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Advancements in automated traffic management using fuzzy logic: Prospects and challenges

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Abstract. This article reviews modern methods of automated traffic flow control based on fuzzy logic, which enables the processing of incomplete or imprecise information – a characteristic feature of dynamic traffic conditions. The aim of this study was to evaluate the prospects and challenges associated with implementing fuzzy logic in transport system management to enhance the efficiency and safety of road traffic. The paper examined the potential and difficulties of using fuzzy logic for traffic light control, its integration with intelligent transport systems, and its combination with artificial intelligence and Internet of Things technologies. Fuzzy logic allows systems to adapt to real-time changes, considering factors such as traffic intensity, weather conditions, and driver behaviour. The article analysed several examples of the implementation of such systems in different countries, particularly Japan, Germany, and the United States, where fuzzy algorithms have demonstrated effectiveness in reducing congestion, improving road safety, and optimising the use of transport infrastructure. The main challenges associated with implementing these systems are also outlined, including the complexity of developing fuzzy logic models, the need for highly trained experts to configure such systems, and the technical and financial barriers encountered during the modernisation of transport infrastructure. Additionally, the study discussed cybersecurity and data protection issues, which are increasingly relevant given the extensive use of data in intelligent transport systems. The practical significance of this work lies in identifying effective solutions and opportunities for their adaptation to enhance the safety and capacity of urban and intercity transport systems

Keywords: traffic optimization; traffic intensity management; information technology integration; adaptation to traffic conditions; transport infrastructure; intelligent transport systems; traffic congestion

Introduction

The increasing number of vehicles and the growing intensity of road traffic necessitate the implementation of modern technologies for the effective regulation of traffic flows, as traditional methods, such as fixed traffic lights, are unable to adapt quickly to real-time changes. The complexity of traffic, influenced by various factors such as weather conditions, driver behaviour, and fluctuations in flow density, calls for adaptive approaches. Fuzzy logic is a

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promising method that accounts for multiple parameters and enables a flexible response to complex traffic situations, thereby helping to reduce congestion, lower emissions, and enhance road safety.

Recent research explored various approaches to automating control processes in the transport sector to ensure the stability and reliability of infrastructure solutions in situations characterised by uncertainty and complex input data. S.K. De & G.C. Mahata (2023) investigated the application of fuzzy logic in a shortage inventory management model that incorporates backorders. Their study demonstrated the effectiveness of fuzzy logic in decision-making under conditions of demand uncertainty, facilitating optimised inventory management. The primary conclusion of the research highlighted fuzzy logic's adaptability to changes in demand, a feature that could be valuable in traffic flow management by optimising resource allocation.

L.M. Markina *et al.* (2021) analysed the application of fuzzy logic in industrial automated systems, demonstrating its ability to adapt parameters to changing conditions. Their study highlighted the potential for adaptive control, which can be utilised to regulate traffic flows by accounting for variations in traffic intensity. S. Lin (2022) examined fuzzy machine learning methods designed for processing large volumes of data in dynamic systems. The integration of fuzzy logic into machine learning enables the handling of imprecise or incomplete data, which is particularly crucial for transport systems that require rapid adaptation to changing traffic conditions.

O.H. Avrunin *et al.* (2021) analysed intelligent automation systems, with a focus on neural network methods for monitoring the technical condition of equipment. Their study aimed to develop a system capable of continuous analysis and failure prediction based on input data, a feature that is essential for the maintenance and reliability of transport networks. V. Bordun (2023) investigated automated traffic control systems for controlled intersections, exploring strategies to reduce congestion and waiting times. The study demonstrated the effectiveness of adaptive traffic light control in enhancing throughput, particularly in large urban areas. The primary conclusion emphasised that integrating automated control systems based on fuzzy logic can significantly optimise traffic management at intersections.

I. Olenych *et al*. (2021) in their book explored the theoretical foundations of fuzzy logic and its application in models of complex systems. The significance of this work lied in its explanation of the principles of fuzzy logic, which form the foundation for the development of adaptive transport systems. The key conclusions of the study indicated that fuzzy logic can effectively facilitate control under uncertain conditions, making it particularly suitable for models requiring rapid adaptation. D. Slavinsky (2023) developed a methodology for multi-criteria analysis of routing algorithms, which can be applied to optimise traffic flow in dynamic conditions.

