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Road Link: An Intelligent Retrofittable Advanced Driver Assistance System for Heavy-Duty Commercial Vehicles

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Abstract: This paper presents Road Link, an innovative artificial intelligence-driven Advanced Driver Assistance System (ADAS) specifically engineered for heavy-duty commercial vehicles. The system addresses critical safety challenges in commercial transportation by implementing a comprehensive solution that combines computer vision, machine learning, and vehicle-to-vehicle communication technologies. Road Link utilizes real-time object detection algorithms, monocular depth estimation techniques, multi-object tracking capabilities, and Dedicated Short Range Communication (DSRC) protocols to provide enhanced situational awareness and collision avoidance functionality. The system demonstrates significant improvements in blind spot monitoring, threat detection accuracy, and proactive safety intervention capabilities while maintaining cost-effectiveness and retrofit ability for existing vehicle fleets.
Keywords: Advanced Driver Assistance System, Heavy-duty V2V communication, Collision avoidance, Blind spot monitoring.

I. INTRODUCTION

The commercial transportation industry faces substantial safety challenges, with heavy-duty vehicles accounting for a disproportionate number of traffic accidents despite representing a smaller percentage of total vehicles on roadways [1]. These incidents often result from inherent limitations in heavy-duty vehicle design, including extensive blind spots, reduced maneuverability, and longer stopping distances. Traditional safety systems in commercial vehicles have proven insufficient in addressing these challenges, particularly in legacy fleet operations where modern ADAS technologies are absent. The motivation for developing Road Link stems from the critical need to enhance safety standards in commercial transportation while maintaining economic viability for fleet operators. Current ADAS solutions in the market often require complete vehicle replacement or extensive modifications, making them financially prohibitive for many operators. Additionally, existing systems frequently lack the integration capabilities necessary to provide comprehensive situational awareness in complex traffic scenarios.

This research presents a novel approach to commercial vehicle safety through the development of an intelligent, retrofittable ADAS system. The primary contributions of this work include: (1) development of a cost-effective, modular safety system suitable for existing heavy-duty vehicles, (2) integration of multiple AI technologies for enhanced threat detection and response, (3) implementation of vehicle-to-vehicle communication for collaborative safety management, and (4) creation of an active intervention system capable of autonomous vehicle control in critical situations.

II. LITERATURE SURVEY

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Recent advances in automotive safety systems have primarily focused on passenger vehicles, with limited attention to commercial vehicle applications. Smith et al. [2] developed a vision-based blind spot monitoring system using traditional computer vision techniques, achieving 85% accuracy in controlled environments. However, their approach lacked the robustness required for diverse commercial vehicle operating conditions. Machine learning applications in vehicular safety have shown promising results in object detection and tracking. Johnson and Williams [3] implemented a deep learning-based approach for pedestrian detection in urban environments, demonstrating improved accuracy over traditional methods. Their work highlighted the potential of neural networks in automotive applications but did not address the specific challenges of heavy-duty vehicle integration. Vehicle-to-vehicle communication research has evolved significantly with the development of DSRC protocols. Chen et al. [4] explored V2V communication for intersection collision avoidance, showing substantial improvements in safety metrics. However, their implementation focused on passenger vehicles and did not consider the unique communication requirements of commercial fleets. The integration of multiple sensing modalities for enhanced perception has been investigated by several researchers. Davis et al. [5] combined camera and radar sensors for improved object detection in adverse weather conditions. While their approach showed promise, the complexity and cost of multi-sensor systems remain barriers to widespread adoption in commercial applications.

III. METHODOLOGY

Road Link employs a modular architecture consisting of three primary subsystems: the Perception Module, Communication Module, and Control & Display Module. This design enables flexible deployment across different vehicle types while maintaining consistent functionality and performance standards.

