Educational Administration: Theory and Practice
2024, 30(5), 14226-14234
ISSN: 2148-2403
https://kuey.net/
Research Article

Review of AI-Based Traffic Management Systems in Urban Mobility

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Citation: Fnu Samaah (2024), Review of AI-Based Traffic Management Systems in Urban Mobility, *Educational Administration: Theory And Practice*, *30*(1), 14226-14234
Doi: 10.53555/kuey.v30i5.6490

ARTICLE INFO **ABSTRACT**

Efficient air management directly impacts the socioeconomic development of smart cities. Developing intelligent and autonomous technologies has enabled autonomous vehicles to have self-learning, perception, global orientation, and decision-making capabilities, providing a technical basis for realizing intelligent traffic management. In recent years, numerous intelligent intersection management systems have shown advantages in heterogeneous traffic management, and a qualitative or quantitative review of their performance is necessary. This paper defines the classification of intelligent intersection management and the procedure for conducting this review. Ninety-three intelligent traffic management systems with various combinations of unsignalized or signalized intersection handling, the position of control objects, and the specific functions of intelligent traffic management are collected to reveal the development trend, technical route, and field application of the current intelligent intersection management system.

Keywords: Traffic Management Systems in Urban Mobility, Industry 4.0, Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Smart Manufacturing (SM), Computer Science, Data Science, Vehicle, Vehicle Reliability

1. Introduction

As artificial intelligence (AI) progresses with increasingly innovative technologies such as machine learning (ML), autonomous management systems (AMS), reinforcement learning (RL), and the Internet of Things (IoT), this development also focuses on solving current and future challenges, including the efficient and sustainable management of deteriorating urban mobility and road networks. Traffic management is necessary to solve the continuous effects of metropolitan areas; however, available traffic management systems currently demonstrate various problems: congestion, pollution, extended journey times, serious accidents, and obsolete urban ecosystems with disparate living conditions. AI and its developing technologies provide new opportunities to revolutionize the principles of urban management, state agencies, and policies utilizing systems with greater efficiency, capacity to innovate, and sustainability. In the framework of traffic management issues, there are many research directions based on the current broad-sense AI nomenclature. In traffic-related studies, machine learning (ML), swarm intelligence (SI), heuristics, reinforcement learning (RL), and others are the most advanced and utilized technological paradigms of AI. Besides these topics, the methods encounter continuous advances, including combinations among considered techniques, and the various case studies demonstrate diverse approaches. The existing works report improvements from spatiotemporal traffic forecasting, another subject of considerable research interest, and the utilization of public cloud services and modern AI-based algorithms in real-time traffic management evaluations. The concept of decentralized malware propagation is another recent topic that studies federated learning in networks, a methodology with interesting implications for the privacy and scalability of AI-based traffic management systems. Despite these promising studies, new opportunities and scientific directions within the traffic management subfield persist. This review classifies traffic management research contributions and identifies the more recent works in numerous application areas; these opportunities guide the discovery of recent topics.

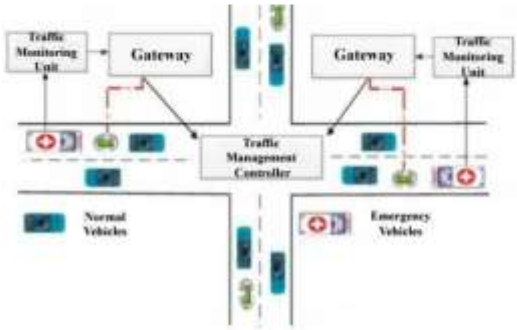

Fig 1: Intelligent Traffic Management System

1.1. Background and Importance of AI-Based Traffic Management Systems

Advanced traffic management systems (ATMS) in urban mobility have gained notable importance for various socio-economic reasons. Be it developed or developing countries, metropolitan areas are the focal point of economic, political, and social interactions—leading to substantial traffic levels. A city's economic development and growth reflects its affluence, quality of life, and urban facilities. Increased commuting distances between homes and work locations can lead to mobility problems such as traffic congestion, longer travel times, increased operating costs for transport operators, and increased vehicle emissions. Evaluating traffic flow planning supports decision-making and allocating resources to solve it. There is a need to reconcile the availability of resources and a certain number of possible actions, always trying to adopt the vision and strategy applicable to the specificities of each stage of traffic development characteristic in each region, according to the needs and the long and short-duration solutions. The high costs of both the public sector and private initiatives are confronted by looking for adequate solutions that can help solve the problems related to the established situation. Urban mobility management is a priority made explicit in local government programs. It is a relevant issue for the quality of life and citizenship of urban communities, as it is essentially an issue of democracy aimed at promoting participation and the right to the city, and it requires local management.

