TRANSPORT
Systems and Technologies
https://tstjournal.org.ua/en

VOL. 29
№1
2026
ISSN 2617-9059 e-ISSN 2617-9058

UDC 681.5:004.5

DOI: 10.32703/2617-9040-2026-47-11

Investigation of the application of LiDAR technology to optimise automatic traffic flow control

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Abstract. The paper examined a topical issue arising from the need to improve the efficiency of urban traffic management through the use of advanced technologies. The purpose of the study was to investigate an approach to optimising the operating modes of traffic lights at intersections based on traffic flow data obtained using Light Detection and Ranging (LiDAR) sensors to improve traffic efficiency and reduce delays. The paper described the method of using LiDAR sensors for calculating turn signals at intersections and further optimising the operating modes of traffic lights based on the obtained data. The study found that, in order to function correctly, the method must include the following stages: placement of LiDAR sensors at key intersection points in order to obtain three-dimensional point clouds reflecting the dynamics of traffic flow; processing and analysis of data generated by the sensor (advanced data processing methods are used, in particular, algorithms for segmentation of point clouds and object recognition); analysis of information about the object's trajectory (in particular, for highlighting and counting return flows from primary LiDAR data); development of a mathematical model of the traffic control system; application of adaptive control strategies for the formation of optimised traffic light modes; development of recommendations for improving efficiency and optimisation on the methods of statistical analysis and machine learning to identify stable patterns and time trends in the structure of traffic; implementation of traffic light objects management. The generalised results of the study showed that the described method can provide an integrated approach and support for automatic adaptive control of traffic lights due to the use of LiDAR technology to collect detailed information about turning movements at intersections and optimise the time of traffic lights, which, as a result, will help to increase the capacity of intersections and reduce congestion in urban transport networks. The results of the study can be used by traffic management bodies and transport infrastructure engineers when designing and optimising traffic light regulation at urban intersections

Keywords: Light Detection and Ranging sensors; object recognition; mathematical model; traffic; real-time correction; machine learning

Introduction

Against a backdrop of rapid growth and increasing complexity in urban traffic, the issue of effective intersection management has become a pressing and urgent concern, as congestion on the road network leads to longer journey times, traffic jams, an increase in the number of accidents, and a negative impact on the environment. It is well known that optimisation of traffic light operating modes involves adapting signal phase durations to fluctuating traffic conditions, thereby minimising delays at intersections and increasing traffic capacity. The implementation of effective optimisation strategies not only helps to improve transport logistics, but also enhances the safety of pedestrians (and other road users) and reduces the negative impact of transport infrastructure on the environment. An intersection is a key element of the road transport network, within which multidirectional traffic flows cross and interact. Therefore, understanding the nature of vehicle traffic at intersections, in particular

Received: 30.01.2026. Revised: 23.05.2026. Accepted: 25.06.2026. Published: 04.07.2026.

Suggested Citation: Korpan, Ya., Fedorov, E., & Utkina, T. (2026). Investigation of the application of LiDAR technology to optimise automatic traffic flow control. *Transport Systems and Technologies*, 29(1), 137-146. doi: 10.32703/2617-9040-2026-47-11.

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turning manoeuvres, is a necessary condition for effective optimisation of automatic traffic light control modes. As a rule, classical approaches to controlling traffic lights are based on the use of predefined action protocols or a limited amount of data received from induction sensors or video systems. Such methods provide a basic level of functioning, but they are weak from the standpoint of adaptation to the conditions of dynamic changes in traffic flows, as noted by P. Li *et al.* (2020). In particular, induction loops described by L. Klein (2001) allow determining only the fact of passing a vehicle, but do not provide detailed information about its trajectory, behaviour, or interaction with other road users. But counting turn signals at intersections provides complete information about the nature and intensity of traffic, which allows correction systems to adapt the time parameters of traffic lights to the specific conditions of a particular intersection and increase the overall efficiency of the entire road transport system.

One of the most promising areas for collecting high-precision spatiotemporal information about vehicle movement is the use of LiDAR technologies. LiDAR technology allows obtaining high-precision spatial data in the form of three-dimensional (3D) point clouds in real time, which provide opportunities for detailed analysis of traffic flows, including the determination of traffic trajectories, speeds, time delays, and the occurrence of conflict situations described by F. Guan *et al.* (2023) and Y. Liang *et al.* (2024). The principle of operation of LiDAR sensors is based on the emission of laser pulses and measuring the time of their return after reflection from objects, which allows creating a detailed 3D spatial model of the environment. In traffic flow monitoring tasks, LiDAR sensors provide accurate detection and tracking of vehicles, pedestrians, and other road users, thus forming an informative database for analysing intersections and further optimising traffic light control modes. Unlike conventional detection tools, three-dimensional point clouds provide the ability to classify objects, determine their trajectories, and analyse return flows in real time, which was confirmed by contemporary research in this area (Saldivar-Carranza *et al.*, 2024). Recent research demonstrated the significant potential of using LiDAR to evaluate the performance of traffic lights and analyse transport processes. In particular, E. Saldivar-Carranza *et al.* (2021; 2024) showed the possibility of forming accurate vehicle trajectories based on LiDAR data, and then obtaining indicators such as delay time, queue length, and intersection throughput. This, in turn, creates prerequisites for the transition from static to adaptive and intelligent traffic management methods.

