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Evolution of Advanced Driver Assistance Systems in Smart Mobility: A Comprehensive Review

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Abstract

The swift development of smart mobility has placed Advanced Driver Assistance Systems (ADAS) as a strategic technology that has the potential of enhancing road safety, traffic efficiency and environmental sustainability. The current ADAS has evolved beyond single driver warning systems as multi modal sensing, sophisticated control algorithms, power electronic actuation and vehicular communication capabilities have been incorporated into the system. In this review, a thorough and systematic discussion on the development of ADAS is presented in terms of interdependence of sensing technologies, control structures and power electronic integration in connected and intelligent transportation systems. The most important sensing modalities are analyzed, such as vision, radar, LiDAR, ultrasonic and inertial sensors, which are of great importance and sensor fusion strategies that promote the perception robustness in the real world. The review also compares classical, model based and AI driven control methods, their usability, limitations and safety of such approaches in partially automated driving. Architectures and layouts used to support ADAS regarding voltage domains, actuation systems, energy efficiency, thermal management are discussed. Besides, the paper examines communication models, safety measures and cybersecurity issues, regulatory trends and ethical dilemma related to partial automation. The new trends of AI driven perception, solid state sensing, integration with electric and autonomous vehicles and the contribution of ADAS to sustainable smart cities are discussed. Lastly, the review can be used to reveal essential research gaps in terms of system level co-design, practical validation and affordability that can be used to inform future research and industrial acceptance of ADAS in smart mobility ecosystems.

Keywords: Advanced Driver Assistance Systems (ADAS); Smart Mobility; Intelligent Transportation Systems; Sensor Fusion; Vehicle Control Architectures; Power Electronics; Connected Vehicles; Automotive Safety; Autonomous Driving; Sustainable Transportation

1. INTRODUCTION

1.1 Background and Emergence of Smart Mobility and Intelligent Transportation Systems

The swift urbanization of cities, rising levels of traffic congestion and rising concerns regarding road safety and environmental sustainability have further stepped up the evolution of smart mobility and Intelligent Transportation Systems (ITS) in the world. Smart mobility focuses on the connectivity of digital technologies, automation and making decisions based on data in order to increase transport efficiency, safety and sustainability. ITS is a combination of sensing, communication and control technologies that allow one to monitor traffic in real time, coordinate vehicles and interact with the infrastructure intelligently [1,2].

Recent developments of embedded systems, artificial intelligence and car communication turned the traditional transportation into a cyber physical ecosystem. Smart mobility is also becoming a key avenue through which governments and the automotive industry believe that the national administrations can reduce congestion, enhance road safety and meet emission reduction obligations per the global climate agreements [3,4].

1.2 History of Vehicle Automation: Passive Safety to Intelligent Assistance.

Safety systems on vehicles have passed through certain technological stages. Initial trends were centered on passive safety through things like seat belts and airbags that helped in case frontal impact involved then anything could be reduced. Active safety systems such as the Anti lock Braking Systems (ABS) and Electronic Stability Control (ESC) followed this stage and helped the driver to retain the control of the vehicle when it is in a critical manoeuvre [5].

Since 2020, a change towards intelligent assistance systems, which are systems that perceive their environment, provide decision making support and actuation support has been observed in the automotive industry. The introduction of technologies like the lane keeping assistance, adaptive cruise control, automatic emergency braking and the blind spot detection systems nowadays are a feature of a modern car. Such systems are largely based on real time sensing, computational intelligence and electronic control, which would signify a shift in the sphere of decision making by drivers to shared control in humans and machines [6,7].

1.3 The Advanced Driver Assistance Systems and their role in the reduction of road accidents and emissions.

According to the world health organization, road traffic accidents are one of the problematic issues that claim the lives of about 1.19 million people each year, most of which are caused by human error [4]. Advanced Driver Assistance Systems (ADAS) directly respond to this problem because they improve awareness, shorten reaction time and intervene in dangerous cases. Empirical research findings suggest that automatic emergency braking and lane departure warning are important features that can minimize rear end and run off road accidents [8,9].