2. Key Components of AI-Based Traffic Management Systems

Traffic management aims to optimize the performance of the traffic network while considering various mobility and safety measures. AI-based methods have been proposed for urban traffic management through multiple applications, including traffic signal control, congestion prediction, and incident management. This paper reviews state-of-the-art AI-based urban traffic management systems using various AI methods such as reinforcement learning, deep reinforcement learning, and neural networks. Several promising AI applications to advance the urban traffic management system are identified. The implementation results of AI-based traffic management systems are also compared to traditional methods. Finally, the trend in using AI in urban traffic management is discussed. One way longitudinal traffic flow can be managed is by controlling the red/green phase splits for intersection traffic signal controllers. This is important as traffic signals cycle in stages, corresponding to assigned green times for each phase, and can be optimized for various cycle times. Conventional signal control strategies such as offline optimization, rule-based, and fixed-time are standard implementations for signal controllers. These controllers can be overcomplicated by requiring fine-tuning, are costly for migrating a system to an adaptive one, and typically assume traffic flow patterns and network infrastructure remain the same over time. Recent advances in artificial intelligence that can learn from large-scale traffic data are potent for comprehending traffic flow dynamics. This underlines the development of data-driven models that adapt to stochastic traffic flow dynamics patterns.

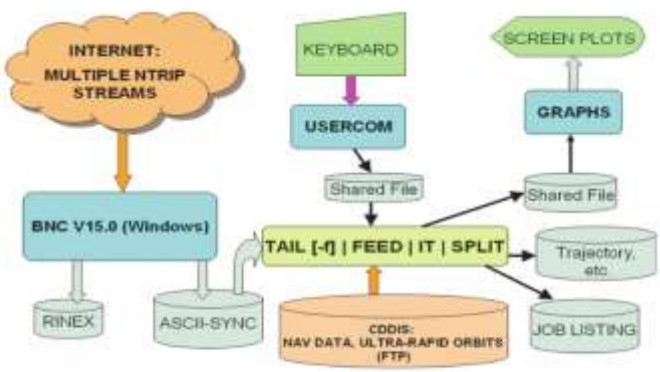

Fig 2 : Real-Time Data Processing System

2.1. Sensors and Data Collection

Traffic management is crucial to everyday urban life. By providing real-time dynamics to the road network, AI technology unleashes the potential for efficiency in transportation. Compared to traditional methods dependent on limited road sensors and citizen engagements, AI produces innovative models using various historical and current data versions, such as CCTV, satellites, GPS probes, IoT, flaming, and LIDAR. In addition, natural language processing (NLP), computer vision, and neural networks improve non-structured data retrieval. The strength of AI is also its fusion of heterogeneous sensor data types for comprehensive and detailed spatio-temporal problem-solving tasks tailored for traffic management. Incorporating unique gate sensors, vehicle/cyclist/pedestrian detection, and anomaly perception substantially improves the modeling precision of AI monitoring approaches. Furthermore, the city residents' 'them and us' perception is removed when large-scale dataset accumulation deploys a shared external collaborative decision-making process for mobility service support. The immediate road resource environment becomes an easy-access AI provision center for personal mobile robotics and automation. With the development of AI techniques such as reinforcement learning, agents designed to control traffic light systems perform better than real-life traffic light controllers. This power inspires the desired traffic equilibria with roadworks, traffic incidents, and public event precautionary plans. Multiple traffic-related multi-agent systems can conduct cross-domain optimization. Empowered by AI, urban mobility performance can reach another stage of research, design, economic, political, and social benefits beyond trade-offs. The methodology is emerging into the vehicle routing problem (VRP) study of sharing mobility-based delivery services in our increasingly congested city. Especially during our urgent use of metropolitan delivery services, one-day delivery services are more frequently observed during post-online purchase times. There is no effective traffic management tool able to regulate the sudden influx of delivery vans. AI encourages new solutions to cooperatively maintain a smooth city logistics system. Ultimately, an increased profit to the supplier and a welcomed customer experience will catalyze sharing service physical task automation.

