Microwaves in Supporting Global Challenges
Microwave Integrated Circuits in Automotive Sensing and Vehicular Communication for Safer Roads and Efficient Traffic

Moritz Kahlert
HELLA GmbH & Co. KGaA, Germany
Brandenburg University of Technology Cottbus-Senftenberg, Germany

1 Introduction

The world faces various global challenges, from environmental sustainability to public health and safety. Among these, road safety is a significant concern, with millions of lives lost yearly due to traffic accidents [1]. Technological progress, especially in automated driving and vehicular communications, has substantial potential to address this problem [2]. Central to these advancements are microwave integrated circuits (MICs), which enable advanced communication and sensing essential for vehicle-to-everything (V2X), cooperative intelligent transport systems (C-ITS), and advanced driver assistance systems (ADASs). MICs pave the way for creating highly precise and reliable radio detection and ranging (radar) and light detection and ranging (lidar) systems, improving the detection and response to road obstacles, thus significantly reducing accident risks and increasing the safety of all road users. Furthermore, MICs enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, allowing for effective traffic management and coordination [3]. These advances help prevent traffic congestion, reduce fuel consumption, and cut emissions. MICs are crucial for integrating and improving electric and hybrid vehicles in sustainable mobility. They ensure efficient energy management and promote the use of renewable energy, thus minimizing the environmental impact of vehicles. Additionally, MICs drive the development and adoption of intelligent transport systems that support a comprehensive and eco-friendly mobility strategy.

This essay delves into the transformative potential of MICs in enhancing global safety by advancing automated driving and V2X technologies. These technologies are not only about making roads safer and traffic more efficient but also about laying the groundwork for a future of sustainable mobility.

2 Global Challenge of Road Safety

Traffic-related injuries are one of the leading global causes of mortality, with the World Health Organization (WHO) estimating that more than one million people lose their lives annually due to road traffic accidents. Furthermore, road traffic accidents are the leading cause of death in children and young adults aged 5 to 29 years [1]. In addition to these deaths, several tens of millions sustain injuries or disabilities. The economic burden of these incidents is also significant, leading to billions of dollars in lost productivity, healthcare costs, and property damage [4].

2.1 Contributing Factors

Numerous factors contribute to the elevated rate of road traffic incidents. These elements encompass human mistakes, such as distracted or impaired driving, poor road conditions, inadequate infrastructure, and vehicle failures. Managing these concerns requires a comprehensive strategy integrating education, law enforcement, engineering, and emergency management. However, technological advancements offer a promising future, especially in automated vehicles and V2X communication.

2.2 Vision Zero

The main objective is to achieve fully autonomous driving with no fatalities, a vision known as *Vision Zero*. Although this vision has not yet been fully realized, every new advance in MICs brings us closer to this goal. In most of today's vehicles, a driver remains actively involved and takes necessary actions. However, the driver will no longer be required in higher levels of autonomy. The vehicle will assume complete control, making the aim of reducing fatalities a technical and regulatory challenge. MICs are at the forefront of this challenge, enabling high-speed data processing and communication for fully automated driving. They play a crucial role in allowing the vehicle to make real-time decisions, such as emergency braking or lane change, based on the data received from various sensors.

3 Automotive Sensing Systems

MICs are the backbone of the functionality of automated vehicles, enabling high-speed data processing and communication required for sensor fusion. This fusion, which combines data from multiple sensors such as radar, lidar, and cameras, is crucial for creating a comprehensive understanding of the vehicle's surroundings and taking further actions, such as routing and traffic prediction. This data must be transported and processed to provide a 360° view of the vehicle's surroundings and take further actions, such as routing and traffic prediction. MICs ensure that these responses are timely, reliable, and accurate, even in dynamic driving conditions.

3.1 Perception Systems

MICs enable high-frequency radar systems to measure distances, relative velocities, and angles between the radar and targets in the environment. Radar systems, operating in the 24 GHz and 77 GHz frequency bands, deliver high-resolution information about the vehicle's environment, including obstacle recognition. These detections are essential for ADASs such as emergency braking assist (EBA), lane change warning (LCW), and exit assistant (EA). MICs are crucial in radar systems as they generate and handle the signals required for accurate sensing. Components like low-noise amplifiers (LNAs), power amplifiers (PAs), mixers, analog-to-digital converters (ADCs), and digital-to-analog converters (DACs) are standard components of these systems, guaranteeing accurate data gathering, collection, and evaluation, even under challenging circumstances.

