systems, multi-agent systems, security and Internet middleware.

The COSIC research group (Computer Security & Industrial Cryptography) was founded in 1979 and currently consists of 7 professors, 6 support staff members, 7 research experts/managers and over 60 researchers.

During the last 15 years, COSIC obtained more than 1200 international reviewed publications in journals and conferences, 13 edited books and 10 patents, and has graduated over 60 PhD students. COSIC's research focuses on the design, evaluation and implementation of cryptographic algorithms and protocols, the development of security architectures for information and communication systems, the creation of security mechanisms for embedded systems and the design and analysis of privacy-preserving solutions.

Researchers from DistriNet, an imec research group at KU Leuven, are pioneering research into methodical fuzzing approaches (for automotive ECUs).

Researchers from DistriNet, an imec research group at KU Leuven, have recently presented the first paper on the topic of automating methodical fuzzing approaches for automotive ECUs. Although their implementation is targeting CAN components, the approach can be generalized to cyber-physical systems with any underlying communication technology.

The fuzzer implementation, as well as instructions to build the sensor harness and to repeat the experiments, are available under an open-source license at https://github.com/timower/caringcaribou/tree/autoFuzz

Conclusion

From automatically unlocking the doors when we walk up to the car to allowing us to take our hands off the wheel on a highway, ...Technology works wonders for making the driving experience more comfortable. But that convenience also comes with safety and security risks, such as car theft through relay attacks or distraction-related accidents when we get a bit too comfortable.

This section of imec's automotive white paper demonstrated three ways in which to **combine comfort with safety and security**:

1. **passive keyless entry** – based on Bluetooth Low Energy or ultra-wide band, combined with secure distance bounding algorithms;

2. **next-generation driver monitoring** – through capacitive, optical and radar sensors and algorithms for noise filtering and sensor fusion;

3. **securing the car's underlying electronics** – by designing secure, low-cost and uncomplicated architectures.

Clearly, uniting driver comfort with safety and security calls for a combination of **hardware and software capabilities**. And it compels you to look for partners within and outside the traditional automotive value chain.

Authors

Christian Bachmann, program manager
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End notes

1 https://www.bbc.com/news/business-49273028

2 P. Zand et al, "A high-accuracy concurrent phase-based ranging for large-scale dense BLE network", IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2019

3 https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812700 (April, 2019)

4 https://www.reportsanddata.com/report-detail/driver-monitoring-system-dms-market (November, 2019)

5 See section 1.1 - Next-generation (anti-collision) sensor technology: making the invisible visible

6 See section 1.1 - Next-generation (anti-collision) sensor technology: making the invisible visible

7 This research project was supported in part by the Intel Lab's University Research Office. It was also partially funded by the Research Fund KU Leuven and by the Research Foundation – Flanders (FWO). It was also partially supported by the German Research Foundation (DFG) as part of the Transregional Collaborative Research Centre 'Invasive Computing' (SFB/TR 89).

8 https://github.com/sancus-pma

9 The vehicular authentication demo can be found at https://github.com/sancus-pma/vulcan

10 Previously published in ACM Transactions on Privacy and Security (TOPS), 2017

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WHITE PAPER AUTOMOTIVE PART 3

Enabling connected cars and smart highways

Contents

Introduction

For cars of the future, ‘on the road’ no longer means ‘offline’. They need to frequently update their software and offer a myriad of digital entertainment options. Moreover, new ADAS features require them to communicate with each other and with the road infrastructure.

In short, cars are becoming ‘IoT devices on wheels’. This means car manufacturers need to think about which wireless network technologies they need to incorporate in order to keep up with current and future connectivity demands.

This third section of imec’s automotive white paper unravels the various candidate technologies for supporting the connected car. It offers you answers to questions such as:

- Is **5G** really indispensable for enabling connected cars?
- How do **cellular and Wi-Fi-based** technologies compare when it comes to enabling cooperative intelligent transport systems (C-ITS)?
- How can OEMs and Tier 1 suppliers anticipate developments towards the **smart highway**?

Setting the scene

The first section of this white paper ('Unlocking the full potential of advanced driver assistance systems') explored how ADAS can optimize our driving experience and increase overall road safety (through features such as adaptive cruise control, pedestrian detection, etc.).

Today, none of those features requires **(wireless) connectivity**. Is this bound to change as the next generation of advanced driver assistance services is introduced? What will be the impact of vehicles talking to one another and to the roadside infrastructure? Will current mobile communication technologies fall short when time comes to meet those requirements? And what about the frequently heard claim that smart and autonomous vehicles will be a main driver for the roll-out of **5G networks**?

This section dives into each of these questions. It outlines the impact the automotive industry (and its increasingly sophisticated communication requirements) will have on mobile networks in years to come – and provides insights into some of the pending issues.