Despite the significant development of traffic light optimisation methods in recent years, most of the available approaches are based on the use of generalised transport data obtained either from a limited number of sources or in a short period of time. This often leads to inefficient adjustment of signal timing parameters, especially in difficult intersections. Therefore, there is a need to apply more accurate and adaptive methods of collecting information to develop sound strategies for optimising the operation of traffic lights, in particular, considering turning manoeuvres of vehicles. Contemporary approaches to traffic light control optimisation involve the use of mathematical modelling, statistical analysis, and machine learning methods, in particular, reinforcement learning algorithms that allow adapting alarm modes to changing traffic conditions (Wei *et al.*, 2018). In particular, P. Li *et al.* (2020) and Y. Hu *et al.* (2025) described reinforcement learning algorithms that demonstrate high efficiency in traffic light optimisation tasks, providing adaptation to changes in the traffic situation in real time. In addition, the use of neural networks, in particular LSTM, which was described by L. Yang & R. Guo (2024) allowed for short-term forecasting of traffic flows, which is an important element of proactive management. Thus, the study of the use of LiDAR technologies to optimise automatic traffic control at intersections is an urgent scientific and practical task aimed at developing intelligent transport systems and improving the quality of urban mobility.

The purpose of this study was to overcome the above limitations by using LiDAR sensors to calculate turn signals at intersections and further optimise traffic light operating modes based on the data obtained. The methodology of the study was based on a comprehensive approach to analysing ways to optimise traffic flows at intersections using LiDAR technologies. In the course of the study, methods of research analysis were applied, which were covered in scientific literature sources. The contemporary approaches to creating adaptive traffic light regulation were analysed. Methods for processing three-dimensional point clouds for segmentation and classification of traffic objects were applied. Methods of mathematical modelling of traffic flows were also used considering statistical data and elements of mathematical training.

Contemporary approaches to optimising traffic light regulation and using LiDAR in transport systems

The task of optimising the time parameters of traffic lights has been in the focus of attention of the scientific community and practitioners for several decades (Guadamuz *et al.*, 2022). The first approaches were based on the use of simple traffic light control schemes with fixed intervals, which were formed based on pre-defined traffic flow models and observation results, or forecasting algorithms (Lv *et al.*, 2015; Ma *et al.*, 2015). Further complexity and branching of the transport network contributed to the transition to more complex optimisation methods, including signal management systems with activation in the presence of vehicles, traffic-oriented regulation, and adaptive traffic light systems. These approaches provide for dynamic adjustment of the duration of signal phases in accordance with current traffic conditions, which reduced delays and increased the efficiency of the functioning of intersections, were investigated by C. Gartner *et al.* (2025). Historically, the calculation of turning manoeuvres of vehicles at intersections was carried out mainly using manual methods, in particular, visual observations, manual counting, and analysis of video recordings, and other approaches, for example, the use of "research" vehicles (Waddell *et al.*, 2020; Mahmud & Day, 2023). Despite the fact that such approaches allow getting useful information, they were characterised by a significant expenditure of time and resources, and a high probability of errors, including those related to the human factor. F. Viadero-Monasterio *et al.* (2024), J. Enayati *et al.* (2024), K. Deng *et al.* (2025) described various technological solutions that were used to automate the information collection process, in particular, induction loop detectors and radar sensors. Machine vision systems are also of great importance (Buch *et al.*, 2011). However, these tools have a number of limitations, including insufficient accuracy, dependence on weather and light conditions, and the complexity of maintenance. In this regard, there is still an urgent need to introduce more reliable and highly accurate methods for collecting data on turning movements of vehicles at intersections.

