Advanced driver assistance systems (ADAS): from safety regulation to metrology-driven calibration environments in the united states

Roman Yurchylo [1]

Received: 2025-09-13
Accepted: 2025-10-20
DOI: https://doi.org/10.5281/zenodo.18943965

Abstract. Federal safety rules, consumer safety rating schemes, and advancements in sensor tech have all contributed to the rapid implementation of Advanced Driver Assistance Systems (ADAS) in the US. However, while the benefits of these systems in reducing crash risks have been established, there is still a lack of scholarship on their impact on automotive diagnostics and service. Set against paradigms of service diagnostics based on measurement and component replacement, ADAS calibration is measurement-precise and critical. This paper contends that the process of ADAS calibration is overly reliant on the completion of steps, with little attention paid to the environment's measurement and calibration. Variables such as floor structure, light level, light stability, and glare can all create blind spots in diagnostics and remain unnoticed. As such, even if calibration is said to be complete, there are likely to be shortcomings. To fill this gap, the paper proposes the first Yurchylo Calibration Environment Passport (YCEP), enacted through a YCEP Quick Test framework. YCEP converts qualitative criteria from workshops to quantitative, objective, and repetitive workshop criteria and applies to stationary and mobile ADAS calibration services to PASS/BORDER/FAIL decider logic. Based on the grounded theory of measurement science, the approach of the YCEP framework improves repeatability, lessens the need for rework, and heightens quality assurance to the U.S. automotive service ecosystem. The author states that environmental diagnostics are a necessity ADAS service quality improvement and will become a standard as systems become more complex and calibration sensitivities increase.

Keywords: Advanced Driver Assistance Systems (ADAS); ADAS calibration; automotive diagnostics; metrology; calibration environment; environmental diagnostics; quality assurance; mobile ADAS services; vehicle safety; sensor calibration.

[1] Master's Degree, Department of History of Ukraine and Methods of Teaching History, Precarpathian University named after V. Stefanyk
https://orcid.org/0009-0006-9059-9126

Introduction

From the last decade, Advanced Driver Assistance Systems (ADAS) have been revolutionizing the automotive industry and have become one of the most important features of all new cars sold in the United States. The combination of federal safety regulations and U.S. consumer crash-test safety ratings have allowed more automotive manufacturers to adopt new safety technologies, such as Automatic Emergency Braking (AEB), Lane Departure Warning (LDW), Lane Keeping Assist (LKA), Blind Spot Detection (BSD), and various pedestrian detection systems [10; 11]. From the premium automotive industry, these systems have become commonplace even in the most affordable consumer automotive models.

Although the safety benefits of ADAS, in the context of the automotive industry, in reducing the number of crashes and injuries, the impact of ADAS technologies systems on automotive diagnostic and service practices has not been considered. The traditional automotive diagnostic processes have been successful in identifying any component failure, mechanical change, or electronic failure of the vehicle.

However, ADAS has introduced solving problems in a whole new way when it comes to the automotive industry, as these systems rely on the vehicle's ability to perceive the environment, as well as the position and alignment of all ADAS components. This has, for the first time, turned calibration into a service that is as critical as any safety-related functions of the vehicle [19]. Now, after even the most routine repair functions such as windshield replacement or bumper repair, suspension work, and even wheel alignment, ADAS calibration has to be completed.

While there are many aspects to consider, the quality of calibration is frequently gauged merely on the completion of the steps of the procedure, often signified by a scan tool declaring the process a success. We contend that this is an overly simplistic view. The process is a measurement process, and the conditions under which measurements are made (floor layout, lighting, glare, etc.) are critical to the success of the calibration [13]. Many factors are indeed considered in the existing statutes and service documents from the OEMs, although they offer little in the way of consistent measurement to verify them. Consequently, there is a significant lack of alignment between the regulatory intent, the OEM process, and the calibration in practice. The main contribution of this paper is to define and analytically defend the Yurchylo Calibration Environment Passport (YCEP) and the YCEP Quick Test. This method induces a different thinking about ADAS calibration, treating it as a measurement problem and structuring a ready for measurement evaluation of the calibration environment, which is a first in the United States, for both fixed workshops and mobile ADAS service configurations.

