

Context-Aware Warning Systems: Leveraging Driving Environment Data for Improved Driver and Road User Warnings

Alexander Stocker^a, Tahir Emre Kalayci^b, Michael Spitzer^c and Gerald Musser^d

Virtual Vehicle Research GmbH, Inffeldgasse 21a, 8010 Graz, Austria

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Abstract: Web technologies, Internet of Things (IoT) frameworks, and modern communication standards are increasingly transforming the automotive sector, giving rise to software-defined vehicles. These vehicles operate as connected entities within a broader digital ecosystem, enabling real-time data exchange with infrastructure, cloud services, and other road users. This ongoing digitalization opens new opportunities to improve road safety through intelligent, context-aware driver assistance systems. Our paper introduces a novel context-aware driver warning system to be developed as part of the ROADGUARD project. The system will fuse data from in-cabin driver monitoring with data about the external driving environment to enhance the accuracy and contextual relevance of safety alerts. Conventional Driver Monitoring Systems (DMS) often rely solely on gaze-based heuristics, which can lead to false positives when environmental context is not considered. Our approach will overcome this limitation by integrating multimodal sensing, AI-driven edge inference, secure data sharing, and adaptive, multi-target warning delivery. Our proposed system architecture is structured around three interconnected subsystems—Sensing, Sharing, and Acting. It will not only enable more precise, real-time alerts for drivers but also cooperative warnings for vulnerable road users such as pedestrians and cyclists. By embedding situational awareness and supporting data-driven improvement via mobility data spaces, our system supports the Vision Zero objective of eliminating traffic fatalities.

1 INTRODUCTION AND MOTIVATION

Web technologies, Internet of Things (IoT) frameworks, and modern communication standards are increasingly permeating the automotive domain (Sterk et al. 2023; Kaiser et al., 2021). This technological convergence is transforming vehicles into connected entities within a broader digital ecosystem, enabling real-time data exchange with cloud services, roadside infrastructure, and other vehicles (Stocker et al., 2017). Simultaneously, vehicles are evolving into software-defined platforms (Liu et al. 2022), moving beyond traditional hardware-centric architectures. This shift toward the software-defined vehicle (Otto et al. 2025) offers greater flexibility, supports over-the-air (OTA)

updates, and facilitates the integration of advanced functionalities such as driving automation, context-aware driver assistance, continuous system optimization, and intelligent decision-making.

Moreover, vehicles are now enabled to leverage a wide range of external data sources (Kaiser et al. 2017), such as real-time traffic information, weather reports, and transportation infrastructure data, to further enhance both safety and driver comfort. By integrating these heterogeneous inputs, vehicles become capable of making context-sensitive decisions (Matalonga et al., 2025), anticipating potential hazards, tailoring warnings to situational risks, and delivering more accurate and timely assistance to drivers (Ebinger et al., 2024).

From a digitalization standpoint, product architectures are undergoing a fundamental

^a <https://orcid.org/0000-0002-3758-1617>

^b <https://orcid.org/0000-0001-6228-1221>

^c <https://orcid.org/0000-0003-2173-9317>

^d <https://orcid.org/0009-0005-6006-588X>

transformation (Yoo et al., 2024). Traditional vehicle development, which focused primarily on mechanical systems and static design paradigms, is giving way to flexible, modular, and software-centric architectures and services (Otto et al. 2025). In this new paradigm, digital innovation, service-oriented design, and platform-based thinking are becoming central (Sterk et al., 2024). As vehicles grow increasingly connected and data-driven (Stocker et al., 2017), value creation is shifting from physical products to digital services—such as real-time diagnostics, predictive maintenance, personalized driver assistance, and subscription-based feature upgrades (Stocker et al. 2021). This evolution not only transforms how vehicles are designed and maintained but also redefines how users interact with and experience mobility.

