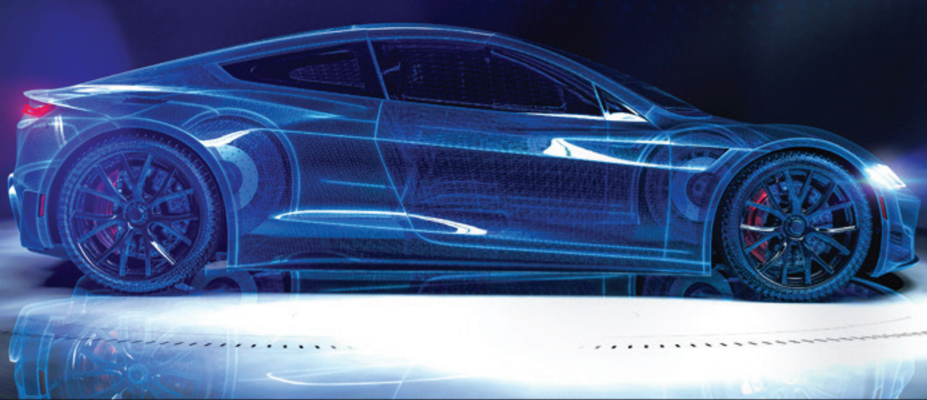
MAKING THE CASE FOR VIDEO EDGE IN THE CONNECTED CAR

Intelligent video is a critical component for driver, passenger, and pedestrian safety



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Executive summary

The connected car market has created an exciting opportunity, where video plays a role in various safety aspects for both driver and passengers, such as pedestrian detection and collision warning. The car records the video locally and transmits it for further analysis in real-time in an emergency. Safety-based video analysis is an emerging trend and a key differentiator in the connected car using standards such as Ethernet Audio Video Bridging (AVB) for reliable delivery of media data in the car network.

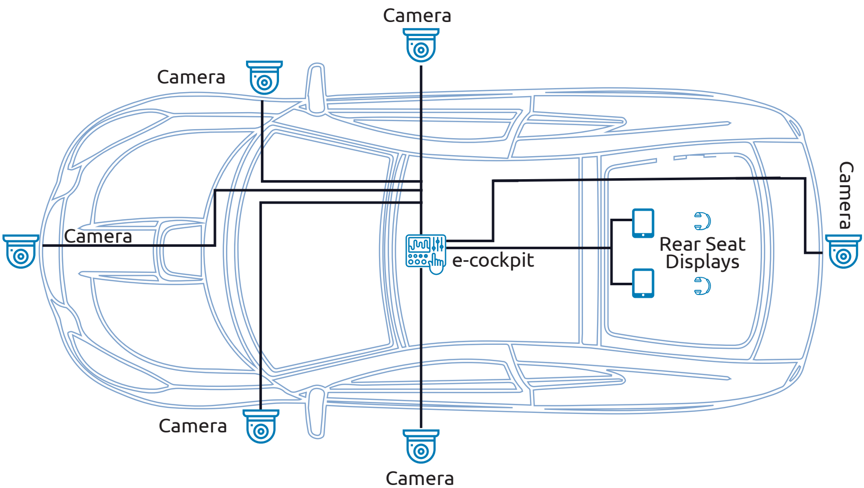


Figure 1: Ethernet AVB-based safety cameras in the connected car

Source: AVnu Alliance

Video cameras in the connected car are becoming a mainstream technology for providing safety-related services. (See Figure 1.) The cameras supported today include forward, reverse, and 360-degree view that combines video from two or three cameras. The split-view consists of left, right, and central views on the main dashboard and lane monitoring, night view, and other features. Also, blind-spot monitoring in the mirrors is becoming a standard option.

Some intelligent cameras are designed specifically for the connected car with their own unique identity database. For instance, they alert the owner if a stranger tries to get into the car or trigger a welcome message for an approved person. In addition, by capturing video from internal and external cameras located in the car, critical information such as a pedestrian crossing, a stop sign, or a parking sign can be presented in an augmented-reality-based display panel providing the driver with additional information.

Managing safety applications on the main dashboard's large screen in the e-cockpit requires a high-powered SoC, such as an Nvidia

SoC or Qualcomm Snapdragon, with a unique HMI for the driver and rear-seat panels. They interface with the video distribution system to process the video data generated from various cameras and provide connectivity to passenger rear-seat screens over Ethernet AVB. The IEEE 802.1 AVB offers a standards-based approach for highly reliable networked transmission for low-latency applications in the connected car. The IEEE 802.1 AVB also supports time-sensitive networking requirements by forming a single network for video entertainment, driver assistance (drowsiness detection), and other safety-critical functions within the car ecosystem. In the near future, connected cars with enhanced wireless connectivity (e.g., Wi-Fi, 4G, and 5G) using V2X technology will allow for much more media content to be consumed in the car network.

This white paper focuses on video safety and security features in the connected car, addressing critical use cases and scenarios being evaluated by OEMs, emerging hardware platforms, and the challenges that need to be addressed.