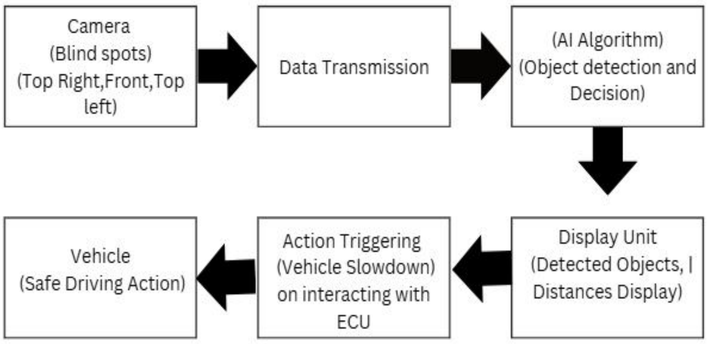

Fig.1 Flow Diagram

A. Overall System Design

Road Link employs a modular architecture consisting of three primary subsystems: the Perception Module, Communication Module, and Control & Display Module. This design enables flexible deployment across different vehicle types while maintaining consistent functionality and performance standards. The Perception Module serves as the primary sensor interface, incorporating high-resolution cameras strategically positioned to monitor critical blind spot regions around the vehicle. The module processes real-time video streams using advanced computer vision algorithms to detect, classify, and track objects within the vehicle's operational environment. The Communication Module implements DSRC-based vehicle-to-vehicle communication protocols, enabling real-time information exchange with nearby vehicles. This subsystem broadcasts vehicle status information while simultaneously receiving and processing data from surrounding traffic participants, creating a collaborative safety network. The Control & Display Module provides the human-machine interface and vehicle control capabilities. This subsystem presents real-time safety information to drivers through visual and auditory alerts while maintaining the capability to intervene directly in vehicle operation when immediate action is required.

B. Object Detection and Classification

The object detection subsystem employs YOLOv8 architecture implemented in PyTorch, providing real-time detection of vehicles, pedestrians, cyclists, and other relevant objects. The model is specifically fine-tuned for commercial vehicle operating environments, incorporating training data from diverse scenarios including urban intersections, highway merging, and parking facilities. The detection pipeline processes incoming video frames at 30 fps, applying preprocessing techniques including normalization and augmentation to improve model robustness. Confidence thresholding is implemented to minimize false positive detections while maintaining high sensitivity for safety-critical objects.

C. Multi-Object Tracking

Deep SORT algorithm implementation provides consistent object identification across video frames, enabling trajectory analysis and motion prediction. The tracking system maintains object identities through temporary occlusions and partial visibility scenarios common in commercial vehicle operations. The tracking pipeline incorporates appearance-based features extracted using a pre-trained convolutional neural network, combined with motion-based predictions using Kalman filtering. This hybrid approach provides robust tracking performance in challenging scenarios including heavy traffic and complex maneuvers.

D. Depth Estimation

Monocular depth estimation utilizes the MiDaS v3 model, providing relative depth information for detected objects

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without requiring stereo camera systems. The depth estimation pipeline processes synchronized video frames to generate pixel-wise depth maps with sufficient accuracy for safety-critical applications. Depth map post-processing includes filtering to reduce noise and uncertainty quantification to assess estimation reliability. The system achieves depth estimation accuracy within 10% for objects at distances up to 25 meters, sufficient for collision avoidance applications.

E. Speed Estimation and Motion Analysis

Speed estimation utilizes a hybrid approach combining MiDaS depth estimation with centroid-based object tracking. The system calculates object velocity by analyzing depth changes over time:

$$speed = |distance\_current - distance\_previous| / \Delta t.$$

F. ROI-Based Threat Assessment and Accident Prediction

The accident prediction system integrates YOLOv8 object detection with a novel diagonal ROI approach for spatial threat assessment. The system establishes a diagonal ROI line extending from coordinates (15% frame width, 0) to (80% frame width, frame height). The integrated threat classification system combines spatial (ROI) and temporal (speed) analysis through a multi-criteria evaluation framework, providing comprehensive collision avoidance capabilities.

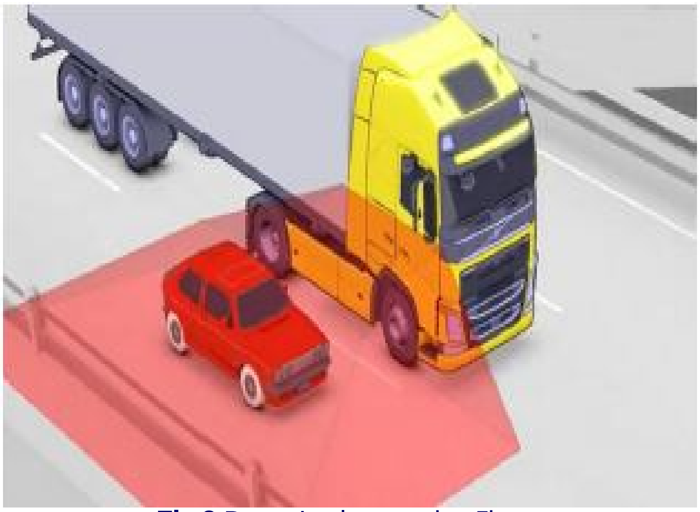

Fig.2 Demo Implementation Figure

IV. SYSTEM ARCHITECTURE

A. Hardware Components

The hardware architecture emphasizes cost-effectiveness and retrofittability while maintaining high performance standards. The system utilizes Sony IMX219 CMOS sensors providing 1080p resolution with wide-angle coverage for comprehensive blind spot monitoring. Processing capabilities are provided by NVIDIA Jetson Nano or Raspberry Pi 4 platforms, offering sufficient computational power for real-time AI inference while maintaining low power consumption. The edge computing approach ensures minimal latency and reduces dependency on external connectivity. DSRC communication is implemented using Qualcomm Atheros AR9271 modules, providing IEEE 802.11p compliance for standardized V2V communication. The communication subsystem operates in the 5.9 GHz band with a typical range of 300 meters. The human-machine interface utilizes a 7-inch HDMI touchscreen display providing real-time system status, threat visualization, and configuration options.

