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MODERN STRATEGIES FOR REDUCING POLLUTION IN TRAFFIC CONGESTIONS: A REVIEW OF CARBON FOOTPRINT-BASED METHODS

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Abstract

The development of deep learning technologies and digital image processing have brought innovative solutions for various fields of activity. One area that has benefited from these technological innovations is urban traffic analysis. Architectures based on convolutional neural networks are used in a wide variety of intelligent systems that rely on image detection and analysis. This micro-review aims to provide a comprehensive overview of strategies for reducing pollution in traffic congestions through carbon footprint-based methods. The emphasis is on methodologies that quantify and mitigate the environmental impact of traffic congestion, combining advances in technology with authority measures. Examining current methodologies, new trends and case studies, this study seeks to highlight modern and effective strategies that can be implemented to provide practical solutions for more efficient and sustainable urban transport and pollution reduction.

***Keywords**: sustainability, carbon footprint, deep learning, image processing, remote sensing*

INTRODUCTION

Urbanization and the rapid growth of motorized transport have led to significant increases in traffic congestion worldwide. According to several research studies, the world's population breathes air containing high levels of pollutants, much of which is attributed to vehicle emissions in congested urban areas. Congested traffic causes delays and economic losses but contributes substantially to environmental degradation by increasing carbon dioxide and harmful emissions (Rusca et al., 2022). As cities continue to expand, addressing the environmental impact of traffic congestion has become a pressing concern and an area of massive research and development.

The concept of carbon footprint has emerged as an important measure for quantifying the environmental impact of various activities, including transportation (Kousoulidou et al., 2013). In the context of traffic management and monitoring, carbon footprint methods provide a systematic approach to assess and mitigate the environmental impact of vehicle emissions (Gao et al., 2023; Rafique et al., 2023). By quantifying emissions, important courses of action can be identified, the effectiveness of mitigation strategies can be assessed, and informed decisions can be made to reduce pollution (Kuneva et al., 2023; Rosu et al., 2023).

The development of sensor technologies and the field of deep learning supported by modern digital image processing techniques have brought to the fore major changes in this direction. For traffic analysis and monitoring, modern society today enjoys a series of best practices and continuous research directions aimed at solving major problems in this context (Zaharia et al., 2023; Dunea et al., 2016).

The ongoing analysis of contexts of this type, research focused on carbon-footprint documentation and the major impact of deep learning described the significant impact of models such as traffic analysis and Intelligent Transportation Systems (ITS). Traditional strategies to alleviate traffic congestion have focused on infrastructure expansion, such as building new roads or widening existing ones. Although these solutions are initially feasible, they quickly become problematic resulting in continuous agglomerations based on the population encouraged to adopt personal vehicles for any type of travel, eventually leading back to congestion. Infrastructure projects are capital-intensive and may be impractical in heavily populated urban areas.

The present work presents a systematic review of modern strategies and techniques for reducing traffic pollution based on carbon-footprint methods. The importance of this review is described by the interdisciplinary approach, bringing to the stage methodologies from environmental science, transport engineering, smart-city and cutting-edge technologies. The key areas that are explored are described by ITS in optimizing traffic flow to reduce emissions, the application of the field of deep learning and image processing in the prediction and management of traffic congestion and the analysis of the impact of these modern strategies. In the same framework, challenges and limitations associated with these strategies and best practices are discussed.

MATERIALS AND METHODS

In order to observe the important research directions and the impact in this field, several impact specialist works were analyzed and focused on an important direction - new trends and the role of deep learning and image processing in reducing the carbon footprint. The extraction and analysis of specialized papers focused on this topic, published between the years 2019 and 2024, was pursued. The databases used for this study were IEEE and Web of Science. The papers were selected based on several criteria oriented towards innovation, number of citations, impact factor and new period. The extraction of specialized papers from the mentioned databases was done by using some key terms, connected by *AND* / *OR* operators, including deep learning, image processing, traffic management, carbon footprint, pollution, artificial neural networks, intelligent transport systems.

