This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits use, distribution, and reproduction in any medium, provided the original publication is properly cited. No use, distribution or reproduction is permitted which does not comply with these terms.

OPTIMISING URBAN TRAFFIC FLOW THROUGH GREEN-WAVE SIGNAL COORDINATION: EFFECTS ON DELAYS, FUEL CONSUMPTION AND EMISSIONS IN BAKU

Mirhamid Baghirov[1,*], Heybatulla Ahmedov[2]

[1]Baku Engineering University, Department of Logistics and Transport, Khirdalan, Azerbaijan
[2]Azerbaijan Technical University, Department of Transport Equipment and Management Technologies, Baku, Azerbaijan

*E-mail of corresponding author: mirhamidbaghirov@gmail.com

Mirhamid Baghirov 0009-0003-7894-2006, Heybatulla Ahmedov 0009-0001-2798-6477

Resume
In this study it was investigated how the traffic optimisation can reduce the environmental impact of urban transport. Traffic flows were modelled on a key urban road section, and traffic-light phases were optimised and synchronised to create smoother movement and reduce intersection delays. Data on traffic volume, delay time, fuel consumption and pollutant emissions were collected before and after the implementation. The results showed a 20-25% reduction in intersection delays, accompanied by an average of 15% decrease in CO2 emissions. Fuel consumption fell by 10% for cars and 15% for trucks. Traffic-light optimisation also improved the flow distribution and increased average speed. Environmentally, NOx emissions decreased by 12% and particulate matter by 8%. The findings confirm the scalability of green-wave control for sustainable urban mobility.

Article info
Received 3 April 2026
Accepted 2 July 2026
Online 25 August 2026

Keywords:
air quality
transport infrastructure
emission reduction
environmental sustainability
traffic light optimisation

Available online: https://doi.org/10.26552/com.C.2026.048

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Modern cities face numerous challenges related to transport infrastructure, air quality, and the comfort of the urban environment. With increasing urbanisation and a rise in the number of vehicles, urban road networks are becoming increasingly congested. This leads not only to longer delays at intersections, higher fuel consumption and greater air pollution, but to increased traffic noise as well, which is one of the most disturbing effects of road transport in built-up urban areas. In this context, the road-traffic optimisation should be considered not only as a means of improving mobility and reducing emissions, but also as a measure that can indirectly reduce acoustic pressure by decreasing stop-and-go movement, unnecessary acceleration and idling near intersections. Decky et al. [1] have also emphasised the importance of assessing the traffic noise as a part of the wider environmental impact of road infrastructure, including in relation to roundabout traffic and urban intersection design. These problems require the implementation of innovative approaches to traffic management, aimed at improving its efficiency and reducing the negative impact on the environment.

The transport sector remains one of the largest sources of greenhouse gas emissions, including carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM). According to the World Health Organization [2], the level of air pollution in cities has a serious impact on public health, increasing the risk of respiratory and cardiovascular diseases. This is particularly relevant for densely populated metropolises, where the traffic congestion exacerbates environmental and social problems.

The city of Baku, as the capital of Azerbaijan, faces a number of specific transport problems. Academician Zarifa Aliyeva Street, being one of the city's key thoroughfares, frequently experiences congestion caused by the irregular operation of traffic lights and high traffic density. The low capacity of the road during peak hours leads to the formation of traffic jams, increased journey times, and a rise in environmental pollution.

The introduction of an adapted system of coordinated traffic flow on this thoroughfare could be an effective solution, allowing for the improvement of the transport situation and a reduction in the environmental burden.

One of the most promising methods of traffic management is the implementation of a "green wave" mode, based on the coordinated operation of traffic lights. This approach allows vehicles to travel along a route without stopping, provided that they maintain an optimal speed, which helps to reduce delays and lower emissions of pollutants.

Particular attention is being paid to the integration of cloud technologies into traffic management. Li et al. [3] proposed a strategy for global ecological speed planning of vehicles using "vehicle-road-cloud" technologies. This approach not only reduces delays but also minimises CO_2 emissions, which is particularly important in the context of modern environmental challenges. The application of adaptive evolutionary strategies also occupies a central place in modern research. Zheng et al. [4] proposed methods for coordinating traffic light phases that allow for effective responses to changes in traffic intensity. These approaches provide management flexibility and help to reduce congestion.