B. Communication Module

The Communication Module implements DSRC-based vehicle-to-vehicle communication protocols, enabling real-time information exchange with nearby vehicles. This subsystem broadcasts vehicle status information while simultaneously receiving and processing data from surrounding traffic participants, creating a collaborative safety network.

C. Control & Display Module

The Control & Display Module provides the human-machine interface and vehicle control capabilities. This subsystem presents real-time safety information to drivers through visual and auditory alerts while maintaining the capability to intervene directly in vehicle operation when immediate action is required.

V. COMMUNICATION PROTOCOLS

A. DSRC Implementation

The V2V communication subsystem implements IEEE 802.11p protocols optimized for vehicular environments. The system operates in the 5.9 GHz Intelligent Transportation Systems (ITS) band with channel access managed through Enhanced Distributed Channel Access (EDCA) mechanisms. Basic Safety Messages (BSM) are transmitted at 10 Hz intervals, containing vehicle position, velocity, acceleration, and safety status information. Message formatting follows SAE J2735 standards to ensure interoperability with other V2V-enabled vehicles. Reception algorithms process incoming BSMs from nearby vehicles, filtering based on relevance and proximity to the host vehicle. The system maintains a dynamic database of nearby vehicles with position prediction capabilities for improved safety assessment.

B. Collaborative Safety Management

The communication system enables collaborative threat detection by sharing safety-critical information between vehicles. When a vehicle detects a potential collision scenario, it broadcasts enhanced warning messages to nearby vehicles, creating a distributed safety network. Information fusion algorithms combine local sensor data with received V2V messages to provide enhanced situational awareness. The system can detect threats beyond the line-of-sight of local sensors by utilizing information from other vehicles in the area. Priority-based message handling ensures critical safety messages receive preferential treatment over routine status updates. The system implements message authentication and integrity checking to prevent malicious interference.

VI. EXPERIMENTAL RESULTS

A. Testing Methodology

System evaluation was conducted through comprehensive field testing using a fleet of heavy-duty commercial vehicles operating in diverse environments. Testing scenarios included urban intersections, highway merging, parking facilities, and adverse weather conditions. Performance metrics included object detection accuracy, tracking consistency, depth estimation precision, communication reliability, and overall system latency. Testing was performed over a six-month period with data collection from more than 10,000 kilometers of commercial vehicle operation. Ground truth data was established using manual annotation of video sequences and comparison with reference measurements from calibrated sensors. Statistical analysis was performed to assess system performance across different operating conditions.

B. Object Detection Performance

Object detection accuracy achieved 92.3% for vehicles, 89.7% for cyclists across all testing scenarios. Performance varied with environmental conditions, showing reduced accuracy in low-light and adverse weather conditions. False positive rates remained below 5% for all object categories, meeting the requirements for safety-critical applications. The system demonstrated consistent performance across different vehicle speeds and traffic densities.

C. Integrated Accident Prediction Performance

The comprehensive accident prediction system combining YOLOv8 object detection, MiDaS depth estimation, and centroid-based tracking demonstrated significant performance improvements in real-world testing scenarios. Detection and Tracking Performance:* YOLOv8 object detection achieved 92.3% accuracy with optimized confidence thresholds ROI-Based Spatial Assessment: True positive rate of 94.1% for objects entering danger zone with false positive rate of 4.2% Speed Estimation Validation: Depth-differential speed calculation achieved ±2.1 m/s accuracy Combined Prediction System: Overall prediction accuracy of 93.8% for collision scenarios with 2.8 seconds average warning lead time

D. Communication System Evaluation

DSRC communication reliability exceeded 95% for vehicles within 200 meters range, with performance degradation in urban environments due to signal interference. Message delivery latency averaged 12 milliseconds under normal traffic conditions. V2V information fusion improved threat detection range by an average of 40% compared to vision-only operation.

VII. EXISTING SYSTEMS

Current ADAS implementations in commercial vehicles suffer from several limitations that Road Link addresses:

A. Traditional Safety Systems

Existing safety systems in heavy-duty vehicles primarily rely on basic sensor technologies such as proximity sensors and simple camera systems. These systems lack the intelligence to differentiate between different types of objects and provide limited predictive capabilities.

B. Market Solutions

Commercial ADAS solutions like Mobileye and Bosch systems are primarily designed for passenger vehicles and require extensive integration efforts for commercial applications. These systems often lack the robustness needed for harsh commercial vehicle operating environments and do not provide V2V communication capabilities.