Overview

According to McKinsey & Company, by 2025, SAE Level 4 autonomy is expected to be technically capable and will address 60-76% of all miles traveled in the US. By 2030, 45% of new cars will reach SAE Level 3, representing global new car sales of between $450 billion to $750 billion.[1] The connected car will incorporate a large number of sensors that communicate with the cloud, other cars, and devices to improve road safety. Over the next decade, close to 461 million cars will be shipped with high-resolution displays and flexible hardware solutions, according to ABI Research.[2]

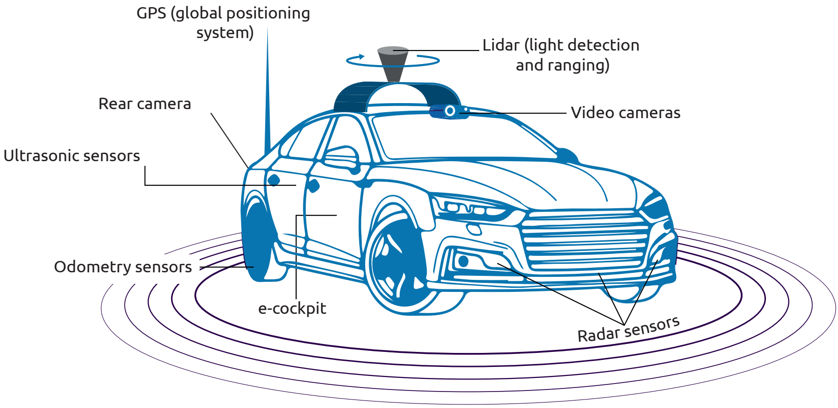
Until recently, however, video has played a limited role in the connected car. The market focus has been on the reception of streaming video to the e-cockpit front-end by providing a certain level of information to the driver when the car is in parking mode. However, there is a shift to extend the video connectivity to rear-seat passenger panels, which is a significant opportunity in the connected car market segment.

The most critical function in the connected car is safety, and video is a key element considered for analysis to provide safety services to drivers and passengers. For example, high-definition video cameras with built-in image analysis and analytics can identify potholes and road wreckage the driver cannot see. Also, the car can communicate with a roadside unit (RSU) and share its observations with other cars in the vicinity to avoid accidents.

1. “The future of mobility is at our doorstep,” Compendium 2019/2020, McKinsey Center for Future Mobility, McKinsey & Company https://www.mckinsey.com/~/media/McKinsey/Industries/Automotive and Assembly/Our Insights/The future of mobility is at our doorstep/The-future-of-mobility-is-at-our-doorstep.ashx

2. Susan Fourtané, “Connected Cars with Infotainment Architecture, Digital Cockpit to Be Mainstream by 2030,” Sep 11, 2020, Interesting Engineering https://interestingengineering.com/connected-cars-with-infotainment-architecture-digital-cockpit-to-be-mainstream-by-2030

Today, most new car models have three or four built-in cameras. Mid-range car models provide support of one camera for rear-view and four cameras to deliver 360-degree views around the car. (See Figure 2.) Some high-end car models provide up to seven cameras, including night vision feature support. The video cameras in the connected car provide safety for drivers and passengers and are becoming key system components. They perform image recognition in the drive and park mode of objects such as pedestrian crossings. In addition, they can superimpose road information, such as speed limits, roadwork, no parking signs, and animals on the driver's head-up display. Artificial intelligence (AI) enabled cameras inside the car also provide safety and security benefits to protect from intruders giving peace of mind on road trips.



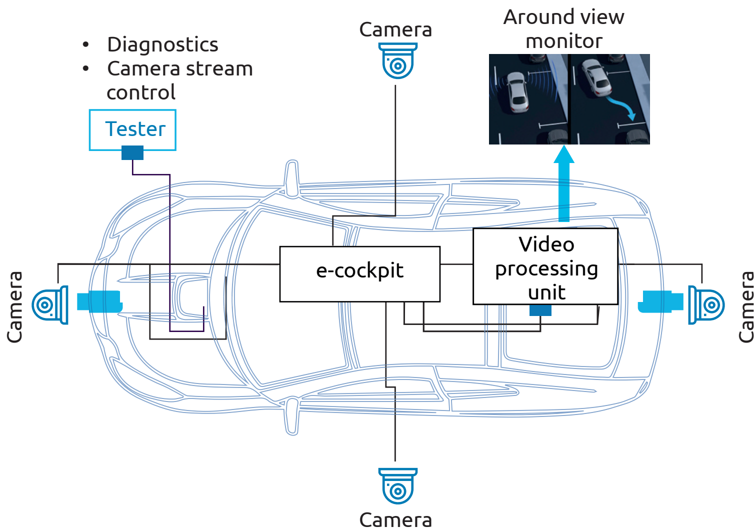


Figure 2: Positioning cameras, odometry and ultrasonic sensors, GPS, Lidar, and radar in the connected car

Source: Public domain (top) and IEEE (bottom)

The variety of video communications services considered for connected cars can generate enormous amounts of data and network traffic.

The base video services, especially for safety applications, will require communications with very low latency and very high reliability. To meet the latency requirement, the data generated from both internal and external cameras located in the car does not need to travel to the cloud platform for image processing. Instead, the video data can be pre-processed and filtered at the edge in the car's e-cockpit by truncating unwanted video data.

Ideally, the video data processed in the e-cockpit provides a shorter response time and a more efficient way of data processing and trimming, better security management, and a limited cellular network burden. Adding AI and machine learning (ML) inference at the edge of the connected car network for processing massive quantities of video data is another vital element of the e-cockpit platform that gives the connected car ecosystem the ability to detect problems early.

The safety driving feature is one of the most critical features in the connected car ecosystem designed to eliminate traffic accidents. To realize this objective, the car's network design should have the ability to display specific data to both drivers and passengers.

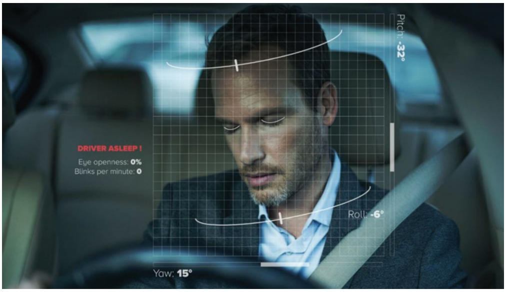
Drivers and passengers risk serious injury or death if medical assistance is slow to arrive at the accident scene. If the car's occupants can provide first responders with their exact location and injuries sustained, survival chances improve. To avoid such outcomes, the car network should have the ability to generate and store real-time video and identify the car's location with the help of GPS before and after the accident happens.

