

ADAS Validation Methodology for Class 8 Commercial Trucks: ACC, AEBS, LDW, and TSR

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Article Info:

DOI: 10.22399/ijcesen.5338

Received : 25 August 2023

Revised : 25 September 2023

Accepted : 02 October 2023

Keywords

Advanced driver assistance systems,
Class 8 trucks,
adaptive cruise control,
automatic emergency braking,
lane departure warning,
traffic sign recognition

Abstract:

Heavy-duty commercial vehicles present advanced driver assistance system validation challenges that passenger-vehicle methods do not fully address, particularly because Class 8 trucks operate with air-brake dynamics, variable payload, trailer articulation, rollover sensitivity, and demanding commercial operating environments. As of 2023, no standardized multi-feature validation framework existed specifically for Class 7 and Class 8 trucks in the United States regulatory context, despite increasing deployment of adaptive cruise control, automatic emergency braking systems, lane departure warning, and traffic sign recognition. This paper proposes a structured five-step validation methodology for Class 8 commercial trucks covering adaptive cruise control, automatic emergency braking systems, lane departure warning, and traffic sign recognition across diesel, compressed natural gas, and battery electric configurations. The proposed framework integrates requirements definition, hazard analysis, scenario matrix development, staged testing, and traceable sign-off evidence. It addresses test scenario development, powertrain variant coverage, pass and fail criteria anchored in applicable regulatory expectations, and release documentation suitable for original equipment manufacturers and suppliers. The methodology recognizes that commercial-truck advanced driver assistance systems do not merely perceive and warn; they interact with air brakes, electronic stability control, engine torque, retarders, regenerative braking, and trailer dynamics. The proposed approach provides a regulation-aligned, variant-aware, and evidence-driven validation path for Class 8 truck platforms and contributes a practical framework for closing the gap between passenger-car validation maturity and heavy-vehicle advanced driver assistance system deployment.

1. Introduction

Advanced driver assistance systems have become increasingly important in heavy-duty trucking because commercial vehicles operate for long durations, travel extensive highway mileage, and frequently carry high-value or safety-critical freight. By 2023, adoption of active safety technologies in Class 8 trucks had grown significantly. The National Highway Traffic Safety Administration and Federal Motor Carrier Safety Administration stated in the 2023 heavy-vehicle automatic emergency braking notice of proposed rulemaking that automatic emergency braking was likely equipped on the majority of Class 8 vehicles, while also noting that many new heavy vehicles still lacked the technology and that no standardized United States heavy-vehicle automatic emergency

braking performance benchmark was yet in force [1]. The regulatory environment was also accelerating. Federal Motor Vehicle Safety Standard 121 establishes the United States air-brake requirements applicable to trucks, buses, and trailers equipped with air-brake systems [2]. Federal Motor Vehicle Safety Standard 136 establishes electronic stability control requirements for heavy vehicles and aims to reduce rollover and directional loss-of-control crashes [3]. In 2023, the National Highway Traffic Safety Administration and Federal Motor Carrier Safety Administration proposed a new Federal Motor Vehicle Safety Standard 128 that would require automatic emergency braking on heavy vehicles above 10,000 pounds gross vehicle weight rating, but this was a proposed rule and not a finalized mandate in 2023 [1]. Class 7 and Class 8 trucks differ fundamentally from passenger vehicles in ways that directly affect

advanced driver assistance system validation. A Class 8 tractor-trailer may operate bobtail, with an empty trailer, partially loaded, or at gross combination weight. Each load state changes stopping distance, brake balance, tire utilization, thermal behavior, and stability margin. Trailer articulation introduces trailer angle, off-tracking, trailer swing, rear swing, and jackknife risk. Unlike passenger vehicles, tractor-trailer combinations do not behave as a single rigid body during turning, braking, or evasive motion. Air-brake architecture is another central distinction. Heavy trucks use pneumatic braking systems rather than hydraulic systems. This introduces reservoir pressure dynamics, compressor behavior, pneumatic delay, brake chamber response, and tractor-trailer brake timing. Any automatic emergency braking or adaptive cruise control command must therefore be evaluated through the braking system regulated by Federal Motor Vehicle Safety Standard 121 [2]. Heavy trucks also have greater rollover sensitivity because of higher centers of gravity, larger cargo volumes, longer wheelbases, and sensitivity to road grade, road crown, wind, and abrupt steering inputs. Electronic stability control in heavy vehicles is therefore not only concerned with yaw stability but also rollover mitigation [3]. Commercial operating environments further complicate validation. Heavy trucks operate on highway corridors, freight terminals, loading docks, construction zones, rural roads, weigh stations, ports, and distribution centers. These domains introduce road markings, signs, objects, lighting conditions, and traffic interactions that are not fully represented in passenger-car validation programs. Longer and taller vehicles also create sensor integration challenges, including larger blind zones, trailer-dependent sensor occlusion, and calibration assumptions that vary across body and trailer configurations. The literature gap is therefore clear. Passenger-car validation methods are mature, but they assume relatively stable mass, hydraulic braking, no trailer articulation, and narrower operational design domains. In contrast, public literature has not provided a multi-feature validation methodology designed specifically for Class 7 and Class 8 trucks across adaptive cruise control, automatic emergency braking systems, lane departure warning, and traffic sign recognition. The 2023 heavy-vehicle automatic emergency braking notice of proposed rulemaking directly acknowledged the absence of standardized United States heavy-vehicle automatic emergency braking performance metrics [1]. This paper contributes a five-step advanced driver assistance system validation methodology for Class 8 commercial trucks. The framework covers requirements