In addition to radar, automated vehicles can utilize lidar and camera systems for environmental perception. While lidar uses laser beams to create detailed 3D maps of the surroundings, cameras provide visual data for object recognition and classification, which offers promising opportunities to use artificial intelligence (AI) and especially machine learning (ML).

MICs play a supporting role in all these systems by enabling the high-speed data processing and communication required for sensor fusion, where data from multiple sensors are combined to create a comprehensive understanding of the environment. Despite each sensor having its advantages and disadvantages, it is their combination that ensures reliable environmental perception. Radar operates effectively regardless of weather and lighting conditions, including fog, rain, and darkness, whereas lidar offers higher-resolution measurements. Data fusion is crucial for creating a detailed point cloud of the surrounding vehicles and detecting objects close to the vehicle.

3.2 Communication and Data Transmission

Effective communication between various vehicles electronic control units (ECUs) is crucial to its operation. MICs facilitate the high-speed data transmission required for vehicle control systems to function seamlessly, ensuring timely, reliable, and accurate responses to dynamic driving conditions.

Furthermore, MICs enable wireless communication technologies such as WiFi, Bluetooth, and dedicated short-range communications (DSRC). These technologies are essential for connectivity, such as communication between vehicles and mobile networks.

3.3 Real-Time Signal Processing and Decision Making

Automated vehicles must process large amounts of data in real-time to make safe and forward-looking driving decisions. MICs provide the processing power to handle complex algorithms and ML models that interpret sensor data, predict potential hazards, and determine appropriate actions. Furthermore, reliable data transmission between different components must be guaranteed to respond in real-time to events, provide suggestions to drivers, or even drive the vehicle automatically. As automation levels increase, the volume of data that must be transmitted and processed is also expected to increase. Additionally, redundant technologies and transmission paths must be in place to guarantee reliable data, even if one or more components fail to operate [2].

3.4 Challenges of MICs for Modern Radar Systems

Modern radar systems have numerous transmit and receive antennas to form an extensive virtual array, allowing for precise angular measurements due to their large aperture. However, a considerable amount of data acquired and processed by the receiving antennas must be transported and handled. These modern antenna systems often exceed 1000 channels, and the data is typically sampled in the gigahertz range. Despite the limited memory and processing capabilities of radar systems, the data must be transferred to a central ECU for processing. All these operations must be conducted reliably and in real-time to depict the vehicle's surroundings accurately and to furnish targets for subsequent actions of ADASs. Furthermore, addressing interference is essential due to the increased use of radar sensors per vehicle. This increases the likelihood of radar interference between different vehicles and self-interference between sensors within the same vehicle, potentially causing ghost targets or missed target detections. MICs are capable of helping the interference mitigation task through efficient signal processing and separation. This can enhance the robustness of radar sensors, particularly as automation levels progress.

4 Vehicular Communication

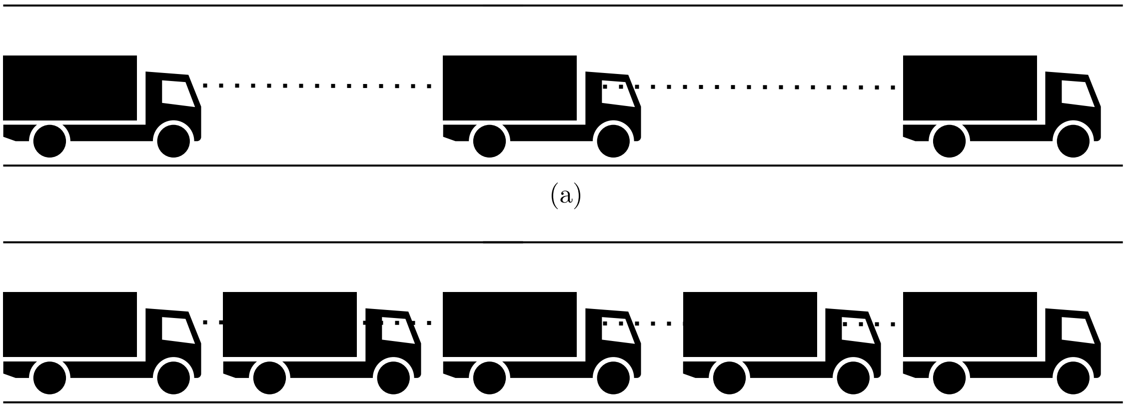
In addition to sensing systems such as radar and lidar, modern vehicles are equipped with communication units to allow direction communication between vehicles and between vehicles and networks, infrastructures, or even pedestrians. Using these communication units, vehicles can build so-called C-ITSs.