The analysis of scientific literature highlighted several aspects of automated traffic management based on fuzzy logic that remain insufficiently explored or require further investigation. The first of these aspects is the development and implementation of adaptive models capable of real-time optimisation of traffic flows using fuzzy logic while accounting for the variability of traffic conditions. The second unresolved aspect concerns the integration of fuzzy logic technologies with other intelligent systems, such as neural networks and machine learning algorithms, to enhance the accuracy of decision-making and congestion forecasting. Additionally, an important issue is the evaluation of the effectiveness of such models on a large scale, particularly when applied to extensive urban networks.

This study aimed to further explore the potential of combining fuzzy logic with machine learning to develop adaptive traffic management systems that minimise congestion and improve throughput in dynamic urban environments. The purpose of this article was to review and analyse modern methods of automated traffic control based on fuzzy logic, as well as to identify the prospects and challenges associated with their implementation in high-traffic and dynamically changing conditions.

Materials and Methods

This study conducted a comprehensive analysis of modern methods for automated traffic flow control based on fuzzy logic. The research employed theoretical analysis to examine the principles of fuzzy logic, its characteristics, and its potential applications. Additionally, synthesis was used to evaluate existing approaches and algorithms for road traffic management. Content analysis methods were applied to review scientific literature exploring the use of fuzzy logic in controlling dynamic transport systems. The study analysed contemporary automated traffic control methods, particularly adaptive traffic light control systems, integrated urban transport control systems, and intelligent highway systems. A comparative analysis was conducted to identify the characteristics, advantages, and limitations of each method. The results of this comparison were processed using graphical methods and presented in the form of diagrams.

The analysis considered the adaptability of automated control systems, their efficiency in processing data rapidly, and their overall impact on road safety. Particular emphasis was placed on the ability of these systems to account for complex external conditions that directly influence traffic, such as weather variations, traffic intensity, and fluctuations in driver behaviour. The study specifically focused on adaptive traffic light control systems and intelligent transport management systems, which have demonstrated effectiveness in managing complex urban traffic networks.

The empirical part of the study involved the modelling of control systems using real data from urban and highway networks. The data were collected through induction loops, infrared cameras, and sensors that recorded traffic flow parameters, including speed, traffic density, and vehicle count. Fuzzy inference algorithms were applied in the analysis, enabling the adaptation of traffic light phase durations in response to real-time changes. Data filtering and evaluation methods were employed to ensure the accuracy and reliability of the modelling process.

The study also examined real-world cases of fuzzy logic system implementation in several countries, including Japan, Germany, and the United States, based on the works of S. Araghi *et al.* (2017) and Z. Pezeshki & S.M. Mazinani (2019). The case study analysis provided insights into the practical application of these technologies, including quantitative indicators such as reductions in congestion, accident rates, and average travel times.

In the final stage of the study, a predictive analysis was conducted to determine the prospects for the development of automated traffic management systems based on fuzzy logic and to assess the challenges associated with their implementation in Ukraine. The findings highlighted the need for modernising transport infrastructure, integrating next-generation sensor technologies, and ensuring a high level of cybersecurity.

Results and Discussion

Fuzzy logic in traffic management

Fuzzy logic, proposed by L. Zadeh (1988), has become a crucial tool for handling imprecise and incomplete information, enabling the modelling of complex processes, particularly traffic flows. Its principles are based on the use of fuzzy sets, where each element has a degree of membership ranging from 0 to 1. This approach allows systems to more accurately represent reality in situations where conditions are continuously changing. Unlike classical binary logic, which permits only the values 0 or 1, fuzzy logic provides flexible state definitions. For example, in traffic light control systems, a gradual scale of traffic intensity from 0 to 1 can be utilised, allowing real-time responses to fluctuating conditions (Atlam *et al.*, 2021).

The concept of fuzzy logic includes fuzzy variables, "if-then" rules, and algorithms that account for situational variables. For instance, a rule might state: "If traffic volume is high and vehicle speed is low, then the green phase of the traffic light should be extended". The use of fuzzy rules enables the system to adjust its decisions dynamically based on current conditions, even when complete information about the road situation is unavailable (Araghi *et al.*, 2015). This is particularly beneficial in urban environments, where traffic flows are subject to constant variations.