Results

Genesis of ADAS and the Rise of Environmental Sensitivity

There were electronically assisted safety systems before ADAS was developed. Examples of such systems are Anti-lock Braking Systems (ABS) and Electronic Stability Control (ESC). These systems depended only on internal vehicle sensors and closed-loop control algorithms. They work independently from external visual conditions. Diagnostic processes focused on checking the sensors, evaluating the actuators, and analyzing the fault codes. Systems based on cameras, radars, and LiDAR shifted the focus of research and development [3; 16].

The modern functions of ADAS rely on the interpretation of lane markings, vehicles, pedestrians, and road geometry. This reliance increases sensitivity to the impacting elements of the system. Unlike previous systems, the perception-based ADAS systems rely on specific geometric relationships between the sensor, vehicle body, and the surrounding environment.

In the U.S. market, this change has been reinforced by safety evaluation and regulation [13]. The testing protocols of the IIHS not only examine the presence of ADAS components, but also the functionality of these components in specific situations [5; 6]. To respond to this, the OEMs have to increase the calibration tolerances to ensure that the system performs consistently under the testing conditions, which increases the technical requirements of the service facilities. [17].

One of the main issues with the evolution of ADAS is that it is possible for the systems to underperform while all components are functioning normally (See Figure 1). While no faults occur that would trigger diagnostics, the system's real-world performance may be poorly functioning. Sloping floors, insufficient illumination, and optical glare may all lead to the calibration diagnostics failing. This is a key difference between the traditional diagnostics and calibration of the of ADAS systems. This difference shows that there is a necessity for increased quality control.

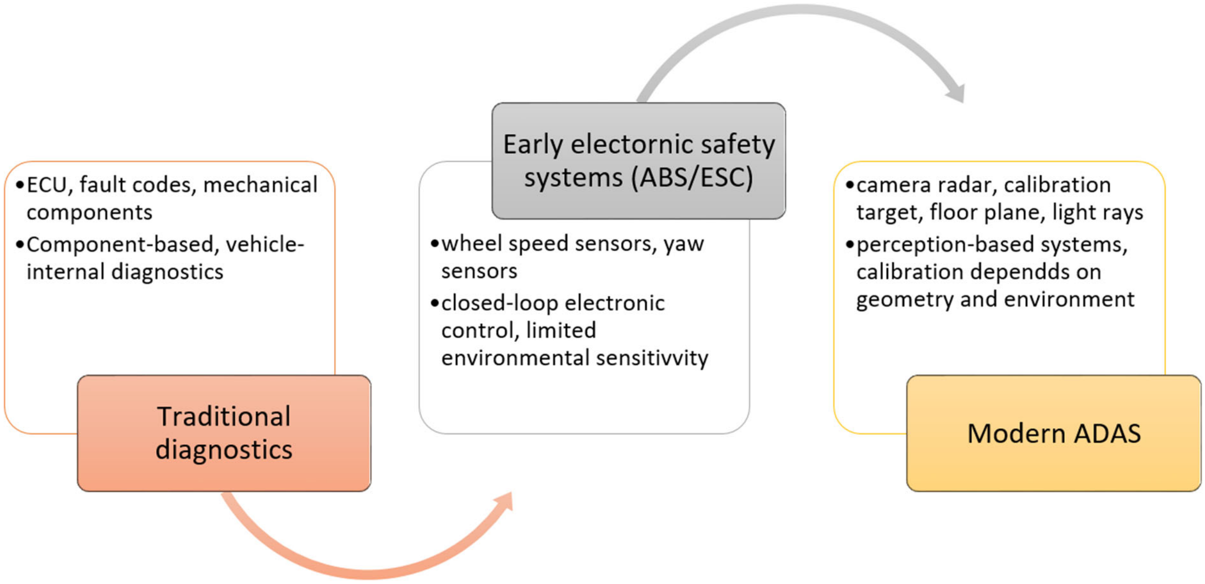

Figure 1. Conceptual evolution of automotive diagnostics from component-based fault detection to environment-dependent ADAS calibration.

U.S. Safety Regulation and the Calibration Blind Spot

1. Regulatory and Rating Drivers in the United States

The rapid adoption of ADAS has been heavily influenced by the regulatory environment in the United States. The NHTSA has implemented the FMVSS No. 127, which states that all new light vehicles must contain an advanced emergency braking (AEB) and pedestrian AEB by 2024 [11]. In line with this, the NHTSA has implemented an assessment program which offers safety ratings based on the ADAS metrics [12]. The performance of the vehicles in the ADAS metrics is a determining factor in the ratings that the manufacturers strive to achieve [5; 6]. This is why it is of the utmost importance for ADAS systems to be implemented to a high functioning standard.