definition, hazard analysis, scenario development, staged testing, and sign-off evidence. It aligns validation with Federal Motor Vehicle Safety Standard 121, Federal Motor Vehicle Safety Standard 136, proposed Federal Motor Vehicle Safety Standard 128, United Nations Economic Commission for Europe Regulation 131, United Nations Regulation 130, and European Union Regulation 2019/2144. It also addresses diesel, compressed natural gas, and battery electric powertrain variants as explicit validation variables rather than background assumptions.

2. Regulatory Framework

2.1 Federal Motor Vehicle Safety Standard 121

Federal Motor Vehicle Safety Standard 121 is the primary United States regulation for air-brake performance. It establishes performance and equipment requirements for vehicles equipped with air-brake systems, including trucks, buses, and trailers. Its purpose is to ensure safe braking performance under normal and emergency conditions [2]. This standard is directly relevant to Class 8 advanced driver assistance system validation because adaptive cruise control and automatic emergency braking commands ultimately act through the service-brake system. Validation engineers must therefore understand pneumatic response, reservoir pressure behavior, brake chamber timing, anti-lock braking system interaction, and brake-distribution requirements before defining pass and fail criteria for automated braking features.

2.2 Federal Motor Vehicle Safety Standard 136

Federal Motor Vehicle Safety Standard 136 is the primary United States electronic stability control standard for heavy vehicles. It establishes performance and equipment requirements for heavy-vehicle electronic stability control systems and is intended to reduce crashes caused by rollover or directional loss of control [3]. This standard applies to truck tractors over 26,000 pounds gross vehicle weight rating with specified exceptions. It is important for advanced driver assistance system validation because electronic stability control forms the stability-control foundation on which adaptive cruise control and automatic emergency braking depend. Automated braking must not destabilize a tractor-trailer combination that electronic stability control is attempting to protect.

2.3 Proposed Federal Motor Vehicle Safety Standard 128

In July 2023, the National Highway Traffic Safety Administration and Federal Motor Carrier Safety Administration published a notice of proposed

rulemaking proposing a new Federal Motor Vehicle Safety Standard 128 for automatic emergency braking on heavy vehicles above 10,000 pounds gross vehicle weight rating [1]. This was a proposed rule in 2023, not a finalized mandate. The proposal included three core test scenarios: stopped lead vehicle, slower-moving lead vehicle, and decelerating lead vehicle. It also included false-activation tests using a steel trench plate and a pass-through scenario. The proposal specified false-activation deceleration limits of no more than 0.25 g peak without manual braking and no more than 0.45 g with manual braking in those false-activation cases [1]. The proposed implementation timeline was three years after a final rule for vehicles already subject to Federal Motor Vehicle Safety Standard 136, and four years after a final rule for vehicles above 10,000 pounds gross vehicle weight rating not already subject to Federal Motor Vehicle Safety Standard 136 [1].

2.4 United Nations Regulation No. 131

United Nations Regulation No. 131 establishes requirements for advanced emergency braking systems on heavy vehicle categories M2, M3, N2, and N3. The regulation defines advanced emergency braking systems as systems capable of automatically detecting an imminent forward collision and activating braking to avoid or mitigate the collision [4]. Regulation 131 is important because it provides an established international framework for heavy-vehicle automatic emergency braking performance. It includes lead-vehicle moving scenarios, stopped-lead-vehicle scenarios, and false-positive considerations.