Fuzzy logic-based control systems enable more effective responses to sudden changes by adapting to real-time conditions. Dynamic risk management methods allow systems to adjust to evolving situations by identifying both reliable and potentially hazardous road users through reward or penalty mechanisms, thereby increasing decision-making accuracy and efficiency in high-intensity environments (Shaikh *et al.*, 2012). Traditional fixed traffic light systems often struggle to adapt quickly to fluctuations, such as sudden surges in traffic during rush hours, frequently resulting in congestion. Fuzzy logic offers the potential to develop more flexible systems capable of making decisions even when faced with incomplete or imprecise information (Koukol & Marek, 2015). This adaptability enables transport systems to maintain smooth traffic flow even in complex conditions, reducing congestion at intersections and optimising road capacity.

The adaptability of fuzzy logic is achieved through the use of incremental values and fuzzy rules, allowing multiple factors to be considered simultaneously, including vehicle speed, roadworks, and congestion on alternative routes. Fuzzy logic demonstrates high efficiency in dynamic environments due to its use of linguistic variables and inference rules, which facilitate the integration of contextual information in real time. This makes it particularly effective for managing complex and unpredictable systems, such as IoT networks, where flexibility and resilience are crucial (Atlam *et al.*, 2021). For example, in cases where alternative routes become congested due to roadworks on main roads, the system can automatically extend the green phase of traffic lights at key intersections, thereby optimising traffic flow distribution and alleviating congestion (Sabar *et al.*, 2017). As a result, traffic light control systems become more resilient to changes and can rapidly adapt to unforeseen circumstances.

The ability of fuzzy logic to effectively process incomplete information makes it highly valuable for applications in urban traffic management, where conditions change rapidly and unpredictably. For instance, fuzzy models enable risk assessment based on data sensitivity, user action history, and the criticality of operations, enhancing adaptability and decision-making accuracy (Li *et al.*, 2013). During peak traffic periods, specific road sections can automatically adjust their operational modes more frequently to alleviate congestion, easing pressure on highways and minimising traffic build-up, even in the absence of precise information about the underlying causes. Consequently, fuzzy logic not only improves road network capacity but also facilitates the more efficient utilisation of transport infrastructure (Pezeshki & Mazinani, 2019).

Fuzzy logic provides flexibility and enables algorithms to rapidly adapt to new conditions by considering the complex interrelationships between various parameters, such as traffic intensity and weather conditions. This capability allows for swift, optimal decisions that help reduce congestion and enhance the efficiency of transport systems in urban environments. Thus, the integration of fuzzy logic-based systems into urban traffic management contributes to the optimisation of transport flows and the more effective use of infrastructure, even under complex and unpredictable conditions.

Modern methods of automated traffic control

Modern methods of automated traffic control based on fuzzy logic enable effective adaptation to dynamic traffic conditions. One of the key approaches is adaptive traffic light control systems, which adjust signal durations in real time based on the current road situation. Data for these systems are collected using inductive and infrared sensors that monitor vehicle speed, traffic volume, and congestion levels at intersections. Fuzzy algorithms analyse these parameters to determine the optimal duration of the green phase, thereby reducing delays at intersections and increasing overall traffic throughput. Such systems respond dynamically to fluctuations in traffic intensity, creating flexible conditions to alleviate congestion, particularly during peak periods (Araghi *et al.*, 2015).

Integrated urban transport management systems coordinate both public and private transport, enabling an even distribution of traffic flows. These systems are based on the principles of fuzzy logic, which allows them to dynamically adjust traffic patterns, prioritising public transport when overall flow levels exceed normal thresholds. Data for such systems are gathered from speed sensors and navigation systems that track vehicles in real time. This dual-function approach ensures that public transport receives priority at traffic lights while simultaneously minimising delays for private vehicles. As a result, traffic flows are more evenly distributed, reducing congestion in city centres – an especially critical factor in areas with high traffic intensity (Pezeshki & Mazinani, 2019).

Fuzzy logic is also widely applied in intelligent traffic management systems on highways, where speed limits and information displayed on electronic signs are adjusted according to real-time conditions. These systems account for factors such as traffic density, vehicle speed, and road surface conditions, receiving continuous input from sensors that detect changes in real time. Based on this data, the system can lower speed limits in congested areas, modify signage in response to deteriorating weather conditions, and provide drivers with timely warnings. This approach helps to reduce road accidents and ensures smoother traffic flow, even under high-load conditions (Wei *et al.*, 2018). The characteristics of automated control methods are summarised in Table 1.