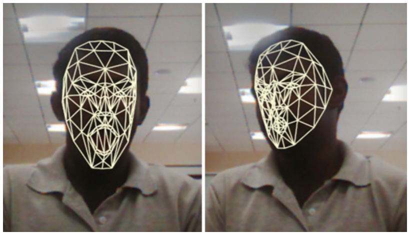
The five safety features of video for driver and passenger safety

The car safety system is the most critical feature of the connected car ecosystem for avoiding and reducing the chance of accidents and injuries on the road. This includes the ability of the car's network to display important data to drivers and passengers of other cars. For example, in an accident, communicating the location of the accident to other cars in the area and to first responders is vital. Here we describe five features where video can save lives.

1. Drowsy driver

The US National Highway Traffic Safety Administration (NHTSA) and the World Health Organization (WHO) have reported that approximately 1.35 million people worldwide die every year due to car accidents. Car accidents often occur due to driver distraction, lack of focus, drowsiness, or intoxication. (See Figure 3.) Many deadly accidents are caused by the driver falling asleep and losing control of the car.





Video cameras tracks the turning of the driver's head indicating distraction

Figure 3: Cameras continuously monitor driver drowsiness and distraction

Source: Public domain (left) and Capgemini Engineering (right)

The solution is for the car's camera to monitor the condition of the driver continuously. If the system perceives the driver is drowsy, it can intervene. This requires built-in intelligence to monitor the driver's gaze, blinking, eye closure, eye-tracking, head position, and other factors. The system can quickly alert the driver using the in-built audio speaker to wake up the driver to avoid an accident. Also, the system can send a message to a family member, who can call the driver's mobile phone to check if they are conscious or send the command to the car's telematics unit to reduce the car's speed without driver assistance.

2. Panic button

Today, drivers want smart cars to keep them safe. To address this challenge, a mandatory panic button is positioned near the main dashboard. (See Figure 4.) For instance, if the driver feels ill while driving, they can use the panic button to request an ambulance or call family members. Or, if an intruder tries to stop or enter the car, the panic button sends a message along with live video to the nearest police station.

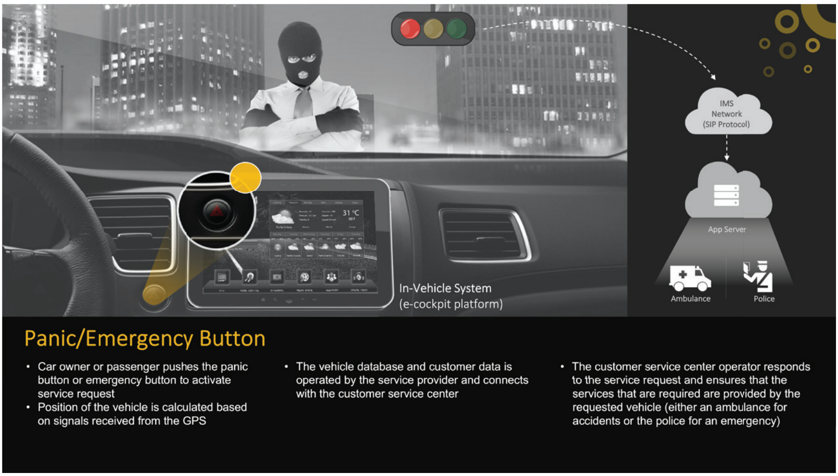


Figure 4: In case of emergency, the driver or passenger can activate the panic/emergency button to request help

Source: Capgemini Engineering

The advantage of the panic button, and the cameras positioned in the car, is to quickly provide information to the authorities to help the driver and passengers in potentially dangerous situations. Manufacturers are adding more cameras in future models that can be placed in watch mode to alert the car owner if their car will be in an accident or if someone is attempting to break into or steal their car.

3. Connecting home and car security

Both homes and cars are getting smarter, and there is a growing demand for systems that connect the two. Car-to-home connectivity enables the control of smart-home devices from the car through voice assistant devices. For example, the MyHome app running on the car dashboard can control your home thermostat, lock doors, close or open blinds, and turn lights on or off. The driver can manage their home appliances from the car with a voice assistant or application built into the e-cockpit platform. (See Figure 5.)

In addition to controlling home appliances from the car, the car surveillance cameras can record any suspicious activity inside the car and share the data with the owner on their home network. Evidence from the car surveillance camera recording can help with insurance claims and legal complications from accidents, theft, or reports filed by passengers. There are special cameras with certain privacy features built-in, where the physical shutter can be disabled to cover any interior video and audio recording.

4. Advanced Driver Assistance System (ADAS)

ADAS improves driving by providing comfort and safety for the driver and improving the car's efficiency. For example, if an accident occurs, ADAS can give the other car information in advance to avoid the collision. Furthermore, ADAS shares the location and video of the car accident with family members and the authorities. ADAS has the potential to significantly reduce the millions of deaths and injuries a year worldwide caused by road accidents. (See Figure 6.)

Figure 5: Home-car connectivity over IMS/SIP

Source: Capgemini Engineering

- Approximately 1.35 million people die in road crashes every year – An average of 3,700 people lose their lives every day on the roads
- An additional 20 to 50 million people suffer non-fatal injuries, often resulting in long-term disabilities
- More than half of all road traffic deaths are pedestrians, bicyclists and motorcylists

Figure 6: The connected car will contribute to reducing road accidents
Source: World Health Organization

One scenario is to use the safety cameras in the car to monitor any accidents that have happened in the area by storing the accident video and sharing it with other drivers nearby on the vehicle-to-infrastructure (V2I) network. ADAS is all about providing the right information at the right time and taking proactive steps to avoid accidents.

Another scenario is the lane departure warning. It generates an alert when the car is drifting out of its lane and alerts the drivers to get back in the lane. The lane departure warning monitors the road for lane markings, taking into account whether the car is on a straight or curved road.