E. Saldivar-Carranza *et al.* (2024) presented a system study based on the use of data from LiDAR sensors as the main source of information. This ensures accurate tracking of the trajectory of objects, correct detection of turns, and independence from lighting. The main focus of the study was on analysing the flow that performs turning manoeuvres and dangerous manoeuvres. The paper described the sequence of operation of the system: data collection, point cloud processing, tracking, data calculation, optimisation of traffic lights. The implementation of the mathematical model and the results of adaptive control (after experimental research and statistical analysis of the results obtained) were presented. As a result, the researchers emphasised that the delay time and queue length were reduced, and the traffic flow capacity was increased. However, given that the study was performed at a limited number of intersections in specific conditions, the question arises of generalising the results. In addition, a detailed analysis of the impact of weather conditions (rain, fog, snow) on LiDAR operation was carried out. The presented system does not have a full assessment of the operation of a combination of several different systems (camera/radar/LiDAR), since LiDAR sensors are not often used without additional functional components.

The paper by A. Ansariyar (2023) presented a study of time distribution using two LiDAR sensors and simulations using OpenCV-based video analysis. The described approach is economically accessible and scalable. The presented algorithm can detect vehicles, track them, and count them (when crossing the control line). The algorithm includes: background selection, background detailing, tracking, and calculations. It uses classical methods of machine vision: Gaussian background subtraction, Canny boundary determination, feature matching. The video stream is processed frame-by-frame and can be used in monitoring systems. The algorithm presented here is designed to measure traffic intensity and provide basic traffic analytics; it is inexpensive and straightforward to implement. However, the disadvantage of this approach to organising the system is a typical weakness of the classic OpenCV approach, i.e., errors in poor lighting, shadows, overlapping objects, rain/fog. This can lead to "loss" of objects, duplication of calculations, and errors when crossing the control line. The information obtained is not sufficient to optimise the operation of traffic lights, because the system records only traffic and does not analyse the type of vehicle and its trajectory (for example, turns).

L. Yang & R. Guo (2024) presented a study of short-term traffic forecasting using a model that smooths out noise in traffic data and predicts time series (SG-LSTM). The use of Particle Swarm Optimisation (PSO) described by them should minimise time delays, reduce queues, and increase throughput. The PSO algorithm is easy to implement and allows quickly finding optimal solutions. Compared to other studies, L. Yang & R. Guo presented a combined approach (forecasting together with optimisation), which significantly improves the efficiency of the system. This approach ensures that the system adapts to changes in traffic during peak hours and when traffic intensity increases/decreases. However, the operation of this algorithm depends on the quality of the current data, and in cases where the data is incomplete or "noisy", the forecast may deteriorate and optimisation becomes less effective. In addition, LSTM requires a large amount of data and does not work well in emergency situations. Computing large amounts of data and then optimising it usually requires large resources, such as using a neural network. PSO does not guarantee overall optimisation, as it can get "stuck" in local solutions, and the results depend on the algorithm parameters. The algorithm does not take into consideration pedestrians and emergencies.

The study by A. Çıldır *et al.* (2023) was devoted to the development of an algorithm for optimal control of traffic lights to minimise traffic delays at intersections. The researchers proposed an algorithm that: analyses the traffic flow; determines the optimal parameters of the traffic light; changes the phase duration, green time, and signal cycle. Mathematical optimisation of the delay considers the traffic intensity, the distribution of flows in directions, the structure of traffic light phases, and the capacity of lanes. The mathematical approach allows using formalised models and the possibility of analytical calculation. The algorithm requires only a basic set of traffic data and can be implemented in existing traffic light systems without using complex sensors. However, the algorithm shows that it is partially adaptive and has a weak response to traffic changes and accidents. In other words, the presented model is simplified and does not consider complex driver behaviour and randomness. The effectiveness of the algorithm results depends on the accuracy of the input data. W. Zeng *et al.* (2022) presented a study on optimising traffic light timing using traffic flow modelling. According to the presented algorithm: a mathematical model of traffic at an intersection is constructed (based on collecting or setting traffic parameters, forming an intersection model); the cycle duration, green time distribution, and signal phasing are optimised; the result is checked through simulation modelling. The described mathematical modelling allows testing various scenarios of traffic intensity and operating modes. This algorithm is well suited for engineering tasks. However, it is known that real traffic is more complex than a model in which some events or behaviours may not be considered. The algorithm also lacks real-time adaptability, meaning that if optimisation is performed, it is offline and does not respond instantly to changes. In addition, the model does not consider all types of road users (pedestrians, cyclists). The modelling accuracy depends on the input data, and as the volume of this data increases, the complexity of modelling also increases. Therefore, it is difficult to apply the presented algorithm to a large number of intersections and coordinate between them.