Debunking a myth: smart, autonomous vehicles do not (necessarily) require a 5G network

Let us first have a look at the frequently heard claim that smart and/or autonomous vehicles will require a 5G mobile network to do their magic. Is this really the case? Short answer: no – not necessarily.

The smart vehicle use-case is a pretty obvious one: none of today's commercially available ADAS features (that make for smarter cars) requires any wireless connectivity. And whereas that might change as the next generation of ADAS is introduced, there is no indication whatsoever that current mobile networks would fail to meet those features' requirements.

So, what about autonomous vehicles and 5G? Well, also here, a reality check might be needed. After all, tests with autonomous vehicles have been ongoing since the start of the previous decade. Today, automotive OEMs even claim to have completed millions of miles of driving on public roads[1]. And guess what: no commercial 5G networks are in place to accommodate any of those tests. Hence, no OEM will claim that the availability of a 5G network is absolutely mandatory for the introduction of autonomous cars.

Obviously, mobile connectivity will play an increasingly important role in accommodating a number of (future) automotive services. Yet, there is no reason to think today's technologies will fall short in meeting the underlying requirements. Think of:

The roll-out of in-vehicle emergency notification (or 'Mayday') systems

As of 31 March 2018, all new car and light van models sold in the EU have to be equipped with eCall devices that automatically alert rescue services in the event of an accident[2]. The aim of this in-vehicle emergency notification system is to reduce the response time in-between road accidents and the arrival of medical assistance.

Mayday services are activated as soon as in-vehicle sensors detect a serious crash. Once activated, the system dials the European emergency number 112 and establishes a telephone link to the appropriate emergency call center. The system sends the time of the incident as well as the position of the crashed vehicle, enabling emergency services to get to the crash site faster.

Clearly, in order to send a distress message to an emergency call center, a stable network connection is needed. From a capacity perspective, however, the burden of in-vehicle emergency notification systems on a network is low.

As a result, the discussion on which mobile communications flavor has sufficient capacity to accommodate in-vehicle emergency notification services is irrelevant. More importantly, further investments in 3G and 4G cellular network roll-outs will be required to achieve complete and stable mobile coverage in geographical terms – removing any white spots.

Telematics

Telematics services track the status of on-board devices and critical car parts (for proactive maintenance, for instance). Many high-end cars have already been equipped with this feature, making use of a standard SIM card that connects to a 3G or 4G cellular network.

Contrary to the Mayday services use-case, guaranteed mobile connectivity is not even required to support telematics: it is not a mission-critical application, so data can simply be exchanged whenever a wireless connection is available.

Automatic over-the-air (OTA) software updates

Automatic **over-the-air (OTA) software updates** have been happening for years on laptops, phones and even TVs. In the automotive industry, the use of OTA updates has been relatively rare. But also here, things have recently started to move.

Most of today's OTA examples in the automotive domain relate to updating non-essential systems, such as navigation maps and sound systems. In general, OEMs have steered clear of remotely updating safety systems or features directly related to driving. For the most part, they require car owners to come to a dealership and have specialized service technicians perform any critical system software updates.

Yet, over-the-air updates can be powerful tools to fix bugs, do recalls and enhance security: according to the NHTSA, only 62 percent of recalled cars ever get repaired – even after the owners have been sent multiple notices[3]. OTA updates could eliminate many of the software-related compliance (and related safety) problems.

Current OTA software updates in automotive typically make use of the existing 4G infrastructure. Alternatively, updates might be pushed at night using the car owner's Wi-Fi network.

It is merely in the longer run – when OTA updates become common practice and bigger (increasingly critical) data packages need to be transmitted – that current networks could start experiencing capacity issues. Only then, 5G networks could make for a more optimal solution.

Dawn of a new era: C-ITS applications that require high throughputs and low latencies

A more immediate need for high-capacity mobile networks comes with the emergence of automotive applications that continuously interact with one another and with the roadside infrastructure. Think of **cooperative intelligent transport systems** (C-ITS) that allow road users and traffic managers to share information on dangerous situations, roadworks, etc.

- **Advanced automatic emergency braking applications** are one example, with info on a car performing an emergency stop being passed on to all other vehicles in its vicinity to avoid chain-reaction crashes.
- Another example includes **(truck) platooning**, the linking of two or more trucks in convoy. The platooning principle enables vehicles to automatically maintain a set (close) distance from each other. The truck at the head of the platoon acts as the leader, with the vehicles behind reacting and adapting to changes in its movement[4].
- A last example is **through-vehicle vision**, enabling car drivers to virtually 'look through' the vehicle that is driving in front of them – by projecting that vehicle's camera feed on the dashboard or the windshield of the rear car.