2.2. Data Processing and Analysis

Traffic data collection and analysis based on traditional detection platforms such as microwave, ultrasonic, and infrared sensors were originally preferred for their reliability and accuracy. With the increasing use of cloud computing leveraging big data technology, using traditional traffic data collection and analyzing methods to meet the new traffic management requests is quite difficult.At present, intelligent transportation systems leverage the latest developments in information and communication technologies such as IoT, cloud computing, and big data, enabling mobile users to monitor and retrieve information at any time, facilitating urban mobility.Data processing is a key analytical software component, responsible for handling the incoming raw data and converting it into cleaned and structured data that algorithms can use. For AI-based traffic management systems, data processing often includes data fusion techniques for adjusting different models and mapping techniques for adjusting coordinates of intersections, such as Google Maps integration. Number plate detection and recognition is a classic example of data processing for visible traffic cameras. Other examples of data processing are tracking detected objects (often using a combination of Kalman filter and naive predictive models), timestamping, path reconstruction from detected events, and propagation of context-rich data.

3. Applications and Case Studies

The applications and case studies provide information on the sources used for data collection and how transportation actors capture, process, and use data. The information presented in this section focuses on the various data sources, data capturing techniques, how and where AI-based techniques are used in traffic management, and the types of traffic congestion identified. The section is subdivided into sources of data, data capturing techniques, and applications of AI-based management that range from highways, urban mobility, pedestrian, and public transportation. The identified traffic management is also discussed. Sources of data are: (i) image data from in-vehicle cameras, CCTV, smartphones, drones, and satellites; (ii) video data from in-vehicle cameras, CCTV, and smartphones; (iii) GPS data from smartphones, in-vehicle devices, How on-Board Units, and Automatic Vehicle Location systems; (iv) trajectories, floating data, trace data, logs from smartphones, in-vehicle devices, Automatic Vehicle Location systems, cameras, satellites, and traveler information systems; (v) travel time and speed over time, congestion length and strength among others from traveler information systems, inductive loop detectors, cameras, GPS based on vehicles traveling on roads.The data-capturing technique discussed here is the use of image data in various modes of transportation. This includes in-vehicle images or pronunciations – There is no contest to access the deployment of in-vehicle systems due to privacy issues. In-vehicle image data if shared could deliver widespread benefits. The publication of data along with proof of anonymization could increase trust in the community, potentially leading to wider consent. The argument of privacy and security capturing images severely limits the ability to utilize this improved traffic management from the information that this novel type of data can offer. In line with privacy standards, future research avenues include the securing of shared data and the proof of anonymization. This analysis proved the potential for innovative management if extended by the widespread deployment of image sensors. Open Dataset Reported – Smartphone images allow researchers to have information from the street level. To bring this type of innovative data from smartphones into practice, potential barriers were addressed that might limit the extent of the use of smartphones for creating a publicly open data set. The benefits of an open data set of street-level images, such as this data might provide, and potential barriers, including privacy and personal rights, were pondered in the research. Principles of reaping the potential benefits while minimizing the potential drawbacks were proposed for interested researchers. A shared street-level in-vehicle data set could fill gaps in current transportation modeling. The research community currently uses data from in-vehicle cameras at the street level to understand the driving environment, but it is not shared with the broader research audience. Experiences learned from these publications are shared, including information about license plate information, and the approach was given on how to anonymize the data and obtain proper permissions for sharing data. Published vehicle image data. The following section discusses case studies of AI-based techniques applied in traffic management of highways, urban mobility, pedestrians, and public transportation, including approaches to address traffic congestion issues. Some bicycle and pedestrian case studies are also discussed.the potential of leveraging image data from various transportation modes, including in-vehicle cameras and smartphones, to enhance traffic management and transportation modeling. It underscores the critical balance needed between the benefits of open data sets, such as improved research and development, and the privacy concerns associated with sharing sensitive image data. Addressing these concerns through robust anonymization techniques and secure data sharing practices is crucial for gaining broader community trust and facilitating wider consent for data utilization in transportation research. The discussion also highlights the ongoing challenges and ethical considerations in integrating these innovative data sources into practical applications for enhancing urban mobility and addressing traffic congestion issues.