2. OEM Procedures and Qualitative Environmental Requirements

While regulations and ratings concentrate on what a vehicle can do, they offer little insight into the service-side infrastructure. OEM calibration instructions often contain environmental prerequisites, such as leveled flooring, uniform lighting, and no reflections [16]. However, these requirements tend to lack sufficiently detailed descriptions, such as missing numeric boundaries or standardized qualitative assessment methods.

In the U.S. context, with its complicated insurance paperwork and litigation, this poses operational difficulties. If calibration results are called into question, service providers lack objective proof that the environment met OEM specifications [7]. Consequently, the service location's calibration becomes a subjective process, leading to inconsistencies.

ADAS Calibration as a Metrological Process

ADAS calibration essentially differs from standard automotive diagnostic methods since it focuses on measurement alignment and not fault detection. It aims to attain a definitive and accurate Geometrical relationship and position between Vehicle Coordinate System, Calibration Targets, and Sensor Perception [4]. This process is guided and must comply with the principles of repeatability, reproducibility, and repeatable certainty [19] for a guaranteed result as promised by the salesman (See Figure 2).

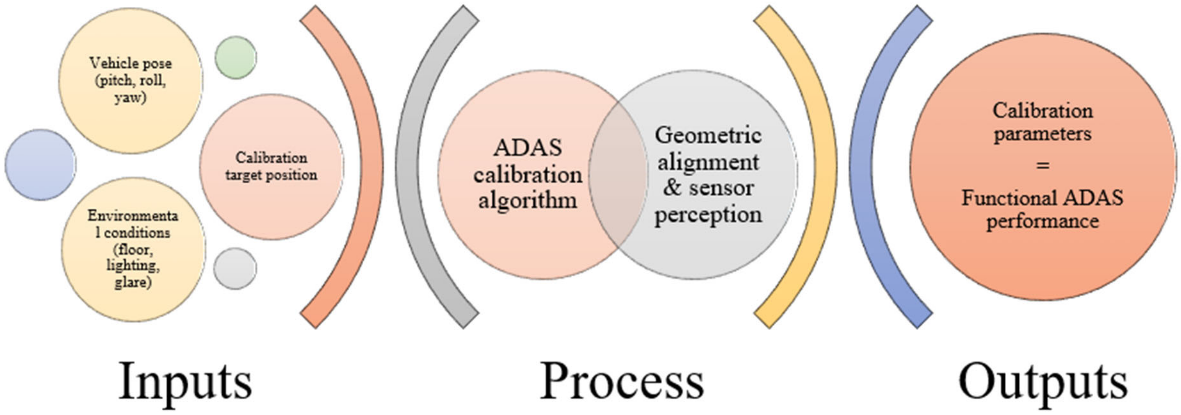

Figure 2. ADAS Calibration as a Metrological Process

In standard diagnostics, the most common and major errors will almost always be identifiable and will always be discrete. Examples include sensor errors, communication errors, etc. However, in most cases, with ADAS, the errors tend to be more systematic, and more to the point, and tend to be unrecognized [4]. Geometrical errors that impair system performance in the real world, can remain present in the Calibration process. This scenario is the reason wires of ADAS systems tend to be very intermittent and difficult to track after making alterations, and the environment is a fundamental factor of success.

Floor geometry also plays a role in vehicle position (pose) during calibration [4; 8]. Even marginally unified slopes or localized irregularities can result in changes to the pitch and yaw angles of the cameras in relation to the calibration target. This can result in the system being biased. The lighting conditions in the environment also change the way the target will be noticed. Consistency during the calibration of the targets is also important to improve the lighting conditions (See Table 1).

Table 1. Key environmental variables influencing ADAS calibration accuracy and their associated risk profiles.

