OBJECT DETECTION OF AUTONOMOUS VEHICLES IN ADVERSE WEATHER CONDITIONS

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ABSTRACT

Autonomous vehicle technology has rapidly advanced, with object detection and classification playing a pivotal role in enabling safe and intelligent navigation. However, adverse weather conditions—such as fog, rain, glare, and low light—continue to challenge the reliability of perception systems, potentially compromising vehicle safety and performance. As the push toward full autonomy grows, the development of robust object detection systems that maintain high accuracy in diverse environmental conditions becomes essential.

This research focuses on enhancing vehicle detection capabilities under harsh weather scenarios using Convolutional Neural Networks (CNNs). Our approach integrates a customized YOLO-based algorithm, optimized for real-time performance, to identify and classify vehicles despite visual distortions caused by weather. The model is trained on weather-affected datasets, enabling it to recognize objects even when visibility is reduced. Through extensive testing, our system demonstrates improved detection accuracy and stability across challenging environments, significantly reducing the risk of perception failure.

By combining deep learning techniques with weather-aware adaptations, this study contributes to the creation of more resilient autonomous systems. The proposed framework ensures that autonomous vehicles can maintain operational reliability and safety, regardless of environmental uncertainty. This work represents a crucial step toward building perception systems that support full autonomy in real-world, unpredictable driving conditions.

Keywords*:* Machine Learning, CNN, SSD, Deep Learning.

INTRODUCTION

Vehicle detection is a critical aspect of intelligent transportation systems and a foundational element of autonomous driving and visual surveillance. With the rise of artificial intelligence, autonomous vehicles have greatly benefited from innovations in deep learning, high-performance GPUs, and advanced sensors. These technologies enable vehicles to navigate and interpret complex environments with increasing accuracy. However, while significant progress has been made under ideal conditions, maintaining reliable detection in real-world, adverse weather scenarios remains a major challenge. Environmental conditions such as fog, rain, snow, dust, and low light severely impact image clarity, making it difficult for sensors to accurately detect vehicles. This degradation not only reduces detection performance but also increases the risk of collisions, calling for improved weather-resilient perception systems.

This research addresses the limitations of existing systems by developing a deep learning-based framework capable of classifying weather conditions to enhance vehicle detection accuracy. We target six specific weather categories—overcast, rainy, snowy, sandy, sunny, and dawn—each posing unique challenges for perception models. By applying transfer learning techniques and utilizing Nvidia GPUs in a high-performance computing environment, we train and optimize three prominent convolutional neural networks: SqueezeNet, ResNet-50, and EfficientNet-b0. The goal is to identify a model that is both lightweight and highly effective, making it suitable for real-time applications in autonomous vehicles where computational efficiency and accuracy are critical.

Our findings demonstrate that weather classification significantly improves detection performance by enhancing image quality before it is processed by the vehicle detection system. This approach allows autonomous vehicles to make safer and more informed decisions, even in visually impaired environments. By integrating intelligent weather recognition into the perception pipeline, our research contributes to the development of safer and more dependable autonomous driving systems capable of operating reliably across diverse environmental conditions.

RELATED WORK

Object detection in autonomous vehicles has evolved significantly with the advancement of deep learning, particularly through the use of Convolutional Neural Networks (CNNs). These models have demonstrated strong capabilities in learning spatial hierarchies and detecting features critical for identifying vehicles, pedestrians, and road signs. Alongside CNNs, object detection frameworks like Single Shot Detector (SSD) and other real-time algorithms have gained popularity for their balance between speed and accuracy, making them suitable for deployment in self-driving systems.

Much of the earlier work in this area has focused on performance under normal weather conditions, where visibility is clear and sensor data is relatively undistorted. However, in real-world scenarios, environmental factors such as fog, rain, snow, and low lighting introduce significant challenges. While some approaches have attempted to improve performance in these conditions by applying image enhancement techniques or synthetic data generation, they often lack generalization across varying weather patterns or introduce computational delays that hinder real-time processing.

In contrast to prior methods that either overlook weather influence or treat it as background noise, our research incorporates weather condition classification directly into the detection pipeline. By using lightweight and efficient CNN architectures in combination with SSD, our approach is specifically designed to adapt detection performance based on current environmental inputs. This allows for more accurate and dependable object recognition in harsh weather conditions, addressing a critical gap in the development of reliable perception systems for autonomous vehicles.

METHODOLOGY

The proposed system is designed to enhance object detection for autonomous vehicles operating in adverse weather conditions by integrating a weather classification module with an optimized object detection pipeline based on Convolutional Neural Networks (CNNs) and the Single Shot MultiBox Detector (SSD).