This digital transformation of the mobility automotive sectors (Stocker et al., 2024; Piccini et al. 2015) holds significant potential to improve one of the most critical aspects of mobility, driving and road safety. By harnessing connected technologies, real-time data, and intelligent systems, vehicles can for instance better detect, predict, and respond to hazardous situations—ultimately reducing the risk of accidents and enhancing protection for both drivers and vulnerable road users.

Inattentiveness and distraction remain among the leading contributors to road accidents globally (Regan et al. 2011). In response, and to move closer to the European Union's Vision Zero objective (European Commission, 2022), aiming to eliminate all traffic-related fatalities, modern vehicles are increasingly equipped with driver assistance and warning systems (Li et al. 2024) designed to detect and mitigate risks in real-time. However, despite these advancements, the persistent rate of road fatalities—especially among pedestrians, cyclists, and motorcyclists (Silla et al. ,2017)—highlights the urgent need for more effective and intelligent safety interventions. Consequently, Physical AI is recognized as a pivotal enabler of digital innovation (Stocker, 2025).

One key limitation of many current driver assistance, warning systems and driver warning apps (Trager et al. 2021) is their tendency to generate false positives (Large et al. 2017), alerts triggered in non-critical situations. These frequent, often unnecessary warnings can lead to driver desensitization, reduced trust in the system, and diminished overall safety benefits (Navarro et al. 2016).

To increase the relevance and effectiveness of in-vehicle driver warning systems, we propose the integration of data and information from both the

external driving environment and in-cabin sources, such as driver state and behaviour. By fusing environmental context—such as road conditions, traffic dynamics, and weather—with insights from driver monitoring systems (e.g., gaze tracking, drowsiness detection, and cognitive load estimation), warning systems can become more adaptive, timely, and personalized. Our multimodal fusion approach has the potential to significantly reduce false positives, increase contextual relevance, and improve driver trust and responsiveness to safety-critical alerts.

Based on the introduction and motivation, Section 2 presents our proposed context-aware warning system for drivers and other road users, situated within the current state of the art in driver warning systems. This section provides a detailed overview of the motivating scenario and the rationale behind our solution concept. Section 3 outlines the solution architecture and its technical foundation, organized around the three core subsystems: Sensing, Sharing, and Acting. Section 4 discusses our approach along with key insights from technological considerations. Finally, Section 5 concludes the paper with a summary and an outlook on future research directions and potential applications.

2 STATE OF THE ART AND ADVANCEMENTS

2.1 Driver Monitoring and Warning Systems

Current Driver Monitoring Systems (DMS) primarily focus on observing the driver within the cabin (Michelaraki et al., 2023), often neglecting the broader external driving context. Moreover, existing digital warning strategies are typically designed to alert the driver alone, overlooking the potential benefit of also communicating risks to nearby road users—especially when the vehicle is operated by a distracted or inattentive driver.

A key limitation of many current inattention and distraction detection approaches is their susceptibility to false positives (cf. Large et al., 2017). These systems may flag off-road gaze behaviour as distraction, even when such behaviour is contextually appropriate, for instance, when a driver is monitoring a child pedestrian near the roadway. Such misclassifications not only reduce the relevance of warnings but can also frustrate drivers, eroding trust in the system. As a result, drivers may choose to