Environmental Variable	Typical Source	Effect on Calibration	Risk Type
Floor slope / unevenness	Workshop floor, drains	Alters camera pitch/yaw	Systematic
Non-uniform lighting	Poor luminaire layout	Target misinterpretation	Systematic
Insufficient illuminance	Low ambient light	Increased noise	Random/Systematic
Optical glare	Windows, glossy surfaces	False features / saturation	Systematic
Lighting instability	Sun movement, open doors	Non-repeatability	Random

Another example of an originating error in a system is optical glare. Cameras, especially wide-angle and surround-view, can have distorted perceptions of the surrounding objects due to reflections from windows, lights, polished floors, or the surfaces of vehicles [8; 15]. Glare does not show anything mechanically wrong, and can result from different times of the day or varying weather, further worsening the consistency of repeated calibrations [18].

From the perspective of measurement science, these remain variables that increase measurement uncertainty, and remain unrecorded or unmeasured in diagnostics scan tools. They only state that the system has completed a calibration algorithm within the embedded software tolerances [8]. Therefore, the procedural success does not confirm the successful measurement. Hence, view it as a metrological process, and it should require the environmental parameters to be controlled and measured [15].

Yurchylo Calibration Environment Passport (YCEP): Concept, Structure, and Scientific Rationale

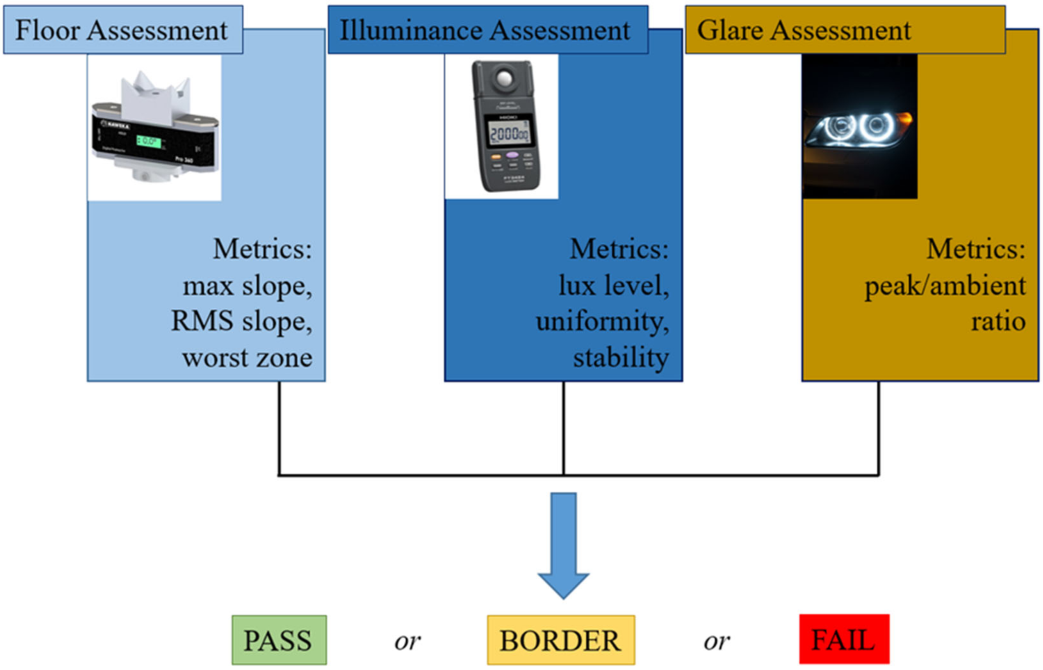

Figure 3. Structure of the Calibration Environment Passport (CEP) Quick Test and its three primary measurement domains.

A suggestion for the YCEP is to offer frameworks that can convert qualitative environmental requirements into something measurable or more tangible. With this suggestion, the environment of the calibration can be viewed as one of the diagnostic modules that would require the same treatment as the diagnostic rigor applied to the sensors, targets, and software. The YCEP is designed around the principle of having a minimal set of measurements that is still adequate for capturing the most salient variables of the environmental uncertainties.

These measurements are framed to be scientifically relevant and operationally feasible to allow for the quick assessment of the environmental uncertainties without interrupting or hindering the flow of the workshop (See Figure 3). The three measurement domains of the YCEP Quick Test are designed to measure the uncertainties in the framework.

1. Floor Geometry Assessment

Using inclinometry, YCEP determines the maximum slope, root mean square (RMS) slope, and identifies the "worst zones". This enables technicians to assess if the floor is generally acceptable for calibration overall, and whether one can safely position it for calibration.