The addressed research topic underlines a considerable evolution of research in recent years (Figure 1). The effectiveness of different strategies was analyzed based on case studies, research papers and experimental results or simulations. From the extensive list of works, studies that did not provide concrete data or that were not relevant to the objectives of the present research were excluded.

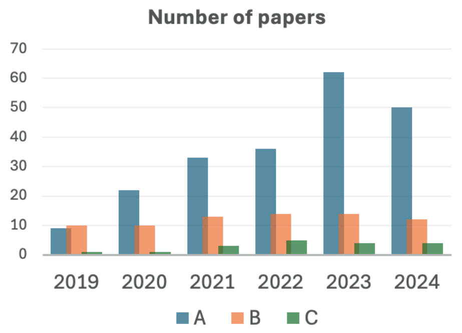

Figure 1. Search results for important terms in the Web of Science database, between the years 2019-2024:
A) (deep learning) AND (traffic emissions),
B) (image processing) AND (traffic emissions),
C) (vehicle detection) AND (neural networks) AND (traffic emissions)

KEY METHODOLOGIES AND NEW TRENDS

The processing of digital images, the integration of deep learning techniques and remote sensing areas have allowed the creation of modern methods for evaluating the carbon footprint in congested urban traffic. In this sense, we distinguish a series of key methodologies as part of the new trends, resulting from the analysis of the current state and the specialized works extracted. Various essential methodologies can be noted in this case: vehicle detection and counting, traffic flow and speed estimation, and emissions calculation and analysis (Rafique et al., 2023).

Convolutional neural networks have revolutionized the field of visual data analysis by extracting essential features from it. Notable studies applying vehicle identification and classification techniques from images and video streams are observed (Petrea et al., 2023).

Architectures of this type can extract complex data and features from images enabling the detection of different types of vehicles. CNNs are trained and evaluated on vast and comprehensive datasets, divided into training, validation and testing subsets. Common metrics for performance evaluation are attached to classification, segmentation or object detection tasks and include precision, recall, accuracy, F1 or mAP scores, calculated using indices of the so-called confusion matrix (Adi et al., 2024).

An important research direction involves the use of CNNs or combinations thereof for the detection and identification of important features in traffic optimization. The authors (Adi et al., 2024) proposed a method based on fusion algorithms for the identification of free parking spaces. The system uses a YOLOv7 model to segment vehicle instances and detect objects using algorithms such as Euclidean distance, intersection over reference (IoR), and intersection over union (IoU).

An intelligent and modern system to detect vehicles was proposed by the authors (Rafique et al., 2023). The system uses data sets comprising aerial images and CNNs, detecting vehicles in different conditions, classifying them and tracking their path using advanced digital image processing areas. A Pyramid Pooling Vehicle Detection module was used to improve detection accuracy by comparing performance using various established datasets such as VAID, VEDAI and DLR3K. The system developed based on new deep learning techniques can identify and track vehicles even in conditions of variable lighting or partial occlusion.

The utility and efficiency of a system based on CNN and deep learning algorithms used on a large scale was presented in the authors' study (Velesaca et al., 2020) to describe an urban video analysis system. The proposed system aims to extract essential information about traffic and pedestrians using urban surveillance cameras, ultimately generating key statistics on detected vehicles and the number of people. The tests were carried out on a university campus, demonstrating the usefulness and efficiency of the system. It is observed in this case that the integration of object detection architectures with advanced digital image processing algorithms (YOLO, SORT) has the role of creating modular and flexible traffic management and carbon footprint estimation systems.

In this way, intelligent systems are developed that can distinguish vehicles in different conditions and contexts (Figure 2). Automatic detection based on these techniques facilitates accurate vehicle identification in real time by providing important data about the context, volume and typology of traffic. Applied technological methods include the use of traditional cameras, thermal cameras or LiDAR in visual data collection.