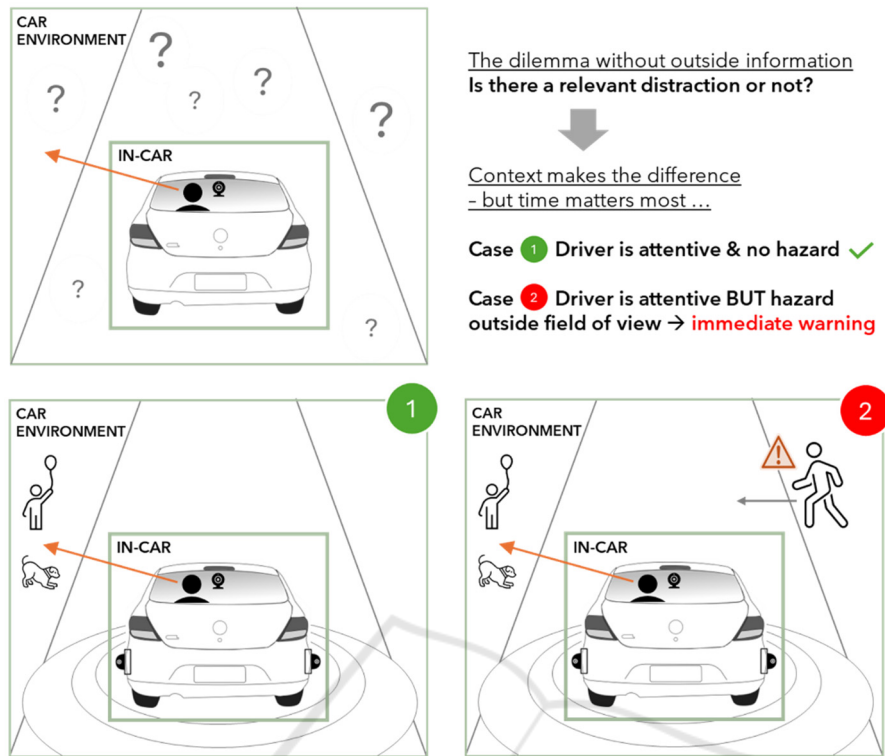


Figure 1: An example scenario that highlights the limitations of conventional systems.

disable these safety features altogether, ultimately compromising their effectiveness.

Furthermore, most DMS architectures treat inattention and distraction as an isolated, driver-centric problem. They rarely consider how driver inattention and distraction might impact other road users in the surrounding environment, nor do they issue proactive alerts to other road users and especially to vulnerable road users who may be at risk due to an inattentive driver. This lack of context-awareness and bidirectional warning mechanisms limits the broader safety potential of current driver monitoring and warning systems.

2.2 Scenario: Context Aware Driver Monitoring

Before outlining our proposed approach, we begin with a user scenario that highlights the limitations of conventional camera-based driver monitor warning systems (Figure 1). These systems often struggle to integrate the detected driver state with a dynamic, contextual understanding of the external environment, which can lead to delayed, inappropriate, or misleading responses.

Imagine a vehicle navigating an urban environment. A camera-based Driver Monitoring

System (DMS) tracks the driver's gaze and eye movements, issuing warnings based on simple heuristics—for example, triggering an alert if the driver looks away from the road for an extended period (see Figure 1, upper box).

As an example, the China NCAP safety rating for driver attention monitoring systems mandates issuing escalation alerts if the driver's eyes are off the road for more than 3 to 5 seconds (Medium, 2025). For Europe, Euro NCAP defines a long distraction as a single instance of the driver's gaze away from the forward road lasting between 3 and 4 seconds (Euro NCAP, 2025).

Now consider the following situation: A driver turns the gaze to the left and keeps watching a dog and a child playing near the curb. The driver is rightfully cautious and remains prepared to brake, as this is an exceptional case where the general trust principle does not apply. Although the driver is acting safely and attentively, the system may still trigger a distraction warning because it lacks awareness of the context—specifically, that the off-road gaze is purposeful and safety-motivated (Figure 1, lower left box). Such false positives can frustrate the driver and lead to disengagement or deactivation of the warning system.