Available scientific research on traffic light regulation optimisation at intersections covers a wide range of methods and algorithms, in particular, mathematical optimisation methods, simulation modelling, and machine learning algorithms (Zeng *et al.*, 2022; Yang & Guo, 2024). The main goal of these studies is to improve the intervals of traffic lights in order to increase the capacity of intersections, reduce traffic delays, and improve overall traffic efficiency. Most of the proposed methods are based on simplified traffic flow models or the use of aggregated data, which does not always adequately reflect the complex dynamics of real traffic. This raises the question of obtaining detailed data on the functioning of intersections, in particular, information on return flows obtained using LiDAR sensors, in order to improve the accuracy of traffic light optimisation algorithms and improve the operational performance of intersections. V. Bandaru *et al.* (2021) described the TScan system, a conditionally stationary LiDAR platform for monitoring traffic flows and analysing road safety. This paper proposed methods for automatic detection, classification, and tracking of vehicles based on 3D point cloud data. It was shown that conditionally stationary LiDAR platforms provide high-precision formulation of vehicle trajectories and facilitate effective analysis of conflict situations and traffic flow parameters in real time.

Despite the existing achievements in the field of automation of traffic light regulation and intersection management, the analysis of open scientific literature indicates the presence of a number of unresolved issues and limitations. In particular, the main problems include: an insufficient number of studies devoted to the direct use of LiDAR sensors for calculating return traffic flows and optimising traffic light control modes; the lack of holistic and unified methodologies for integrating data obtained using LiDAR in the traffic light optimisation model; the complexity of practical implementation of adaptive strategies for controlling traffic lights in real time using LiDAR data; the need for thorough validation and evaluation of the proposed approaches based on real experiments and comparative analysis with conventional methods. Overcoming these gaps and limitations will contribute to the further development of methods for optimising traffic light regulation at intersections and the development of more effective and efficient urban traffic management strategies.

Application of LiDAR technologies for monitoring traffic flows

The expansion of LiDAR technology is conditioned by the ability to form detailed three-dimensional point clouds that reflect the spatial characteristics of the environment. A number of academic papers have examined the use of LiDAR sensors to address various transport-related problems, including the detection and classification of vehicles, the estimation of their speed, and the analysis of the structure and intensity of traffic flows. Thus, T. Raj *et al.* (2020) reviewed the main scanning mechanisms of LiDAR systems used in intelligent transport systems and autonomous transport. The researchers compared mechanical MEMS-based flash memory and optical phased array LiDAR architectures based on scanning speed, spatial resolution, field of view, and reliability criteria. It was shown that the development of advanced LiDAR systems is aimed at moving to solid-state technologies that can provide high-precision 3D perception of the road environment in real time. The main advantages of LiDAR sensors are the contactless and unobtrusive nature of data collection, high measurement accuracy and versatility in use, which makes them suitable for monitoring intersections and obtaining detailed traffic information. The number of studies devoted to the direct use of LiDAR for calculating turning manoeuvres and optimising traffic light control modes remains limited. O. Kilani *et al.* (2021) presented one of the options for using mobile LiDAR data to assess visibility at urban intersections. The researchers proposed a method for spatial analysis of the coverage space based on 3D point clouds, which helps to automatically identify areas of limited visibility and potentially dangerous sections of road infrastructure.

Research shows that to ensure the adaptability of the system, it is advisable to use stationary LiDAR sensors that are installed at key points to provide comprehensive coverage of both the intersection and the area of approaches to the intersection. The location of sensors is determined considering the geometry of the intersection, the number of traffic lanes, the presence of pedestrian crossings, and potential traffic jams. Thus, A. Emtenan & C. Day (2020) and E. Saldivar-Carranza *et al.* (2024) argued that the effectiveness of vehicle tracking systems significantly depends not only on the type and characteristics of LiDAR sensors, but also on their spatial location. They offer a method for optimal sensor placement, which should ensure maximum coverage of the road zone (minimise "blind spots") and stable detection of vehicles. They considered the LiDAR sensor not as an autonomous local sensor, but as part of an intelligent road infrastructure, Vehicle-to-Infrastructure, and a cooperative intelligent transportation system. The researchers proposed a mathematical and geometric model for determining the optimal height of the LiDAR sensor installation, the optimal viewing angle, and the area of intersection monitoring coverage. Each sensor is calibrated to match the coordinate system with the global crosshair reference system. This is a prerequisite for minimising blind spots. A single time system is used to synchronise timestamps, which allows correctly combining data from multiple sensors.

Figure 1 shows the algorithm of the method of using LiDAR sensors and data from them to adjust and optimise the timing of traffic light objects at an intersection (or group of intersections). LiDAR sensors are used to detect and track individual vehicles approaching, entering, and exiting intersections, and pedestrian traffic near and at crosswalks. Figure 1 shows that the obtained LiDAR data in the form of a three-dimensional point cloud goes through several processing stages – noise filtering, sensor offset correction, and point cloud alignment, which ensures accurate reflection of the spatial configuration of intersections, removal of static objects (buildings, pillars, road signs), segmentation of moving objects, and point clustering to form individual vehicles. To ensure the integrity and accuracy of the collected data, quality control procedures are applied, including checking sensor calibration, evaluating the completeness of data sets, and comparing them with available real-world observations or reference data (if available). Space-time smoothing algorithms are used to reduce the impact of weather conditions and random errors.