A third scenario is forward collision warning, considered as one of the active safety features in the connected car that warns the driver of an imminent frontal collision. The forward collision warning scans the road ahead and alerts the driver with a visual, audible, and tactile warning message so they can slow or stop the car.

Another ADAS feature is a pedestrian detection warning that alerts the driver when a pedestrian is detected within three to twenty-five feet from the car. The warning system can distinguish between humans and other objects. (See Figure 7.)

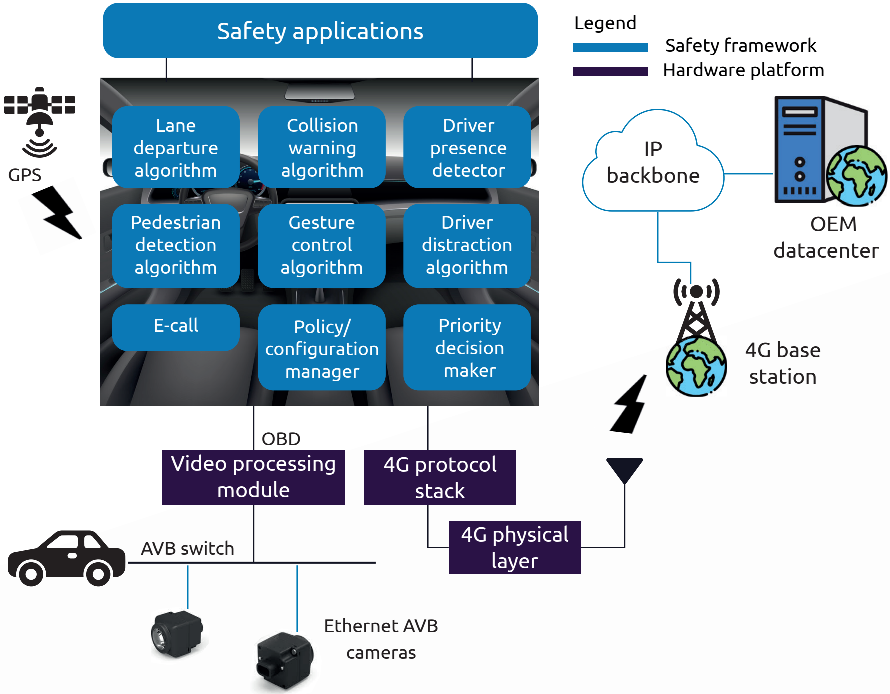
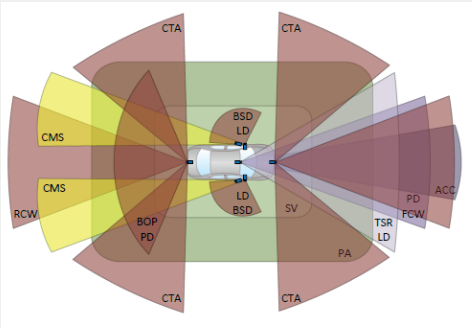


Figure 7: ADAS framework for the connected car

Source: Capgemini Engineering

The ADAS framework in the e-cockpit interfaces with the Ethernet AVB cameras. The ADAS middleware framework contains sophisticated algorithms to manage the safety features and quickly respond to the driver to avoid accidents. There are many other ADAS concepts identified in the autonomous car. (See Figure 8.)



ACC – Active Cruise Control
BOP – Back Over Protection
BSD – Blind Spot Detection
CMS – Camera Monitoring System
CTA – Cross Traffic Alert
FCW – Front Collision Warning
LD – Lane Detection
PA – Parking Assist
PD – Pedestrian Detection
RCW – Rear Collision Warning
SV – Surround View
TSR – Traffic Sign Recognition

Figure 8: ADAS features
Source: IEEE

5. Gesture-based control mechanism

Driver distraction is one of the leading causes of road accidents worldwide. Gesture recognition simplifies the interactions between the driver and the e-cockpit embedded platform to reduce the instances of driver distraction. Gesture-based control systems enable the driver to interact with natural hand and head gestures. (See Figure 9.) Some high-end car models have touchless interaction between driver and passengers using gestures. In addition, voice-assisted devices such as Alexa and Google Home can provide a natural, intuitive, seamless user experience in the connected car network.

	Gesture	Feature mapping
1.	Wave right	Selection of next media file
2.	Wave left	Selection of previous media file
3.	Move up	Volume increase
4.	Move down	Volume decrease
5.	Press forward	Play the selected media file
6.	Move backward	Stop playing the media file
7.	Hand near head	Initiate the voice call
8.	Hand away from head	Disconnect the voice call

Figure 9: Gesture control options in the connected car

Source: Capgemini Engineering

If there is a lot of noise in or around the car, voice-assisted systems between the driver and e-cockpit platform may not work. Gesture-based commands are an alternate. Also, gestures could be a better option for physically disabled drivers. Camera-based gesture devices embedded in the e-cockpit platform allow the driver to send a message without taking their eyes off the road. One challenge with gesture-based control is that in some instances, both hands are being used by the driver simultaneously, such as steering and shifting gears.

Seamless handover: data switching on the move

When the car communicates with the internet cloud, the biggest challenge is seamless network connectivity to ensure the driver and passengers get all required services from the service provider. (See Figure 10.) Wireless network connectivity provided by mobile network operators (MNOs) has become a key competitive differentiator in today's connected car market.