It is this type of service, requiring high throughputs and the lowest possible latency, that will push current mobile network technology to its limits. Which inevitably leads us to the next question: which technology is up for the job in the longer run? Should we continue to look at **(more advanced) 4G networks** – or should we bet on **5G**, **point-to-point mmWave** or **satellite communications**?

4G, 5G or ITS-G5 / DSRC: which mobile comms flavor best suits the C-ITS use-case?

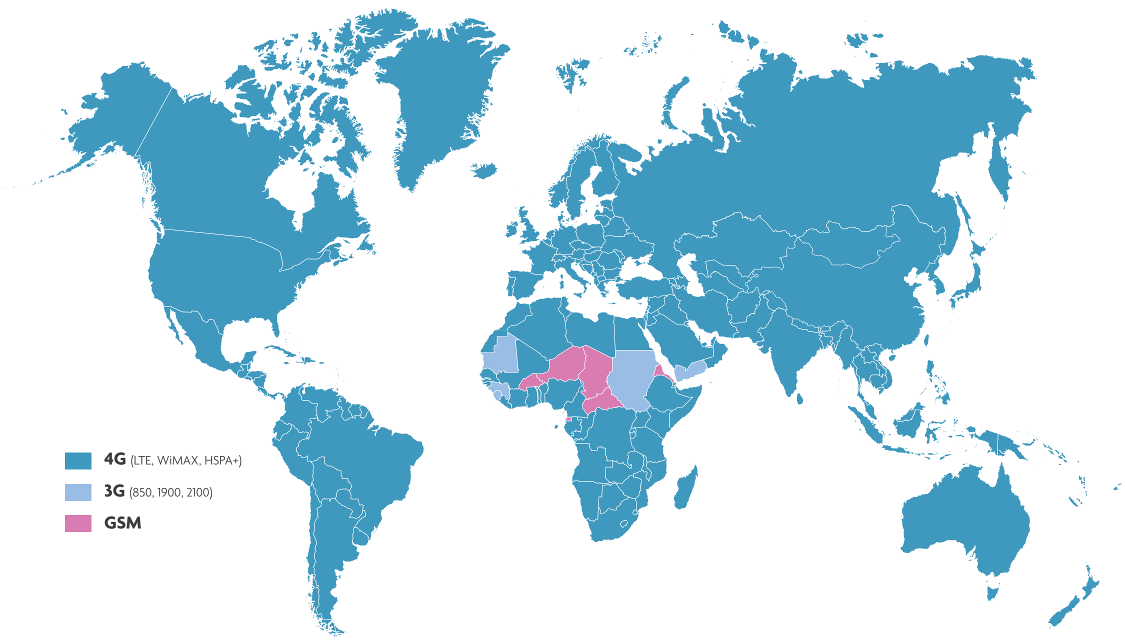
In the past few months, the European Commission has been working on new regulations to facilitate the deployment of C-ITS. Yet, to ensure a successful C-ITS roll-out, the various stakeholders will first need to agree on a standard for (short-range and long-range) **vehicle-to-vehicle** and **vehicle-to-infrastructure** communication.

In particular, a struggle is going on between (**4G** and **5G**) cellular networks – operating in licensed frequency bands – on the one hand and unlicensed, Wi-Fi-based **ITS-G5**[5] on the other hand.

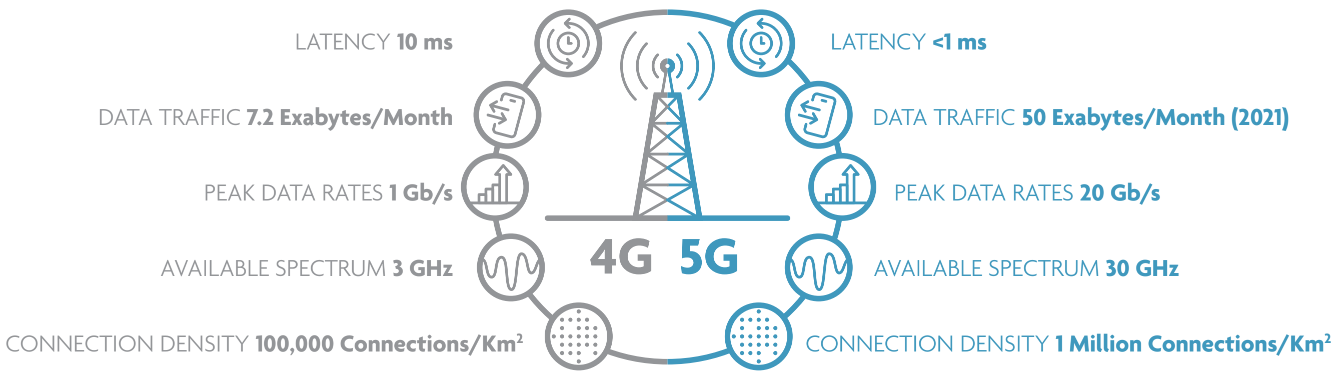
From a long-range communication perspective, things are pretty clear. Anticipating the roll-out of 5G networks – which come with even faster speeds, less congestion and lower latencies than today's widely deployed 4G networks – 4G cellular technology has been complemented with the **cellular vehicle-to-everything** (C-V2X) standard.

