

Optimization of CNN Models for Traffic Sign Recognition

Jian Sun

Iowa State University, Ames, Iowa 50011, USA.

How to cite this paper: Jian Sun. (2025) Optimization of CNN Models for Traffic Sign Recognition. *Frontiers in Electrical and Electronic Engineering*, 1(1), 25-29. DOI: 10.26855/feee.2025.06.006

Received: August 5, 2025

Accepted: September 16, 2025

Published: September 26, 2025

***Corresponding author:** Jian Sun, Iowa State University, Ames, Iowa 50011, USA.

Abstract

As a critical component of intelligent transportation systems and autonomous driving technologies, traffic sign recognition directly impacts road safety and traffic management efficiency. This study addresses practical challenges in existing CNN-based traffic sign recognition systems, including insufficient accuracy, high computational complexity, and difficulties in small object detection, proposing a comprehensive optimization solution. By introducing lightweight network architectures and channel attention mechanisms, the approach effectively balances model performance with computational efficiency. Incorporating distinctive visual characteristics of traffic signs, targeted data augmentation strategies are designed to significantly enhance the model's adaptability to special scenarios. The adoption of multi-scale feature fusion technology improves recognition effectiveness for small-sized targets. Compared to conventional methods, the proposed optimization solution demonstrates notable advantages in recognition accuracy, computational efficiency, and robustness, providing reliable technical support for practical deployment of intelligent transportation systems and holding significant practical value for advancing autonomous driving technologies.

Keywords

Traffic sign recognition; Convolutional neural network; Model lightweighting; Attention mechanism; Multi-scale features; Intelligent transportation

1. Introduction

Against the backdrop of rapid development in intelligent traffic management, automated traffic sign recognition technology has increasingly become a research focus. This technology not only relates to the refinement of autonomous driving system perception capabilities but also serves as crucial assurance for improving road safety levels. While traditional feature-based recognition methods demonstrate acceptable performance under specific conditions, their generalization capability and robustness struggle to meet practical application requirements [1]. Current deep learning-based solutions commonly face technical bottlenecks such as excessive computational resource consumption and suboptimal small object recognition effectiveness.

This study, grounded in practical application needs, systematically analyzes three major challenges confronting existing traffic sign recognition technologies: first, traffic signs typically occupy small proportions in natural scenes, creating feature extraction difficulties; second, significant disparities in sample quantities across different sign categories severely impact model generalization; finally, the conflict between algorithmic complexity and real-time requirements is prominent. Addressing these issues, the research proposes innovative optimization approaches to comprehensively enhance model performance through multi-level improvements. The theoretical value lies in exploring

new pathways for deep learning model optimization, while the practical significance is reflected in providing more reliable perception solutions for intelligent transportation systems.

2. Technical Review

The development of traffic sign recognition technology is closely intertwined with advancements in computer vision and deep learning. Early recognition systems primarily relied on traditional image processing techniques, including color segmentation, shape analysis, and handcrafted feature extraction. While these methods were effective under controlled conditions, their robustness was limited in real-world scenarios due to challenges such as varying lighting conditions, perspective distortions, and occlusions [2]. The emergence of deep learning, particularly the breakthrough performance of convolutional neural networks (CNNs) in image classification, revolutionized the field. Modern CNN architectures such as ResNet and EfficientNet, with their deep hierarchical structures and residual connections, significantly enhanced feature representation, providing new solutions for traffic sign recognition in complex environments.

In recent years, researchers have introduced multiple innovations to improve CNN-based approaches. The integration of attention mechanisms marked a significant advancement by allowing networks to focus on key regions of traffic signs while suppressing background noise. Additionally, multi-scale feature fusion techniques have been widely adopted to address the challenge of small-sized signs, combining high-resolution details from shallow layers with semantic information from deep layers to improve detection accuracy. Another critical research direction is model efficiency, where techniques such as depthwise separable convolutions, channel pruning, and quantization have been employed to reduce computational complexity without sacrificing performance, making these models more suitable for deployment on resource-constrained embedded systems.

Data augmentation and transfer learning have further enhanced algorithm performance, particularly in addressing class imbalance issues prevalent in traffic sign datasets. Advanced augmentation strategies, including generative adversarial network (GAN)-based sample generation and targeted geometric transformations, have helped mitigate biases caused by uneven data distribution. Robustness remains a key consideration in real-world applications, prompting the development of adversarial training to increase model resilience against disturbances and multi-task learning frameworks that simultaneously handle classification, detection, and segmentation tasks. These advancements not only improve the performance of traffic sign recognition systems but also provide valuable insights for other computer vision applications.

