Sustainable Edge AI and IoT-Based Smart Transportation System for Real-Time Road Condition Analysis

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Abstract: The advancements of intelligent transportation systems and sustainable urban infrastructure are discussed, focusing on the need for energy-efficient road monitoring solutions in real-time. Anomalies that may occur in the roads, such as potholes, cracks, bumps, and rough road surfaces can significantly impact the overall safety and effectiveness of the transportations and fuel consumption rates. Conventional approaches used for inspecting anomalies in roads are mainly manual processes, costly, time-consuming, and not designed for real-time transportation monitoring systems. Recent innovations and progressions in the fields of AI and IoT have improved the accuracy in anomaly detection but many existing solutions are based on cloud-centric designs, which increase the computational costs and energy usage. The paper introduces a Sustainable AI-driven IoT framework for real-time detection of anomalies on roads and smart transportation systems. This framework uses multi-sensors IoT technology for gathering data, lightweight edge-based AI algorithm to analyse the collected data in real-time, federated learning model for training models and connected vehicle communication for transmitting data. The core principle behind this framework is green intelligence in transportation, where the goal of the system is to minimize communication costs and dependency on clouds while optimizing computing performance. Moreover, the framework allows for mobility and maintenance management and sustainable infrastructure design. Finally, important research gaps and potential research directions for smart transportation systems are identified

Keywords: Sustainable AI; IoT; Edge AI; Smart Transportation; Road Anomaly Detection; Intelligent Transportation Systems; Green Computing

Introduction

In this research work, we explore the importance of transport infrastructure in contributing to economic growth, urban development, and sustainable mobility. The condition of the roads is crucial for influencing car safety, fuel economy, transport costs, traffic congestion, and environmental pollution. The presence of road anomalies such as potholes, cracks, speed bumps, and bad surface contributes significantly to road accidents, car damages, traffic delays, and increased CO_2 emissions due to poor driving conditions. Existing road inspection methodologies primarily utilize manual methods, expensive vehicle surveys, or vision-based infrastructure systems for observing anomalies. While these systems provide reliable observation results, they suffer from multiple drawbacks, including high cost of implementation, unsustainability, late detection, and lack of real-time performance. Furthermore, traditional distributed AI-based systems require considerable computation resources and power consumption. The recent emergence of IoT, artificial intelligence, edge computing, and vehicle-to-everything communication technology brought significant innovation into modern intelligent transportation systems (ITS). Smart IoT sensors with built-in accelerometers, gyroscopes, global positioning system module, and IMU provide real-time road anomaly detection services. At the same time, machine learning techniques enable accurate road anomaly recognition and prediction based on IoT sensor streams. However, current ITS road monitoring solutions suffer from several problems. The majority of modern intelligent systems still use cloud-oriented architecture that imposes high communication latency, extensive bandwidth usage, potential privacy threats, and high energy requirements for AI execution. Therefore, the sustainability of AI for the future transportation system requires the development of energy efficient and adaptive computing systems for IoT sensors. This paper proposes an edge and AI-driven Sustainable IoT system for road health monitoring and transportation intelligence based on multi-sensor fusion, federated learning, connected vehicles, and edge computing for ITS.

Background and Motivation

Modern intelligent transportation systems have become an indispensable part of any contemporary smart city architecture. Governments and transportation authorities have been gradually moving towards automated systems capable of monitoring infrastructure and predicting its state and traffic. Intelligent road anomaly detection deserves a lot of attention because of its clear relevance to sustainability and safety in transportation. Badly maintained roads create additional rolling resistance and fuel consumption, thus increasing greenhouse emissions and harming the environment. Damaged roads make cars consume more resources and increase risks of accidents. Thus, intelligent road anomaly detection and maintenance can help create a more sustainable system of transportation through proactive maintenance and optimal routing. Recent trends in sustainable artificial intelligence (AI) aim at energy-efficient computing and minimum impact on the environment when using AI models. Sustainable AI approaches are especially relevant in applications where millions of interconnected devices constantly produce and consume data – such as transportation systems. The reason for carrying out this research is a need to create an intelligent and sustainable transportation system framework.

Literature Review

A number of previous studies have been dedicated to the development of AI and IoT-enabled intelligent transportation systems to detect road anomalies and enable smart mobility. First, Katariya et al. [1] designed an anomaly detection framework called VegaEdge which relies on edge AI algorithms for highway anomaly detection based on IoT sensing. The framework exhibited excellent anomaly detection performance with AUC metrics reaching 0.94. Still, the framework paid little attention to the long-term sustainability of energy resources. Second, Solaas et al. [2] conducted a systematic analysis of current anomaly detection strategies for connected vehicles. According to the authors, the use of convolutional neural networks and LSTM models enables highly effective transportation sensing. Meanwhile, certain difficulties associated with real-time implementation, scalability, and efficient energy inference remain unsolved. Third, Ejaz et al. [3] created a combined edge-cloud architecture for road anomaly detection. By implementing local processing at the edge, the framework succeeded in decreasing the communication bandwidth usage by around 70%. However, no attention was paid to the issues of inference energy consumption and computational carbon footprints. Fourth, Reis et al. [4] designed efficient Edge AI models to perform anomaly detection in IoT environments. The framework offered substantial improvements in terms of low-power computations and energy inference. However, it was not applicable for transportation or automotive anomaly detection tasks. Fifth, Wong et al. [5] created an anomaly detection system for smart transportation systems with sustainable vehicular communication and green computing features. Although the framework improved communication processes, no sensor fusion was implemented to monitor road health. Sixth, Shit and Subudhi [6] suggested an advanced AI–blockchain integrated framework for anomaly detection in autonomous transportation systems. The design of such a framework enhances security and reliability of communication but raises concerns about computational complexities. Seventh, Zareei et al. [7] created ML models for pothole detection based on smartphone sensors. Although it allowed for cost savings, this technique does not provide adaptive AI optimization or collaborative learning. Finally, Prabha et al. [8] introduced Edge AI–enabled IoT framework for real-time anomaly detection in smart infrastructure. The study highlights the importance of edge processing to decrease the network overhead and communication latency. As seen, significant progress in terms of AI applications in transportation sensing was achieved. Yet, there is still much room for improvement in the field.