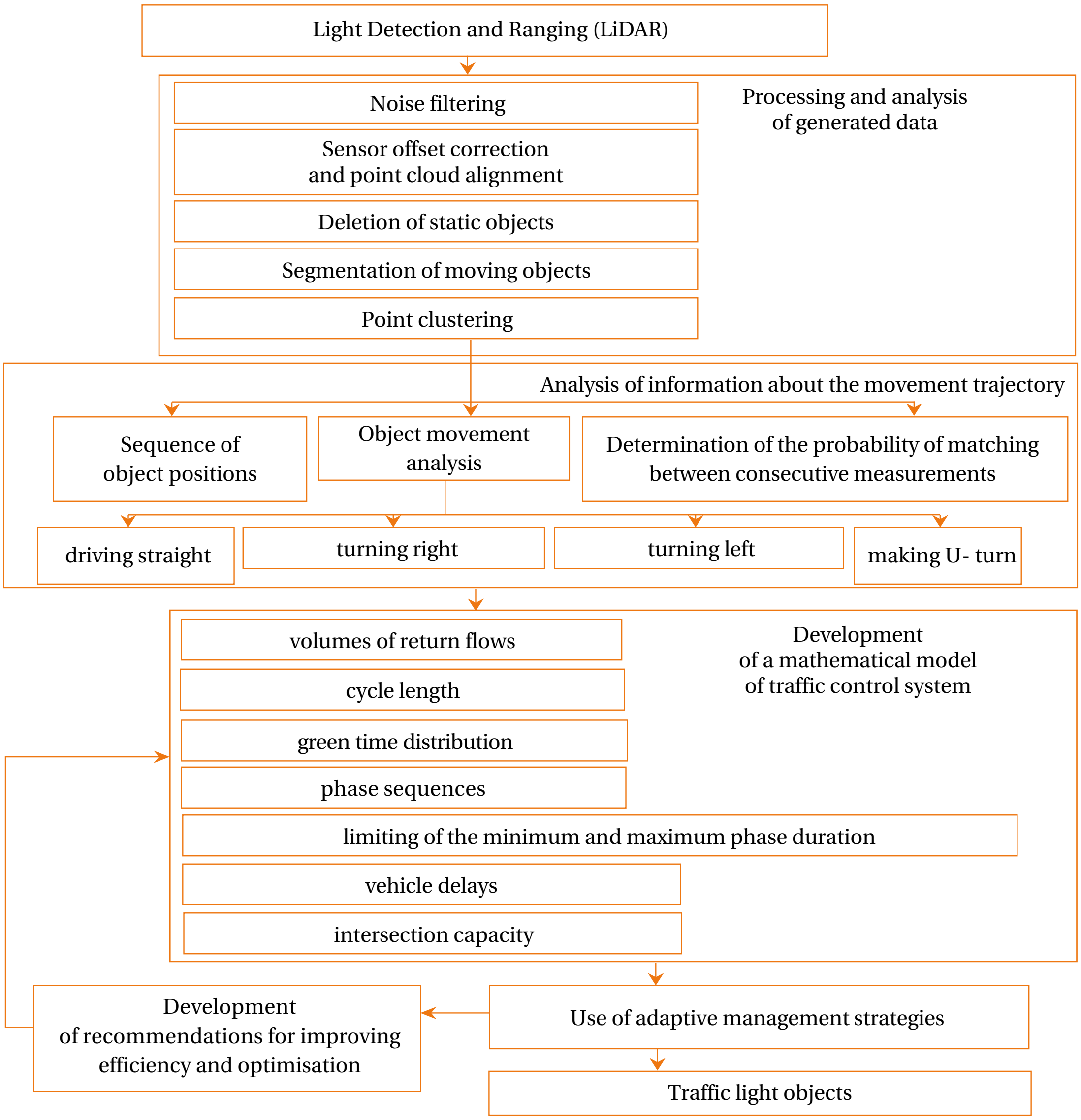

Figure 1. Algorithm for applying LiDAR technologies to optimise automated traffic management at intersections
Source: compiled by the authors