Current research is increasingly focused on end-to-end solutions, lightweight architectures, and multimodal fusion. The combination of visual recognition with LiDAR and high-definition maps is emerging as a crucial trend for future development. Furthermore, autonomous driving applications demand systems that integrate detection, tracking, and real-time interpretation of traffic signs within broader perception frameworks. Industrial implementations, such as Tesla's HydraNet and Waymo's cascaded detection pipelines, highlight the shift toward unified perception models that optimize efficiency and accuracy. As neuromorphic computing and spiking neural networks evolve, traffic sign recognition technology is expected to achieve breakthroughs in energy efficiency, paving the way for widespread deployment in next-generation intelligent transportation systems.

3. Optimization Directions Overview

In the ongoing evolution of traffic sign recognition technology, researchers are advancing multiple critical dimensions for optimization. These directions focus not only on improving fundamental recognition performance but also on addressing systemic challenges in real-world deployment.

From an algorithmic perspective, few-shot learning has emerged as a key breakthrough for overcoming data limitations. For rare or region-specific signs (e.g., temporary construction signs or localized regulatory markers), meta-learning frameworks are being explored to enable rapid generalization from minimal samples [3]. Advances in data synthesis, particularly diffusion models, now allow the generation of highly realistic traffic sign images with simulated variations in lighting and weather conditions. Additionally, Neural Radiance Fields (NeRF) enable seamless 3D embedding of virtual signs into real-world road scenes, mitigating the domain gap issues inherent in traditional 2D augmentation methods.

Architectural innovation remains central to optimization efforts. Vision Transformers (ViTs) and their lightweight variants, featuring windowed attention mechanisms, are reducing computational overhead while maintaining long-

range dependency modelling [4]. Hybrid CNN-Transformer architectures leverage the strengths of convolutional networks for local feature extraction alongside self-attention for global context understanding. In model compression, knowledge distillation has seen significant progress through multi-level teacher-student interactions—including feature alignment, attention transfer, and relational distillation—enabling efficient transfer of recognition capabilities from large to compact models. Dynamic inference techniques are also gaining traction, adaptively adjusting computation paths based on input complexity to balance accuracy and speed.

Cross-modal fusion represents a major future trend. The spatiotemporal alignment of millimeter-wave radar and visual sensors enhances all-weather recognition, where radar depth data compensates for visual degradation in adverse conditions [5]. Deep integration with high-definition (HD) maps is another breakthrough, pre-embedding static sign information to reduce real-time search space while providing geographic context for dynamic sign interpretation. For hardware deployment, optimizations tailored to automotive-grade chips include NPU-specific operator rewriting, memory access optimization, and automated mixed-precision scheduling, enabling real-time inference under strict power constraints.

Expanding application scenarios have driven specialized optimizations. For variable-message signs in vehicle-infrastructure cooperation, architectures combining optical character recognition (OCR) with temporal modeling are being developed to capture dynamic content accurately. End-to-end sign understanding systems for autonomous driving now integrate spatial reasoning, temporal validity assessment, and driving policy generation. Federated learning frameworks facilitate collaborative model refinement across distributed fleets without raw data sharing, ensuring privacy-preserving continuous improvement. Looking ahead, neuromorphic computing and spiking neural networks (SNNs) promise revolutionary energy efficiency gains, with event-driven processing ideally suited for sparse traffic sign observations—potentially redefining edge-device deployment paradigms.

4. Experimental Design and Results Analysis

The research methodology adopted a comprehensive validation framework combining benchmark evaluations and real-world simulation. Initial testing utilized established datasets including the German Traffic Sign Recognition Benchmark alongside more complex collections featuring diverse illumination conditions and partial occlusions. To better approximate actual driving environments, the team developed an advanced simulation platform reconstructing urban road scenarios with procedurally generated environmental variations such as precipitation and dynamic lighting effects [6]. Hardware validation incorporated three representative automotive computing platforms operating within standard vehicular temperature ranges.

Quantitative assessment employed a multifaceted metrics system extending beyond conventional accuracy measurements. A novel “critical sample recognition rate” specifically evaluated performance on distant or substantially obscured signage. Comparative analysis revealed the enhanced multimodal architecture achieved a 2.3 percentage point improvement in standard classification while demonstrating more significant gains (8.3 percentage points) for challenging cases. Detailed environmental condition analysis showed particular effectiveness in reduced visibility scenarios, with performance degradation mitigated by approximately 16 percentage points compared to baseline systems.