2.5 United Nations Regulation No. 130

United Nations Regulation No. 130 establishes approval provisions for lane departure warning systems on heavy road vehicles. It applies to relevant M2, N2, M3, and N3 categories and defines requirements for lane departure warning behavior [5]. This regulation is directly relevant to Class 8 lane departure warning validation because it anchors expected warning behavior, lane-marking interpretation, suppression logic during intentional lane changes, and driver-warning performance.

2.6 European Union Regulation 2019/2144

European Union Regulation 2019/2144, known as the General Safety Regulation, establishes type-approval requirements for motor vehicles and includes safety requirements for vehicle categories including M2, M3, N2, and N3 [6]. For heavy commercial vehicles, the regulation is relevant because it strengthens the European safety framework for technologies such as advanced

emergency braking, lane departure warning, vulnerable-road-user detection, and intelligent speed assistance. It provides an important comparative regulatory reference for global Class 8 platform development. European safety studies have also highlighted the growing importance of integrated advanced safety technologies for reducing heavy-vehicle crash risk and improving road safety outcomes [19].

3. Related Work

Passenger-car advanced driver assistance system validation is comparatively mature. It includes established approaches for radar, camera, lidar, sensor fusion, object classification, scenario-based testing, hardware-in-the-loop testing, closed-course testing, and naturalistic driving exposure. Passenger-car frameworks also operate within regulatory environments such as light-vehicle electronic stability control and automatic emergency braking requirements. However, passenger-car validation assumes hydraulic brakes, relatively fixed vehicle mass, no articulated trailer, shorter wheelbases, and narrower use environments. These assumptions do not transfer cleanly to Class 8 commercial trucks. Heavy-vehicle braking dynamics, longitudinal control behavior, and stability response further complicate ADAS validation because articulated trucks exhibit substantially different vehicle-dynamics characteristics than passenger vehicles [11]. The heavy-vehicle evidence base supports the safety value of advanced driver assistance systems but remains less mature from a validation-methodology perspective. Insurance Institute for Highway Safety research published in 2020 found that forward collision warning and automatic emergency braking significantly reduced rear-end crash rates in large trucks, with forward collision warning associated with a 44 percent reduction and automatic emergency braking associated with a 41 percent reduction in rear-end crash rates [7]. Cooperative and adaptive cruise-control architectures have also been extensively studied in intelligent transportation research, particularly regarding longitudinal stability, following-distance control, and automated vehicle coordination [12]. Lane departure warning has also been studied in the large-truck context. The AAA Foundation for Traffic Safety estimated the costs and benefits associated with equipping large trucks with lane departure warning systems [8]. By 2023, production availability of commercial-truck advanced driver assistance systems was growing. Kenworth announced optional Lane Keeping Assist availability for new Class 8 T680, T880, and W990 trucks in 2022 [9]. Bendix described Wingman

Fusion as capable of reading most North American roadside speed-limit signs, warning the driver when traveling above the posted limit, and briefly de-throttling the engine at higher overspeed thresholds [10]. Nevertheless, the literature lacked a public, structured, multi-feature validation methodology for Class 7 and Class 8 trucks covering adaptive cruise control, automatic emergency braking systems, lane departure warning, and traffic sign recognition across powertrain and trailer variants. This paper responds to that gap by proposing a validation framework that is regulation-aligned, variant-aware, and suitable for original equipment manufacturer and supplier sign-off processes. Broader ADAS engineering literature has additionally emphasized the importance of sensor fusion, human-machine interaction, driver-warning strategies, and validation traceability in safety-critical driver-assistance systems [13].

3.1 Research Gap and Contributions

Although advanced driver assistance systems have been extensively studied in passenger vehicles, the research landscape for Class 7 and Class 8 commercial trucks remains comparatively fragmented. Existing studies primarily focus on individual technologies such as automatic emergency braking, lane departure warning, or adaptive cruise control independently, rather than evaluating these systems through a unified validation framework tailored specifically for heavy-duty commercial vehicles. Moreover, many publicly available validation approaches are derived from passenger-car methodologies, which assume hydraulic braking systems, relatively fixed vehicle mass, shorter wheelbases, and non-articulated vehicle dynamics. These assumptions are not directly transferable to Class 8 tractor-trailer platforms, where braking behavior, trailer articulation, load variability, and rollover sensitivity significantly influence advanced driver assistance system performance. Another limitation in current literature is the absence of a comprehensive end-to-end validation methodology aligned with the operational realities of commercial trucking. Existing regulatory frameworks, including Federal Motor Vehicle Safety Standard 121, Federal Motor Vehicle Safety Standard 136, proposed Federal Motor Vehicle Safety Standard 128, United Nations Regulation 130, and United Nations Regulation 131, define performance expectations and compliance requirements for specific safety systems [1][5]. However, these regulations do not provide a complete validation methodology that integrates requirements definition, hazard analysis, scenario development, staged testing, and release sign-off into a unified engineering process. As a