2. Illumination Measurement

One measures lighting at the height and shutter plane of the calibration target with all measurements accomplished in lux. Apart from the absolute value of the lux, YCEP values the evenness and stability of light over time, as uneven light and temporal variations can adversely affect calibrations, even if the average lux value is sufficient.

3. Glare Evaluation

Using the peak-to-ambient ratio, YCEP evaluates the contrast in brightness of the regions around a glare source and the target to assess the source of glare that could obstruct the camera. This metric captures risks that are often overlooked in traditional procedures yet are critical for optical systems.

Table 2. YCEP Quick Test decision categories and corresponding operational actions.

CEP Result	Environmental Status	Operational Decision	Recommended Action
PASS	Conditions within limits	Proceed with calibration	None
BORDER	Marginal conditions	Proceed with mitigation	Lighting adjustment, repositioning
FAIL	Conditions outside limits	Do not calibrate	Relocate or reschedule

YCEP Quick Test results can be classified into one of three outcomes: PASS, BORDER, or FAIL. This logic is designed to be simple, allowing for quick go/no-go assessments with traceability. Users who receive a BORDER classification will be provided with guidance to mitigate the result; this may include repositioning the vehicle, changing the light conditions, or adding a temporary shield to reflective surfaces. From a scientific standpoint, CEP is aligned with the universally accepted principles of measurement control, whereby subjective assessments of the environment are transformed into objective assessments (See Table 2). From an operational perspective, it allows technicians, managers, insurers, and OEM stakeholders to communicate using a common terminology, diminishing uncertainty and enhancing reliability.

Application of YCEP in the United States: Stationary and Mobile ADAS Services

The automotive service ecosystem in the U.S. is a perfect example of a location where YCEP can be implemented. ADAS calibration is done in a number of different places, including OEM dealerships, independent repair shops, and mobile calibration service providers. Each presents different sets of challenges when it comes to the ambient conditions. YCEP, on the other hand, is the solution as it brings standardization in calibration to stationary workshops (See Figure 4). Even a single location may show inconsistencies in the quality of calibration that is done, due to differences in floor leveling, the arrangement of lighting, or the location of service bays in relation to windows [9].

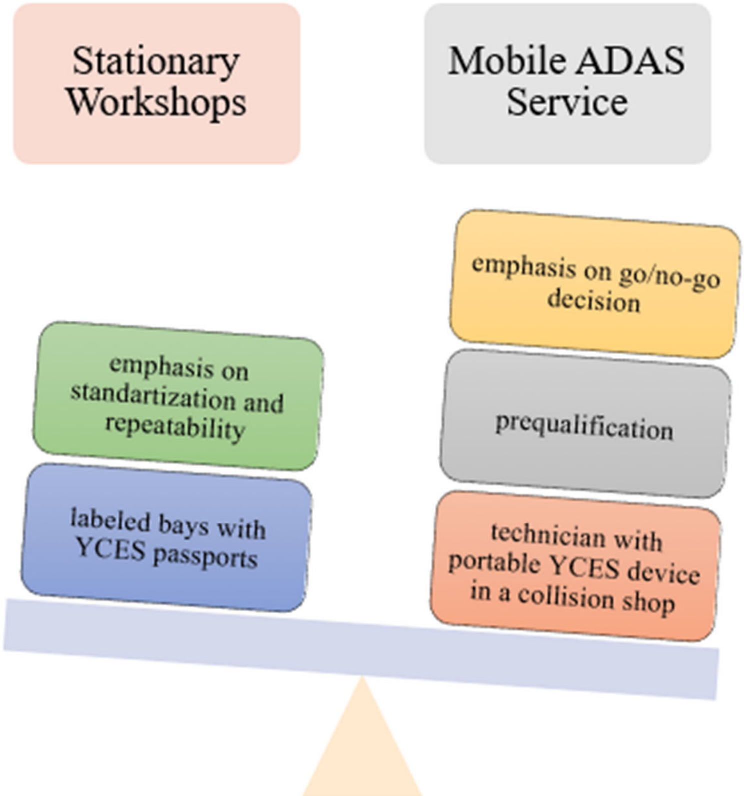

Figure 4. Application of the CEP framework in stationary workshops and mobile ADAS calibration services.

When a service provider passport is issued to each service bay, there is guaranteed repeatability, regardless of which technician is doing the service. The YCEP data collected over time will show, among other things, how the environmental conditions may have changed over time due to lighting changes, moving equipment, or other structural modifications.