Table 1. Main characteristics of automated traffic control methods based on fuzzy logic

Method	Description	Advantages	Disadvantages	Application
Adaptive traffic light control systems	Adjust traffic light phase durations based on traffic intensity at intersections, using data on vehicle count and speed collected from induction and video sensors.	Increase traffic throughput and reduce delays at intersections.	Highly dependent on sensor reliability and system settings.	Urban intersections, central areas of cities with high traffic intensity.
Integrated urban transport management systems	Coordinate the movement of public and private transport, ensuring priority for public transport, particularly during peak hours.	Ensure faster public transport movement and evenly distribute traffic flows.	May lead to delays for private transport.	City centres, areas with high traffic density.
Intelligent highway systems	Regulate speed limits and update information signs in real time, considering traffic density and vehicle speed.	Reduce accident rates and enhance safety under varying traffic intensity conditions.	Require continuous monitoring of sensor data status.	Highways, high-speed zones, roads with heavy traffic.

Source: created by the authors based on Z. Pezeshki & S.M. Mazinani (2019) and S.K. De & G.C. Mahata (2023)

The automated traffic control methods described, based on fuzzy logic, enable effective optimisation of traffic flows through adaptive solutions and the ability to respond swiftly to changing conditions in real time. Each of the examined methods has specific application features: from traffic regulation at urban intersections, where an adaptive traffic light control system reduces average delay times by 15 seconds, to high-speed traffic flow management on highways, where intelligent systems achieve a 50% reduction in congestion.

Figure 1 clearly illustrates the key performance indicators of each method – average delay time, traffic density, and congestion reduction – under various road conditions. The data demonstrate that each approach has distinct advantages tailored to specific needs, enhancing the flexibility and adaptability of the transport system. As a result, congestion is reduced, traffic flow is optimised, and overall road safety is improved, contributing to the efficient utilisation of transport infrastructure.

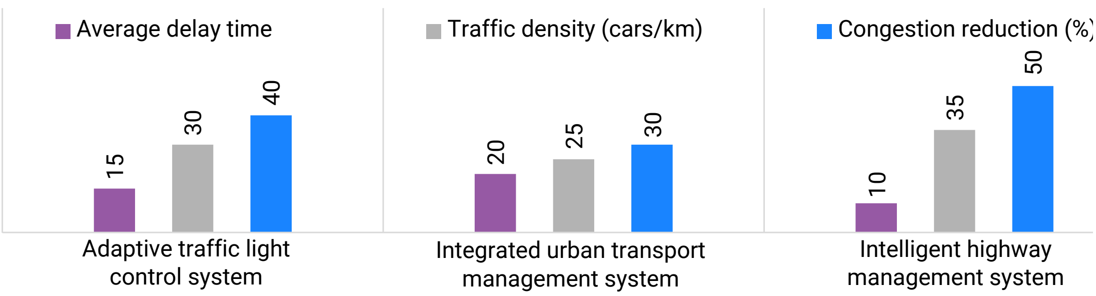

Figure 1. Graph of different traffic management methods effectiveness
Source: created by the authors based on S. Araghi *et al.* (2015), H. Wei *et al.* (2018), Z. Pezeshki & S. Mazinani (2019)

Modern automated traffic management methods based on fuzzy logic not only enhance traffic efficiency but also offer high adaptability to changing conditions. By responding dynamically to real-time situations, these systems optimise road capacity, minimise delays, and contribute to improved traffic safety on city streets and highways. Figure 2 compares three key traffic management methods: adaptive traffic light control, integrated urban transport systems, and intelligent highway control systems.

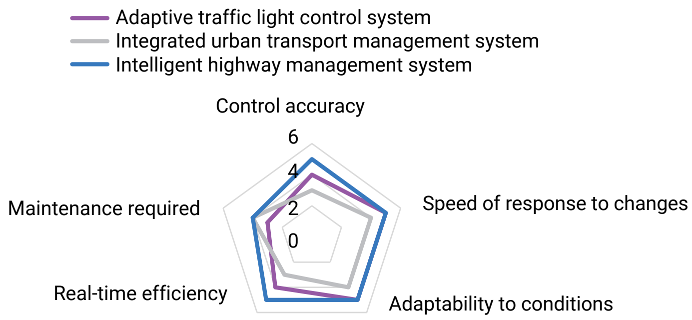

Figure 2. Comparison of traffic management methods by key parameters
Source: created by the authors based on S. Lin (2022)

Each method differs in key characteristics, including control accuracy, response speed to changes, adaptability to conditions, real-time efficiency, and maintenance requirements. Notably, the intelligent highway system demonstrates high performance across all aspects, making it particularly advantageous for expressways with high traffic density. In contrast, the adaptive traffic light system (Fig. 3) proves most effective in reducing delays at intersections, making it well-suited for urban environments with heavy traffic.