Segmented point cloud clusters are classified as vehicles or pedestrians based on geometric characteristics (dimensions, height, shape) and kinematic parameters (speed, direction of travel). In the study by X. Xu *et al.* (2022), segmentation of LiDAR point clouds was considered as a key stage in the operation of SLAM systems with combining data from multiple sensors. The researchers noted that LiDAR spatial points are grouped into clusters to highlight geometric features of the environment, in particular, planes, contours, and individual objects. For this purpose, both classical clustering methods and deep learning methods for semantic segmentation were used. Dedicated clusters were used for localisation, mapping, object tracking, and road scene analysis tasks. Thus, for example, H. Zhou *et al.* (2020) proposed a method for semantic segmentation of a point cloud based on a cylindrical representation of space. The researchers performed spatial clustering of points by cylindrical voxelisation, which enabled more efficient grouping of LiDAR points in road scenes. Based on the generated voxel clusters, the neural network performs semantic segmentation of vehicles, pedestrians, and other road objects.

Another approach was presented by J. Zhang *et al.* (2026), who divided the algorithm of work into: collection of LiDAR data (fixing point clouds, determining spatial coordinates, collecting information about intensity), scene processing (segmentation, object detection, clustering, tracking), situation interpretation (analysis of traffic flows; definition of conflict situations, behavioural analysis, anomaly detection). To track trajectories, as a rule, a multi-step tracking algorithm was used, which considered the sequence of changes in the position of an object, predicting its further movement, and the probability of correspondence between consecutive measurements. This allows accurately reconstructing the mathematical model of the trajectory of vehicles passing through intersections, and the direction of movement of pedestrians. This approach was described by X. Weng *et al.* (2020), who presented an approach to 3D tracking of multiple objects based on LiDAR data, in which vehicle tracking was performed by combining traffic forecasting and establishing correspondence between consecutive observations. The researchers used the Kalman filter to estimate the future position of objects and the Hungarian algorithm to link 3D bounding rectangles between frames. The effectiveness of multi-step tracking for formulating stable vehicle trajectories in a dynamic road environment was shown.

After determining the trajectories, each vehicle is classified according to the type of manoeuvre, such as driving straight ahead, turning right or left, or making a U-turn (where applicable). Classification is based on the analysis of changes in the angle of the trajectory and its spatial position relative to the intersection geometry. Rotational movements are counted within the specified time limits. The length of queues is determined based on the spatial distribution of vehicles within a given LiDAR scanning area. J. Zhao *et al.* (2019) presented the concept of queue estimation, which is implemented through point cloud segmentation, vehicle clustering, trajectory tracking; spatial fill analysis. In other words, the queue length is determined based on the spatial position and accumulation of vehicles in the stationary LiDAR observation area. The study by S. Cao *et al.* (2021) proposed the concept of an intelligent multimodal traffic monitoring system. Such a concept is presented as a system that must simultaneously perceive different types of objects, analyse their interaction, and form a high-precision digital representation of the road scene. When analysing multimodal interactions, particular attention is paid to the dynamics between cars, pedestrians, and cyclists. The system considers "conflict zones", road crossing behaviour, and dangerous interactions.

Optimisation of traffic light regulation based on LiDAR data

The obtained values of traffic intensity and cornering distribution are used as input parameters to describe a mathematical model for optimising traffic light regulation. In modern traffic light control systems, various mathematical optimisation models are used, which are aimed at minimising delays. The classic Webster method is based on the analytical determination of the optimal duration of the traffic light control cycle and phase distribution, considering the intensity of traffic flows (Zhang *et al.*, 2021; Liang *et al.*, 2024). The TRANSYT model is designed to optimise the operation of a group of interconnected traffic light objects by minimising delays and the number of vehicle stops in the network (Qadri *et al.*, 2020; Kim *et al.*, 2023). The MAXBAND method provides coordination of traffic light regulation by maximising the "green wave" and creating the largest possible lane of continuous traffic flows in two directions (Dai *et al.*, 2016; Lan *et al.*, 2026). Simultaneously, contemporary adaptive intelligent transport systems use methods of dynamic programming, optimisation with a moving horizon, maximum load regulation, and reinforcement learning. Most optimisation models consider the spatial and temporal distribution of traffic flows, queue parameters, and real-time traffic state forecasting. Such integration involves the creation of mathematical optimisation models that consider: the volume of return flows; cycle length; distribution of green time; phase sequences; limiting the minimum and maximum duration of phases; vehicle delays; intersection throughput. In addition, machine learning techniques can be used to identify permanent patterns based on historical data and dynamically adjust the signal timing in response to changes in traffic conditions. For example, J. Ugirumurera *et al.* (2023) proposed a method for predicting traffic light regulation parameters based on the analysis of mobile vehicle data using machine learning algorithms. The researchers showed that vehicle trajectory data can be used to estimate cycle duration, red zone time, and other signal synchronisation parameters without direct access to traffic light controllers. The paper uses XGBoost and neural networks to analyse transport trajectories and identify patterns of traffic light phases.