C-V2X allows 4G networks to better support the (long-range) exchange of (often less time-critical) data between vehicles and the surrounding ITS infrastructure.

Interestingly, though, C-V2X not only supports long distance communication. Its Direct C-V2X mode also supports short-range communication (just like ITS-G5) – using the same, unlicensed ITS band as its Wi-Fi contender. That is where things get a bit more complicated.



4G world coverage map (December 2019). Source: WorldTimeZone.com



Comparing the performance of 4G and (future) 5G networks. Source: AT&T Policy Forum.

Accommodating short-range C-ITS communication: ITS-G5 / DSRC versus Direct C-V2X

ITS-G5 (also referred to as dedicated short-range communication or DSRC) was defined 10 years ago. Since then, it has been tested extensively. And commercial products have been available for a while. The technology is backed by a significant group of car manufacturers and technology providers.

At the other end of the spectrum, an equally important group of automotive players and technology vendors is supporting the introduction of Direct C-V2X. This standard was finalized much more recently (in September 2016). So far, only prototype platforms have been available for pre-commercial pilot testing. Still, the technology can already count on the support of a fair share of believers.

As of today, it is unclear which technology option will prevail:

- In Europe, the European Commission's initial proposal to make ITS-G5 the default standard for direct, short-range vehicle-to-vehicle communication (in support of time-critical services) was rejected in July 2019.

- In the US, a dedicated spectral band (from 5.980 GHz to 5.925 GHz) has been allocated to DSRC-based ITS applications since 1999. Yet, an act to roll out DSRC technology in all vehicles was never passed.

- Countries in Asia are divided as well: while Japan has opted for ITS-G5 / DSRC technology, the Chinese government has clearly expressed its preference for Direct C-V2X.

This ongoing uncertainty has led a number of car manufacturers and suppliers to start using both technologies. However, ITS-G5 / DSRC and Direct C-V2X have not been developed to work together in the same spectral band. Using both technologies might lead to hiccups and less reliable communication.

It is expected that this debate will continue to go on for quite some time. As summarized in the table on the next page, both technology options have their own specific characteristics, advantages and disadvantages. In order to really know which technology best suits the automotive use-case, further testing will anyhow be necessary.

Making a case for (point-to-point) mmWave and satellite communication solutions

While 60 GHz point-to-point mmWave solutions offer even higher bandwidths and more rapid data throughputs than the technologies discussed so far, there is not a single credible business case (yet) for the introduction of such technology when it comes to enabling ADAS and C-ITS.

But mmWave could have a role to play when tremendous amounts of data need to be exchanged. Think of autonomous vehicles doing a massive data dump of everything they have seen and encountered along the way (for AI training or 3D mapping purposes, for instance), or cars sharing all sensor fused data with all other cars – and the road infrastructure – in their vicinity.

Whereas today's 4G networks would easily get overwhelmed in such scenarios, point-to-point mmWave solutions could accommodate a wide range of new applications. What is the point, for instance, of equipping crossroads with scores of expensive cameras when one could leverage all onboard sensors from all cars in the neighborhood to make those crossroads safer? That being said, to accommodate point-to-point mobile networks, heavy investments will first be required to build the proper infrastructure.

Satellite communication could be useful to provide mobile coverage in (rural) areas where the roll-out of cellular technologies is not economically feasible. Leveraging low-orbit satellites, mobile connectivity could be provided using the same frequencies as those used for 5G communication. Today already, some automotive OEMs are exploring how they could leverage the low-orbit satellite initiatives from e.g. Amazon or Inmarsat.

Characteristics	ITS-G5 / DSRC	Direct C-V2X
How does it work?	Using the (unlicensed) Wi-Fi spectrum (IEEE 802.11p standard) Making use of a distributed coordination function (DCF) to limit message collision (but which might cause these messages to be delayed) Latency will increase as more devices share the spectrum	Using cellular 4G LTE technology (operating in the licensed spectrum) Making use of orthogonal frequency division multiplex (OFDM) modulation schemes – which provide the spectral efficiency to achieve high data rates but also permit multiple users to share a common channel OFDM also makes for a greater signal reliability
Range	500 to 1,000 meters	500 to 1,000 meters As it leverages novel coding techniques, the range of Direct C-V2X will be slightly greater than the range of ITS-G5 / DSRC – provided conditions are right
Scalability	A higher numbers of vehicles (higher density) will lead to a higher number of message collisions and delays; more tests required	Higher numbers of vehicles (higher density) will lead to a higher number of message collisions; more tests required
Availability	Commercially available chipsets	Very recent technology No commercial chipsets available
Maturity level	Very mature Extensively tested	So far, large-scale tests have only been conducted in lab settings
Interoperability	The working group that is developing the new IEEE 802.11bd standard considers backward compatibility with the current 802.11p standard a priority	5G-V2X (as from release 15) is not backward compatible with Direct C-V2X (release 14): the two flavors are supposed to operate in different frequency bands (and to be used for complementary use-cases)