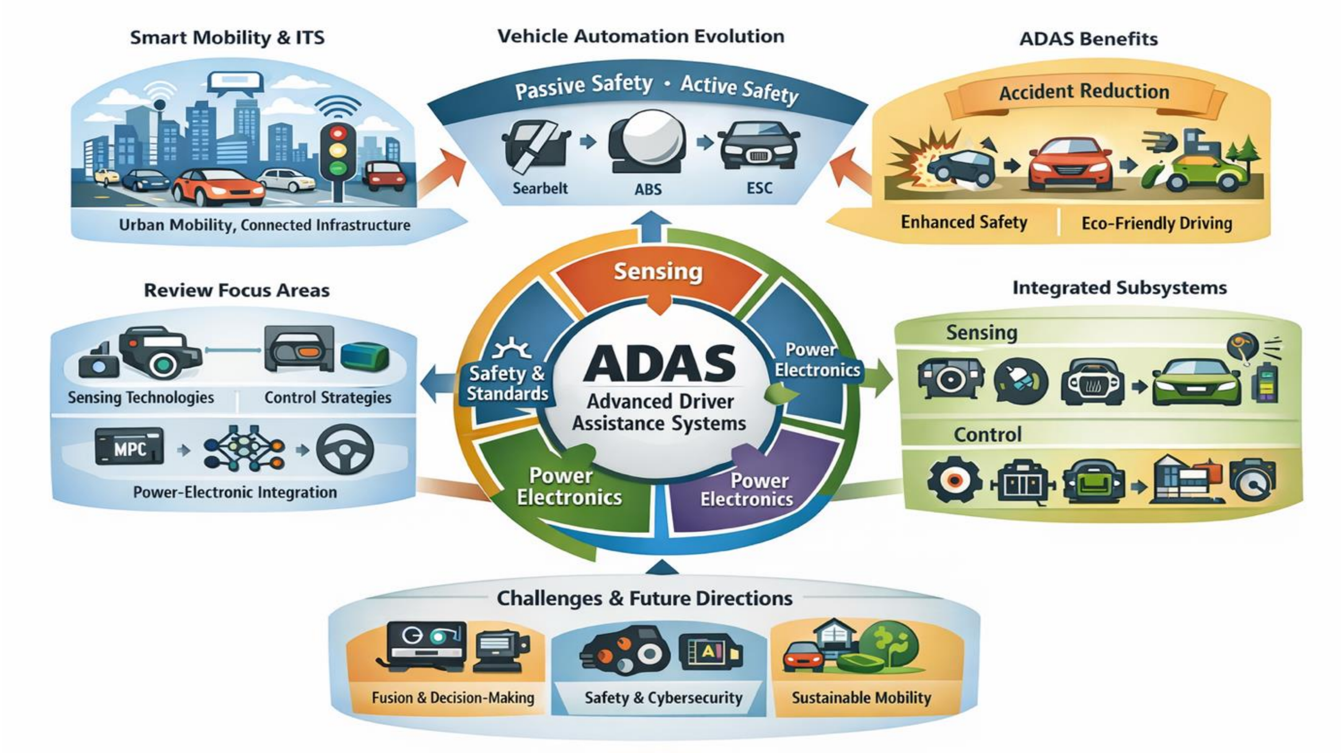
In addition to safety, ADAS is also associated with environmental sustainability, as it allows driving behavior to become smoother, speed management to be more efficient and the stop and go traffic to be decreased. The adaptive cruise control and eco driving assistant systems have been reported to reduce fuel consumption and tailpipe emissions, especially in the city traffic [10]. This is why ADAS is gaining greater and greater attention as a technology that not only provides safety but also becomes one of the main facilitators of low emission and energy efficient mobility.

1.4 Sensing, Control and Power Electronic Subsystems Requirement Integrated Analysis.

Although ADAS performance is defined by the contribution of single components, the close interactions between sensing, control and power electronic subsystems determine its real life performance. The ADAS platforms nowadays have heterogeneous sensors and their outputs are required to be processed and fused at high reliability with severe time constraints [11,12].

Control algorithms convert the outputs of the perception into vehicle actions and this necessitates robustness, safety guarantees and adaptability to the uncertain environment. At the same time, the features place powerful requirements on the power electronics, such as the voltage regulation, actuator drives, thermal management and energy efficiency, especially in electric and hybrid cars [13,14].

The majority of the available literature addresses sensing, control or power electronics separately. Nevertheless, incomplete analysis does not reveal the interactions at a system level, trade offs and propagation of failures. Hence, these subsystems should be analysed as a whole and provide a holistic and integrated review to comprehend the influence of these subsystems on the reliability, scalability and readiness of ADAS to be deployed and used in smart mobility.



1.5 Objectives, Scope and Organization of the Review

The main goal of this overview is to take a critical look at the development of the Advanced Driver Assistance Systems in the wider framework of smart mobility, especially sensing technologies, control strategies and power electronic integration. The review will focus on the synthesis of emerging events that have been reported in the last 2-5 years, the trends in technology and the gaps in research that have remained to be addressed.

The areas covered by this paper are sensor architecture, perception and fusion, control methodologies, power supply, actuation electronics, system integration and safety. The paper follows the following structure: the further sections discuss sensing technologies, control frameworks and power electronic subsystems, as well as the integration issues, standards and research perspective.

2. Concept and Classification of Advanced Driver Assistance Systems (ADAS)

2.1 Definition and Functional Objectives of ADAS

Advanced Driver Assistance Systems (ADAS) are a type of embedded vehicles technology that aims at aiding, supplementing and even automating motor functions by constantly monitoring the surroundings and helping the driver make an informed decision and control the car. ADAS consists of sensing, computing and actuation to ensure better road safety, driving comfort and traffic efficiency, but not completely reliance on human control [6].

The main functional aims of ADAS are to avoid the collision, improve the situational awareness, reduce the driver workload and increase the operational efficiency. ADAS can solve the problem of human perception and reaction time, especially when dealing with complicated or high stress situations, by generating warnings in real time, applying countermeasures in steering or braking and modifying vehicle behaviour [7,8]. These goals are much more consistent with the global road safety plans which put more emphasis on preventive but reactive methods of safety [4].