Now imagine that, simultaneously, a pedestrian

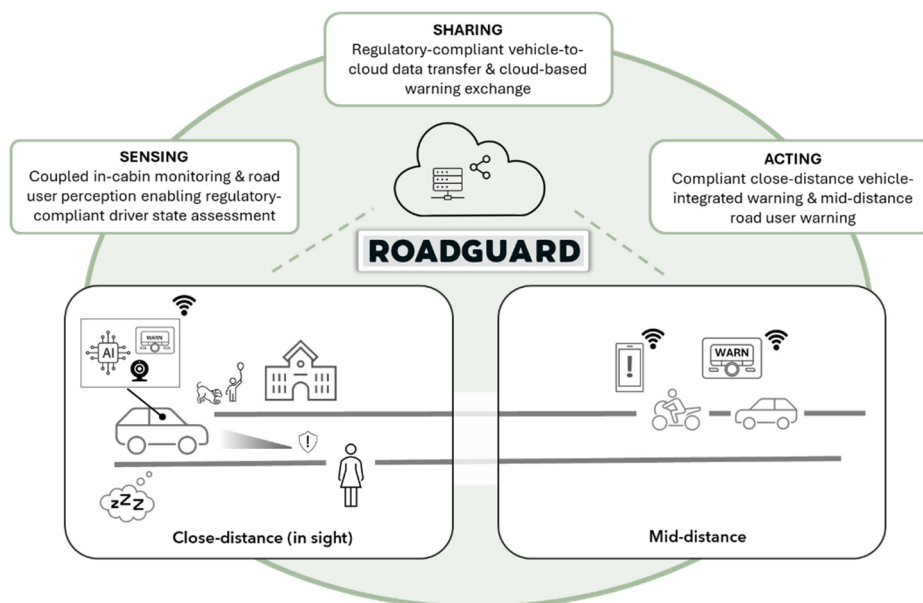


Figure 2: The proposed context-aware driver monitoring and warning solution.

begins crossing the street from the right—outside the driver’s current field of view, as their attention remains focused on the child and dog. The driver fails to notice the pedestrian, significantly increasing the risk of a potentially fatal collision. Crucially, the current Driver Monitoring System (DMS) would not issue any alert in this situation because it lacks situational awareness of the external environment and the evolving traffic scenario (Figure 1, lower right box). Additionally, the pedestrian is not warned that the driver’s attention is elsewhere, leaving them vulnerable. Finally, other road users remain unaware, too, when a driver’s attention is diverted away from the road.

3 SOLUTION APPROACH

Our proposed solution to be developed in the *roadguard* project⁵ is structured around three core subsystems essential for context-aware driver monitoring and warning: Sensing, Sharing, and Acting (Figure 2). Together, these components form an integrated framework for comprehensive safety monitoring that addresses both the driver and surrounding road users. At the heart of this architecture are AI-enabled edge devices, which enable real-time analysis and decision-making directly within the vehicle.

The Sensing subsystem captures data from both inside and outside the vehicle, including driver state, environmental context, and potential hazards, thereby handling manifold data integration challenges on the vehicle edge computer (cf. Kalayci et. al. 2021). The Sharing subsystem manages the secure transmission of relevant data across vehicles and infrastructure, with a strong emphasis on data privacy and regulatory compliance. The Acting subsystem plays a pivotal role in delivering context-sensitive warnings, not only to the driver but also to nearby vulnerable road users, thereby enhancing situational awareness for all parties.

Our tripartite framework aims to address the shortcomings of current driver warning systems by ensuring that relevant information is captured, securely exchanged, and acted upon in a timely and context-aware manner. The ongoing digitalization of the automotive sector—coupled with advancements in web technologies, IoT frameworks, and standardized communication protocols—provides a robust foundation for implementing such an integrated system.

3.1 Sensing System: Contextual Data Acquisition and Processing

The sensing system at the core of our approach consists of two complementary subsystems designed

⁵ Roadguard project description: <https://projekte.ffg.at/projekt/5126443>

to monitor both the driver's state and the external driving environment. This dual-sensing strategy provides a comprehensive and context-aware understanding of risk, which is crucial for delivering effective and timely warnings to drivers and other road users.

The in-cabin sensing unit focuses on assessing the driver's attention and cognitive state. It incorporates dual near-infrared (NIR) stereo cameras positioned to unobtrusively monitor the driver's head and eye movements. Computer vision algorithms process the stereo video streams to perform gaze estimation, blink detection, head pose tracking, and fatigue analysis. Driver state classification algorithms then generate outputs such as attentive versus inattentive, drowsy versus alert, and gaze-on-road versus gaze-off-road indicators.