A high-level comparison between ITS-G5 / DSRC and Direct C-V2X. Source: imec

Whichever technology ultimately gets selected, there is one important criterion that should be high on decision-makers' agendas: interoperability (both between successive generations of the same technology family, and between different technology families). Since wireless technologies evolve at a much faster pace than the lifetime of a car, it only makes sense for newer vehicles to continue to support legacy communication technologies.

In short: today's mobile communication technologies (and those that are in the works – such as 5G) are perfectly capable of supporting the requirements of the automotive industry for the foreseeable future. The immediate challenges especially relate to expanding the mobile communications infrastructure (to provide more stable and wider coverage), rather than addressing any significant technological shortcomings.

Wireless communication technologies such as **Bluetooth**, **ultra-wideband (UWB)** and **Wi-Fi** have no role to play in the context of assisted driving, C-ITS and autonomous vehicles. Those wireless communication flavors – and their application domains in the automotive domain – are tackled more in-depth in the second installment of this white paper series that specifically talks about the keyless entry systems, driver monitoring and secure signal distribution.

Side note: the comms requirements of (tomorrow's) in-car communication & entertainment systems

Today, cars are equipped with a (4G) modem and sim card. Using this sim card, an in-vehicle Wi-Fi hotspot can be set up to stream content to the public 4G network – and back. Typical use-cases include kids watching Netflix or browsing the Internet, or a driver listening to Spotify or a podcast.

The approach of setting up a mobile hotspot comes with a number of advantages. Using the car's antenna (mounted on the outside), for instance, makes for a better connectivity and signal quality than what can be achieved by the antenna of one's mobile phone.

But there is also a weak spot in this scenario, i.e. the life expectancy of the underlying modem. Typically, (the modem in) one's smartphone is replaced every two years – with its performance continuing to increase. A car, however, is meant to keep on driving for 10+ years – without its modem getting replaced (or coming at a serious cost). As such, a car's modem quickly gets out-of-date, thereby losing its capability to support users' ever-growing communication and entertainment requirements.

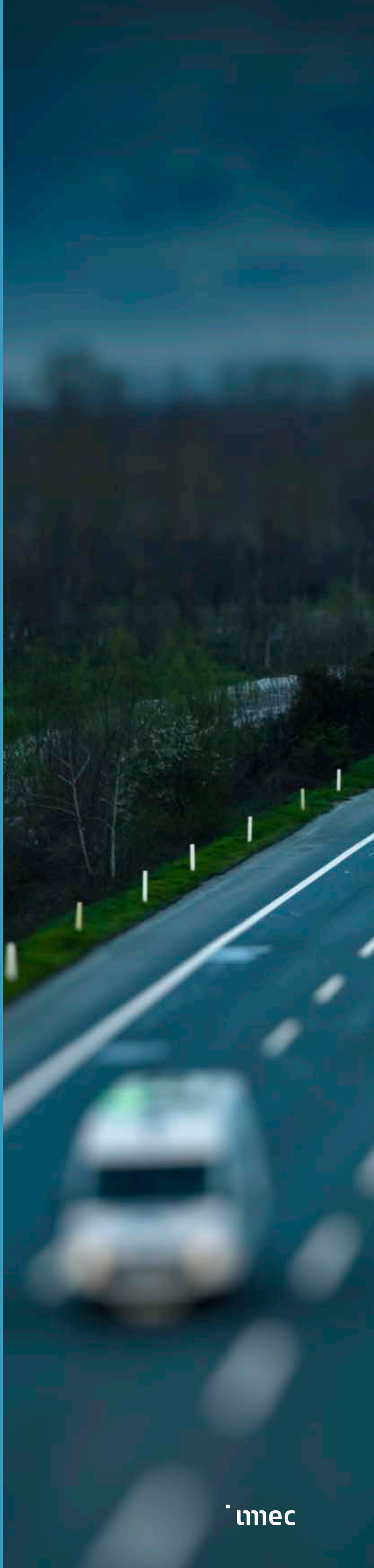
imec expertise

Imec pioneers research into compact, high-throughput and power-efficient solutions for next-generation wireless communication.