2.2 ADAS Maturity and Levels of Driving Automation.

The maturity of ADAS technologies is usually compartmentalized based on the levels of driving automation framework as agreed upon by the Society of Automotive Engineers (SAE). This system defines automation of vehicles into Level 0 (no automation) and Level 5 (full automation), with Level 1 and Level 2 being mostly used by the ADAS and Level 3 being partially applied under the control conditions [6].

Single function assistance that is offered at Level 1 includes lane departure warning or adaptive cruise control. The level 2 systems are integrated systems that have several assistance features, which allow the system to have longitudinal and lateral control at the same time under the supervision of the driver. The shift to Level 3 conditional automation also comes with more responsibility on the part of the system, although it also puts forth the challenge of driver takeover, system reliability and safety validation [15,16]. ADAS maturity cannot simply be determined by the number of features but by system reliability, sensor redundancy, decision making strength and quality of human machine interaction and all of them define real world deployability as well as safety performance [17].

2.3 Safety Versus Comfort ADAS Feature.

The features of ADAS can be divided into two groups, namely safety oriented and comfort oriented features, depending on their operational purpose. Safety oriented ADAS will either avoid accidents or reduce their severity since they intervene in the critical situations. Automatic emergency braking, forward collision warning, lane keeping assistance and blind spot detection can be given as examples. The direct objectives of these systems are the reduction of crash leading factors, i.e., distraction, delayed reaction and misjudgement [8,9].

Conversely, comfort based ADAS functions aim to decrease the workload of a driver and improved driving comfort instead of the actual safety intervention. This category includes adaptive cruise control, traffic jam assist, parking assistance and information systems of speed limit. Though also comfort oriented features, they indirectly help to increase the safety by reducing the stress and fatigue of drivers in the case of a long or congested road [17,18].

Contemporary ADAS systems are becoming more and more a combination of both types to reflect a safety comfort goals collision in the design of smart vehicles.

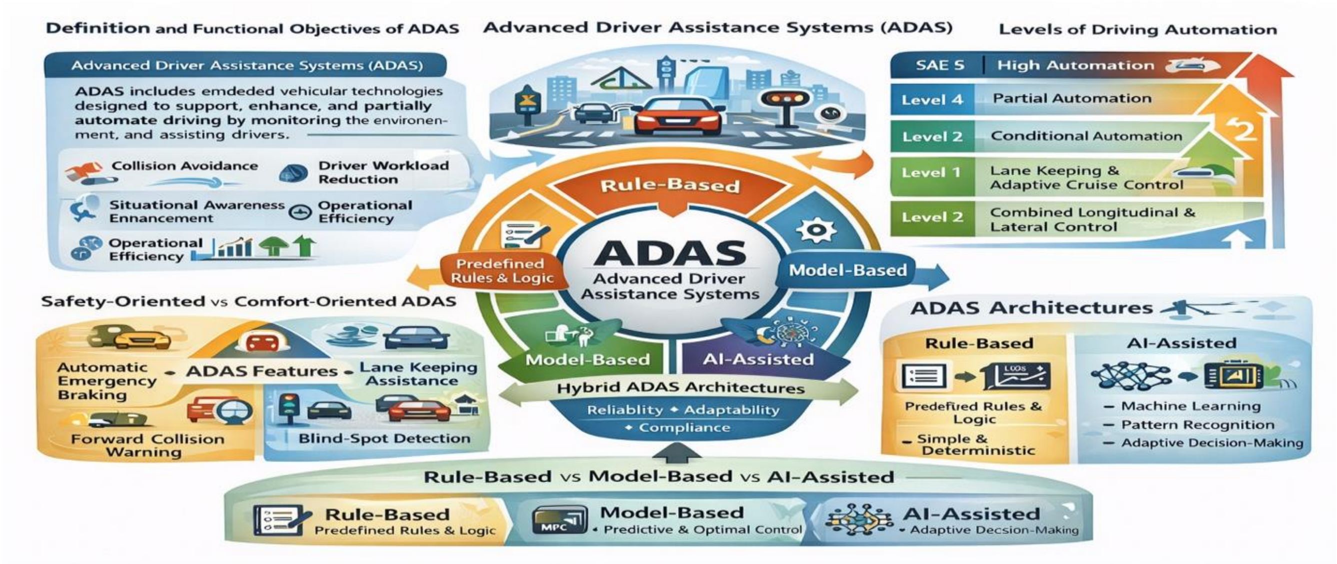
2.4 AI Assisted, Model Based and Rule Based ADAS Architectures.

The approaches of ADAS architecture have evolved considerably thus moving away the deterministic logic based systems to the data based intelligent systems. Rule based ADAS architectures are based on allowed thresholds and decision rules that are based on expert judgments and regulation guidelines. These systems are computationally efficient and understandable; however, they have few adjustability to complex and uncertain driving conditions [17].

Model based architectures use mathematical models of the vehicle dynamics and the interaction with the environment and make use of predictive and optimal control techniques. ADAS can predict the future and impose safety limits through techniques like model predictive control (MPC), which is why they can be applied in lane keeping and collision avoidance systems [5,19].