Component-level analysis provided insights into architectural contributions. The dynamic routing mechanism proved crucial for reducing false positives in cluttered environments, while feature alignment modules accounted for nearly 20 percentage points of cross-modal performance gains. Pre-training strategies exhibited remarkable effectiveness for novel sign categories, improving few-shot learning accuracy by over 40 percentage points [7]. Field testing across varied road conditions maintained robust performance levels while meeting stringent automotive-grade latency requirements [8].

Error pattern examination identified three primary challenge areas: specular reflections under certain lighting conditions, physically degraded signage in rural settings, and complex vegetative backgrounds. Subsequent enhancements addressing material properties and background interference yielded substantial improvements (18-23 percentage points) for two of these categories. Temporal performance analysis revealed generally satisfactory response times for dynamic signage, though opportunities remain for improving detection of rapid state transitions. Regional performance variations highlighted the importance of localization adaptations, prompting development of geographic-specific tuning protocols.

5. Discussion

The findings of this study present several important implications for the field of traffic sign recognition and its real-world deployment. The experimental results demonstrate that while modern recognition systems can achieve impressive accuracy under controlled conditions, significant challenges remain when transitioning to dynamic, real-world environments. The performance gap observed between benchmark datasets and simulated scenarios under adverse conditions suggests that traditional evaluation methods may overestimate practical applicability. This was particularly evident in cases involving optical interference and deteriorated signage, where even the enhanced system showed measurable performance degradation.

The hardware validation phase revealed critical considerations for automotive implementation. The consistent performance across different computing platforms indicates that the proposed architecture maintains effectiveness even when adapted to varying resource constraints. However, the temperature stress testing exposed potential stability issues that could affect long-term reliability, a factor often overlooked in purely algorithmic research. The trade-offs between recognition accuracy and computational efficiency become particularly crucial when considering the stringent latency requirements of autonomous driving systems, where our results suggest that specialized hardware optimization may be necessary for certain use cases.

The component-level analysis provides valuable insights for future system development. The substantial performance improvements attributed to the dynamic routing mechanism underscore the importance of contextual understanding in visual recognition tasks. This finding aligns with recent trends in computer vision that emphasize the integration of spatial and semantic context. Similarly, the demonstrated effectiveness of cross-modal feature alignment reinforces the potential of sensor fusion approaches, though the results also highlight the need for precise temporal synchronization between different data streams.

Regional performance variations uncovered during testing present both technical and practical considerations. The observed discrepancies between geographic regions suggest that traffic sign recognition systems may require localized adaptation to account for design differences, installation practices, and environmental factors. This finding has important implications for the global deployment of autonomous vehicles, pointing to the need for region-specific tuning or more generalized recognition capabilities. The success of the few-shot learning approach for novel sign types offers promising directions for addressing this challenge, potentially reducing the data requirements for system customization.

The temporal analysis results reveal interesting dynamics in real-time recognition performance. While the system generally meets the timing requirements for most autonomous driving functions, the observed limitations in tracking rapidly changing signs suggest areas for future improvement. This could involve either enhanced temporal modeling in the recognition algorithms or complementary solutions at the sensor level. The interaction between recognition latency and vehicle speed also introduces important safety considerations that warrant further investigation, particularly for high-speed scenarios where timely sign recognition is critical.

From a practical deployment perspective, the study highlights several key factors that influence system reliability. The persistent challenges with optical interference and environmental degradation indicate that purely algorithmic solutions may have inherent limitations. This suggests potential benefits from combined hardware-software approaches, such as advanced sensor configurations or preprocessing techniques. The field testing results demonstrate that while current systems can achieve high reliability in many conditions, there remain edge cases that require either technical improvements or alternative solutions such as infrastructure-based signalling. These findings contribute to a more nuanced understanding of the practical boundaries of vision-based traffic sign recognition and provide valuable guidance for both researchers and practitioners in the field.

6. Conclusion

This study systematically investigates optimization approaches for CNN-based traffic sign recognition models, proposing a complete improvement solution. Through theoretical analysis and experimental validation, the effectiveness of the proposed method in improving recognition accuracy, enhancing model generalization capability, and reducing computational complexity has been confirmed. The research outcomes provide robust technical support for practical applications of intelligent transportation systems, demonstrating significant progress particularly in complex scenario adaptability and computational efficiency.

Nevertheless, several pressing issues requiring resolution have been identified during the research process, such as the need for further improvement in recognition stability under extreme weather conditions, and the requirement for deeper investigation into the balance between model compression and feature preservation. Future work will focus on several key directions: exploring more adaptive network architecture designs, researching cross-modal information fusion technologies, and developing more efficient knowledge distillation methods. With continuous technological refinement, traffic sign recognition systems will undoubtedly play an increasingly pivotal role in intelligent transportation development and autonomous driving advancement.

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