Imec research covers the entire spectrum of wireless communication – from Bluetooth, ultra-wideband and Wi-Fi to 4G (LTE) and 5G technologies.

Imec research includes mmWave phased array transceivers, record-breaking ADCs, reconfigurable low-noise frequency synthesizers, tunable duplexers, protocols to support network optimization, and more. No other large research and technology organization has this combination of insights and technological expertise.

Building on that knowledge, imec is ideally placed to objectively assess the pros and cons of the various technology options you might be exploring.



Use-case: connected and automated driving on European motorways

Connected and automated driving is high on the EU's agenda. Affirming its ambition in this domain, the European Commission has been setting up a series of funded projects to investigate how European motorways can optimally support the introduction of connected driving applications. One of these projects – **CONCORDA** – specifically dealt with the wireless communication requirements linked to truck platooning. CONCORDA ran from October 2017 till June 2020.

Rallying a consortium of 26 partners across the automotive and telecom industries, along with research organizations such as imec, CONCORDA studied – under real traffic conditions – the interoperability and performance of wireless network technologies that enable **vehicle-to-everything (V2X) communication**.

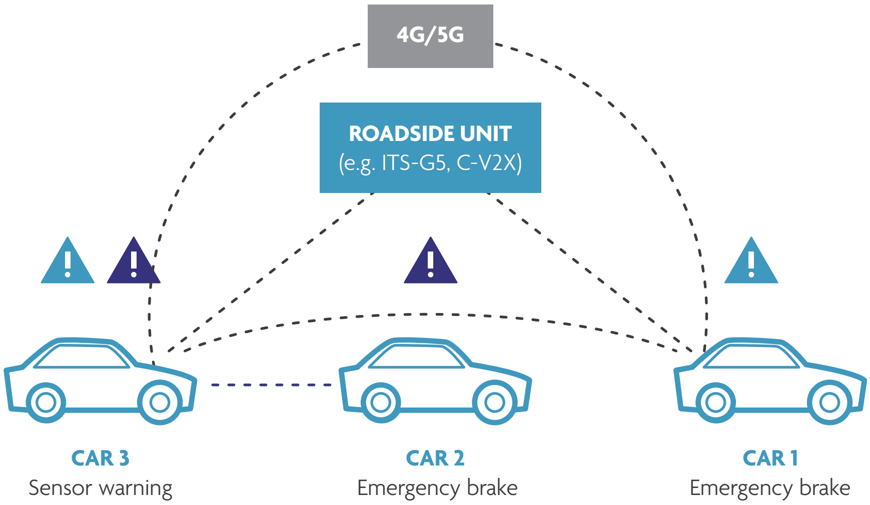
Bart Lannoo – senior business developer at IDLab-Antwerp (an imec research group at the University of Antwerp) – shares some of the project's main findings and calls out two key recommendations for the automotive industry.

Comparing 4G (LTE) and ITS-G5 / DSRC for highly reliable, low-latency V2X communication

"Connected and automated driving applications – such as truck platooning – require highly reliable and low-latency V2X communication to accommodate features such as automatic emergency braking. In the framework of CONCORDA, we explored which technology option best suits the V2X communication use-case: (long-range) 4G LTE or (short-range) ITS-G5 / DSRC," explains Bart Lannoo.

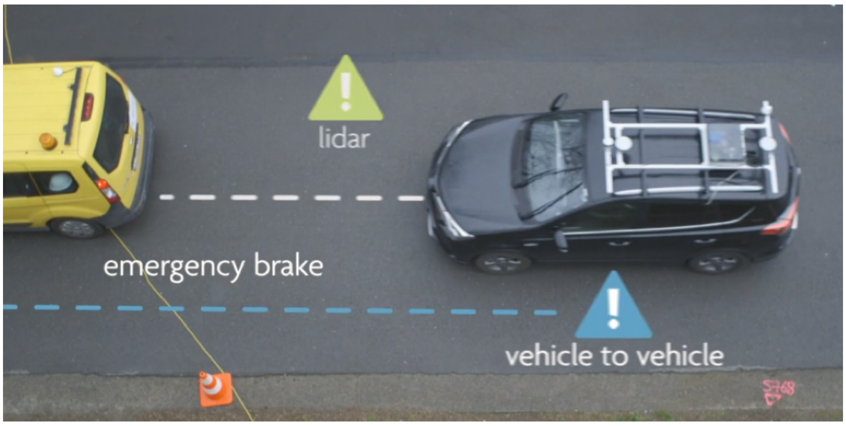
A test bed was set up to objectively compare the performance of both technologies in a real-life scenario; a scenario that featured a three-car platoon, including:

- A platoon leader, equipped with a car-mounted communication unit that supports both 4G LTE and ITS-G5 / DSRC
- A vehicle in the rear, equipped with a similar unit – as well as a lidar system
- A (non-connected) vehicle driving in-between.