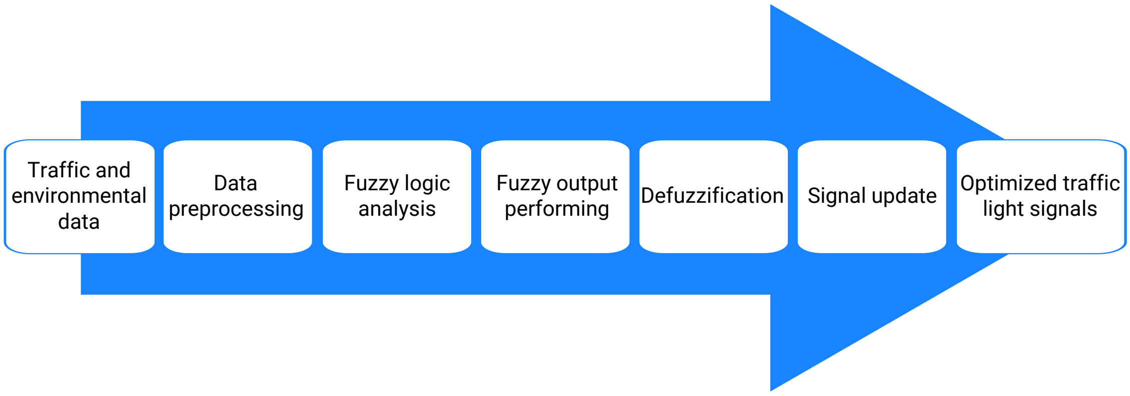

Figure 3. Adaptive traffic light control
Source: created by the authors based on Z. Zhou *et al*. (2017)

The flowchart of the adaptive traffic light control system based on fuzzy logic illustrates the decision-making stages within such a system. In the initial step, traffic flow data – including traffic volume, speed, and weather conditions – is collected using sensors and cameras. This is followed by data processing, where the information is filtered and verified to ensure accuracy.

The system then analyses the data using fuzzy logic, applying membership functions to determine the optimal duration of traffic light signals. The fuzzy output is converted into precise timing adjustments for the green phase, allowing traffic signals to be updated in real time in response to traffic conditions. Continuous performance monitoring enables the system to react swiftly to changes, thereby reducing delays and improving overall traffic throughput.

With the advancement of autonomous vehicles, fuzzy logic is becoming an integral component of driverless car control systems. Autonomous vehicles operate in highly dynamic traffic environments where quick decision-making – such as changing lanes, avoiding obstacles, or maintaining a safe distance from other road users – is crucial. Fuzzy logic enables these systems to adapt to complex and evolving conditions, ensuring real-time safety and efficiency.

Advantages and challenges of implementing fuzzy logic in automated traffic management systems

The implementation of fuzzy logic in automated traffic management systems offers significant advantages, as this approach effectively processes incomplete and uncertain data – an inherent characteristic of dynamic transport systems. One of the key benefits of fuzzy logic is its ability to enhance road capacity through adaptive traffic flow control. Fuzzy systems enable flexible adjustments to traffic light phase durations, the setting of speed limits, and decision-making processes based on real-time data, including traffic intensity, vehicle speed, and overall road conditions.

Effective traffic flow management reduces congestion, which is particularly crucial in cities with high traffic volumes, where delays and road congestion can result in substantial economic losses. By implementing fuzzy logic, optimal traffic flow distribution can be achieved, leading to more efficient utilisation of existing road infrastructure. Additionally, the integration of fuzzy logic with modern technologies such as artificial intelligence and the Internet of Things (IoT) facilitates the development of intelligent systems capable of adapting to rapid changes in the road environment, ultimately enhancing overall road safety (Pezeshki & Mazinani, 2019).

A second key advantage is the improvement of road safety, enabled by the ability of fuzzy systems to consider multiple risk factors. These systems can analyse weather conditions, vehicle speed, traffic intensity, and other variables that influence accident probability. Due to their ability to rapidly adapt to changing conditions, fuzzy systems can automatically adjust traffic lights and speed limits, helping to prevent hazardous situations on the roads (Avrunin *et al.*, 2021). This proactive approach contributes to a reduction in road accidents and enhances overall safety, making it one of the primary benefits of modern transportation systems.