An external sensing unit captures the driving context and detects potential hazards. This subsystem includes RGB cameras and utilizes object detection (cf. Kalayci et al. 2022) and tracking models to identify vulnerable road users (VRUs), other vehicles, and static obstacles in real time. Additionally, trajectory prediction models forecast the likely motion of detected road users, enabling the system to anticipate emerging threats.

All sensor data, both internal and external, are processed and fused on a dedicated in-vehicle edge device equipped with AI inference capabilities. This local processing unit enables real-time decision-making under strict latency constraints. It evaluates

whether the driver's current behaviour is safe within the given environmental context and determines whether a warning should be issued to the driver, to nearby or mid-distance road users, or if data should be securely shared externally with connected infrastructure or vehicles, in full compliance with data privacy standards.

3.2 Sharing System: Secure Data Exchange and Ecosystem Integration

Selected data, such as instances of critical driver states or high-risk scenarios, are transmitted by the Sharing subsystem through secure communication channels to a centralized server infrastructure. This transmission process adheres to data protection regulations and ensures both the confidentiality and integrity of sensitive information.

Once received, the data on the driver state follows two primary pathways: integration into a training data repository and contribution to other data spaces. A subset of the collected data is anonymized and stored in a dedicated training dataset to support the ongoing enhancement of machine learning models for driver state monitoring as well as environmental perception and prediction. By incorporating real-world examples into the training pipeline, the system enables adaptive learning and continuous performance refinement.

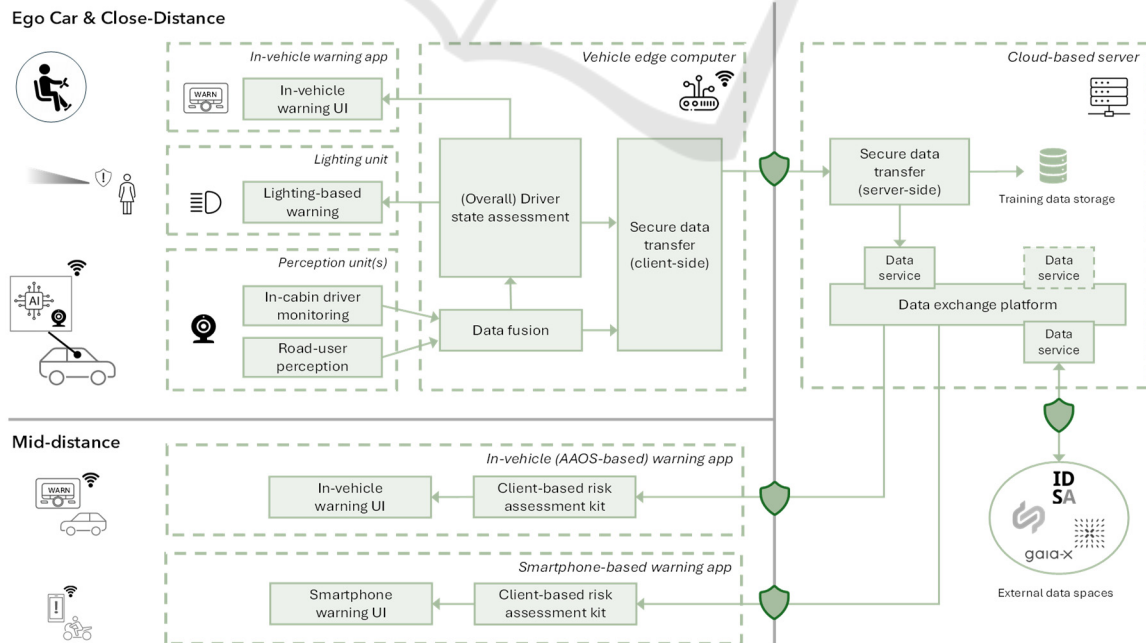


Figure 3: The proposed high-level architecture of the solution.