result, validation practices across manufacturers and suppliers often remain inconsistent, feature-specific, and heavily dependent on internal company procedures. Furthermore, current validation literature rarely addresses the influence of commercial-truck powertrain diversity on advanced driver assistance system behavior. Diesel, compressed natural gas, and battery electric trucks exhibit different braking characteristics, torque response behavior, regenerative braking strategies, and weight distributions. These factors directly affect adaptive cruise control, automatic emergency braking, and vehicle stability performance, yet they are frequently underrepresented in existing validation methodologies. To address these gaps, this paper proposes a structured and regulation-aligned validation methodology specifically designed for Class 8 commercial trucks. The primary contributions of this research are summarized as follows:

1. **Proposed Five-Step Validation Framework:** The paper introduces a systematic five-step validation methodology consisting of requirements definition, hazard analysis, scenario development, staged testing, and sign-off package creation. The framework establishes traceability between requirements, test evidence, and release decisions.
2. **Variant-Aware Validation Methodology:** Unlike conventional passenger-vehicle approaches, the proposed methodology explicitly incorporates load state, trailer configuration, wheelbase, axle layout, tire condition, and environmental variability into the validation process.
3. **Multi-Feature Validation Integration:** The framework integrates validation strategies for adaptive cruise control, automatic emergency braking systems, lane departure warning, and traffic sign recognition within a unified methodology rather than treating each feature independently.
4. **Powertrain-Aware Testing Strategy:** The research incorporates diesel, compressed natural gas, and battery electric truck configurations as explicit validation variables, including considerations related to regenerative braking, brake blending, engine braking, and torque-control behavior.

5. **Regulation-Aligned Validation Approach:** The methodology aligns validation activities with applicable United States and international regulatory frameworks, including Federal Motor Vehicle Safety Standard 121, Federal Motor Vehicle Safety Standard 136, proposed Federal Motor Vehicle Safety Standard 128, United Nations Regulation 130, United Nations Regulation 131, and European Union Regulation 2019/2144.

Collectively, these contributions establish a practical and academically grounded validation framework intended to improve the consistency, traceability, and safety assurance of advanced driver assistance systems deployed in heavy-duty commercial trucks.

4. Proposed Validation Methodology

The proposed validation methodology consists of five steps: requirements definition, hazard analysis and feature safety definition, scenario development, staged testing, and sign-off package creation. The methodology is designed specifically for Class 8 commercial trucks and recognizes that advanced driver assistance system performance depends on vehicle mass, trailer configuration, braking architecture, powertrain behavior, sensor placement, and operating environment.

4.1 Step 1: Requirements Definition

Requirements definition establishes the regulatory, customer, fleet, safety, and engineering requirements for each advanced driver assistance feature. For a 2023 Class 8 platform, the regulatory baseline should include Federal Motor Vehicle Safety Standard 121 for air-brake systems, Federal Motor Vehicle Safety Standard 136 for heavy-vehicle electronic stability control, proposed Federal Motor Vehicle Safety Standard 128 scenarios for automatic emergency braking, United Nations Regulation 131 for heavy-vehicle advanced emergency braking systems, United Nations Regulation 130 for lane departure warning systems, and European Union Regulation 2019/2144 for the broader European safety framework [1][6]. Customer and fleet requirements may extend beyond regulation. Fleets may require performance at specific highway speeds, support for particular trailer types, operation in regional weather conditions, integration with fleet telematics, or defined driver-alert strategies. Requirements should be written in measurable form. For example, an adaptive cruise control requirement should specify speed range, following-gap tolerance, deceleration limits, driver override behavior, and degraded-

mode response. The output of this step is a feature-level requirement set that becomes the foundation for hazard analysis, scenario selection, instrumentation planning, and sign-off traceability.