A third significant advantage is the integration of fuzzy logic with emerging technologies such as artificial intelligence, machine learning, and the Internet of Things (IoT), which creates new opportunities for developing more intelligent and adaptive traffic management systems. The combination of these technologies allows systems to self-learn, adapt to changes in driver behaviour, predict potential variations in road conditions, and make real-time decisions (Wei *et a*l., 2018). For example, fuzzy logic can be applied in the control of autonomous vehicles, facilitating their safe interaction with other road users and enhancing the efficiency of road infrastructure utilisation.

The implementation of automated traffic control systems based on fuzzy logic presents several significant challenges that can complicate both deployment and operation. The complexity of developing fuzzy logic models necessitates meticulous tuning of membership functions and fuzzy inference rules, requiring expert involvement and increasing both time and resource costs. This process slows the real-world deployment of such systems and demands extensive preparation.

Another major challenge is the preparation of the necessary infrastructure. Effective operation requires the installation of induction and infrared sensors, surveillance cameras, and weather monitoring sensors – an expensive and technically demanding process. The costs are particularly high in cities with dense transport networks, where the need for comprehensive traffic monitoring significantly increases infrastructure requirements.

Additionally, integrating fuzzy logic-based systems with existing traffic control systems poses a considerable challenge. The diversity of system architectures and data transfer protocols creates barriers to seamless interaction between components. Ensuring compatibility between legacy and modern technologies is essential, requiring further technical and financial investment.

Processing large volumes of data in real time presents another significant challenge, as such systems require substantial computing power. Large datasets from multiple sensors must be analysed rapidly to ensure efficient system operation (Shmelov, 2021). This necessitates additional costs for technical support and demands optimisation of data storage and processing to maintain system stability. Another critical issue is the absence of universally accepted standards for fuzzy logic control systems, which complicates their scalability and integration at different levels of transport infrastructure. The lack of unified approaches to the development and implementation of such systems creates barriers to their adoption, not only at the municipal level but also at national and international levels, thereby limiting the potential for establishing an integrated transport network.

The implementation of fuzzy logic-based traffic control systems also requires significant financial investment, which can pose challenges for countries with limited budgets or resources. The development, configuration, and integration of these systems involve not only software and hardware expenses but also the modernisation of transport infrastructure. This financial burden can be particularly challenging for countries struggling with severe traffic congestion but lacking the resources for large-scale investment.

Furthermore, although fuzzy logic is specifically designed to handle imprecise or incomplete data, the accuracy and reliability of input data remain crucial to system performance (Koukol & Marek, 2015). If sensors collecting traffic data provide inaccurate readings or transmit information with delays, the system may make incorrect decisions, leading to inefficient real-time operation – an issue that is particularly critical under heavy traffic conditions.

Lastly, cybersecurity and data protection present significant challenges, as intelligent transportation systems using fuzzy logic process vast amounts of information collected from sensors, video cameras, and other sources. This makes such systems potentially vulnerable to cyberattacks, which could have serious consequences for both traffic safety and data confidentiality. Safeguarding systems against unauthorised access and ensuring secure data management are essential considerations that must be addressed during the implementation phase.

Global experience in the use of automated traffic control systems

Fuzzy logic has been successfully implemented in numerous countries to enhance the efficiency of automated traffic control systems, enabling dynamic adaptation of traffic flow management to changing conditions. A notable example is Japan, where fuzzy algorithms are extensively used, particularly in major cities such as Tokyo and Osaka. In these urban areas, fuzzy logic dynamically adjusts traffic light timings based on traffic intensity, weather conditions, and time of day. According to research by S. Araghi *et al*. (2017), these systems have reduced traffic congestion by 20% and decreased average travel times by 12% during peak hours, leading to more efficient traffic flow and shorter commute times for city residents.

In Germany, fuzzy logic has been widely applied on motorways, where fluctuating traffic conditions and adverse weather frequently impact road safety. Fuzzy algorithms are used to automatically adjust speed limits based on real-time data on traffic density across different road sections. Integration with meteorological services allows for the immediate reduction of speed limits in cases of fog, rain, or snowfall. Studies have shown that this approach has led to a 15% decrease in highway accidents and an 18% reduction in overall congestion, ensuring stable road capacity even under challenging conditions (Araghi *et al*., 2015; Koukol & Marek, 2015).