4.1 Improving Road Safety and Traffic Efficiency

V2X communication, which includes V2V, V2I, vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P) interactions, is a promising technology to improve road safety and traffic flow [3]. These communications allow vehicles to exchange information on their speed, position, trajectory, and more, allowing them to anticipate and react more effectively to potential hazards. Although the sensors mentioned in the previous section are vehicle-dependent, communication allows the exchange of inter-vehicle information, providing an additional safety layer.

MICs enable the high-frequency, low-latency communication required for V2X systems, such as Wireless Local Area Network (WLAN) or Long Term Evolution (LTE). MICs ensure reliable real-time data exchange between vehicles and their surroundings by integrating transceivers, antennas, and signal processing components. This feature allows for timely warnings about traffic conditions, road hazards, and other critical factors, thereby preventing accidents and saving lives [5].

DSRC and cellular V2X (C-V2X) are the leading technologies driving V2X communication. DSRC operates in the 5.9 GHz band and facilitates direct communication between vehicles and infrastructure, while C-V2X leverages existing cellular networks to offer greater coverage and enhanced capabilities. MICs are vital in both DSRC and C-V2X systems. They facilitate the creation, transmission, and reception of microwave signals essential for these forms of communication technology. Advances in MIC design, such as developing highly integrated transceiver modules, enhance the performance and efficiency of DSRC and C-V2X systems, increasing their effectiveness in supporting automated driving and intelligent transportation systems. These advances are crucial to reducing traffic accidents and improving overall road safety. In addition, visible light communication (VLC) has been discussed for implementation of V2X communication in the recent years offering promising opportunities [6, 7].



(a)

(b)

Figure 1: A representation of a platooning scenario in (b), where (a) shows a conventional highway scenario where trucks are spaced farther apart. Platooning enables driving with reduced fuel consumption and emissions using V2V communication between the trucks.

4.2 Environmental Impact

By optimizing traffic flow and reducing congestion, C-ITS also contributes to environmental sustainability. MICs enable the communication and coordination required for eco-friendly driving strategies, such as adaptive cruise control (ACC) and platooning, which can reduce fuel consumption and emissions [8]. An illustration of a platooning scenario is shown in Fig. 1.

Furthermore, MICs are incorporated into the energy management systems of electric and hybrid vehicles. They track and refine the operations of power electronics, battery management systems, and charging infrastructure. By effectively controlling energy flows, the range of the vehicle is extended, and energy consumption is reduced. Furthermore, MICs facilitate ongoing real-time monitoring and diagnostics of vehicle systems. This supports preventive maintenance, which prolongs the life of vehicles and ECUs and preserves their efficiency. Particularly in fleet management, MICs assist in optimizing maintenance schedules and enhancing operational sustainability [9].

4.3 Intersection Safety

Intersections are among the most common sites for traffic accidents. V2I communication can significantly enhance intersection safety by allowing vehicles to communicate with traffic signals and other infrastructure. MICs facilitate this communication, allowing vehicles to receive real-time information about signal changes, potential hazards, and other road users in blind spots, such as behind walls. This information enables vehicles to adjust their speed and trajectory, reducing the likelihood of collisions [10]. An illustration of V2X communication in an intersection scenario is shown in Fig. 2.