An interesting approach using machine learning was presented in the paper by S. Eteifa *et al.* (2021), who proposed a method for predicting phase change moments coordinated by adaptive traffic lights using a neural network. It was shown that deep recurrent neural networks can effectively model time dependencies in traffic light intersections and predict future signal changes based on historical transport data. The methodology was focused on the use of connected mobile vehicle systems and intelligent transport systems. Existing interval parameters of signals at the intersection are estimated based on models created as a result of real observations of traffic and the volume of return flows. The analysis showed inefficiencies in signal phasing and time distribution between phases, which leads to a decrease in the "performance" of intersections and an increase in vehicle delays. Potential optimisation areas were identified, in particular, adjusting the duration of signal cycles, green light time, and phase sequence. This allows increasing the efficiency of the intersection and reducing traffic jams.

Statistical methods are usually used to process calculations of rotational movements and traffic flow data, in particular, regression analysis and hypothesis testing. This approach allows identifying correlations, patterns, and statistically significant effects. Data analysis shows that the LiDAR-based system provides high accuracy in determining vehicle trajectories and classifying turning manoeuvres. Thus, for example, in comparison with conventional methods of data collection (manual calculations, inductive loops, video surveillance, etc.), the LiDAR-based method demonstrates: higher stability of data acquisition; reduced error in object classification; better identification of complex manoeuvres (in particular, left turns in a dense flow); accuracy and reliability of the received information. The system is capable of operating in conditions of varying traffic intensity, including peak periods. It was determined that an integrated approach to data collection and analysis using LiDAR contributes to understanding the dynamics of object movement at intersections, optimising the duration of signals, and improving the overall efficiency of traffic flow in the urban environment. Calculations of the number of turning manoeuvres obtained using LiDAR sensors are integrated into the optimisation algorithm to form informed decisions on traffic light synchronisation. The model incorporates observed volumes of turning movements, the distribution of directions, and the temporal variations in traffic flows. Based on the use of real-time traffic data, the algorithm can dynamically adjust the duration of signals, which allows adapting to changing traffic conditions and minimising delays at the intersection.

During traffic signal optimisation, several key parameters and constraints are considered: the geometry and configuration of the intersection, including lane layout restrictions, prohibited turning movements, and the presence of pedestrian crossings; traffic flow characteristics, reflecting traffic volumes, vehicle arrival rates, and traffic composition (e.g., passenger cars, lorries, and bicycles), which enable realistic modelling of traffic dynamics; signal timing constraints, including minimum and maximum green times, cycle lengths, and phase sequences to ensure technical feasibility and compliance with traffic regulations; and coordination with adjacent intersections, whereby signal synchronisation with neighbouring intersections is considered to optimise capacity and improve traffic flow along arterial corridors. Sensitivity analysis is performed to assess the impact of parameter variations and uncertainties on the performance of the optimisation algorithm. This analysis allows identifying critical parameters and assessing their impact on the results of synchronisation of traffic light signals. Reliability testing is necessary to determine the stability of the algorithm to changes in traffic conditions, sensor failures, or interruptions in communication systems. In the future, after applying the optimised time parameters of the signals, it is necessary to constantly monitor and collect data to evaluate the effectiveness of changes. LiDAR sensors continuously record turning movements at intersections, providing real-time feedback on traffic dynamics and intersection performance. Video cameras or other monitoring systems may be used to supplement LiDAR data, thereby providing additional information about events at the intersection and improving the accuracy of assessments of the effectiveness of the optimisation strategies implemented.

The expected efficiency of optimised signal timings is estimated by several key indicators, such as: reducing the average delay time of vehicles at the intersection; reducing the length of queues of traffic flows, especially during peak hours; increasing the number of vehicles crossing the intersection per unit of time; increasing throughput (reducing the total time of movement of vehicles through the intersection); more uniform load distribution between phases; reducing emissions of harmful substances into the environment and fuel consumption due to increased efficiency of traffic flow. Optimisation will allow using the available green time more efficiently and reducing capacity losses due to inconsistent phases.

Conclusions

The research presented in this paper was devoted to the topical issue of improving the efficiency of the functioning of transport intersections by improving approaches to optimising traffic light regulation. The analysis of scientific publications showed that most of the existing optimisation methods are based on aggregated or limited information content, which significantly reduces the efficiency of decision-making, especially in complex and dynamic situations. In the course of the study, the expediency of using LiDAR technologies as a source of three-dimensional space-time information about the movement of vehicles, pedestrians, and other road users was substantiated. It was shown that the use of three-dimensional point clouds enables high-precision detection, tracking, and classification of objects. This, in turn, creates prerequisites for the correct determination of both the usual intersection and turning manoeuvres, and the assessment of the intensity of traffic flows and the development of an expanded set of parameters necessary for optimising the control of traffic light objects.