The CONCORDA test set-up – featuring a three-car platoon. Source: imec

"We were particularly interested in measuring the reaction time of the rear (connected and lidar-equipped) vehicle as the platoon leader – and the vehicle in-between – would hit their brakes. As expected, the rear car's lidar system issued a timely warning as soon as it saw the vehicle in front coming to a stop. But, more interestingly, we were also able to confirm that the car's V2X communication module – through which it was directly linked to the platoon leader – made for an even quicker reaction time."



The V2X communication module outperformed lidar's reaction time. Source: imec

"Moreover, when comparing 4G LTE and ITS-G5 / DSRC, we noticed that both (generally) come with an acceptable latency: about 15 milliseconds in the case of ITS-G5 / DSRC and approximately 40 to 50 milliseconds when 4G LTE is concerned. In other words: both flavors come with a reaction time which largely outperforms that of human drivers."

"But there is more to it. Particularly from a stability perspective, 4G LTE seems to come with a caveat: in response to varying network conditions, its latency tends to spike at irregular intervals. This makes 4G LTE less reliable for truly time-critical applications," Bart Lannoo says.

Adding (4G) Direct C-V2X to the mix

Initially, the CONCORDA test bed was used to compare (long-range) 4G LTE and (short-range) ITS-G5 / DSRC technologies. In a second stage, however, short-range (4G) Direct C-V2X was added to the mix as well.

"When comparing Direct C-V2X and ITS-G5 / DSRC, it is difficult to say which technology option is better from a range perspective," states Bart Lannoo. "In some tests, packet loss appeared after 200 meters already. The channel that is used (176 versus 180) seems to have an impact – but further investigation in this matter is required. That being said, due to propagation effects, the lower channel (176) seems to perform slightly better."

"When latency is concerned, ITS-G5 / DSRC (with a latency < 6 ms) scored better than Direct C-V2X (10 ms < x < 50 ms) – due to C-V2X's scheduling design," he adds.

What makes a smart highway truly 'smart'?

Scores of research projects are laying the groundwork for tomorrow's 'smart highway' initiatives. As described, CONCORDA demonstrated that technologies exist to make vehicles talk to one another and to the roadside infrastructure. Yet, a smart highway encompasses more than just the mobile connectivity piece.

For one, it needs connected sensors, cameras, traffic lights, etc. to collect as much information as possible. Other questions that need to be addressed include the need for computing power (and where in the network this should reside), interoperability between technologies, and scalability (as the number of connected vehicles increases). Research into each of these domains is ongoing. Only in a next step can the various pieces be brought together to come to a really smart highway.

From a business perspective, as well, questions remain – including who will pay for the roll-out of smart highways. Should this be the telco, the road operator, or a new type of stakeholder?

Whatever the outcome of the above discussions, smart highways are definitely a step in the right direction to to ramp up the throughput of our highways and to make traffic increasingly safe.

Industry recommendations

CONCORDA not only resulted in an objective comparison between various vehicle-to-everything communication technologies. It also led to some broader take-aways that could be particularly relevant for automotive OEMs and tier-1 suppliers.

Anticipate regional differences by combining several wireless communication technologies

Since the selection – and deployment – of mobile communication technologies is the responsibility of telecom operators and local/regional regulatory bodies, different regions are likely to opt for different standards and comms flavors.

"Hence, today, it seems a safe bet for automotive players to make sure that their communication modules for connected and automated driving support a combination of short-range and long-range communication technologies – thereby leveraging advanced network orchestration techniques to swiftly switch from one technology to the other," says Bart Lannoo.

"Make sure that modules for connected and automated driving support a combination of short-range and long-range communication technologies."

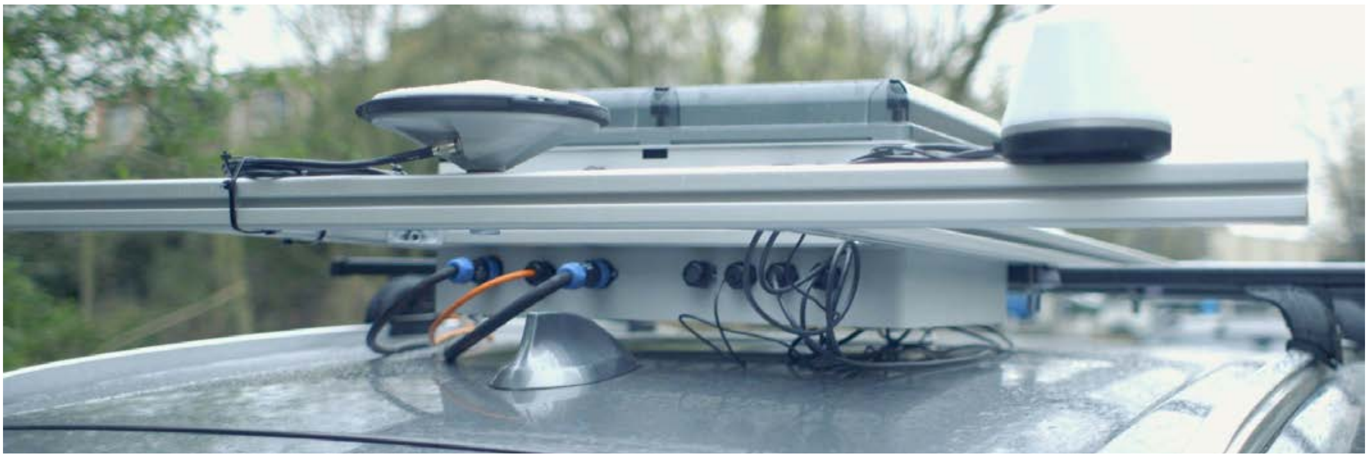
Do not take mobile connectivity for granted