4.2 Step 2: Hazard Analysis and Feature Safety Definition

The second step identifies feature-specific hazards and maps each hazard to test scenarios, vehicle variants, instrumentation requirements, acceptance criteria, and residual-risk arguments. For Class 8 trucks, hazards include missed braking, late braking, excessive braking, false braking, missed lane departure, nuisance lane warnings, incorrect speed-limit display, sensor blockage, sensor misalignment, powertrain torque-control errors, brake-pressure faults, and driver override conflicts. Hazard analysis must account for heavy-vehicle dynamics. A false automatic emergency braking event in a passenger vehicle may be uncomfortable, but a false automatic emergency braking event in a loaded tractor-trailer may create rear-end risk, cargo shift, jackknife risk, or following-traffic hazards. Similarly, late braking with a full gross combination weight load may leave insufficient stopping margin even when the same algorithm performs acceptably in a lightly loaded condition. The output of this step is a feature safety definition that identifies hazards, causal mechanisms, detection methods, test coverage, acceptance thresholds, and residual-risk positions. Functional safety considerations should also align with ISO 26262 principles for road-vehicle safety engineering [17]. In addition, Safety of the Intended Functionality (SOTIF) concepts are increasingly relevant for ADAS validation because perception systems may behave incorrectly even in the absence of hardware or software faults [18].

4.3 Step 3: Scenario Development

Scenario development converts requirements and hazards into a structured validation matrix. The scenario matrix should cross each feature against load state, trailer configuration, axle layout, wheelbase, powertrain type, tire condition, brake configuration, sensor package, software version, and environmental condition. Load states should include bobtail, empty trailer, partial payload, and full gross combination weight. Trailer configurations should include no trailer, standard dry van, refrigerated trailer, tanker, and flatbed. Powertrain types should include diesel, compressed natural gas, and battery electric configurations. Environmental conditions should include dry pavement, wet pavement, fog, night operation, glare, construction zones, worn lane markings, and temporary work-zone signs. This matrix prevents

validation from becoming a set of idealized demonstrations. Each scenario must include initial conditions, target conditions, success criteria, safety margins, instrumentation requirements, and stop criteria. Scenario development should also identify which combinations are representative, which are worst-case, and which are required for regulatory alignment.

4.4 Step 4: Staged Testing

Testing should proceed in stages to reduce risk and increase diagnostic value. The earliest stage should include simulation and model-in-the-loop testing. These activities allow engineers to explore wide scenario ranges without exposing test drivers or vehicles to safety-critical events. Software-in-the-loop and hardware-in-the-loop testing should follow. These stages validate software logic, sensor interfaces, controller behavior, brake-command logic, and diagnostic states. Brake-system bench testing should be used for air-brake timing, pressure dynamics, reservoir behavior, and anti-lock braking system interactions. SAE J1939 and controller area network replay should verify communication timing, fault handling, and diagnostic behavior within heavy-duty vehicle communication architectures [16]. Closed-course testing should then validate repeatable safety-critical scenarios using calibrated targets, synchronized data acquisition, accurate positioning systems, controlled environmental conditions, and documented brake and tire preparation. Finally, public-road or fleet shadow testing should collect real-world exposure data, including false-positive candidates, lane-marking variability, traffic-sign variability, driver interaction data, weather exposure, and construction-zone behavior.

4.5 Step 5: Sign-Off Package

The final step is the creation of a traceable sign-off package. This package should include a requirements traceability matrix linking every requirement to test evidence, complete test results for all scenarios, deviation logs with root-cause closures, calibration limits, environmental operating limits, sensor alignment procedures, residual-risk justifications, and release recommendations. For Class 8 trucks, sign-off must explicitly define the validated configuration. It should state which tractor models, trailer types, load states, wheelbases, powertrains, brake configurations, sensor packages, and software versions are covered. A validation result for one diesel tractor and dry van trailer should not automatically be treated as valid for a battery electric tractor with a tanker trailer unless a

documented equivalence argument supports that conclusion.

5. Feature-Specific Validation

5.1 Adaptive Cruise Control

Adaptive cruise control maintains a selected speed and following gap behind a lead vehicle by controlling engine torque, powertrain response, and service brakes. The 2023 heavy-vehicle automatic emergency braking proposal defined adaptive cruise control as a system that follows a lead vehicle at a preselected gap by controlling the engine, powertrain, and service brakes [1]. For Class 8 trucks, adaptive cruise control matters because long-haul drivers spend extended periods on highways, where consistent following-gap management can reduce workload and limit harsh braking events. Normal-operation scenarios should include steady following at highway speeds, lead-vehicle acceleration, lead-vehicle deceleration, cruise resume, mild braking, and gap maintenance across multiple load states. Edge-case scenarios should include cut-in vehicles, lead-vehicle cut-out, curves, grades, low-friction surfaces, heavy load, empty trailer, and slow-moving traffic. Fault scenarios should include radar blockage, incorrect lead-vehicle selection, brake-torque limitation, engine-torque fault, communication delay, degraded sensor confidence, and driver override conflict. Instrumentation should include high-accuracy global navigation satellite system measurement, radar object data, camera lane and object data, J1939 powertrain data, brake pressure, wheel speeds, acceleration, jerk, yaw rate, and driver-control inputs. Pass and fail criteria should include headway error within a defined band, speed error within tolerance, jerk below the specified comfort and safety limit, maximum deceleration not exceeded, lead reacquisition time within specification, and driver override respected.