In parallel, relevant portions of the data are shared with broader mobility data ecosystems using standardized protocols and interoperable connectors (e.g., GAIA-X, IDSA). This facilitates data exchange with external stakeholders such as traffic management authorities, urban planners, and fleet operators—enabling coordinated intelligence and the development of advanced mobility services.

This dual-purpose data sharing approach simultaneously supports real-time safety interventions and long-term system advancement through collaborative learning and ecosystem-wide integration.

3.3 Acting System: Context-Aware Warning Presentation

The Acting subsystem is responsible for issuing context-sensitive warnings based on the combined analysis of driver state and external environmental data. It differentiates between warnings intended for the ego vehicle—namely the driver and in-vehicle systems—and those aimed at external road users in close or mid-range proximity.

Warnings for the driver are delivered through a dedicated user interface implemented as an application running on the Android Automotive Operating System (AAOS) (cf. Sterk et al., 2023). This interface receives warning signals from the sensing subsystem and provides real-time alerts using visual cues such as screen overlays, ambient lighting, or flashing icons, and auditory feedback such as tones or voice prompts. This configuration ensures that the driver receives immediate and relevant notifications in situations involving distraction, inattention, or emerging hazards.

For vulnerable road users in the immediate vicinity of the vehicle, the system uses lighting-based external warning signals. These can include flashing headlights or taillights, projection-based indicators, or dynamic lighting effects that visually communicate a distracted driver state or imminent danger. These warnings are designed to increase the situational awareness of pedestrians and cyclists, particularly when the driver is not fully attentive.

For road users at mid-range distances—such as nearby vehicles or motorcycles—cooperative warnings are issued via connected applications. In vehicles equipped with AAOS, a connected warning app receives relevant driver state information from the sharing subsystem and displays appropriate alerts. For motorcycles and other vehicles not equipped with AAOS, a standalone Android mobile application is under development to receive and visualize warnings.

If the data-sharing mechanism supports sufficiently low-latency communication, both in-vehicle and environmental perceptions - such as distractions caused by other road users - can be shared in near real-time to provide warnings to approaching drivers. This approach extends the system's safety reach beyond the immediate surroundings of the vehicle and supports broader cooperative awareness, which is especially valuable in urban and mixed-traffic environments.

4 TECHNICAL CONSIDERATIONS

This position paper proposes a context-aware driver monitoring system that integrates in-cabin data with environmental information to deliver more effective and relevant driver warnings. Unlike conventional driver monitoring systems, which often suffer from false-positive rates due to focusing on in-cabin information only and neglecting external context, the proposed approach fuses multiple data sources and leverages AI-driven edge computing to enhance decision-making. By combining insights from driver behavior with real-time environmental perception, the system not only improves the accuracy and timeliness of driver alerts but also extends safety benefits to vulnerable road users through cooperative warnings. This context-aware design shows strong potential to advance road safety, reduce distractions from unnecessary alerts, and create a more proactive and adaptive warning framework.

However, several challenges remain. Ensuring robust and reliable sensing under diverse real-world conditions—such as adverse weather or complex urban environments—requires ongoing refinement of perception algorithms and models. Advanced AI frameworks play a crucial role in this process by enabling adaptive learning, sensor fusion, and context-aware interpretation of multimodal data. Leveraging techniques such as deep learning and transfer learning allows the system to improve over time by incorporating new data and handling edge cases more effectively. Moreover, implementing AI models on resource-constrained edge devices demands efficient architectures and optimization strategies to balance accuracy with real-time performance and power consumption. Addressing these challenges is essential to maintain high detection accuracy, reduce false positives, and ensure the system's resilience in diverse driving scenarios.