In the United States, fuzzy logic is a key component of intelligent transportation systems (ITS), which are widely deployed in cities with high traffic volumes, such as Los Angeles and New York. These systems enable real-time traffic data analysis and facilitate the redirection of traffic flows in cases of congestion or accidents. The application of fuzzy logic within the ITS of Los Angeles has resulted in a 10% reduction in average travel times and a 25% decrease in congestion during peak hours. In New York, the adoption of such systems has contributed to an 8% reduction in CO_2 emissions from transportation by optimising routes and minimising idle time in traffic jams (Wei *et al*., 2018; Pezeshki & Mazinani, 2019).

Global experience demonstrates the effectiveness of fuzzy logic in automated traffic management systems for reducing congestion, minimising accidents, and improving road capacity. In countries such as Japan, Germany, and the United States, fuzzy algorithms are employed to dynamically adjust traffic lights, regulate speed limits, and redirect traffic flows based on real-time conditions, weather variations, and time of day. The results indicate significant reductions in travel times, congestion, and transport-related emissions, making these systems an essential tool for enhancing the efficiency and sustainability of transport infrastructure.

Prospects for the development of automated traffic management systems

The future development of automated traffic management systems based on fuzzy logic encompasses several promising areas that offer new opportunities to enhance their efficiency and adaptability. One of the most significant advancements is the integration of fuzzy logic with artificial intelligence (AI) and machine learning technologies. This combination will enable the creation of more autonomous systems that can not only respond to real-time traffic conditions but also predict potential road issues. Such integration will allow these systems to automatically adjust their control algorithms to prevent congestion and emergency situations, thereby contributing to overall road safety improvements (Nguyen *et al*., 2016).

Another key area of development is the advancement of sensor technologies, which provide critical data for traffic management systems. Enhancing the accuracy and speed of data transmission from sensors that monitor traffic parameters, weather conditions, and road surface quality will significantly improve system efficiency. Next-generation sensors will offer more precise and timely information, enabling traffic management systems to respond to changes more quickly and accurately. This improvement will be particularly beneficial for managing traffic flow in high-density urban areas and under challenging weather conditions.

Another key area of development is the creation of global intelligent transport networks that integrate individual city and regional traffic management systems into a single, unified system. Such networks will optimise traffic flows not only within individual cities or regions but also at national and even international levels, facilitating seamless transport management across broader geographic areas (Avrunin *et al*., 2021).

Additionally, advancements in Big Data processing methods represent another crucial direction in the evolution of modern transport systems. The development of more sophisticated techniques for handling large volumes of traffic data will reduce processing times, enabling more efficient decision-making based on accurate and timely information. Improved data analysis capabilities will enhance the ability to predict traffic fluctuations and adapt management strategies to real-time conditions, thereby minimising congestion and reducing accident risks.

The findings of this research highlight the significant potential of fuzzy logic in optimising automated traffic flow management, as supported by numerous studies in the field. For instance, the study by H.F. Atlam *et al*. (2021) demonstrated the effectiveness of fuzzy logic in decision-making under conditions of uncertainty – a crucial factor in transportation systems. Their approach, initially designed for an access control system, enables risk modelling and adaptive adjustments to management parameters. This method closely parallels the application of fuzzy logic in dynamic traffic light control, where real-time adjustments improve traffic efficiency and flow management.

C. Zhao *et al*. (2018) proposed a method for intersection traffic control that utilises both current and previous signal phases to adjust the directions of dynamic waiting lanes, thereby minimising average traffic delays. Their control model, optimised using a genetic algorithm, demonstrated 31.8% reduction in intersection delays compared to existing systems. The study further indicated that the model's effectiveness increases as traffic volumes rise, making it particularly promising for managing congestion. These findings align with the results of the current study, reinforcing the potential of adaptive traffic management solutions.

Z. Pezeshki & S.M. Mazinani (2019) examined the advantages of neuro-fuzzy models, which integrate neural networks with fuzzy logic, demonstrating their high efficiency in predicting energy consumption. Although their study focused on a different domain, the underlying principles of neuro-fuzzy approaches remain highly relevant for transportation systems, where adaptive decision-making is crucial. Their analysis underscored similar traffic optimisation strategies, particularly the integration of fuzzy logic with artificial intelligence, which significantly enhances system adaptability.