The uncertainty in the environment is even more pronounced in mobile ADAS calibration. Mobile service technicians work in collision repair shops that often were not equipped to perform tasks that require optical measuring systems. Without a pre-survey, the chances of the calibration results being unsuccessful or marginal is high. This then creates the need to do the work over again, which causes disruption of the schedule and increases the service provider's liability [14].

YCEP manages this risk by using pre-qualification and real-time screening. Prior to resource deployment, service providers assess partner sites to determine if calibration can be done under current conditions. YCEP Quick Test acts as a quality gate, allowing technicians to decide if they should start the calibration process.

Economically, this is very pertinent to the US market, where the costs and difficulties associated with ADAS-related repairs are significant [1]. YCEP manages operational efficiency and cost management by minimizing failed calibrations and the need for repeat visits.

Implications for the Automotive Service Industry and Workforce

The expansion of ADAS technology has transformed the automotive service industry with new technical requirements and changing professional competencies [2]. The role of automotive technicians has changed; they are not just mechanical/electrical experts, they are measurement practitioners, responsible for managing all things geometric and optical. YCEP has strong implications for improving the workforce. It advocates for literacy surrounding measurement, whereby, technicians understand the importance not just of procedures, but of the possible variations, in the surrounding atmosphere. This helps promote the achievement of better, more consistent outcomes, and reduces reliance on experiential judgment. From an organizational point of view, YCEP gives the opportunity to transition from reactive troubleshooting to proactive quality assurance.

Rather than service providers merely diagnosing and repairing calibration failures, they can do more to anticipate and control environmental variables. This anticipatory, preventive approach is consistent with the more general principles of quality management and continuous improvement [17; 18].

YCEP can also serve as a strategic differentiator in the more competitive service markets in the U.S. Providers that document and standardize calibration environments will be able to provide more assurance to insurers, fleet operators, and OEM partners, and over time this will help shape industry standards.

Table 3. Operational and strategic benefits of CEP adoption in the U.S. ADAS service market.

Stakeholder	CEP Benefit	Practical Outcome
Technicians	Objective guidance	Reduced uncertainty
Service managers	Standardized QC	Fewer reworks
Insurers	Documented conditions	Easier claim resolution
Mobile operators	Pre-qualification	Fewer failed visits

Future Outlook: Environmental Diagnostics as Standard Practice

Continuing advancements in system complexity and sensor quantity will result in even greater narrowing of calibration tolerances. As more diagnostics become more commonplace, this trend indicates that environmental diagnostics will be on par with the other necessary diagnostics. YCEP-like frameworks can become a scalable standard toward industry-wide standardization, both supporting the intention of the regulation and improving real-world safety outcomes.

Conclusion

With the rapid uptake of ADAS technologies in the United States, a paradigm shift has occurred in automotive diagnostics, with the field moving away from component-based fault detection towards measuring, and calculation-based fault detection. This indicates that field calibration quality is inextricable from field environmental conditions and that current procedural methodologies fall short of any guarantee of uniformity. With the introduction of the Calibration Environment Passport framework, this research introduces a viable method of determining calibration readiness, founded in practical metrology. As more advanced ADAS systems are developed, these methodologies will become increasingly important in ensuring that the safety systems function as designed throughout the entire lifecycle of the vehicle.

References

1. AAA. (2023). Cost of advanced driver assistance systems (ADAS) repairs. https://newsroom.aaa.com/wp-content/uploads/2023/11/Report_Cost-of-ADAS-Repairs-FINAL-23.pdf
2. Agrawal, A., Lee, E., & Yi, K. (2023). A robust calibration method for multi-modal sensors with non-overlapping fields of view. IEEE Sensors Journal, 23(19), 23334–23345. https://doi.org/10.1109/JSEN.2023.3300957