4.4 Vulnerable Road User Protection

More than half of all road traffic deaths are among vulnerable road users (VRUs), including pedestrians, cyclists, and motorcyclists [1]. V2X communication can also protect

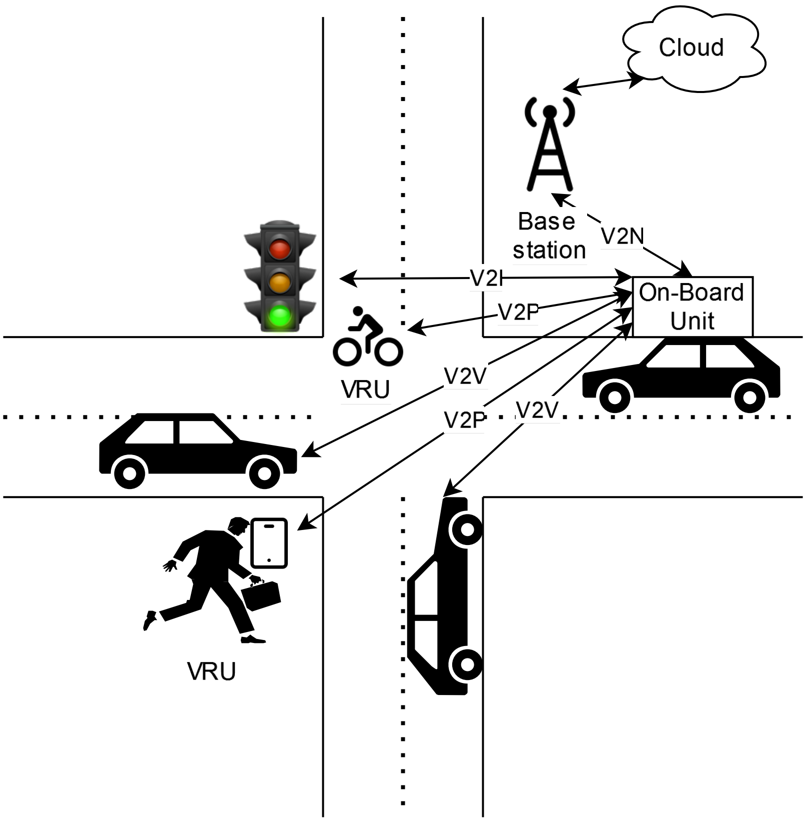


Figure 2: An illustration of vehicle-to-everything (V2X) communication at an intersection, encompassing vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) communications.

VRUs, such as pedestrians and cyclists. V2P communication allows vehicles to detect and communicate with pedestrians and cyclists nearby, providing warnings and alerts to drivers and the VRU, such as sensing messages to their mobile phones. MICs are integral to implementing V2P systems, enabling the reliable and timely exchange of information necessary for these safety features [11].

4.5 Joint Communication and Sensing

Recent research also suggests that communication and sensing systems combine to provide both functionalities in a single device. For example, V2V communication could be enabled by radar systems that not only sense their environment but also can transmit messages to nearby vehicles without requiring additional infrastructure in the environment. These sensors are denoted joint radar and communication (JRC) systems, where integrating communication in a sensing system is possible, or integrating sensing in a communication system is also possible [12]. The operation principle is illustrated in Fig. 3. MICs provide the functionality to support these functions, where each feature requires specific implementations.

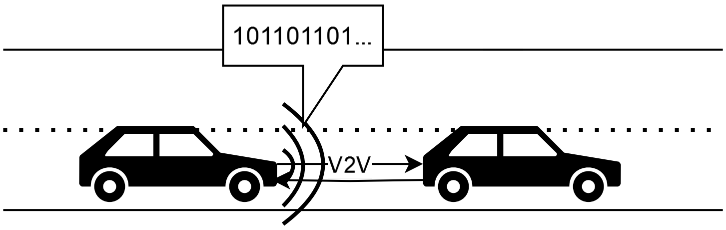


Figure 3: A representation of the joint radar and communication (JRC) operational principle. Besides sensing, the radar system can transmit messages using vehicle-to-vehicle (V2V) communication, such as exchanging details about utilized frequency bands.

4.6 Challenges of MICs for Vehicular Communications

1. **High-Frequency Signal Processing**: Wireless high-frequency signals, often in the gigahertz range, form the basis for vehicular communications, facilitating rapid and reliable data exchange between vehicles and infrastructure. MICs are engineered to handle these high-frequency signals effectively, enabling the miniaturization and integration of essential electronic components like amplifiers, filters, and oscillators needed for such communications. This advancement renders V2X communication systems more compact, energy-efficient, and powerful.