A newer application of AI assisted ADAS architectures has emerged within the last few years owing to improved machine learning and deep neural networks. These systems also facilitate powerful perception and recognition of patterns and adaptive decision making in unstructured traffic situations. Nevertheless, explainability, safety validation and computational overhead issues continue to pose a major problem when scaling to large scale [7,12].

The adoption of conditional algorithm, designs and artificial intelligence strategies indicates the need to adopt hybrid ADAS designs to create a competent mix of reliability, responsiveness and compliance with laws and regulations.



ADAS includes emdeded vehicular technologies designed to support, enhance, and partially automate driving by monitoring the environen-ment, and assisting drivers.

3. Sensing Technologies in Advanced Driver Assistance Systems (ADAS)

3.1 Vision Based Sensors

The sensing of vision is at the core of numerous ADAS functionalities because of the capability to provide rich semantic data of the driving scene. ADAS camera systems are usually categorized based on the type of monocular, stereo or surround view and each system has varying depth perception and field of view capabilities. Monocular cameras have been shown to be cheap and extensively used, whereas stereo and surround cameras are capable of greater depth estimation and situational awareness necessitating challenging driving conditions [20,21].

Visions sensors facilitate the processes of critical perception, including the detection of lanes, recognition of objects and pedestrians, recognition of traffic signs and lights and driver monitoring. The latest developments in convolutional neural networks and transformer based frameworks have made the vision based perception systems highly accurate and robust in structured traffic conditions [12,22].

But camera based systems are still sensitive to any changes in light, bad weather, shadow, glare and occlusions and may lead to poor detection. The night time driving, fog, rain and limited sight of objects also remain as a problem, requiring complementary senses and advanced preprocessing methods to make operational safety [17,23].

3.2 Radar Systems

Radar cameras are also crucial in ADAS as they give safe distance and speed estimates regardless of the amount of light. The automotive radar systems generally fall into short range radar (SRR), mid range radar (MRR) and long range radar (LRR), each designed to be used in a specific application (blind spot detection, cross traffic alert and adaptive cruise control) [24].

The radar based ADAS properties are adaptive cruise control, forward collision warning and automatic emergency braking, in which the estimation of relative speed and range are crucial. Recent frequency modulated continuous wave (FMCW) radars working at 77-81 GHz have a high resolution and better object discrimination [25,26].

One of the strengths of radar systems is that it works well with bad weather conditions like rain, fogs and dusts when optical sensors are mostly ineffective. However, radar has some drawbacks, such as the angular resolution limitations and multipath reflections, which also require combining it with other sensing modalities to classify objects correctly [24].

3.3 LiDAR Systems

The Light Detection and Ranging (LiDAR) systems enable accurate three dimensional environment perception through the emission of laser pulses and measurement of time of flight to create dense point clouds to represent the environment. LiDAR is an efficient method that allows estimating the distance precisely, recognizing the shape of objects and mapping them in high resolution, which is especially useful when it comes to obstacle detection and free space estimation in ADAS [27,28].

LiDAR sensors with high resolution greatly boost the mapping of the environment and the localization performance in urban environments where it is very complex. Solid state LiDAR technologies have also led to more reliable designs by decreasing the mechanical complexity and increasing the longevity [29].

Although this has been made, the inability of LiDAR devices to access ADAS in mass market is still limited by cost, susceptibility to environmental pollution, data analysis challenges and issues of scalability. The mentioned aspects remain an impediment to mass implementation, especially in low price car segments [20,29].

3.4 Ultrasonic and Inertia Sensors.

Ultrasonic sensors are mostly applied in ADAS regarding short range perception, especially in parking aid, obstacle detection and low speed manoeuvring. These sensors work at ultrasonic frequencies and they can be used as reliable proximity sensors with a small range of operation and are inexpensive to use in near field applications [30].

The IMUs (Inertial Measurement Units) that are composed of the accelerators and the gyroscopes complement the perception system, by making available the motion and orientation information. IMUs with a combination with Global Navigation Satellite Systems (GNSS) make it possible to obtain precise data on the location and movement of the vehicle, especially in areas where the inputs of satellite navigation are weak or absent, including tunnels and urban canyons [31,32].

This combination of ultrasonic sensors with inertial and GNSS measurements increases the accuracy of low speed navigation and helps in the effective support of maneuvers in limited areas.

3.5 Sensor Fusion Strategies

Due to the nature of individual sensors, sensor fusion has emerged as a viable prerequisite to stable ADAS perception. Fusion strategy involves the use of complementary sensing modalities, which are cameras, radar, LiDAR and inertial sensors, to increase robustness, accuracy and fault tolerance [11,23].

Current ADAS uses probabilistic fusion algorithms such as Kalman filters, extended Kalman filters, particle filters and Bayesian inference algorithms to coordinate the heterogeneous sensor data with dissimilar uncertainty attributes. Fusion frameworks based on deep learning have also become available, so end to end perception pipelines with multi sensory inputs processed together are also possible [12,17]. The key advantages of an effective sensor fusion include high reliability of perception in challenging scenarios, minimization of false detections and redundancy needed by safety critical ADAS functions.