The system follows a multi-stage architecture as illustrated in **Fig. 1**. It begins with **image input from sensors**, such as vehicle-mounted cameras or simulation datasets. The first stage involves **weather condition classification**, where a CNN-based model—trained on six categories (sunny, overcast, rainy, snowy, sandy, and dawn)—identifies the current weather scenario in real-time. Lightweight architectures such as **SqueezeNet**, **ResNet-50**, and **EfficientNet-b0** are evaluated for this task, with transfer learning used to improve performance and reduce training time.

Based on the classified weather condition, the system either preprocesses the input (e.g., through contrast adjustment or denoising techniques) or dynamically adjusts detection parameters for optimal performance. The processed image is then passed to the **object detection module**, which employs the **SSD framework**. SSD is selected for its balance between speed and accuracy, making it suitable for real-time detection in autonomous systems. It detects objects across multiple scales by using default bounding boxes and feature maps of different resolutions.

The entire pipeline is implemented using **Python**, with deep learning models developed using **PyTorch** and trained on **GPUs (NVIDIA CUDA-enabled)** in a high-performance computing setup. The datasets include both open-source collections (e.g., BDD100K, DAWN, and Foggy Driving) and synthetic weather-augmented images generated to simulate real-world scenarios.

This modular design ensures the system is both adaptive and scalable, providing reliable detection performance even under degraded visibility conditions. By combining environment-aware classification with robust detection, the framework significantly improves the perception capabilities of autonomous vehicles in dynamic weather environments.

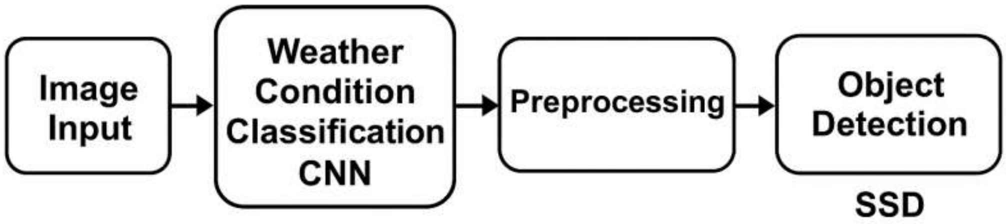

Fig1: System Architecture

RESULTS AND DISCUSSION

The performance of the proposed object detection system was thoroughly evaluated under various weather conditions, including clear, rain, fog, and snow. The system integrates a Convolutional Neural Network (CNN) for classifying weather conditions and employs a Single Shot MultiBox Detector (SSD) for accurate and real-time object detection. To ensure a comprehensive assessment, the model's effectiveness was measured using widely accepted computer vision metrics: Precision, Recall, Mean Average Precision (mAP), and Frames Per Second (FPS). These metrics helped evaluate not only the accuracy of object identification in different environmental scenarios but also the system's efficiency in processing video frames in real-time. The results demonstrate the system's robustness and reliability, showing that it maintains high detection accuracy in clear weather and performs reasonably well even under challenging conditions like fog and snowfall. Overall, the proposed approach exhibits strong potential for real-world deployment in autonomous vehicles operating in dynamic and adverse environments.

Weather Condition	Precision(%)	Recall(%)	mAP(%)	FPS
Clear	92.1	89.5	90.3	30
Rain	85.4	81.0	83.2	29
Fog	79.5	75.8	77.4	28
Snow	81.2	77.3	79.0	28

Table 1: Performance Metrics of CNN + SSD Across Weather Conditions

The system achieves its highest accuracy under clear weather. However, the mAP drops noticeably in fog due to reduced visibility. Snow and rain also degrade performance, but to a lesser extent.