Figure 2. Vehicle detection examples using YOLO models

Among the more advanced methods are research directions that use modified, hybrid or combined CNN architectures to create intelligent systems for detection and analysis of digital images (Zhang & Fu, 2025). Some of the advanced modifications made to CNNs aim to improve accuracy, efficiency, and scalability. By aggregating the predictions of several models, the ensemble method can achieve better accuracy and generalization than any individual CNN in the ensemble (Figure 3). In the same framework, modifications to existing architectures can improve the accuracy of models in various tasks, starting from basic models and exploring various architectural modifications and parameter optimization. In general, ensemble methods are based on the idea that combining the outputs of multiple models leads to better predictions because different models may capture different aspects of the data.

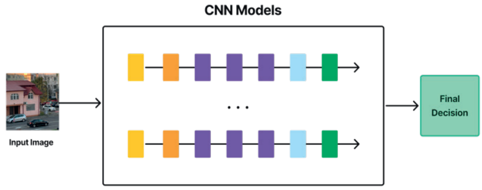

Figure 3. Example of CNN Ensemble

The study (Zhang & Fu, 2025) presents an efficient method for traffic estimation in congested intersections using a combination of neural networks and attention mechanisms. The proposed system uses the power of the SSD model for the object detection task and the ResNet architecture for the feature extraction part. A SENet attention mechanism is integrated to improve performance by emphasizing relevant features and suppressing others. On the other hand, a feature fusion model is used to improve the detection of small objects, a major challenge in traffic scenes with crowded contexts. The method was tested in real intersections, outperforming traditional methods and achieving an accuracy of 88.5% and a latency of only 12 milliseconds. The paper points out that the method can be applied in real intersection scenes for adaptive traffic light management and traffic risk detection, providing a fast and accurate solution for traffic density monitoring.
For applications of estimating traffic conditions and determining flow density, advanced image analysis techniques and specially designed algorithms for object location and tracking are used (Figure 4).

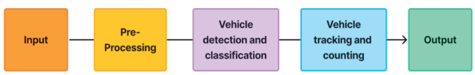

Figure 4. Traffic flow detection

The article (Chen et al., 2021) proposes a traffic flow detection system based on deep learning and edge computing. For the proposed system, the authors used the YOLOv3 architecture for vehicle detection and DeepSORT for real-time tracking. Both areas have been optimized to run efficiently on edge devices such as the Jetson TX2. Compared to classic cloud computing models, it is observed that the proposed approach improves the speed and accuracy of video data processing for traffic monitoring systems. Experimental results show an average accuracy of 92.0% and a processing speed of 37.9 frames per second on the edge device, which enables real-time detection of traffic flow. The study highlights the robustness of the method under varying lighting and occlusion conditions, highlighting its importance for intelligent monitoring management systems. The work contributes to the field of traffic monitoring systems by providing an efficient and accurate solution using advanced computer vision techniques with potential application in real-world intelligent transportation systems. The paper also highlights the potential of such methods to create intelligent systems, ultimately helping to reduce traffic congestion and pollution.
By applying architectures based on neural networks and models based on optical flow one can track the movement of vehicles in different frames. These ultimately allow estimation of vehicle speed and general flow. On the other hand, the analysis of such data brings to the fore important information regarding traffic patterns, congestion areas, and a deep understanding traffic dynamics in various areas and under various natural conditions (Labib et al., 2018).
An important framework in this research uses data obtained from the previously mentioned detection and classification applications to develop models for estimating emissions of CO_2 or other types of pollutants. By correlating the types of vehicles with the behavior observed in traffic, speed or various conditions, the specific emissions can be calculated (Zaharia et al., 2023). This framework lays the foundations for methods focused on carbon-footprint assessment. Modern methods and new trends highlight models such as COPERT, PEMS or similar ones successfully used to estimate emissions based on relevant factors (Kousoulidou et al., 2013; Rešetar et al., 2024).
On the other hand, the authors' study (Gao et al., 2023) brings to the forefront a clear picture of the limitations and opportunities related to the reduction of carbon emissions in the life cycle of electric cars. Although electric vehicles have the role of reducing carbon emissions from transport, their negative impact is found in the production area, during the manufacture of