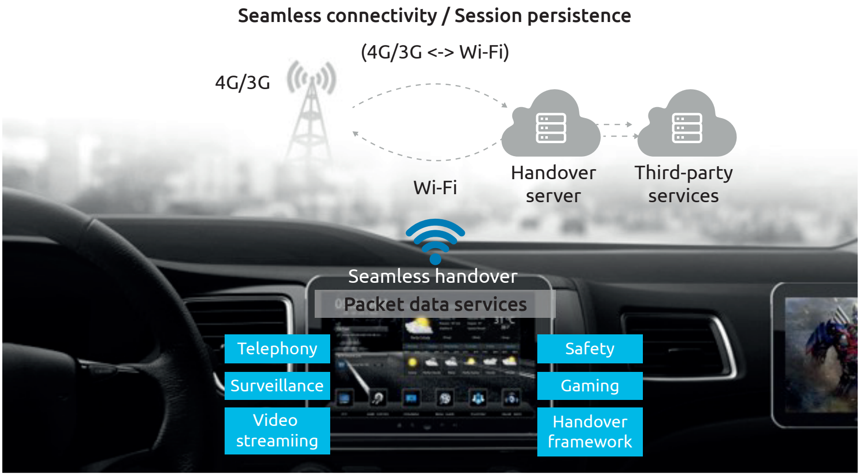


Figure 10: Seamless handover with different wireless networks

Source: Capgemini Engineering

Soon, high-quality, uninterrupted connection to LTE-Advanced, Wi-Fi hotspots, and 5G will become crucial to keeping drivers and passengers safe and secure. Regardless of the mobile or cellular network, the user expects a high-quality seamless mobility experience in all environments and circumstances. The connectivity between the car and the OEM service center should be integrated seamlessly over any wireless network and secure data transmission for critical safety applications based on the handover algorithm. (See Figure 11.)

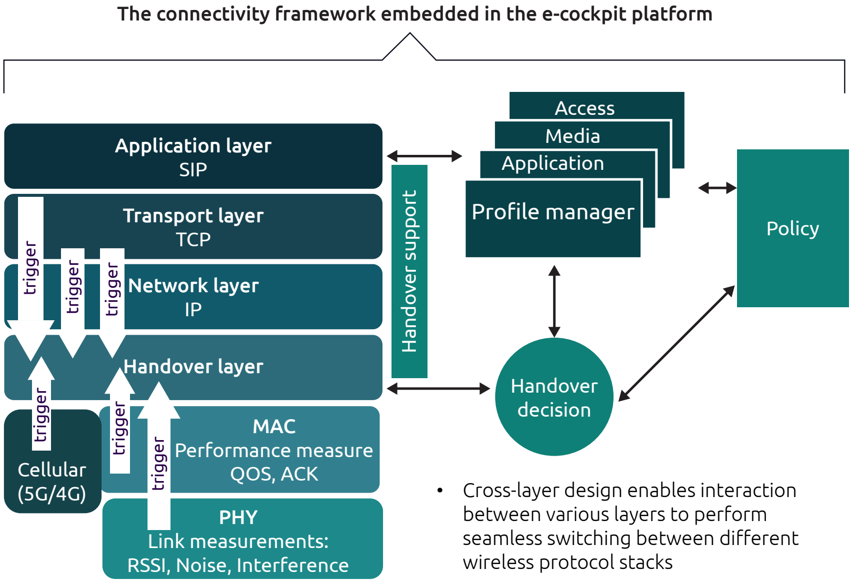


Figure 11: The seamless handover algorithm ensures secure transmission of data

Source: Capgemini Engineering

Car data should be monitored and transmitted securely to avoid tampering, eavesdropping, and denial of service (DoS) attacks. Always-on connectivity allows the connected car to share deep insights about the car's performance and driver behavior with the OEM datacenter and safety-related data like roadside assistance and remote car locking from the cloud. The futuristic always-on request for the connected car should provide higher bandwidth and throughput for in-car data communications based on the always best connected (ABC) model. With the seamless connectivity feature supported in different car models, the OEM can meet end-user expectations in the following areas:

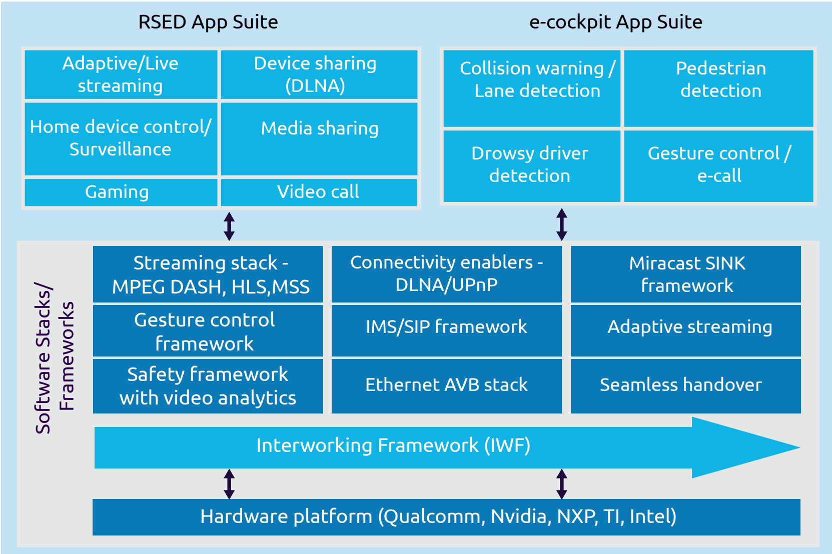
- Design, monitor, and classify the handover patterns before and after switching
- Implement user policies for safety applications during switching
- Provide service-level monitoring and reporting to actively manage and shift the wireless connectivity under different conditions
- Generate substantial savings in data traffic costs with enhanced productivity

Next-generation embedded platform: the e-cockpit

Video-specific safety use cases for the connected car include next-generation e-cockpit design utilizing high-end SoCs, such as ARM-based processors with DSPs, middleware software protocols, and algorithms to process video, audio, and location data using GPS, telematics, and V2X. (See Figure 12.) The e-cockpit platform make decisions quickly to provide certain critical information to the driver, passengers, and family members connected remotely.