In our sharing subsystem, choosing between streaming services and simple REST interfaces involves important trade-offs related to data processing and fusion capabilities. Streaming services typically require significant preprocessing and formatting of data before transmission. This upfront processing can limit flexibility downstream, as the data arrives in a more fixed, aggregated form, reducing the ability to perform on-the-fly merging or complex fusion with other data sources at the receiver's end. On the other hand, REST interfaces, where data is requested and received in discrete chunks, allow for more dynamic handling. Since data arrives in smaller, more raw pieces, it enables real-time or on-demand computations and merging at the receiver. This approach preserves the flexibility to adapt processing strategies based on current context, system state, or additional inputs, improving the overall responsiveness and accuracy of fused information. Therefore, while streaming services can be beneficial for continuous high-throughput data flows, they may constrain adaptability due to early-stage preprocessing. RESTful approaches offer greater flexibility for on-the-fly calculations and data fusion but may introduce some latency due to the request-response nature. Selecting the appropriate method depends on the specific requirements for latency, processing load, and fusion complexity in the sharing subsystem.

As a first step and proof of concept, a simple REST-based approach will be implemented. In this setup, compressed messages containing basic information—such as hazard type, time and position—will be transmitted to the sharing component. Receivers can retrieve these messages based on a self-defined area of interest, allowing for flexible control over update frequency and the volume of data processed at once. Additionally, the sharing backend will automatically filter out outdated information, reducing both data transfer and computational load on the receiver side. In a production-grade system, a hybrid approach combining streaming, on-demand requests, and potentially locally cached historical data on the receiver side could offer an effective solution. This setup would minimize data transfer, enable fast message processing, and maintain flexibility in selecting the type of data and update frequency according to the receiver's needs.

The Acting subsystem connects the system's insights to real-world safety actions by delivering context-aware warnings to drivers and nearby road users. Leveraging IoT principles and web technologies, it enables seamless communication and

interaction across vehicles and devices. Integration with Android Automotive OS (AAOS) allows the system to deploy flexible, app-based warnings inside the vehicle using native features like visual alerts and sounds. Externally, the subsystem uses connected lighting systems and projection-based signals to warn vulnerable road users such as pedestrians and cyclists in real time. Additionally, via secure web-based APIs and standardized data-sharing protocols, mid-range warnings are pushed to other vehicles or mobile apps—extending situational awareness through cooperative communication within an IoT-enabled mobility ecosystem. This combination of modern web standards, edge computing, and IoT connectivity ensures adaptive, reliable, and comprehensive warning delivery that enhances safety both inside and beyond the vehicle.

Privacy and data security are critical considerations, especially given the sensitive nature of driver state data and the need for secure data sharing across vehicles and infrastructure. User acceptance and trust also hinge on minimizing intrusive or excessive warnings, necessitating careful calibration of system sensitivity and thoughtful human-machine interface design.

A central aspect of our system design is strict compliance with data protection and privacy regulations, reflecting the dual nature of sensing both inside and outside the vehicle. In-cabin driver monitoring involves sensitive personal data, such as driver images, which require explicit user consent and stringent handling procedures. To address this, driver-related data is processed locally on the vehicle's edge device and remains within the vehicle unless lawful data sharing with explicit consent occurs as managed by the secure data transfer module, thus minimizing data exposure.

Conversely, external environmental monitoring captures anonymized, non-identifiable information about road users and hazards in public spaces, which generally does not require individual consent but follows privacy-by-design principles. The overall architecture enforces stringent data governance, ensuring personal data does not leave the vehicle without proper safeguards, while external sensing enhances safety without infringing on individual privacy rights.

5 CONCLUSION

Our concept of a context-aware driver warning system demonstrates how integrating in-cabin monitoring with environmental sensing, enabled by

IoT and Web technologies, can significantly enhance road safety. By leveraging edge AI and secure data sharing, our system will deliver timely, relevant alerts to drivers and other road users alike. Our tripartite framework—Sensing, Sharing, and Acting—addresses key limitations of conventional approaches, reducing false positives and expanding cooperative awareness.

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