2. **Data Transmission Rate and Bandwidth**: V2X communication demands a high data transmission rate and substantial bandwidth to relay real-time information, including speed, position, braking, or even video data between vehicles and infrastructure. MICs have to deliver exceptional performance in managing these data volumes to transmit signals with high efficiency, thereby enhancing communication quality and reliability. This is especially crucial in urban settings, e.g., intersection areas, with numerous vehicles and infrastructure components communicating concurrently.

3. **Reliability and Robustness**: Vehicle communication systems are required to operate dependably in challenging environments and adverse weather conditions. MICs should be designed to endure extreme temperatures, vibrations, and other environmental challenges by incorporating a compact design and durable materials. They must guarantee that V2X communication systems remain reliable despite interference or environmental variations.

4. **Interference Avoidance**: In communication networks where many vehicles and infrastructure units communicate simultaneously, there is a high potential for interference between signals. MICs are designed to help minimize this interference by accurately separating and filtering high-frequency signals. By using advanced circuit technologies in MICs, interfering frequencies or signals can be efficiently blocked, increasing the quality and stability of V2X communications.

5. **Integration of 5G and Future Communication Standards**: The next generation of vehicular communications will rely heavily on 5G networks and future wireless standards. MICs enable the integration of radio frequency components required to utilize 5G and later networks to achieve ultra-low latency and high data

rates. This will be critical for the real-time communication required for autonomous driving and intelligent transportation systems.

6. **Cost and energy efficiency**: Another important aspect of MICs in V2X systems is their energy efficiency. Since vehicles are dynamic platforms, the communication systems need to be energy efficient to minimize power consumption. MICs help to reduce power consumption by optimizing signal processing and transmission.

5 Standardization, Challenges, and Future Research Directions

While automated driving continuously improves, many open and unsolved questions remain. This includes not only technological questions but also legal ones. However, this section discusses the technological challenges for MICs to improve the path to fully automated driving further.

5.1 Standardization

Currently, vehicles predominantly function autonomously of other vehicles. However, this will change with the adoption of V2V communication. This system enables the sharing of hazard information, as well as the coordination of activities such as radar transmissions to prevent interference between vehicles and their detection systems.

Achieving the full potential of MICs in autonomous driving and V2X communication requires collaboration between stakeholders in industry, academia, and regulatory bodies. Standardizing communication protocols and ensuring interoperability between different systems is essential to creating a cohesive and effective transport network. MICs will play a crucial role in these efforts by providing the hardware foundation for standardized communication systems.

Crucial standardizations are established in International Organization for Standardization (ISO) 26262, which deals with the functional safety of electrical and electronic systems in production vehicles. This standard is supported by ISO 21448, which emphasizes autonomous driving systems and ADASs that depend on MICs for the abovementioned sensors. In Society of Automotive Engineers (SAE) J3016, the levels of driving automation ranging from Level 0 (no automation) to Level 5 (full automation) are outlined. Vehicles and their sensing systems are classified into one of these levels, offering various driving functionalities, such as traffic jam chauffeurs or lane change warnings. Most modern vehicles fall into Level 2 or Level 3 categories, where the driver is assisted and, in certain situations, the vehicle can take control. However, the driver remains responsible and must resume control within a specified period. The ongoing research aims at higher levels of autonomy, moving toward Level 5, where no driver is necessary. The vehicle handles all actions and is accountable for all decisions.

5.2 Challenges

While MICs offer significant advantages, they also face challenges that must be addressed to realize their potential fully. These include:

1. **Signal Interference and Clutter**: Radar systems containing MICs often face interference from other electronics and environmental obstructions, like guard rails. Utilizing advanced signal processing methods can enhance the quality of radar signals.

2. **Power Efficiency**: As the complexity and functionality of MICs increase, so does their power consumption. Improving power efficiency is crucial for extending the operational life of automated vehicles and V2X communication systems. An example of power efficiency improvement is using 1-bit ADCs in automotive radar systems. Instead of sampling the received signals with full resolution, the data are only sampled by 1-bit ADCs. This improves the power efficiency dramatically, thereby reducing heat.

3. **Thermal Management**: Managing the heat generated by MICs is a significant challenge, particularly in high-power applications. Developing effective thermal management solutions is necessary to ensure the reliability and longevity of MICs. Furthermore, thermal management is required because heat can impact performance and reliability. Innovations in semiconductor materials can offer higher efficiency and improved thermal management.