The next-generation e-cockpit embedded platform design will help to provide a complete 360-degree view of the car's surroundings. The driver can search for any obstacles around the car and check the rear and front side views inside the car simultaneously using in-car cameras. The video processing unit enabled in the e-cockpit can process digitized video data transmitted from multiple cameras from the car network and compose a unified image to the driver using the e-cockpit's high-performance graphic processing unit (GPU).

e-cockpit embedded platform



Hardware benefits from e-cockpit platform for safety use cases

- Leveraging powerful media processing capabilities for achieving high media performance for video streaming and surveillance
- Using hardware accelerators for video decoding, scaling, and rendering
- Leveraging the powerful and low-power hardware acceleration for HD video decoding from the processor platfrom for high-quality video rendering
- Leveraging the flexible display support from the hardware platform for rendering multiple streams on the same display unit

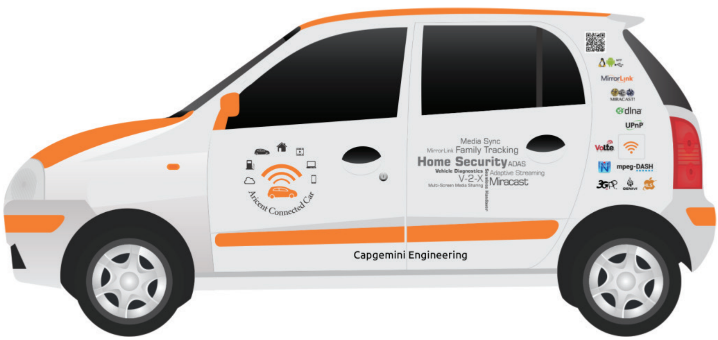


Figure 12: Software architecture of the e-cockpit platform and the Capgemini concept connected car

Source: Capgemini Engineering

The high-end core application processors enabled in the e-cockpit, such as Freescale, Nvidia, and Qualcomm, trigger the hardware and software components to predict the distance between the two cars to avoid a collision, lane crossing, or hitting a pedestrian. The e-cockpit platform supports HD video playback that covers streaming HD content to the dashboard and the passengers' back-seat displays by accessing online content from the internet.

The e-cockpit supports in-car camera views fixed around the car, capturing both external and in-car views to improve surveillance and safety. OEMs are turning to Ethernet AVB to simplify cabling, networks, and interfaces and reduce operating costs. (See Figure 13.)

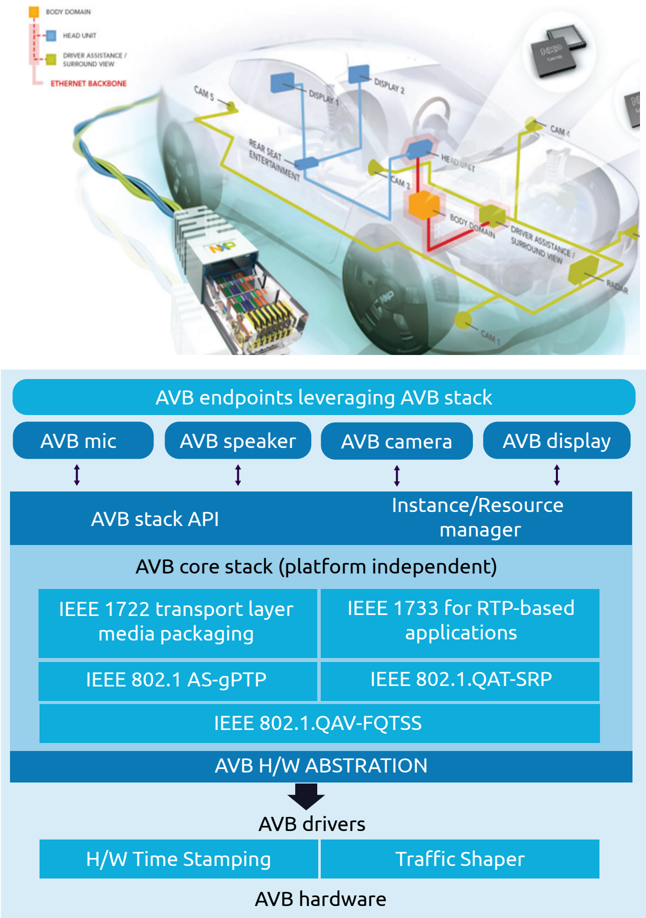


Figure 13: Video data processing based on Ethernet Audio Video Bridging

Source: NXP (top) and Capgemini Engineering (bottom)

ADAS relies on the Ethernet AVB network in many safety scenarios because of its high bandwidth and flexibility. The Ethernet AVB stack includes protocols such as IEEE 1722a AVTP, IEEE 802.1AS, 802.1QAV, 802.1QAT, and IEEE 1722a because they can transmit higher density video data streams more flexibly than an analog-based camera. The 100 Mbps for a video transmission has become insufficient for today's connected cars. The industry has moved towards using 1 Gbps over a single twisted pair with speeds of up to 10 Gbps that are being evaluated by the standard bodies.

Five key safety challenges

Video is a critical safety requirement in connected car design and applications. However, challenges include software and hardware elements that must be managed when threats are detected in the car ecosystem. The e-cockpit platform, which is the primary interface between the system components, must be capable of receiving, processing, and analyzing video feeds from multiple camera devices. Here are five specific video safety challenges.

Challenge 1: Bandwidth issues, network latency, and congestion

The video sessions initiated by passengers from rear-seat entertainment devices (RSEDs) such as video, audio, games, and home surveillance, and the e-cockpit that streams different types of content, require sufficient network bandwidth to and from the car network to handle the multiple sessions connected to the cloud. Sometimes, the e-cockpit takes too long to receive data from the external streaming server hosted by the mobile network operator on the cloud, or some chunk of video or audio data gets blocked due to heavy cellular network traffic. Also, during video streaming from the cloud, it is possible to transmit the video feed from the e-cockpit outside the network for specific critical safety applications, such as e-call or pedestrian crossing, where the bandwidth required is much higher.