Research Gaps

Based on the literature review and the criteria for identifying gaps in LGPR research, the following gaps can be identified:

- Most systems focus on accurate detection without paying much attention to sustainable metrics of AI such as energy efficiency and greenhouse gases.
- A number of road surveillance platforms rely heavily on centralized cloud computing infrastructure, leading to high levels of communication delay and overheads.
- Many existing AI models are highly computationally complex and thus cannot be deployed in low-power edge devices.
- Very little work has been done on federated learning and collaborative intelligence in connected cars.
- Lack of adaptive techniques that can dynamically adjust the AI model based on energy and traffic condition data.
- Current models only focus on classification and do not address predictive road degradation.
- Lack of integration between IoT sensor data fusion, edge-based AI, and V2V/X communication techniques.

Problem Statement and Research Objectives

There are several constraints that are prevalent in the current road-monitoring systems, such as lack of real-time detection, high implementation cost, high computational requirements, dependence on cloud infrastructure, and poor scalability. The AI systems that have been developed up to now require a significant amount of energy, and cannot provide sustainable smart transportation solutions. Thus, the requirement for development of an energy-efficient, scalable, and sustainable AI-powered smart transportation system has emerged.

The main research goals of this project are:

- To design a multi-sensor data fusion scheme for IoT-based real-time road anomaly detection.
- To create an energy-efficient edge computing architecture driven by Sustainable AI for intelligent transportation systems.
- To incorporate lightweight AI architectures to be utilized in edge devices.
- To facilitate federated learning and collective intelligence through the use of V2V and V2X communications.
- To design flexible AI processes able to allocate resources in the most efficient manner.
- To conduct predictive analysis of road degradation and prevent infrastructure failure.

Proposed Framework and Methodology

The designed Sustainable Edge AI and IoT-based Smart Transportation System combines IoT sensor fusion, lightweight Edge AI, federated learning, and V2V/V2X communication techniques to achieve real-time analysis of the status of the roads. The aim is to offer real-time analysis of the road surfaces in an energy-efficient manner, with minimum latency and scalability without being overly dependent on cloud services and high communication costs. IoT sensors including accelerometers, gyroscopes, GPS, and IMU sensors keep recording data about the road surfaces through their installed vehicles.

In addition to that, the design makes use of federated learning and V2V/V2X communication to enhance collaborative intelligence, privacy protection, and smart traffic management. Sustainability principles have been included for efficient computation, better inference, and ecological monitoring of transportation.

Table 1. Proposed Framework and Methodology

Component	Description	Expected Outcome
IoT Sensor Layer	Collects real-time road condition data using multi-sensor fusion	Continuous road monitoring
Edge AI Layer	Performs lightweight real-time anomaly detection on edge devices	Low-latency intelligent processing
Federated Learning	Enables collaborative model learning among connected vehicles	Improved scalability and privacy
Communication Layer	Supports V2V and V2X data sharing	Smart transportation coordination
Data Preprocessing	Noise filtering, normalization, and feature extraction	Improved detection accuracy
AI Model Development	Trains lightweight CNN and TinyML models	Energy-efficient edge intelligence
Sustainability Evaluation	Measures energy usage, latency, and communication overhead	Green intelligent transportation

Expected Outcomes, Future Experimental Design, and Conclusion

Based on the discussion and design presented, the sustainable Edge AI and IoT-based smart transportation system is likely to provide enhanced road condition analysis through minimal computing and communications costs. With the use of lightweight Edge AI technology, IoT sensor fusion, federated learning, and V2V and V2X communication technologies, the framework can provide increased scalability, safety, and sustainability in smart city transportation applications. The proposed solution will allow to obtain higher road anomalies detection accuracy, lower energy consumption and latency rates, optimized bandwidth usage, and increased predictability of intelligent transportation infrastructure maintenance. To conduct future experiments, it will be necessary to implement and deploy the IoT sensors on the smart vehicles to collect real-life road condition data. Lightweight models will need to be trained and optimized for the Edge deployment. Comparisons between Cloud AI and Edge AI technologies will be conducted based on the accuracy, precision, recall rate, and F1 score achieved. The federated learning techniques will be tested in connected vehicular communication environments to check their efficiency in increasing intelligence while protecting data privacy. Finally, the performance will be measured with the use of accuracy, precision, recall rate, F1 score, latency rate, bandwidth consumption, and energy per inference measurements. In conclusion, this study proposes an innovative sustainable and scalable solution to intelligent transportation based on the integration of Edge AI, IoT sensing, and connected vehicular technologies. With the use of this framework, it will be possible to reduce the reliance on cloud computing resources in transportation monitoring systems, improve energy efficiency, and create more environmentally friendly intelligent transportation infrastructure. Furthermore, the study makes significant contributions to several emerging fields of research, including Green Intelligent Transportation, Sustainable AI, and Smart Infrastructure Systems.

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