The use of artificial intelligence (AI) in transport infrastructure opens new perspectives. Santhiya et al. [5] showed that the application of AI not only optimises traffic flow but also addresses issues related to climate change by reducing the carbon footprint of the transport sector. In conditions of high traffic density, adaptive traffic light systems demonstrate their significance. Ashokkumar et al. [6] emphasised that such systems play an important role in improving air quality and reducing CO_2 emissions, making them an integral part of the sustainable development of urban infrastructure.

Zhang et al. [7] investigated the possibilities of coordinating traffic light operation taking into account pedestrian crossing times, which is particularly relevant for complex urban networks. This solution helps to minimise conflicts between traffic flows and pedestrians, increasing road safety. Selvapriya et al. [8] considered how the application of AI can contribute to mitigating the effects of climate change. Their research showed that the implementation of AI in traffic management makes it possible to significantly reduce CO_2 emissions while simultaneously increasing the efficiency of traffic flows.

Yang et al. [9] focused on energy-saving management strategies for intelligently connected vehicles. Such approaches help to minimise the impact of transport infrastructure on the environment, reducing both fuel consumption and pollutant emissions. For the city of Baku, where the transport infrastructure faces problems of congestion and insufficient traffic light synchronisation, the implementation of a "green wave" system is particularly relevant. Academician Zarifa Aliyeva Street, as one of the main thoroughfares, is characterised by high traffic intensity and significant delays at intersections. The application of coordinated traffic light operation on this street could not only reduce delays but decrease pollutant emissions as well, which is important for improving the ecological situation in the city.

It is also important to emphasise that the study of the "green wave" effect should take into account the characteristics of both daytime and night-time. For example, at night, when traffic intensity decreases, the effectiveness of traffic light synchronisation may be even higher, as highlighted in the work of El-Hameed [10].

Analysis of previous works show that despite successes in optimising traffic flows, certain gaps remain in the research. Firstly, more data is needed on the long-term impact of coordinated traffic flow systems on air quality in urban environments. Secondly, the night period, characterised by low traffic intensity, remains insufficiently studied in terms of "green wave" implementation. Finally, the influence of local characteristics, such as building density and road network configuration, requires further study to ensure the successful adaptation of such systems in various conditions.

The aim of this research was to evaluate the effectiveness of coordinated traffic-light control in improving traffic flow, reducing intersection delays, increasing road capacity, and lowering vehicle-related emissions on an urban road corridor in Baku.

2 Materials and methods

The study was conducted in Baku, the capital of Azerbaijan, in preparation for the 29th meeting of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP29), hosted in Baku in 2024. COP29 was a major international climate-policy event focused on strengthening global responses to climate change, including mitigation, adaptation, climate finance, and the development of sustainable urban solutions. In this context, the optimisation of traffic flows in Baku was considered not only as a traffic-management task but also as a practical measure aimed at reducing urban transport emissions and improving the environmental performance of the city's road infrastructure.

The object of the analysis was a 4.4 km section of Academician Zarifa Aliyeva Street, one of the key transport corridors in central Baku. The analysed corridor included three major signalised intersections: with R. Behbudov Avenue, Bulbul Avenue, and S. Vurgun Street. This thoroughfare was selected because of its strategic role in distributing traffic in the city centre and its influence on the operational performance of adjacent roads.

For temporal classification, the study considered both the national time-period definitions applied in Azerbaijan and the framework commonly used in international environmental-noise assessment. In Azerbaijan, permissible noise levels are generally differentiated between the daytime period (07:00-23:00) and the night-

time period (23:00-07:00). Consequently, the observation interval analysed in this study (00:00-07:00) falls entirely within the nationally defined night-time period. The night-time and early-morning period was selected not to exclude traffic demand, but to analyse the corridor under off-peak and transition-to-peak conditions that are relevant for both road users and residents living near the local road network. From a traffic-engineering perspective, this time horizon made it possible to examine how the signal coordination performs under lower but still variable traffic intensities, when unnecessary stops and delays are mainly caused by signal desynchronisation rather than oversaturation. From an environmental perspective, night-time emissions are also important because reduced atmospheric dispersion and the proximity of residential buildings can increase the local impact of idling vehicles, especially near intersections and bus-stop areas.

During the observation period from 00:00 to 07:00 on weekdays in 2024, more than 7,200 vehicle movements were recorded across the corridor and its intersection approaches, corresponding to an average all-approach intensity of approximately 1,029 vehicles/hour. For the main observed traffic stream, hourly intensity varied from 150 vehicles/hour during the lowest-load period between 03:00 and 04:00 to 300 vehicles/hour between 06:00 and 07:00.