Table 1: Sensing Technologies Used in ADAS

Sensor Type	**Configuration / Type**	**Key Functions**	**Advantages**	**Limitations**	**Typical ADAS Applications**
Vision Sensors	Monocular, Stereo, Surround view	Lane detection, object & pedestrian recognition, traffic sign recognition	Rich semantic information, low cost	Sensitive to lighting, weather, occlusion	Lane keeping assist, traffic sign recognition
Radar Sensors	Short , Mid , Long range radar	Distance & velocity estimation	Robust in fog, rain, dust	Limited angular resolution, multipath reflections	Adaptive cruise control, collision warning
LiDAR Sensors	Mechanical & solid state LiDAR	3D mapping, object shape detection	High accuracy & resolution	High cost, processing complexity	Obstacle detection, environment mapping
Ultrasonic Sensors	Short range ultrasonic	Proximity sensing	Low cost, reliable at low speed	Very limited range	Parking assist, obstacle detection
Inertial Sensors (IMU)	Accelerometers & gyroscopes	Motion & orientation estimation	Works without external signals	Drift over time	Vehicle localization & stability control
GNSS	GPS / Multi constellation	Global positioning	Wide coverage	Signal loss in tunnels & urban canyons	Navigation & route guidance
Sensor Fusion	Kalman filter, Bayesian, Deep learning	Multi sensor perception	High robustness & redundancy	Computational complexity	Autonomous perception & decision making

4. Control Architectures for Advanced Driver Assistance Systems (ADAS)

4.1 Classical Control Techniques

The classical methods of control continue to be applicable in ADAS because they are simple, reliable and can be done in real time. Proportional-Integral-Derivative (PID) controllers, as well as state space control, are used frequently in braking, steering and longitudinal vehicle control. The controllers can adjust the speed of vehicles, yaw rate and lateral deviation, according to onboard sensor feedback [5,33].

In braking mechanisms like a car automatic emergency braking and adaptive cruise control, the PID based strategies are used to stabilize the response in the braking mechanism in the event of a nominal driving condition. State space models allow a systematic approach to model vehicle dynamics, as well as allow tuning controllers to multi variable systems [34].

Classical control techniques are however limited to deal with non linear vehicle motion, actuators and dynamically varying traffic conditions. The issues of stability and robustness are also important design considerations, particularly when the parameters are unpredictable, the road friction changes and sensor noise. Recent research focuses on the enhancement of robustness by using gain scheduling and disturbance observers in order to increase the utility of classical controllers in the contemporary ADAS systems [17].

4.2.1 Model predictive control (MPC)

MPC has also become a leading control approach to ADAS because it explicitly manages constraints on the system and the future vehicle behavior. MPC is a type of optimization problem that includes vehicle dynamics, actuator constraints and the safety constraints in terms of vehicle dynamics inspired over a limited representation horizon [19,35].

MPC has found extensive applications in lane keeping assistance, adaptive cruise control and collision avoidance, among other ADAS applications, where it is important to keep safe distances and paths. The fact that MPC is capable of streamlining steering and braking activities without violating road limits and obstacles constraints predisposes it to intricate driving conditions [36].

Although it has benefits, MPC adds complexity in computations which may pose a problem in real time execution on embedded automotive systems. The current trends include minimizing the computational efforts with the help of linearized models, explicit MPC and learning assisted prediction models, which allow a practical implementation of them in production cars [18,37].

4.3 AI based and Learning based Control.

AI assisted and learning assisted control measures mark a major change in the development of ADAS that allows the system to respond to dynamic and uncertain traffic conditions unstructured conditions. The use of fuzzy logic control, artificial neural networks, reinforcement learning and other techniques enables ADAS to infer complex control policies via data as compared to merely existing literature [7].

The fuzzy logic controllers are also especially useful in dealing with uncertainty and inaccuracy in driver behavior and environmental perception. Neural network controllers make it possible to have a nonlinear mapping between sensor signals and control signals to allow adaptive steering and speed control [12,22]. In the context of trajectory planning and decision making, reinforcement learning has been the focus of the interest, with agents training the optimum behavior through interacting with simulated and real environments [38].

Nonetheless, issues pertaining to explainability, safety verification and generalization are critical issues of discouragement to mass usage. The recent research focuses on hybrid control structures where the learning based units are used in conjunction with the rule based or model based safety layers to guarantee the safe functioning of ADAS [17,18].

4.4 Human Machine Interaction and joint control.

Human Machine Interaction (HMI) is one of the key elements of ADAS, especially within systems that have shared control power between the automation and the driver. Shared control architectures are designed to assist the driver and maintain situational awareness and ensure a smooth transition between automated control and manual control [15,16].

With vision based and physiological sensors, driver tracking systems determine driver focus, weariness and willingness to assume control. Such systems are necessary when it comes to conditional automation, in which case timely and safe takeover is a must. It has been demonstrated that the lack of trust or excessive dependence on ADAS by the driver may adversely affect the safety, which is why clear feedback about the system and the user friendly interface design should be emphasized [39,40].