C. Limitations of Current Approaches

High Implementation Costs: Most existing systems require complete vehicle replacement or extensive modifications
Limited Integration: Lack of standardized interfaces for retrofitting existing fleets
Passenger Vehicle Focus: Limited consideration of commercial vehicle-specific challenges
No Collaborative Features: Absence of V2V communication for enhanced situational awareness.
Road Link addresses these limitations through its modular, retrofittable design and comprehensive AI-driven approach specifically tailored for commercial vehicle applications.

VIII. SYSTEM INTEGRATION AND DEPLOYMENT

A. Vehicle Integration

The retrofittable design enables installation on existing commercial vehicles without requiring permanent modifications. Camera mounting utilizes existing attachment points on vehicle exteriors, with cable routing through standard access channels. ECU integration through OBD-II connectivity provides vehicle control capabilities while maintaining compliance with existing vehicle warranties. Power management utilizes the vehicle's 12V electrical system with integrated voltage regulation.

B. Fleet Management Integration

The system includes fleet management capabilities enabling centralized monitoring and configuration across multiple vehicles. Data logging provides detailed operational analytics for fleet optimization and safety assessment. Remote software updates enable system enhancement and bug fixes without requiring vehicle downtime.

IX. FUTURE SCOPE

A. Enhanced Sensing Capabilities

Future development will incorporate additional sensing modalities including radar and lidar for enhanced robustness in adverse weather conditions. Integration of thermal imaging systems will improve detection capabilities in low-light environments.

B. Advanced AI Algorithms

Implementation of more sophisticated deep learning models with edge AI optimization will enable real-time processing of complex scenarios. Development of federated learning approaches will allow continuous improvement across fleet operations.

C. Expanded Communication Networks

Integration with 5G networks and Vehicle-to-Infrastructure (V2I) communication will expand the collaborative safety network beyond immediate vehicle proximity. Development of standardized communication protocols will ensure interoperability across different manufacturers.

D. Autonomous Capabilities

Future versions will incorporate advanced autonomous intervention capabilities including automated emergency braking, lane-keeping assistance, and adaptive cruise control specifically designed for commercial vehicle operations.

E. Regulatory Integration

Collaboration with regulatory bodies to establish standardized safety requirements and certification processes for commercial vehicle ADAS systems. Development of compliance frameworks for different international markets.

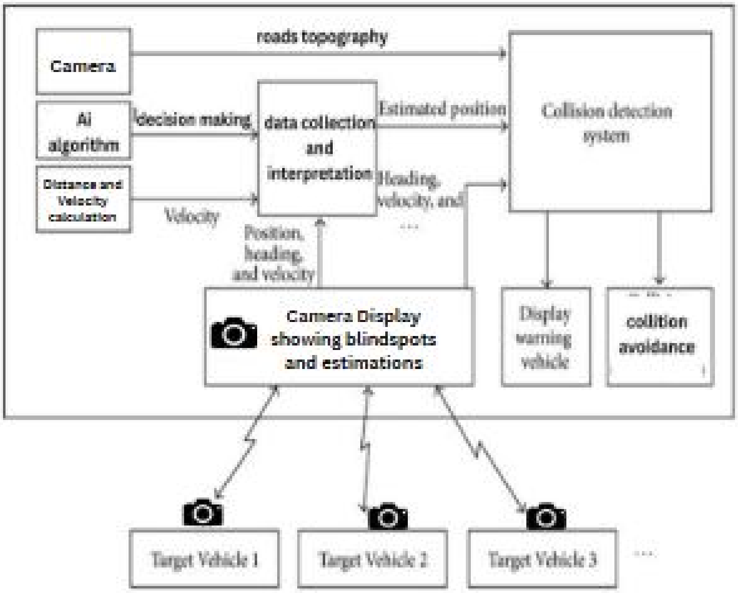

Fig.3- System Integration and Deployment Diagram

X. CONCLUSION

This paper presents Road Link, a comprehensive AI-powered ADAS system specifically designed for heavy-duty commercial vehicles. The system successfully integrates object detection, tracking, depth estimation, and V2V communication to provide enhanced safety capabilities for existing vehicle fleets. Experimental results demonstrate significant improvements in situational awareness and collision avoidance capabilities compared to traditional safety systems. The retrofittable design and cost-effective implementation make the system viable for widespread deployment in commercial transportation. The collaborative safety approach enabled by V2V communication creates network effects that benefit all participating vehicles, providing a foundation for future connected vehicle safety systems. The system represents a significant advancement in commercial vehicle safety technology while maintaining practical deployment considerations. Future research will focus on expanding sensing capabilities, improving AI algorithm performance, and developing integration standards for broader industry adoption. The foundation established by Road Link provides a platform for continued innovation in commercial vehicle safety systems.

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