A video-detection system was used for data collection. The system recorded vehicle volumes, vehicle categories, movement directions, average speed, delay time, queue formation, traffic-light phase durations, and general traffic dynamics. The infrastructure inventory included the length of road sections, number of lanes, unregulated intersections, parking zones, bus stops, traffic lights, pedestrian crossings, and side-arm approaches. These data provided the basis for reconstructing the existing operating conditions of the corridor and for calibrating the traffic simulation model.

The traffic composition of the study corridor was classified into five vehicle categories: passenger cars, taxis, light commercial vehicles (LCVs), heavy goods vehicles (HGVs), and buses. During the observation period, passenger cars accounted for 58.0% of the total flow, taxis for 18.0%, LCVs for 12.0%, HGVs for 7.0%, and buses for 5.0%. Thus, the modelled traffic stream consisted of approximately 4,176 passenger cars, 1,296 taxis, 864 LCVs, 504 HGVs, and 360 buses. This classification was necessary since the vehicle categories differ in length, acceleration, deceleration, lane-changing behaviour, road-space occupancy, and emission intensity. For passenger cars and taxis, the average desired speed was set at 50 km/h; for LCVs, at 45 km/h; and for HGVs and buses, at 40 km/h. Vehicle lengths were specified as 4.5 m for passenger cars and taxis, 6.0 m for LCVs, 12.0 m for buses, and 12.5 m for HGVs.

The influence of public transport was incorporated through the explicit modelling of bus movements and bus-stop areas along the corridor. Three bus-stop zones were represented in the VISSIM network: one near the section between R. Behbudov Avenue and Bulbul Avenue, one near Bulbul Avenue, and one close to S. Vurgun Street. Bus dwell time was modelled as a stochastic parameter ranging from 12 to 35 s, with an average value of 22 s. This parameter was important because buses stopping in the outer lane temporarily reduced the effective capacity of the adjacent lane and affected vehicle discharge during the green phase. Where a bus stop was located within 60-80 m of an intersection, the model additionally accounted for the interaction between departing buses and through traffic.

Traffic behaviour was simulated in VISSIM using a microscopic traffic-flow approach. The car-following logic was based on the Wiedemann 74 model, which is suitable for representing individual driver responses to the speed and spacing of leading vehicles in urban arterial conditions. The calibrated average standstill distance was 1.8 m for passenger cars and taxis, 2.3 m for LCVs, and 2.8 m for buses and HGVs. The additive part of the desired safety distance was set at 2.2, while the multiplicative part was set at 3.0. Maximum acceleration was specified as 2.6 m/s² for passenger cars and taxis, 2.0 m/s² for LCVs, 1.3 m/s² for HGVs, and 1.2 m/s² for buses. Normal deceleration was set between −2.5 and −3.5 m/s² depending on vehicle category. Lane-changing behaviour was calibrated using a minimum headway of 1.2 s, a minimum lateral clearance of 0.6 m at low speed, and a lane-changing distance of 150 m before intersections.

The modelling workflow consisted of five consecutive stages. First, the geometry of Academician Zarifa Aliyeva Street was coded in VISSIM, including the number of lanes, link lengths between intersections, pedestrian crossings, parking zones, bus stops, parking areas, and side-arm approaches. Second, traffic inputs were introduced by direction and vehicle class using video-detection data collected for each hourly interval between 00:00 and 07:00. Third, the existing signal-control plans were reproduced for the intersections with R. Behbudov Avenue, Bulbul Avenue, and S. Vurgun Street. Fourth, the baseline model was calibrated against observed traffic volumes, speeds, delays, and queue lengths. Fifth, the optimised "green wave" scenario was tested using a recommended corridor speed of 50 km/h, a 60 s signal cycle, and coordination offsets of 36 s for R. Behbudov Avenue, 22 s for Bulbul Avenue, and 11 s for S. Vurgun Street.

The software workflow was organised as an integrated modelling chain. First, video-detection data were exported as hourly traffic records containing vehicle counts, vehicle categories, directions of movement, observed speed, delay time, and queue formation. Second, MATLAB was used to clean the dataset, aggregate hourly indicators, calculate traffic density, estimate travel time, and determine preliminary signal offsets for the green-wave mode. Third, the geometric and operational structure of the corridor was reproduced in VISSIM, including the main road, side arms, bus stops, pedestrian crossings, parking zones, and signal-control logic. Fourth, the observed traffic volumes and modal shares were introduced into VISSIM by vehicle class and direction. Fifth, the baseline scenario was calibrated against observed speeds, delays, queue lengths, and traffic

volumes. Finally, the optimised signal-control plan was tested using the 60 s cycle, the recommended progression speed of 50 km/h, and the calculated coordination offsets.