5.2 Automatic Emergency Braking System

An automatic emergency braking system detects an imminent forward collision and automatically applies or supplements service braking. The 2023 notice of proposed rulemaking defined automatic emergency braking as a system that detects imminent collisions and automatically controls service brakes to avoid or mitigate a collision [1]. The safety case is supported by Insurance Institute for Highway Safety research showing that automatic emergency braking reduced rear-end crash rates in large trucks by 41 percent [7]. Additional research has further demonstrated the importance of expanding front crash prevention coverage across broader operational scenarios [14].

Normal-operation scenarios should be anchored in the 2023 proposed test structure: stopped lead vehicle, slower-moving lead vehicle, and decelerating lead vehicle. These should be tested with and without manual braking and across representative vehicle masses and trailer configurations. Edge cases should include partial overlap, high closing speed, curves, grades, low friction, metallic road plates, construction-zone lane shifts, parked vehicles near the lane, shadows, and heavy-load operation. Fault scenarios should include camera blockage, radar blockage, sensor misalignment, brake-pressure fault, anti-lock braking fault, electronic stability control fault, object misclassification, and communication timing errors. Instrumentation should include target position, ego-vehicle position, speed, acceleration, brake pressure, pneumatic response time, wheel speed, anti-lock braking activity, electronic stability control activity, steering input, yaw rate, and sensor classification logs. The preferred pass criterion for lead-vehicle tests should be no contact. For false activation, the 2023 proposal specified no more than 0.25 g peak deceleration without manual braking and no more than 0.45 g with manual braking in the proposed false-activation cases [1].

5.3 Lane Departure Warning

Lane departure warning monitors lane markings and warns the driver when the vehicle unintentionally drifts out of its lane. For commercial trucks, lane departure warning addresses fatigue, distraction, and long highway exposure that contribute to lane departures, sideswipes, and run-off-road crashes. United Nations Regulation 130 provides a relevant heavy-vehicle regulatory basis for lane departure warning systems [5]. Normal-operation scenarios should include clear lane markings, left and right unsignaled departures, dashed and solid lane lines, and departures at different lateral velocities. Edge cases should include worn markings, missing markings, construction markings, road-edge confusion, exit ramps, glare, rain, snow, and intentional turn-signal use. Fault scenarios should include camera obstruction, windshield contamination, calibration error, speed-signal loss, yaw-rate sensor fault, and incorrect lane-model generation. Instrumentation should include lane position, lateral velocity, camera lane confidence, vehicle speed, steering input, turn-signal status, warning timing, and driver response. Pass and fail criteria should include correct lane detection, warning before or at lane departure, correct left and right departure identification, suppression during intentional signaled lane changes, acceptable false-

warning rate, and correct degraded behavior when lane markings are unavailable.

5.4 Traffic Sign Recognition

Traffic sign recognition uses camera perception to detect speed-limit signs and present the recognized limit to the driver or use it in overspeed warning logic. Bendix described Wingman Fusion as capable of reading most North American roadside speed-limit signs, warning the driver above the posted limit, and briefly de-throttling the engine at higher overspeed thresholds [10], [20]. Normal scenarios should include standard speed-limit signs, repeated signs, roadside signs, overhead signs, and speed-zone transitions. Edge cases should include temporary work-zone signs, electronic signs, dirty signs, occluded signs, adjacent-road signs, truck-specific speed limits, school zones, and disagreement between map and sign data. Fault scenarios should include camera blockage, global positioning system error, stale map data, sign classifier error, incorrect unit conversion, and failure to distinguish signs intended for adjacent lanes or ramps. Instrumentation should include camera detection logs, recognized sign class, recognized speed value, vehicle speed, map speed, display latency, driver warning timing, and overspeed intervention status. Pass and fail criteria should include correct detection rate, correct speed-value recognition, display latency within specification, false-positive rate below threshold, false-negative rate below threshold, correct handling of adjacent-lane signs, and correct handling of temporary work-zone signs.