Recent works aim at maximizing the takeover time, trust calibration as well as workload control with emphasis on adaptive HMI strategies that are responsive to the state of drivers and traffic complexity. It is now acknowledged that effective shared control structures are a necessary condition to enable the safe deployment of advanced ADAS and more autonomous driving systems of the future [41].

Table 2: Control Architectures in Advanced Driver Assistance Systems (ADAS)

Control Architecture	Control Techniques	Key Applications in ADAS	Advantages	Limitations	Representative Studies (2020–2025)
Classical Control	PID, State space control, Gain scheduling	Adaptive cruise control, Automatic emergency braking, Steering control	Simple design, Real time feasibility, High reliability	Limited handling of nonlinear dynamics, Sensitivity to uncertainties	[17,33,34]
Model Predictive Control (MPC)	Optimization based control, Constraint handling	Lane keeping assistance, Collision avoidance, Trajectory tracking	Predictive capability, Explicit constraint handling	High computational complexity, Hardware dependency	[35,36,37]
AI Based Control	Fuzzy logic, Neural networks	Adaptive steering, Speed control	Handles uncertainty, Nonlinear mapping	Explainability issues, Data dependency	[12,22]
Learning Driven Control	Reinforcement learning, Deep learning	Decision making, Trajectory planning	High adaptability, Self learning capability	Safety validation challenges, High training cost	[7,18,38]

Shared Control & HMI	Driver monitoring, Takeover management	Conditional automation	Improved safety	Trust calibration challenges	[39,40,41]

5. Power Electronic Integration in Advanced Driver Assistance Systems (ADAS)

5.1 Power Supply Architecture for ADAS

ADAS is increasingly becoming more functional, a trend that has greatly transformed the architecture of automotive power supply. The conventional 12 V electrical systems which had been adequate in earlier times to cover simple electronic loads are becoming ineffective to serve the high load sensors, electronic control units (ECUs) and electromechanical actuators. Thus, the trend in modern cars in favor of 48 V mild hybrid designs and high voltage (HV) systems of electric and hybrid cars is becoming a reality [13,42].

Radar subsystems, LiDAR subsystems, camera arrays and high performance processors are components of ADAS that require constant and continuous power supply. This involves advanced power budgeting, redundancy and fault tolerant design, especially where the safety related functions such as brake by wire and steering assistance having to be enhanced. Recent publications point to the significance of dual voltage domain, isolated DC-DC converters and smart power distribution units in order to provide reliability and adherence to the requirements of functional safety (ISO 26262) [43,44].

Other factors that degrade power supply reliability are transient loads, electromagnetic interference and thermal stress. Consequently, power electronic design has integrated to become an important facilitator of scaled and reliable deployment of ADAS.

5.2 Electronics in Actuation Systems Power.

ADAS is based strongly on electrically actuated subsystems to convert control decisions to real vehicle actions. The systems include electric power steering (EPS), brake by wire and electronically throttle control as substitutes or supplements of mechanical connections that allow quicker response, enhanced accuracy and better integration with automation control strategies [14,34].

These actuation systems use power electronics as the key to their operation based on the inverters, DC-DC converters and motor drive units. The components control voltage and current to electric motors, therefore, allowing a proper control of torque under different load conditions. Several new developments in wide bandgap semiconductor devices like silicon carbide (SiC) and gallium nitride (GaN) have been shown to be more efficient in switching, better in power density and thermal need and are, hopefully, get increasingly successful in ADAS applications [26,30].

Power electronics in combination with control and sensing systems make the system more responsive and allows fault detection in real time. Nonetheless, it also presents such issues as electromagnetic compatibility and safety certification, which have to be tackled with the thorough system level co-design.

5.3 Thermal Management and Energy Efficiency.

With the extended capabilities of ADAS, energy efficiency is the critical design factor, especially when the electric and hybrid cars are considered, where auxiliary power consumption directly affects the driving range. Inverters, converters and motor drives have power losses that lead to low system efficiency and high thermal stress. One of the key research areas is the reduction of conduction and switching losses caused by the optimal circuit topology and complex semiconductor materials, in turn [10,45].

Pulp electronics and high switching frequency create a lot of heat and thermal management of ADAS power electronics has become difficult. Weak heat dissipation will reduce the reliability of components, increase aging and reduce the safety of systems. The recent works emphasize employing sophisticated cooling methods, such as liquid cooling, conceptual heat or pipes and co-designing thermal and electrical thermal in order to achieve the observable and sustainable integrated cooling to ensure the safe operating temperatures about peak load conditions [17,46].

Power electronic integration that is energy efficient is not only improving the reliability of ADAS but also advanced the sustainability targets by lowering the vehicle energy usage and emissions.

6. Communication and System Integration

6.1 In-Vehicle Networks for ADAS

ADAS is based on an efficient and reliable in-vehicle communication network that allows real time data exchange between sensors, electronic control units (ECUs) and actuators. Classic buses like Controller Area Network (CAN) and Local Interconnect Network (LIN) are still employed broadly in control over high tempo and economic processes. The fact that they have very low bandwidth, however, limits their applicability to data intensive ADAS functions [47].