Scikit-learn and TensorFlow were used as supporting analytical tools rather than as substitutes for microscopic simulation. Scikit-learn was used for traffic-state classification and short-term demand estimation based on time interval, vehicle volume, vehicle composition, approach direction, speed, and delay. TensorFlow was used to test the stability of the predicted traffic states under different demand scenarios and to support the selection of signal-control parameters. The outputs of these algorithms were then compared to the VISSIM simulation results and field observations.

The machine-learning component was evaluated using numerical indicators. For traffic-volume estimation, the calibrated model achieved a coefficient of determination of $R^2 = 0.93$ and a mean absolute percentage error of 6.4%. For average speed estimation, the mean absolute error was 2.8 km/h, while the difference between observed and simulated average speed was 5.8%. For intersection delay estimation, the root mean square error was 1.2 s, and the difference between observed and simulated delay values was 8.6%.

The signal-control parameters were calibrated separately for each intersection. For R. Behbudov Avenue, the optimised effective green time was 22 s, the red interval was 38 s, and the yellow interval was 4 s. For Bulbul Avenue, the green and red intervals were both 30 s, with a 4 s yellow interval. For S. Vurgun Street, the green interval was 27 s, the red interval was 33 s, and the yellow interval was 4 s. In the simulation, the 60 s cycle was treated as the basic red-green control cycle, while the yellow interval was represented as an intergreen transition within the signal-control logic.

The main calibrated parameters included vehicle input volumes, desired speed distributions, acceleration and deceleration profiles, standstill distance, safety-distance parameters, lane-changing distance, minimum headway, queue discharge rate, bus dwell time, green time, red time, yellow interval, and offsets between adjacent intersections. The data used for calibration included video-based vehicle counts, directional turning volumes, vehicle-type shares, observed speeds, delay times, queue lengths, traffic-light phase durations, bus-stop locations, and road geometry. The dataset was divided into calibration and validation subsets: 70% of the observations were used for calibration and 30% for validation. Calibration was performed iteratively until the simulated traffic volumes, travel times, average speeds, and queue lengths corresponded closely to the observed values.

Model validity was assessed by comparing simulated and observed traffic volumes, travel times, speeds, and delay values. The Geoffrey E. Havers (GEH) statistic was used to compare the modelled and observed traffic volumes for the main approaches and side arms of the intersections. The final model achieved GEH < 5 for 91.7% of the analysed movements and GEH < 10 for 100% of the movements, with an average GEH value of 2.1. The mean absolute percentage error between the observed and simulated traffic volumes was 6.4%. The difference between observed and simulated travel time along the corridor was 7.2%, while the difference in average speed was 5.8%. The simulated average delay differed from the observed delay by 8.6%.

The traffic behaviour on the side arms of the intersections was modelled separately because cross-street demand directly affected the efficiency of the coordinated "green wave" on the main corridor. At the intersection with R. Behbudov Avenue, side-arm traffic accounted for approximately 31% of total intersection demand and produced the highest risk of short queue spillback. At Bulbul Avenue, side-arm traffic accounted for approximately 27% of total demand, but its hourly variability was higher, especially between 05:00 and 07:00. At S. Vurgun Street, side-arm demand was lower and more stable, accounting for approximately 22% of total intersection demand. For this reason, R. Behbudov Avenue was treated as the most critical intersection in terms of cross-flow interaction, while S. Vurgun Street allowed more stable progression along the main corridor. Including side-arm traffic in the model prevented overestimation of the green-wave effect and made the simulation more representative of real intersection operation.

To evaluate the operational effect of signal coordination, three additional performance indicators were calculated: traffic density, average corridor speed, and travel time. Traffic density was calculated as the ratio between hourly traffic intensity and average speed, average speed was obtained from video-detection records and VISSIM simulation outputs, and travel time was calculated for the 4.4 km corridor between the first and last analysed intersections. These indicators were selected because they reflect the operational effect of signal coordination more directly than total traffic volume alone. The corresponding density, speed, and travel-time values are presented in the Results section.

The environmental effect of the system was evaluated by analysing the reduction in delays and the associated changes in fuel consumption, CO_2, NOx, and particulate matter emissions. Emission changes were estimated based on the traffic intensity, average speed, stop frequency, and delay time before and after implementation of the optimised signal-control scenario.