"Even in the 21st century, guaranteeing full mobile coverage – also in rural areas – is no mean feat to achieve," continues Bart Lannoo. "As a result, car manufacturers should never take mobile connectivity for granted. Instead, they should make sure that tomorrow's cars are able to function equally well in a stand-alone mode. Connectivity should simply be regarded as an extra means to get sensory info in and out of the car," he concludes.

Imec's contribution to the CONCORDA project

In the framework of CONCORDA, imec researchers set up a state-of-the-art test bed for vehicular communication. Leveraging car-mounted communication units that support 4G LTE, Direct C-V2X and ITS-G5 / DSRC (and that can flexibly switch between these technologies), imec has been able to evaluate these wireless communication flavors thoroughly and objectively.

Going forward, imec's communication units will be extended with 5G technology as well. In parallel, imec researchers have been developing a software-defined radio (SDR) platform that enables them to quickly prototype new standards – even if the required hardware is not yet ready.



Imec's car-mounted communication units support 4G LTE, Direct C-V2X and ITS-G5 / DSRC (and allow to flexibly switch between these technologies) for thorough and objective testing. Source: imec

Conclusion

There is no doubt that tomorrow's cars will need wireless connectivity – both inside the vehicle and to communicate with the outside world. The question is which of the many contending technologies will be chosen.

5G seems to be the standard answer. But that would imply a one-size-fits-all approach that does not match with the **varied connectivity needs** of future vehicles. This section of imec's automotive white paper therefore discussed the available networking technologies for different applications:

- **ADAS features** such as in-vehicle emergency notification, telematics and OTA software updates that can do with (improvements of) current network technologies;
- **C-ITS applications** that require high throughput and low latency;
- **critical software updates** that involve the exchange of tremendous amounts of data.

As yet, there is no industry-wide consensus of which technology to use. Moreover, there is a real possibility that different regions will apply different standards. It is therefore essential for actors in the automotive industry to **support a wide range** of technologies.

Authors

Bart Lannoo, senior business developer
Michael Peeters, program director
Wim Van Daele, news and science editor

End notes

1 https://arstechnica.com/cars/2020/01/waymo-is-way-way-ahead-on-testing-miles-that-might-not-be-a-good-thing/ (January 7th, 2020)

2 Source: European GNSS Agency (GSA)

3 Source: Digitaltrends.com

4 Source: European Automobile Manufacturers Association (ACEA)

5 Note: in Japan and the US, ITS-G5 is also known as direct short-range communication (or DSRC)

General Conclusion

This white paper presented three ways in which technology will shape the car of the future. Is there a **common takeaway** from these three stories? We believe there is.

1. When it comes to ADAS systems, many sensor technology improvements are needed. But in the end, **no single technology** option covers all ADAS requirements. Delivering a full perceptive (3D) model and acting upon it will be the job of smart algorithms.

2. Equally, technologies that protect the car's integrity and monitor the driver's health are dependent on **hardware as well as software** innovations. For example: algorithms for secure distance bounding to fend off relay attacks and for sensor fusion to extract accurate health information from multiple sensors.

3. Finally, future vehicles will have very varied connectivity needs. Moreover, there is not yet an industry-wide consensus of which technology to use. And there is a real possibility that different regions will apply different standards. It is therefore important for actors in the automotive industry to **support a wide range** of technologies.

All this points towards a landscape where partners from within and outside the traditional automotive value chain will need to **work together** – more closely than ever. And where you need to **keep multiple technologies on your radar** if you want steer the right course.

As a technology-agnostic R&D center, imec can help you to investigate, compare and validate different approaches. **If you're interested in working with us feel free to contact Philip Pieters, business development director at philip.pieters@imec.be and he will soon be in touch.**