Challenge 2: Distraction and the need for AI analytics

It is unlikely that the driver cannot monitor multiple camera feeds fetched from many interior and exterior cameras continuously on the e-cockpit platform during drive mode. (See Figure 14.) So, there is a need to generate alerts for the driver based on the video captured. However, since other video processing devices like interior cameras, Lidar, and radar are located in the car that generates video, AI-based solutions will be critical to managing the alerts. The video data can be trained or modeled to detect objects accurately that the driver cannot monitor.

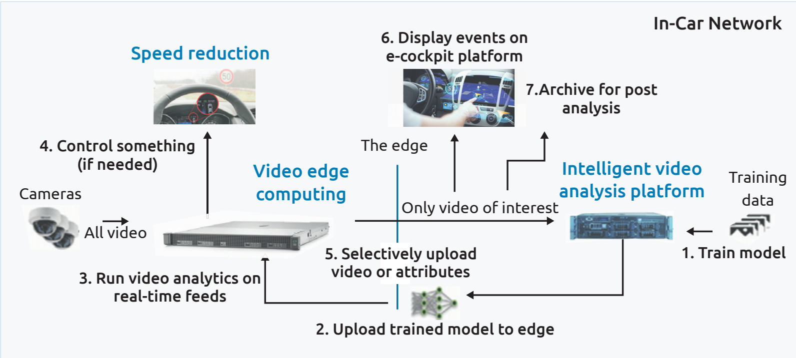


Figure 14: Video analytics at the edge of the car network

Source: Capgemini Engineering

AI- and ML-based video analytics is becoming a defacto standard in today's world, where video analytics detects and distinguishes between video objects and extracts, identifies, and analyzes behaviors and related attributes. AI/ML classifies the video data to be used for intelligent decision-making in various safety-related scenarios. This approach replaces the need to transmit all the data to the cloud and expect the cloud to do the analytics, which is impossible considering the network bandwidth required for each car. Sending every bit of video data from many cameras to a traditional data control center or the cloud for processing becomes too slow.

In addition, this approach would be too expensive given the bandwidth needed for all the video feeds and the high risk of possible data corruption or snooping by car hackers when critical safety data is sent over the internet. The edge-based video analytics is the best method for processing video inside the camera or in the e-cockpit platform. These options eliminate the need to send large amounts of video data to OEM data-centers for analysis. It also reduces bandwidth costs, accelerates response time, and decreases the risk of data corruption and hacking.

Challenge 3: Data storage

Storing valuable video data locally for analytics and analysis requires more video storage capacity in the connected car's e-system. How much more depends on the user's requirements. Since the video transmission to the cloud requires a lot of bandwidth, the cost of storing and accessing video on the cloud at a later date can increase the cost.

Challenge 4: Data security

Security is a big challenge in the connected car, including data, device, and network security. Justifiably, car owners want to know if the car surveillance data transmitted from the car network to the end user or the OEM center is secure. The most critical challenge is how to manage user privacy to protect the video data transferred from the car to the network where hackers can eavesdrop on the video data and inject false data during transmission. False data can change surveillance functionality and compromise integrity, which must always be maintained.

Challenge 5: Selecting the best video encoder/decoder

Ensuring quality video streaming for remote car surveillance requires selecting suitable video decoders and encoders to handle the live streams at the hardware platform (i.e., the e-cockpit platform) with hardware accelerator support exposed from the hardware platform design via required plug-ins like Open Media Acceleration (OMX).

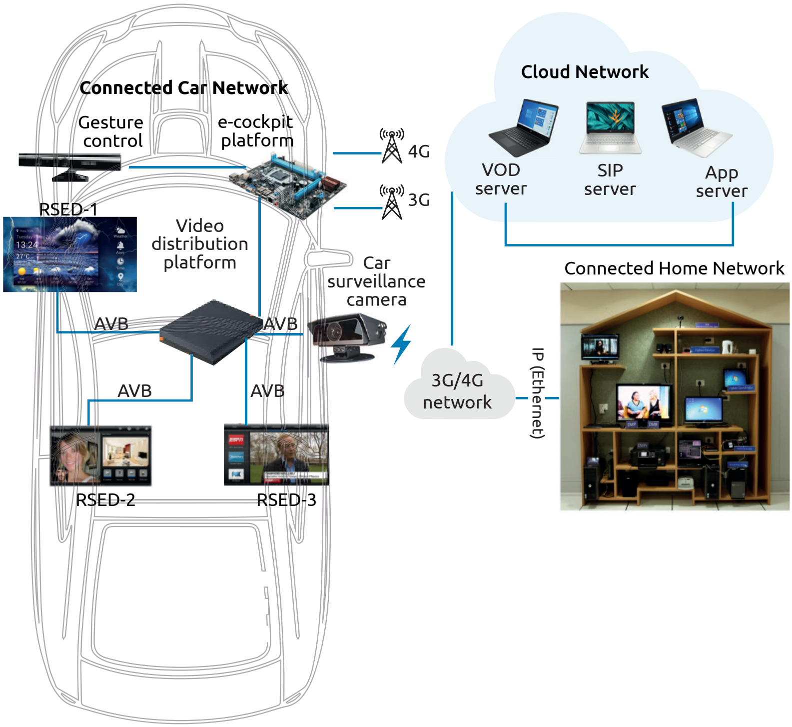


Figure 15: Critical challenges identified in the connected car ecosystem and home network

Source: Capgemini Engineering

In the connected car network, video plays an essential role in ensuring the safety of the driver, passengers, and other road users. With the emergence of autonomous cars, the enhanced wireless network needs to support 4G, 5G (emerging), and Wi-Fi. With expanded network coverage, the e-cockpit and the RSED can play a variety of media content, such as High Efficiency Video Coding (HEVC), from the main dashboard in the e-cockpit. Similarly, if a home intrusion occurs, the video from the home surveillance cameras can be accessed and viewed on the rear-seat panels in the car. (See Figure 15.)