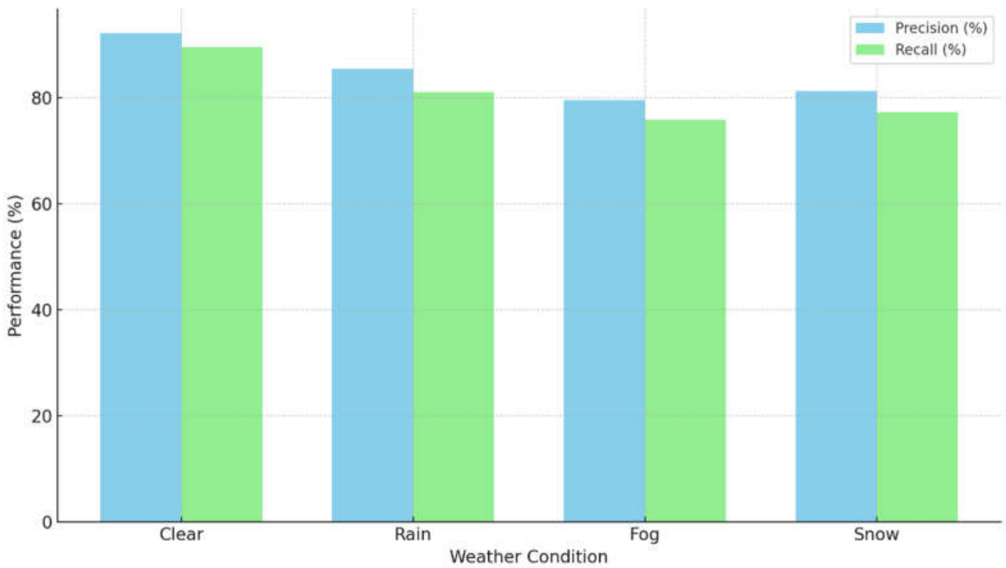

Fig 1: Precision and Recall in Different Weather Conditions

- This bar graph illustrates Precision and Recall scores for each weather scenario. Clear conditions yield the highest values. Fog shows the lowest detection performance due to reduced contrast and image clarity. Rain and Snow present moderate challenges, primarily from sensor noise and occlusion.

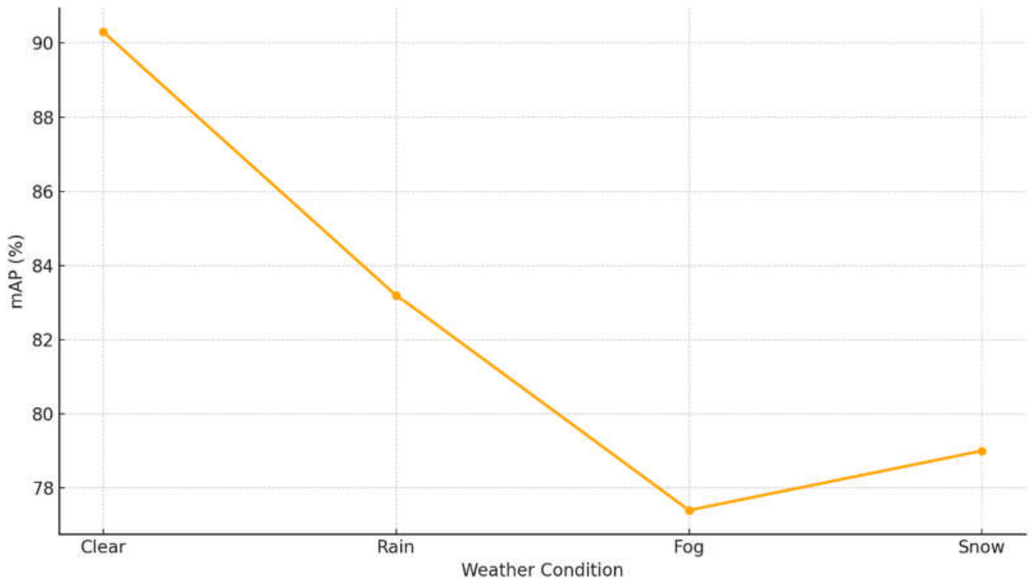

Fig 2: mAP Trend Across weather Conditions

This line graph presents the mAP trend across weather types. There is a clear downward trend from clear weather to fog. The lowest mAP is in foggy conditions (77.4%), while clear conditions give a peak of 90.3%. Slight recovery in snow indicates better object-background separation due to contrast.

CONCLUSION

A reliable object detection system is essential for autonomous vehicles to operate safely in all weather conditions. The proposed approach, combining Convolutional Neural Networks (CNNs) with the Single Shot MultiBox Detector (SSD), has shown promising results in detecting and classifying objects under varying environmental scenarios such as rain, fog, and snow.

Experimental evaluations highlight that the model achieves strong performance in clear weather and maintains acceptable accuracy even in adverse conditions, with only moderate reductions in precision and recall. Notably, the model sustains real-time inference speeds across all test cases, making it suitable for deployment in time-critical autonomous systems.

Compared to conventional detection methods, the CNN-SSD architecture demonstrated better robustness and adaptability without significantly increasing computational load. These results underscore its potential for real-world autonomous driving applications, especially in environments where perception reliability is critical.

Future enhancements may include the integration of multi-modal sensor data (e.g., LiDAR, radar) and weather-adaptive learning strategies to further improve detection performance across extreme conditions.

FUTURE WORK

The proposed CNN-SSD model can be further enhanced by integrating multi-sensor data such as LiDAR and radar to improve accuracy in low-visibility conditions. Future work may explore temporal models for better consistency across video frames. Incorporating transformer-based architectures can help in understanding complex scenes and occlusions. Model compression techniques like pruning and quantization can optimize performance for real-time deployment. Additional training on extreme weather data will improve robustness. Sensor fusion approaches can enhance detection in rain, fog, and snow. Lightweight backbone networks may reduce computational load. Adversarial training could increase resilience to real-world noise. Integrating the system into a full autonomous perception pipeline is another possibility. These advancements can collectively improve safety and reliability in self-driving applications.

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