6. Powertrain Variant Considerations

Advanced driver assistance systems do not only perceive and decide; they also command torque reduction, braking, retarder behavior, regenerative braking, or brake blending. Powertrain type therefore directly affects validation outcomes and must be treated as a validation variable rather than a background assumption. Diesel trucks require validation of engine torque cut, engine braking, transmission downshifts, retarder coordination, downhill operation, and trailer brake blending. A diesel tractor with a loaded trailer may respond differently to an adaptive cruise control or automatic emergency braking command than the same tractor with an empty trailer because tire utilization, brake balance, and deceleration build-up change with load. Retarders add another deceleration source that must be coordinated with service braking. Compressed natural gas trucks may differ from diesel trucks in torque response, engine-brake capability, packaging, mass distribution, and service access around fuel tanks and sensors.

Validation must confirm that adaptive cruise control and automatic emergency braking still achieve required deceleration, gap control, warning timing, and stability behavior even when compressed natural gas powertrain response differs from the diesel baseline. Sensor packaging should also be checked because alternative-fuel tank layouts may affect mounting position, serviceability, and calibration access. Battery electric trucks introduce regenerative braking and brake blending as major validation topics. A battery electric truck may rely heavily on regeneration during normal deceleration, but regeneration can be limited by battery state of charge, battery temperature, motor limits, or traction constraints. Automatic emergency braking and adaptive cruise control validation must prove that the vehicle still achieves predictable and stable deceleration when regeneration is high, reduced, or unavailable. Battery electric truck validation should also consider battery-pack mass distribution, high-voltage safety interlocks, thermal derating behavior, and the transition from regenerative to friction braking under emergency conditions. Commercial trucking operational studies have additionally shown that crash involvement patterns in heavy vehicles are strongly influenced by operational exposure, roadway environment, and driver workload conditions [21].

7. Discussion

The proposed methodology addresses common failure modes that become more severe in heavy trucks than in passenger vehicles. For automatic emergency braking systems, major risks include late detection, missed detection, object misclassification, insufficient speed reduction, excessive brake jerk, unstable brake blending, and false activation. False activation is particularly important in commercial trucks because unnecessary braking at highway speed can create risk for following traffic and can destabilize a

combination vehicle. The proposed Federal Motor Vehicle Safety Standard 128 false-activation scenarios using a steel trench plate and pass-through test reflect this regulatory concern [1]. Previous heavy-truck safety research has also emphasized the importance of advanced safety technologies in reducing commercial-vehicle crash severity and improving operational safety performance [15]. For adaptive cruise control, common issues include poor cut-in response, unstable following gap, harsh braking, slow lead reacquisition, grade-related speed overshoot, and uncomfortable transitions among throttle, engine braking, retarder braking, regenerative braking, and service braking. These issues are more difficult in Class 8 trucks because load state, trailer behavior, brake lag, and powertrain response vary widely. For lane departure warning, the most common validation challenges include worn markings, construction zones, glare, snow, rain, road-edge confusion, ramps, and temporary lane shifts. Nuisance warnings are a practical safety concern because professional drivers who experience excessive false alerts may distrust or disable the system. For traffic sign recognition, common challenges include missed signs, incorrect speed values, detection of signs intended for adjacent roads, confusion between truck-specific and passenger-car speed limits, work-zone sign interpretation, and map-sign disagreement. A broader validation challenge is repeatability. Heavy trucks require long test distances, careful load preparation, brake-temperature control, large safety buffers, and precise scenario setup. The 2023 proposed heavy-vehicle automatic emergency braking procedures included defined speeds, headways, path tolerances, lighting conditions, wind limits, and yaw-rate limits, demonstrating that repeatability was already a regulatory concern in 2023 [1].

Table 1. Five-Step ADAS Validation Methodology for Class 8 Commercial Trucks

Step	Validation Stage	Purpose	Key Inputs	Key Outputs
1	Requirements Definition	Define regulatory, customer, fleet, and safety requirements for each ADAS feature.	FMVSS 121, FMVSS 136, proposed FMVSS 128, UNECE R131, UNECE R130, EU Regulation 2019/2144, fleet operating requirements.	Feature-level requirements, regulatory baseline, validation scope, operating design conditions.
2	Hazard Analysis and Feature Safety Definition	Identify hazards associated with ACC, AEBS, LDW, and TSR and link them to validation evidence.	Feature requirements, vehicle architecture, brake system design, sensor layout, powertrain variant, trailer configuration.	Hazard list, safety goals, failure modes, detection methods, pass/fail thresholds, residual-risk arguments.
3	Scenario Development	Build a scenario matrix covering feature behavior	Load state, trailer type, axle layout, wheelbase,	Scenario matrix, initial conditions, success criteria,