In order to overcome these shortcomings, FlexRay and Automotive Ethernet have become more popular. FlexRay also has deterministic timing and fault tolerance which is why it is used in safety critical systems like brake by wire and steer by wire systems. Time Sensitive Networking (TSN) and in particular, Automotive Ethernet help to support high rate sensor data packets with cameras, radar and LiDAR and maintains low latency, but synchronization is limited [48].

Current day ADAS systems are gradually transitioning to hybrid network designs that mix existing protocols with Ethernet backbones to compromise on performance, cost and backward compatibility. Such a co-location is essential towards scalable system architecture and future proof vehicles platforms [36].

6.2 Vehicle to vehicle and Vehicle to infrastructure communication.

In addition to in-vehicle integration, Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication are useful in improving the effectiveness of ADAS. The new technologies allow cars to communicate on speed, position, traffic information and hazards, thus expanding situational awareness beyond the sensor range of line of sight [2]. The latest introduction of cellular vehicle to everything (C-V2X) technology and 5G-based communication has reduced latency, reliability and coverage to implement cooperative perception and coordinate maneuvers. Intersection collision warning, cooperative adaptive cruise control and platooning are applications that are based on V2V and V2I data communication [49,50].

Nevertheless, reliability in communication and interoperability as well as spectrum allocation is still a challenge especially in mixed traffic usage where both connected and non connected vehicle are used. The studies are also giving more attention to the hybrid models of perception bearing in mind that onboard sensing is utilized with communicated information to improve robustness [51].

6.3 ADAS contribution to Connected and Cooperative Mobility.

As a facilitating layer, ADAS connects and cooperative mobility between onboard intelligence and external communication systems. In cooperation driving, the work of ADAS functions makes use of common data to foresee the dynamics in the traffic, optimize the vehicle behavior and avert motor collisions. Such a collaborative tool takes ADAS out of a vehicle based paradigm and into a system of systems mobility model [52].

The traffic efficiency and environmental sustainability are also facilitated by connected ADAS due to the facilitation of the flow of traffic, decreased stop and go behavior and synchronized speed adjustment. It has been observed that a collaborative deployment of ADAS may help stop and decrease congestion and exchanges in metropolitan paths dramatically [10,53].

7. Safety, Standards and Regulatory Framework

7.1 Functional Safety Standards for ADAS

The deployment of ADAS involves a critical need to be assured of safety, as it is part of safety related functions of the vehicles. The ISO 26262 standard is a general guideline on functional safety of automotive electrical and electronic systems that emphasizes on the hazard analysis, risk evaluation and lifecycle oriented safety management. To guarantee the deterministic behavior and fault tolerance of systems, ISO 26262 processes are more frequently brought into the system design by the developers of ADAS [54].

As an extension of functional safety, the Safety of the Intended Functionality (SOTIF) standard considers risks occurring due to system constraints, perception and misuse instead of hardware defects. SOTIF is specifically applicable to the case of perception based features of ADAS systems, e.g., object detection and lane recognition, where defective or obscure information about the surrounding environment can result in unsafe traffic behavior [55,56].

Combined, ISO 26262 and SOTIF form a two level safety standard, which is now being used as a regulatory foundation of highly automated ADAS.

7.2 ADAS Cybersecurity Implications.

Increasing connectivity of ADAS adds cybersecurity risks, which may affect vehicle security and privacy of users. Such attack surfaces are in-vehicle networks, wireless communication interfaces and over the air software update mechanisms. Attacks on the ADAS functions have the potential of controlling the sensor data or command controls, which is a severe safety hazard [57].

New regulatory solutions include secure by design measures, intrusion detection, encryption and authentication solutions to mitigate ADAS systems. The automotive cybersecurity management systems are standards that need risk assessment to be performed on a constant basis and over the lifecycle of the vehicle [58,59].

7.3 International Regulatory Vehicles and Compliance issues.

International authorities are engaged in the active revision of rules regulating vehicles safety standards to reflect ADAS and increased automation. Europe, North America and East Asia are requiring or highly promoting the development of particular ADAS functions, such as the automatic emergency braking and lane keeping assistance, in new cars [60,61].

However, regulatory harmonization is still problematic because of the disparity in legal systems, the availability of infrastructure and models of liability. Immediate technological change further makes compliance tricky because it tends to overcome regulatory changes. This means that the manufacturers have to deal with complicated certification processes, but still need to maintain interoperability and safety in different markets [52,62].

8. Challenges and Limitations

8.1 Sensor Uncertainty and Perception Errors

Although there have been great advancements in the sensing technologies, sensor uncertainty and errors in perception are the leading limitations to ADAS. Illumination variations, weather and occlusion can cause problems with vision sensors, whereas radar and LiDAR sensors have issues with the misclassification of objects, multipath reflections and sparse point cloud depiction. Such ambiguities can cause false positive or false negatives, especially when dealing with a challenging urban area [17,23].

Fusion of sensors helps to eliminate several of these limitations but fusion algorithms require accurate calibration and synchronization. The safety risk of perception errors in rare or corner case conditions remains, which is why it is necessary to actively develop uncertainty modelling and test it on the real world conditions [20,63].