Capgemini Engineering point of view

Video-based solutions for the connected car that manage safety bring many advantages for both drivers and passengers. While video continues to evolve safety features in the connected car ecosystem, video analytics creates even more value by enhancing safety and surveillance. Analytics addresses significant challenges in the connected car and emerging autonomous cars. Video analytics at the edge delivers proactive, predictive results efficiently and effectively by providing immediate emergency response to drivers and passengers.

The connected car market segment is leading the evolution of wireless connectivity. As a result, automakers are creating unique business opportunities for enhanced safety that fulfills user expectations of having a trouble-free driving experience. The next-generation e-cockpit platform, based on emerging SoCs from multiple tier-1 suppliers, provides a central access point to services, creating efficient ways for drivers and passengers to enjoy a seamless, safe driving experience.

The next-generation e-cockpit platform will act as a connectivity hub in the connected car allowing various interfaces including 4G, 5G, Bluetooth, Wi-Fi, Ethernet AVB, CAN, and USB drivers. Various middleware protocols and frameworks such as RTSP/RTP/RTCP, MPEG- DASH, HLS, HTTP-PD, DLNA, IMS/SIP, ADAS, V2X, and other related applications will be merged in a single e-cockpit embedded platform. (See Figure 16.)

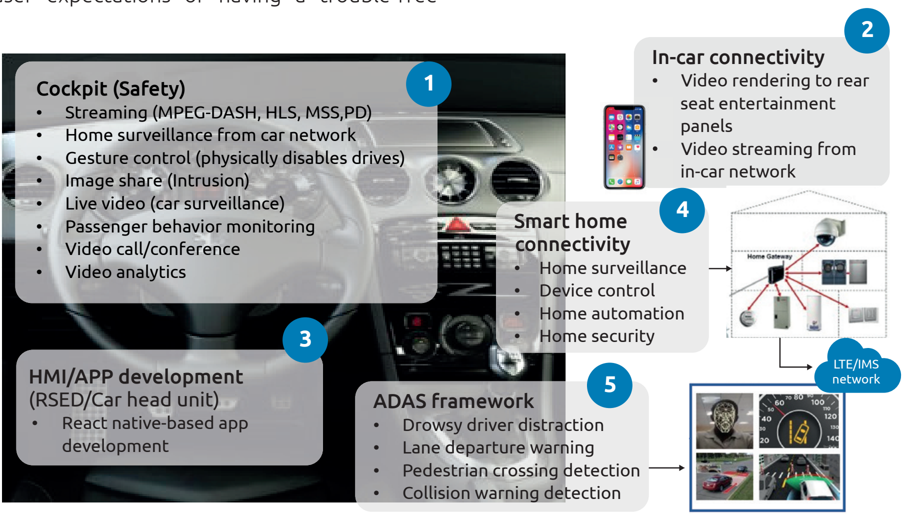


Figure 16: Video-specific scenarios and applications in the connected car ecosystem

Source: Capgemini Engineering

Carmakers are improving their car network designs to ensure safety, including incorporating edge-based devices that perform various operations inside the car. For example, Amazon AWS recently introduced a new hardware device called Panorama with ML features that allow autonomous carmakers to provide computer vision (CV). The system handles multiple concurrent video streams received from different in-car cameras located around the car to make predictions locally in the edge car network, with high accuracy and low latency. The Panorama CV hardware device interfaces IP-supported cameras, where standard IP-based cameras cannot operate due to hardware limitations. This feature enables camera makers to build new edge-based cameras with computer-vision models of certain safety algorithms like object and pedestrian detection, lane departure warning, and collision detection with ML services offered by AWS.

Conclusion

The adoption of the connected car is fueled by demand for safety-related features, which is accelerating car sales. From a safety perspective, video is capable of handling various safety aspects. However, to meet customer expectations, a high-definition camera and video image analysis that uses Lidar are required in the e-cockpit. The system uses light waves (shorter wavelengths) that work at a higher frequency and measure distance by using laser light surrounding the car and radar that uses radio waves (longer wavelengths) for the adaptive cruise control systems.

The next-generation e-cockpit platform can make decisions based on the local data processing received in real-time from different cameras enabled by the in-car network. This capability improves the overall driving experience for passengers and enhances safety by avoiding accidents, reducing traffic congestion, and providing assistance to stranded drivers.

4G is used today for car connectivity providing decent bandwidth for streaming the video content. Based on the evolving 3GPP R16/R17 standard, the cellular connectivity to be fitted into all new cars is likely to be 5G-ready. It will support short-wavelength radio signals and integrated radio antennas with better performance than smartphones. The car acts as a reliable 5G access point, providing network bandwidth, Ultra-Reliable Low-Latency Communications (URLLC) mode for low latency, and higher throughput. 5G also provides increased reliability and an all-in-one experience for drivers and passengers.

The combination of advanced software, new SoC platform design, and emerging 5G network design will unlock the future of driving. The car will become an OEM-branded communications hub offering superior driver and passenger safety and other value-added services. 5G technology enables autonomous driving and connected ecosystems with AI, and provides more sophisticated services, creating more value for consumers. Autonomous cars and smart homes will be integrated in the near future, creating a seamless connected environment.

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Vijay plays a strategic leadership role building connected IoT solutions in a number of market segments including consumer and industrial IoT. He has over 25 years of experience and has published 19 research papers, including IEEE award-winning articles. He is currently pursuing a Ph.D. at the Crescent Institute of Science and Technology, India.

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