batteries, compared to vehicles with internal combustion engines. Finally, the authors note solutions for reducing the carbon footprint through various best practices.
Integrating such models with the power of deep learning and digital image processing architectures enables accurate and real-time assessment of the carbon footprint generated by various traffic conditions. Considering these features, the studies highlight the robustness of the approaches under varying illumination and occlusion conditions, highlighting their importance for intelligent traffic management systems. Each work contributes to the field of traffic monitoring systems by providing efficient and accurate solutions using advanced computer vision techniques with potential application in real-world intelligent transportation systems.

RESULTS AND DISCUSSIONS

Continued, relevant research and the impact of deep learning techniques and advanced image processing for carbon footprint analysis and calculation note both significant opportunities and notable challenges.
For the topic of using deep learning architectures, one of the main obstacles is represented by the quality and availability of data. To train and develop accurate deep learning models, a considerable volume of high-quality data covering various scenarios and traffic conditions is required. Moreover, the collection of this data can be problematic when we bring up various aspects related to the existing infrastructure and restrictions related to video surveillance and personal data protection.
The complexity of digital image analysis and processing models as well as carbon footprint and emission estimation models are other major challenges. The increased complexity associated with these techniques can make interpretation of results difficult and bring high implementation and operating costs.
In this context, the observed future research directions include new methods of visual data analysis and techniques to improve the accuracy of the developed models. Efficient architectures, model compression and optimization techniques, or advanced vision transformer models are key steps in achieving these goals.
Validation and limitations of studies may also include issues such as data generalizability - differences between urban environments and challenges in transferring models between them, data quality - impact of datasets, bias and class imbalances, and computational resources. Advanced deep learning models require significant computational power to train and deploy in real time. This can lead to high implementation costs, both in terms of the hardware required and the associated power consumption
On the other hand, the set of available information can be improved by integration with other data sources. Data from various sensors, air quality sensors and IoT areas can provide a more complete picture of the impact of traffic on the environment. This multimodal approach can provide new insights and research directions ultimately contributing to the accuracy of estimates and precise modeling of the relationship between traffic and pollution.
The concept of the 'Big Data Value Chain' can significantly enhance the management of data in efforts to reduce pollution in traffic congestions. This framework, which includes stages such as data acquisition, storage, processing, analysis, and utilization, enables a comprehensive approach to managing the vast amounts of data generated by traffic systems. By leveraging this framework, cities can optimize traffic flow, reduce emissions, and make informed decisions to improve urban air quality (Ionitescu et al., 2024).
Addressing privacy issues for large-scale deployment may include local processing techniques, data encryption and anonymization as well as edge computing devices.

CONCLUSIONS

As urban areas continue to face the dual challenges of transport congestion and environmental pollution, there is an important requirement for policies that address both concerns simultaneously. Carbon footprint-based methods offer a viable approach to measuring and mitigating the environmental effects of traffic congestion and aims to outperform or assist existing traditional methods. Their applications are diverse, and they manage to offer fast and efficient solutions in relation to existing problems.

Following the details presented in this study, the new trends in advanced image processing, deep learning and best practices associated with the topic of carbon footprint reduction strategies can create systems and techniques successfully applied in the modern and continuously developing society. Current research initiatives comprise upon the efficiency of ensembles and integrating CNNs with other architectures, resulting in a variety of hybrid and optimal deep learning systems for advanced image processing. Despite the considerable challenges in using image processing and deep learning for carbon footprint assessment in congested urban transport, future research avenues present encouraging possibilities.

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