A comprehensive approach to LiDAR data processing was proposed, which included stages of noise filtering, point cloud alignment, segmentation of moving objects, clustering, multi-step tracking, and vehicle classification by manoeuvre type. Based on the results obtained, “direct” and “return” traffic flows were calculated, the length of queues was estimated, and other characteristics of the transport process were determined. This detailed data allowed moving from simplified models to a more detailed description of the actual dynamics of traffic at intersections. It was established that the integration of the obtained parameters into mathematical models of traffic light regulation optimisation provided the possibility of adaptive adjustment of the time characteristics of signals based on current traffic conditions. In particular, consideration the volume of return flows, intersection geometry, phase constraints, and variations in traffic intensity helps to more reasonably determine the cycle duration, green time distribution, and phase sequence. This allows increasing the capacity of intersections, reducing vehicle delays, and optimising the use of existing infrastructure.

An analysis of data collection methods has shown that the revised approach is characterised by the stability and informativeness of its results. In particular, it provided identification of complex manoeuvres (including left turns in dense traffic), reduced the probability of counting errors, and improved the quality of output data for optimisation algorithms. This substantiates the feasibility of using LiDAR as a basic technology for building contemporary traffic monitoring and management systems. However, a number of limitations and areas for further research have been identified. In particular, additional study is required into the impact of weather conditions on the quality of data obtained from LiDAR sensors, ensuring the system's resilience to sensor and data transmission channel failures, and the integration of LiDAR with other data sources (video, radar systems). The investigation of these issues is necessary to improve the reliability and completeness of observations. An important task is also to scale the proposed approach to a network of interconnected intersections and validate it in real-world operation conditions. The results obtained indicate a significant potential for using LiDAR technologies in the tasks of optimising automated traffic management. The proposed approach lays the foundations for the development of a new generation of intelligent traffic management systems capable of enhancing the efficiency of the urban road network, improving road user safety, and reducing the negative impact of transport on the environment.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Дослідження методу застосування LiDAR-технологій для оптимізації автоматичного керування транспортним потоком

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Анотація. Робота присвячена дослідженню актуального питання, яке зумовлене необхідністю підвищення ефективності керування міським дорожнім рухом шляхом використання сучасних технологій. Метою роботи було дослідження підходу до оптимізації режимів роботи світлофорів на перехрестях на основі даних про транспортні потоки, отриманих із застосуванням датчиків Light Detection and Ranging (LiDAR), для підвищення ефективності дорожнього руху та зменшення затримок. В роботі представлено опис методу використання датчиків LiDAR для підрахунку поворотних потоків на перехрестях та подальшої оптимізації режимів роботи світлофорів на основі отриманих даних. При досліджені було встановлено, що для коректної роботи метод повинен включати наступні етапи: розміщення датчиків LiDAR у ключових точках перехрестя з метою отримання тривимірних хмар точок, що відображають динаміку транспортного потоку; обробка та аналіз згенерованих датчиком даних (застосовуються сучасні методи обробки даних, зокрема алгоритми сегментації хмар точок та розпізнавання об'єктів); проведення аналізу інформації про траєкторії руху об'єкту (зокрема для виділення та підрахунку поворотних потоків із первинних LiDAR-даних); формування математичної моделі системи керування рухом; використання адаптивних стратегій керування для формування оптимізованих режимів роботи світлофорів; розробка рекомендацій щодо підвищення ефективності та оптимізації на основі методів статистичного аналізу та машинного навчання для виявлення стійких закономірностей і часових тенденцій у структурі транспортного руху; здійснення керування світлофорними об'єктами. В роботі приведено узагальнені результати дослідження, які показали, що описаний метод може забезпечувати комплексний підхід та підтримку автоматичного адаптивного керування світлофорними об'єктами завдяки використанню LiDAR-технології для збору детальної інформації про поворотні рухи на перехрестях та оптимізації часу світлофорних сигналів, що в підсумку сприятиме підвищенню пропускної здатності перехресть і зменшенню заторів у міських транспортних мережах. Результати дослідження можуть бути використані органами управління дорожнім рухом та інженерами транспортної інфраструктури під час проєктування й оптимізації світлофорного регулювання на міських перехрестях

Ключові слова: датчики Light Detection and Ranging; розпізнавання об'єктів; математична модель; рух транспорту; корегування в реальному часі; машинне навчання