4. **Integration Levels**: Higher integration levels can diminish the size and cost of MICs, making them more attainable and functional for extensive application. Progress in semiconductor manufacturing techniques is crucial for this advancement. Enhancements in the integration level are vital because space in vehicles for integration is constrained. Increasing numbers of radar systems are installed in vehicles, often behind bumpers. However, this space is unlikely to expand. Therefore, the integration space for MICs should be as efficient as possible to facilitate the installation of additional radar systems.

5. **Balancing Cost and Performance**: Cost efficiency is critical in commercial automotive systems. Although advancements in MIC technology are beneficial, the cost aspect must always be considered when designing new MICs.

5.3 Future Research Directions

Future research in MICs for autonomous systems and vehicular communications is likely to focus on several key areas:

1. **Higher Frequency Bands**: Exploring using higher frequency bands, such as the millimeter-wave spectrum, to achieve greater bandwidth and data rates for communication systems. Moreover, higher frequency bands are less congested than lower frequency bands, e.g., 120 GHz and 300 GHz bands.

2. **Integration with AI**: MICs can be integrated with AI and ML algorithms to improve data processing and interpretation in autonomous vehicles and C-ITS. AI can help optimize communication protocols, improve the accuracy of sensor data interpretation, and detect anomalies in the data, such as interference.

3. **Sensor Fusion**: Enhancements in sensor fusion are necessary for autonomous driving to create a dependable understanding of the vehicle's environment in various situations, including bad weather. MICs play a crucial role in processing and integrating the sensor data.

4. **Robustness under Adverse Weather and Environment Conditions**: Autonomous vehicles need to function safely in diverse weather conditions including rain, fog, snow, and extreme heat. Numerous sensors, especially lidar and cameras, face limitations in these situations. Consequently, research aims at creating more reliable sensors and enhancing algorithms to accurately process faulty or incomplete data, enabling precise decision-making even in challenging conditions.

5. **Reaction Time and Real-Time Processing**: Another significant challenge is the demand for high computing power and rapid data processing. Autonomous vehicles are required to handle millions of data points each second and make instantaneous decisions, particularly in unpredictable traffic conditions. Developing effective MICs and swiftly responsive algorithms remains a key research area.

6. **Enhanced Security**: Implementing sophisticated security measures within MICs to protect against cyber threats and maintain the integrity of communication networks. Secure MICs are crucial to protecting the data transferred between vehicles and infrastructure. Furthermore, security must address deliberate interference attacks that reduce the likelihood of target detection, thereby raising the risk of erroneous decision-making.

7. **Scalability and Cost-Effectiveness**: Creating scalable and cost-effective MIC solutions to facilitate the widespread adoption of autonomous systems and V2X technologies. This includes developing new manufacturing techniques and materials that reduce costs without compromising performance.

8. **Infrastructure**: Creating and deploying a robust infrastructure for V2I communication is essential for enabling interactions between vehicles and infrastructure. This type of communication needs to be efficient, reliable, and robust. If these conditions are met, it can significantly benefit automated driving.

9. **Misc**: Additionally, there are numerous unsolved regulatory, social, and ethical issues. Nevertheless, these topics fall beyond the scope of this technology-focused work and are discussed in other literature.

This list includes just a few of the possible future research domains. However, MICs can be applied beyond these specified areas.

6 Conclusion

MICs are at the forefront of the global challenge of road safety and efficiency. By enabling high-frequency, low-latency communication and sophisticated sensing, MICs are indispensable for the development and deployment of autonomous vehicles and cooperative transportation networks. These technologies promise to reduce traffic accidents, save lives, and improve the efficiency of transportation networks. Integrating MICs into various transportation sectors is a technological advance and a critical step toward addressing one of the most pressing global challenges, namely road safety. By leveraging MIC capabilities, safer, more efficient, and more sustainable world can be created, significantly reducing the human and economic toll of road traffic accidents. The path toward this future is complex and requires continued innovation, collaboration, and investment in MIC technology. However, the potential benefits make it an endeavor worth pursuing with vigor and determination. As research and innovation in MIC technology progress, even more significant advances in road safety and connectivity can be expected, paving the way for a future where autonomous driving and intelligent transport systems are crucial in creating safer, more intelligent, and more sustainable traffic.

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