Step	Validation Stage	Purpose	Key Inputs	Key Outputs
		across vehicle variants and operating conditions.	diesel/CNG/BEV powertrain, tire condition, brake configuration, software version, environment.	instrumentation plan, safety margins.
4	Staged Testing	Validate feature performance progressively from virtual testing to track and fleet exposure.	Simulation models, software-in-the-loop setup, hardware-in-the-loop rigs, brake bench data, J1939/CAN data, closed-course targets.	Simulation results, bench results, track results, public-road shadow data, deviation reports.
5	Sign-Off Package	Create traceable release evidence for validated vehicle configurations.	Test evidence, deviation logs, calibration data, environmental limits, sensor alignment data, residual-risk assessment.	Requirements traceability matrix, release recommendation, covered configurations, known limitations, final safety case.

Source: Developed by the author based on proposed Class 8 ADAS validation methodology and applicable regulatory requirements [1][2][3][4][5][6].



Figure 1. Five-Step ADAS Validation Framework

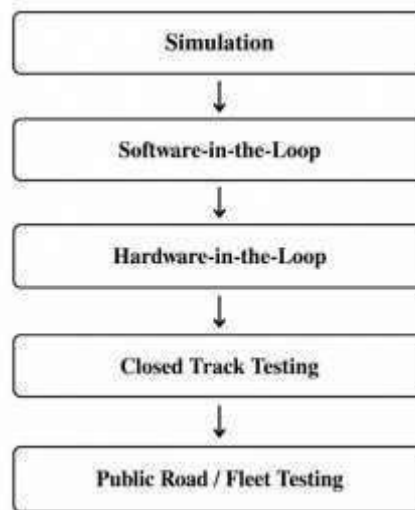


Figure 2. ADAS Validation Test Ecosystem **Source:** Developed by the author based on staged automotive validation practices and heavy-vehicle ADAS testing workflows [1], [11], [13], [17].

Feature	Normal Scenarios	Edge Cases	Fault Conditions	Key Metrics
ACC	Highway following	Cut-in vehicles	Radar blockage	Gap error, jerk
AEBS	Stopped vehicle	Curves, grades	Sensor fault	TTC, deceleration
LDW	Clear lanes	Worn markings	Camera obstruction	Warning timing
TSR	Standard signs	Work zones	GPS mismatch	Recognition accuracy

Source: Developed by the author based on commercial vehicle ADAS validation requirements and prior safety research [7], [8], [11][12][13].

8. Conclusions

This paper proposed a structured advanced driver assistance system validation methodology for Class 8 commercial trucks covering adaptive cruise control, automatic emergency braking systems, lane departure warning, and traffic sign recognition. The framework consists of five steps: requirements definition, hazard analysis and feature safety definition, scenario development, staged testing, and sign-off package creation. Its central value is that it treats Class 8 trucks as distinct validation platforms rather than scaled-up passenger vehicles. Three recommendations follow from the analysis. First, validation must be designed specifically for commercial trucks rather than copied from passenger-vehicle methods. Federal Motor Vehicle Safety Standard 121 and Federal Motor Vehicle Safety Standard 136 should form the United States heavy-truck foundation, while proposed Federal Motor Vehicle Safety Standard 128 scenarios, United Nations Regulation 131, United Nations Regulation 130, and European Union Regulation 2019/2144 should inform automatic emergency braking and lane departure warning validation structure.

Second, each advanced driver assistance feature should be validated across normal scenarios, boundary scenarios, degraded environments, and fault scenarios crossed with vehicle variants including load, trailer, wheelbase, powertrain, brake configuration, and sensor package. Both false negatives and false positives must be treated as safety-critical outcomes.

Third, original equipment manufacturers and suppliers should build traceable safety cases rather than relying on isolated track demonstrations. The sign-off package should connect every requirement to test evidence, every failure to root-cause closure, and every release decision to a documented residual-risk argument.

The original contribution of this paper is a structured, multi-feature, variant-aware validation framework specifically for Class 8 commercial trucks. By integrating regulatory alignment, vehicle configuration coverage, staged testing, and traceable release evidence, the methodology provides a practical foundation for safer and more consistent deployment of advanced driver assistance systems in heavy-duty commercial vehicles.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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