O. Avrunin *et al*. (2021) explored intelligent automation systems for monitoring the technical condition of transport, ensuring uninterrupted traffic flow. Their findings confirmed the importance of processing real-time data for adaptive control and highlight the critical role of sensor reliability, a fundamental aspect of fuzzy logic-based transport systems. The conclusions drawn from these studies validate the findings of the current research, demonstrating that adaptive fuzzy logic-based systems contribute to optimising traffic flow in large cities. The analysis of research results confirmed that fuzzy logic is a universal and effective tool for enhancing automated traffic management.

Conclusions

The study of modern methods of automated traffic flow control based on fuzzy logic has provided valuable insights into the prospects and challenges of their implementation in transport systems. These findings highlighted the potential of fuzzy logic to enhance traffic management efficiency and improve road safety. The analysis confirmed that fuzzy logic enables traffic control systems to effectively adapt to changing traffic conditions and optimise traffic flow management. The research examined the theoretical foundations of fuzzy logic in automated traffic control systems, assessed existing traffic light control algorithms, and explored the integration of fuzzy logic with intelligent transport systems and emerging technologies, such as artificial intelligence (AI) and the Internet of Things (IoT). The results confirmed that implementing such systems contributes to reducing congestion, increasing road capacity, and enhancing road safety, particularly in cities with high traffic intensity. Furthermore, an analysis of case studies from Japan, Germany, and the United States validated the effectiveness of fuzzy algorithms in decreasing congestion and improving transport infrastructure efficiency.

The overall findings reaffirm that fuzzy logic is a promising tool for transport automation, allowing systems to adapt dynamically to real-world traffic conditions. Its implementation helps address key urbanisation challenges, such as traffic congestion and high accident rates. Moreover, combining fuzzy logic with AI and IoT technologies unlocks new possibilities for the development of intelligent transport systems capable of adaptive and efficient real-time traffic management.

However, certain challenges remain, including the complexity of developing fuzzy logic models, integration with existing traffic management systems, and high implementation costs. Future research could focus on developing standardised methodologies that facilitate the integration of fuzzy logic with other advanced technologies in transportation systems. Expanding experimental data and improving automated control methods could be key steps towards the further evolution of intelligent transportation systems, ultimately enhancing transport infrastructure and improving the quality of life in urban environments.

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Conflict of Interest

The authors declare no conflict of interest.

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Огляд сучасних методів автоматизованого керування трафіком на основі нечіткої логіки: перспективи та виклики

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Анотація. Стаття присвячена огляду сучасних методів автоматизованого керування транспортними потоками на основі нечіткої логіки, яка надає можливість обробляти неповну або нечітку інформацію, що є характерним для динамічних умов дорожнього руху. Метою цього дослідження була оцінка перспектив і викликів впровадження нечіткої логіки в управління транспортними системами для підвищення ефективності та безпеки дорожнього руху. У роботі акцентовано увагу на перспективах та викликах використання нечіткої логіки для керування світлофорами, інтеграції з інтелектуальними транспортними системами, а також на її поєднанні з технологіями штучного інтелекту та Інтернету речей. Нечітка логіка дозволяє адаптувати системи до змін у реальному часі, враховуючи такі фактори, як інтенсивність руху, погодні умови та поведінкові особливості водіїв. У статті наведено аналіз низки прикладів впровадження таких систем у різних країнах світу, зокрема в Японії, Німеччині та США, де нечіткі алгоритми демонструють ефективність у зниженні заторів, підвищенні безпеки на дорогах та оптимізації використання транспортної інфраструктури. Також окреслено основні виклики впровадження цих систем, серед яких складність побудови моделей нечіткої логіки, необхідність високої експертної підготовки для налаштування таких систем, а також технічні та фінансові бар'єри, що виникають під час модернізації транспортної інфраструктури. Окрім того, обговорено питання кібербезпеки та захисту даних, що стають актуальними в умовах використання великих обсягів інформації в інтелектуальних транспортних системах. Практична цінність цієї роботи полягає у визначенні ефективних рішень та можливостей їх адаптації для підвищення безпеки та пропускної здатності міських та міжміських транспортних систем

Ключові слова: оптимізація дорожнього руху; керування інтенсивністю трафіку; інтеграція інформаційних технологій; адаптація до умов руху; транспортна інфраструктура; інтелектуальні транспортні системи; затори