3. An, P., Ding, J., Quan, S., Yang, J., Yang, Y., Liu, Q., & Ma, J. (2024). Survey of extrinsic calibration on LiDAR–camera systems for intelligent vehicles: Challenges, approaches, and trends. IEEE Transactions on Intelligent Transportation Systems, 25(11), 15342–15366. https://doi.org/10.1109/TITS.2024.3419758
4. Beltrán, J., Guindel, C., De La Escalera, A., & García, F. (2022). Automatic extrinsic calibration method for LiDAR and camera sensor setups. IEEE Transactions on Intelligent Transportation Systems, 23, 17677–17689. https://doi.org/10.1109/TITS.2022.3155228
5. Insurance Institute for Highway Safety. (2024). Pedestrian automatic emergency braking test protocol (Version IV). https://www.iihs.org/media/f6a24355-fe4b-4d71-bd19-0aab8b39aa7e/5ZH5qg/Ratings/Protocols/current/test_protocol_pedestrian_aeb.pdf
6. Insurance Institute for Highway Safety. (2024). Vehicle-to-vehicle front crash prevention 2.0 test protocol (Version I). https://www.iihs.org/media/b46269d5-0cd2-4342-8303-f4cef5f9f120/MzQN5Q/Ratings/Protocols/archive/FCP_2.0_test_protocol_v1_0424.pdf
7. Kullgren, A., Kusano, K. D., & Sherony, R. (2023). Automatic emergency braking effectiveness in the United States: A retrospective crash-based evaluation. Traffic Injury Prevention, 24(1), 1–7. https://doi.org/10.1080/15389588.2022.2131403
8. Li, L., Pao, W. Y., Howorth, J., Agelin-Chaab, M., Roy, L., Komar, J., Knutzen, J., Baltazar, A., & Muenker, K. (2024). An investigation of ADAS camera performance degradation using a realistic rain simulation system in wind tunnel (SAE Technical Paper 2024-01-1972). SAE International. https://doi.org/10.4271/2024-01-1972
9. Liu, X., Deng, Z., & Zhang, G. (2025). Targetless radar–camera extrinsic parameter calibration using track-to-track association. Sensors, 25(3), 949. https://doi.org/10.3390/s25030949
10. National Highway Traffic Safety Administration. (n.d.). Driver assistance technologies. https://www.nhtsa.gov/vehicle-safety/driver-assistance-technologiesNational Highway Traffic Safety Administration. (2024a). Final rule: Automatic emergency braking systems for light vehicles (FMVSS No. 127). https://www.nhtsa.gov/sites/nhtsa.gov/files/2024-04/final-rule-automatic-emergency-braking-systems-light-vehicles_web-version.pdf
11. National Highway Traffic Safety Administration. (2024b). New Car Assessment Program (NCAP) final decision notice: Advanced driver assistance systems roadmap. https://www.nhtsa.gov/sites/nhtsa.gov/files/2024-11/NCAP-Final-Decision-Notice-Advanced-Driver-Assistance-Systems-Roadmap-11182024-web.pdf
12. National Institute for Automotive Service Excellence. (2024). Servicing vehicles with ADAS (webinar). https://www.ase.com/press-releases/servicing-vehicles-with-adas-1-hour-webinar
13. Qiu, Z., Martínez-Sánchez, J., Arias-Sánchez, P., & Rashdi, R. (2023). External multi-modal imaging sensor calibration for sensor fusion: A review. Information Fusion, 97, 101806. https://doi.org/10.1016/j.inffus.2023.101806
14. Rövid, A., Vincze, Z., Pálinkás, T., Kocsis, M., Serrano, V., & Szalay, Z. (2025). Reference platform for ADAS camera system evaluation. Sensors, 25(6), 1690. https://doi.org/10.3390/s25061690
15. Sun, C., Wei, Z., Huang, W., Liu, Q., & Wang, B. (2023). Automatic targetless calibration for LiDAR and camera based on instance segmentation. IEEE Robotics and Automation Letters, 8(2), 981–988. https://doi.org/10.1109/LRA.2022.3191242

16. Tan, Z., Zhang, X., Teng, S., Wang, L., & Gao, F. (2024). A review of deep learning-based LiDAR and camera extrinsic calibration. Sensors, 24(12), 3878. https://doi.org/10.3390/s24123878
17. Tran, K. B., Carballo, A., & Takeda, K. (2024). LiDAR–360° RGB camera–360° thermal camera targetless calibration for dynamic situations. Sensors, 24(22), 7199. https://doi.org/10.3390/s24227199
18. Xu, J., Li, R., Zhao, L., Yu, W., Liu, Z., Zhang, B., & Li, Y. (2022). Cammap: Extrinsic calibration of non-overlapping cameras based on SLAM map alignment. IEEE Robotics and Automation Letters, 7, 11879–11885. https://doi.org/10.1109/LRA.2022.3207793