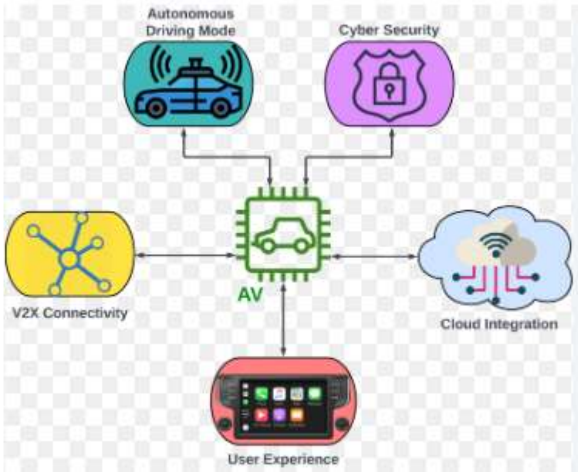

Fig 3 : Evolution of Artificial Intelligence and Learning Algorithms

3.1. Traffic Flow Optimization

This is a technology review article to accurately document and summarize the developments in AI-based traffic management in the context of future urban mobility. Traditional traffic management is based on predefined rules and works well within certain limitations. However, the increasingly complex traffic environment due to denser inter-urban collaborations has limited traffic management. AI-based methods, especially those with reinforcement learning, provide an attractive way to perform complicated control given large-scale traffic data. Here, with no limitation under application domain or technical details, we aim to summarize state of the art and provide guidance on the feasibility, reliability, cost, acceptance, and even potential risks of AI application for general traffic management in future intelligent transportation systems.Traffic flow control is probably the best-known application of AI for traffic management and a reason. AI-based traffic signal control can optimize traffic flow subject to traffic volume variation online, which is a complex problem for traditional optimization and control methods. Reinforcement learning, especially its deep version, has been at the driver's seat of this revolution. Major initiatives have popped up all over the world with high impact and visibility for both academics and industrial developers. A less directly measurable but still significant advantage of traffic flow optimization is the decrease of emissions and improved urban environment. Control of traffic signals has a direct positive impact on the planet by decreasing the waiting time, thus cutting down gas and power consumption. The environmental impact is probably a neglected but promising application of AI in urban mobility. Some existing applications are using AI methods to develop systems, such as a machine learning algorithm aiming to predict driving conditions and traffic flow.

4. Challenges and Limitations

There are many areas in both the deployment and challenges faced by intelligent traffic systems, which are limitations or subjects of both current and ongoing research throughout the community. This is such a complex field of academic and practical industrial value, thus proving beneficial for future research from the viewpoint of both system improvements and industry deployment studies.Very few products have exploited the Internet-of-Things (IoT) type sensors and are more akin to smart city-type solutions. It is known that the real operational value of AI in intelligent traffic solutions lies in enabling AI production networks, with AI decision-making networks, across a city-scale IoT. Additionally, such an operationally costly city-scale network can only be practically useful based on cost-effective and scalable IoT infrastructure. While there are a small number of vendors that have combined IoT streams into machine learning solutions, there are not any that have operationalized the management across such a large-scale operational problem.

Fig 4: A sample intelligent city scenario.