8.2 Calculability and Real Time hardware Constraints.

The current ADAS is based on high resolution sensor and sophisticated algorithms, which lead to high computational requirements. Perception and decision making pipelines based on deep learning demand high performance processors that are able to execute their tasks in real time with limited latency. Safety critical systems like collision avoidance and emergency braking are particularly difficult to ensure that they are determined by time [7,12].

The decision trade-off between complexity and the real time constraints of algorithms restricts the application of the more complex AI models to production vehicles. Although there is some partial solution in the form of hardware accelerators and edge computing platforms, the achievement of performance power consumption and cost balance is an unsolved issue [30].

8.3 Energy use and Economic savings Trade Offs.

The use of many sensors, electronic control units and actuators further adds to the power consumption and cost of the system in ADAS equipped vehicles. Including high resolution cameras, LiDAR sensors and processors with high computing power cause more load on the vehicle electrical system, especially in electric vehicles, where the consumption of auxiliary power directly affects the driving range [10,13].

Cost has still been a significant impediment to mass take up of ADAS in both entry level vehicles and emerging markets. To achieve a balance between performance and cost, this requirement can lead to less sensor redundancy (or simpler to control architecture), therefore, weakening robust and safe behavior [29,44].

8.4 Ethical and Legal Partial Automation Problems.

The semi automation presents some complicated ethical and legal matters, especially on where the responsibility lies among the driver and the automated system. The role and responsibility of control and decision making in conditional and semi automated driving mode lead to ambiguity of control authority and responsibility of decision making liabilities and complicate the issue of liability to accident and the legal accountability [64,65].

There are also ethical issues in inevitable cases of collision, which might require trade offs between various safety results in the case of ADAS decision making. Despite the fact that automated driving ethical frameworks are increasingly debated, converting them into verifiable and certifiable system behaviour is one of the greatest challenges [66,67].

9. Emerging Trends and Future Directions

9.1 AI Enabled Perception and Decision Making

The use of artificial intelligence will find more central role in future development of ADAS. Deep learning, self supervised learning and reinforcement learning are improving the perception accuracy, predictive behavior and adaptive control in a complex traffic environment. The new studies are on explainable and safety conscious AI to enhance trust and regulatory acceptance [7,68].

Combining learning based learning with rule based safety layers are a good direction that could be taken to ensure flexibility and stability in next generation ADAS.

9.2 Solid State LiDAR and Next Generation Radar.

Solid state LiDAR and high resolution radar technological development is solving the weaknesses in the cost, resilience and scaling. Solid state LiDAR removes moving parts, enhancing its reliability and allowing it to be easily integrated, which is suitable in mass market cars [28,29].

In the same way, a next generation radar system based on higher frequencies and advanced signal processing is also capable of providing a better angular resolution and object classification. The developments will likely increase the perception robustness, especially in unfavourable environmental conditions [24,26].

ADAS has been becoming more and more connected with autonomous and electric vehicle architectures in which electrified powertrains and software defined architectures are used to complete the entitlement to perception, control and actuation tighter. Distributed computing can be scaled through one platform and centralized computing platforms said to enhance updates via the internet of things and speed up innovation time [69,70].

This convergence advocates the incremental advancement of driver assistance to greater automation of vehicles without compromising on safety and energy.

9.4 ADAS Usage in Sustainable and Smart Cities.

ADAS leads to sustainable and intelligent urban movement because it allows safer driving behaviour, reduces traffic jams and decreases emissions. The related ADAS functions facilitate the collaborative traffic control, eco-driving and efficient infrastructure resource utilization. Research has shown that a large scale deployment of ADAS can also have a drastic impact on traffic management and the environmental condition in cities [1,53].

10. Research Gaps and Open Issues

Nevertheless, despite the fast development, there are still a number of research gaps that have not be addressed. Unified sensing control power co-design structures, which system level interaction trade offs in a co-design, are lacking. The current solutions mostly address these subsystems independently to minimize optimization opportunities [37].

There is limited real world validation in mixed traffic conditions, that is, involving human driven vehicles, partially automated vehicles and connected vehicles. Moreover, scalability and affordability to developing economies cannot be easily guaranteed and in this regard, cost effective architectures should not jeopardize safety and reliability [44,63].

11. Conclusion

This review presents an in-depth overview of the technological development of Advanced Driver Assistance Systems that includes sensing technologies, control architectures, power electronic integration, communications and regulatory factors. The evolution of single assistance applications into complex and smart systems brings out the increasing complexity and significance of ADAS in contemporary mobility.

The results can highlight that ensured integration of sensing, control, communication and power electronics would be a key element of the reliable, scalable and safe deployment of ADAS in the ecosystems around smart mobility. Future development will be important in dealing with the existing issues associated with perception uncertainty, computational efficiency, energy consumption and regulatory compliance.

To sum up, interdisciplinary studies over a long period, mass real life testing and control systems that are adaptive are the key to enhancing the pace and achieving the full potential of ADAS in the connected, autonomous and sustainable transportation networks.

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