4.1. Privacy and Ethical Concerns

With the ever-increasing sophistication of artificial intelligence and its application in the context of smart urban mobility, there is a growing challenge of privacy concerns and ethical considerations. Given the nature and extent of data that is collected, processed, and analyzed, there is warranted concern about the surveillance of people in the public realm. Who has access to the data? How is the collected data stored and processed? Who is the decision-maker, and what are the implications of such decisions? Key questions arise, such as whether end users should/could own and control the data generated by their devices, and whether to allow a level of autonomy to the machines to make decisions using the processed information. User trust is a significant factor in the acceptance of systems, and persuading trust policies is increasingly becoming part of the research effort in connected and autonomous vehicle studies.There are issues, often overlooked, associated with the chronic unease linked to the connectivity that outages cause, and the cybersecurity risks and lack of resilience that are manifest in both intelligent transport systems and vehicles. Furthermore, privacy-concerned regulations and policies that usually change on a national or even local level can lead to deviations in architecture evolution and deployment of next-generation markets and services. It has been shown by security researchers that such chaos in regulations and policies might lead to local monopolies and network fragmentation that might stop further improvement of infrastructure. Even when compliance with privacy-related regulations is forced, unscrupulous individuals attempt to bend regulations if not break them, and groups of organized criminals exploit any loopholes that they might find. This privacy threat of privacy violation and data breach needs to be evaluated using metrics that show the level of reproducibility and the level of trace overall systems represent.

5. Future Directions and Innovations

We summarize the research articles published in the period 2009–2020 for AI-based traffic management systems and propose the trends, research gaps, and future directions. In the future, algorithms of this core element can be further improved by better exploiting the potentialities offered by deep learning techniques by refining the parameters that define the dynamic net transition, avoiding the traditional method of fixing them using empirical experience. The core building block of deep learning traffic management solutions is the prediction of the future state of the road network. This can be an extension of the predictive capabilities of the intelligent actuation, but one key difference is that traffic estimates follow the road geometry at all times.Given the amount of experimental work, performance evaluation, and benchmark testing, we are confident that introducing AI and machine learning algorithms in the context of smart cities will have an increasingly important impact, not only at a theoretical level but also from real-life scenarios in urban mobility problems. This aspect calls on automotive intelligent systems to be effective and fault-tolerant, especially under critical conditions. In vehicular ad-hoc networks (VANET) as well as on future vehicle-to-everything (V2X)-based infotainment platforms, the integration of the results obtained from the AI components of the mesoscopic traffic prediction with those of the control system can generate added value and improved autonomous driving experience. Fast prototyping and smart integration of the Network On Chip (NoC) reconfigurable computing paradigm with other control approaches is also an interesting path to pursue, making eventual developments easily practical and exploitable.

Fig 5: Urban Traffic Management System.

6. Conclusion

The review of AI-TMS in urban mobility is made to understand the trends of technological development, the effects of AI-based traffic management systems in urban space, and AI's impact on future urban mobility. AI faces several challenges for practical solutions in traffic, such as highly mixed traffic, the information disparities problem, the data distribution shift problem, and the unstable scenario of traffic. The review results raise some important issues in AI traffic systems, social challenges of AI traffic management, and exploitation of AI in traffic control strategies.In the process of reviewing AI-based traffic management systems and optimization models developed to solve these problems, we describe various technical methods of data-driven AI applications. As it is difficult to finalize specific technologies for actual application, AI is likely to have a great impact on the future development of such systems due to its proven and prospective impact on traffic. However, there are not many places to introduce AI traffic systems because each city administration has a limited budget. To introduce converging technologies in various fields and create practical solutions, a wide range of cities and researchers need to share available data and understand challenges that arise on the national and international scales for AI in urban mobility.

6.1 Future Trends

Given the growing interest and the material implementation of AI-based smart mobility projects, it is expected that there will be a massive adoption of these systems in different areas of traffic management in the short term. Specifically, among the most relevant future lines of EMT systems, there is the movement towards interconnected devices and the development of a new generation of mobile applications that enable citizens to assess the environmental impact of each trip. For this reason, many cities have already implemented various types of devices to sense the environment, such as mobile applications and cameras. Even fictional cameras can already contribute much real-time data that influences traffic management. Currently, most EMTs are simple cameras connected to video recorders and computers. The main objective is to find the parameters that manage the periodic signal in urban areas or road sections at the signalized intersections, use the global algorithm to optimize them and manage the network rigorously. The modern traffic management system paradigm uses AI, big data, and IoT. In the following, then, some of the areas most affected by the advent of AI-based mobile applications that measure or reduce the environmental impact of mobility are described. In addition to this research area, many more specific and in-depth pioneering AI research areas focus on the individual aspects of traffic congestion, each of which we will review in the following. Some applications are already available; others are still under test and various configurations are already being considered at other project stages.

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