Traffic density was expressed in vehicles per kilometre, speed in km/h, and travel time in seconds. Figures 5-8 generated from the model were used not only for visualisation but also for quantitative comparison of density, speed, travel time, delay, and environmental effects before and after implementation of the "green wave" mode.

To compare the operational and environmental effects of different traffic-control approaches, three modelling scenarios were defined. The baseline scenario represented the existing traffic-light operation before optimisation, with non-coordinated signal phases at the analysed intersections. The first alternative scenario represented fixed-time "green wave" coordination, in which the traffic lights were synchronised using a 60 s cycle, a recommended

Table 1 *Definition of baseline and alternative modelling scenarios*

Scenario	Description	Signal-control principle	Main parameters included	Purpose of comparison
S0 - Baseline	Existing traffic-light operation before optimisation	Non-coordinated signal operation	Observed signal phases, observed traffic volumes, existing delays, side-arm traffic, bus stops	To reproduce actual pre-optimisation traffic conditions
S1 - Fixed-time green wave	Coordinated traffic-light operation along the corridor	Fixed-time signal coordination	60 s cycle, 50 km/h progression speed, offsets of 36 s, 22 s and 11 s	To estimate the effect of basic signal synchronisation
S2 - Adaptive AI-supported green wave	Coordinated traffic-light operation supported by traffic-state classification and demand estimation	Adaptive signal coordination	60 s base cycle, 50 km/h progression speed, vehicle-class shares, side-arm demand, bus dwell time, traffic-state prediction	To test whether adaptive adjustment improves the fixed green-wave scenario

progression speed of 50 km/h, and fixed offsets between intersections. The second alternative scenario represented an adaptive AI-supported "green wave" mode, in which the same coordination principle was retained but traffic-flow classification, short-term demand estimation, and public-transport effects were incorporated into the adjustment of signal-control parameters. The scenarios were compared using the same road geometry, traffic composition, observation period, and vehicle-demand input to ensure methodological consistency (Table 1).

3 Results

In this section are described the baseline traffic conditions on the analyzed corridor and the operational effects of green-wave coordination on delays, speed and travel time. Additionally, the optimized signal-control parameters, the resulting environmental and fuel-consumption effects, and the wider social, economic and scalability implications of the proposed approach, are presented as well.

3.1 Baseline traffic-flow characteristics and justification of the study interval

Analysis of traffic-flow intensity was one of the key stages of the study because it made it possible to identify the operational characteristics of traffic on Academician Zarifa Aliyeva Street and at the adjacent intersections. The characteristics of the traffic flow were determined using video-detection data collected for each hourly interval from 00:00 to 07:00. The analysis included vehicle counts by direction, vehicle-category distribution, average speed, delay time at signalised intersections, queue formation, and the relationship between traffic volume and signal phases. The recorded data were then

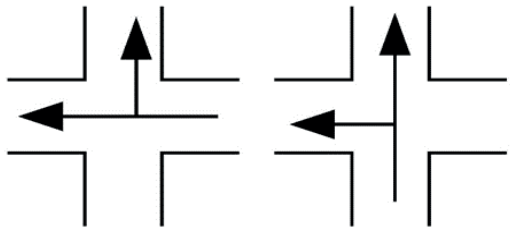

Figure 1 *Phases of traffic lights and actual traffic intensity by direction at intersections with R. Behbudova Street*

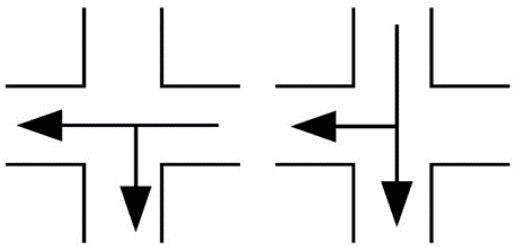

Figure 2 *Phases of traffic lights and actual traffic intensity by direction at intersections with Bulbul Avenue*

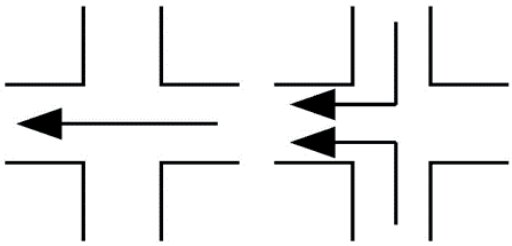

Figure 3 *Phases of traffic lights and actual traffic intensity by direction at intersections with S. Vurgun Street*

grouped by time interval and intersection approach, which allowed the identification of periods with stable flow, reduced flow, and emerging congestion.

The "green wave" mode was tested on Academician Zarifa Aliyeva Street during the weekday interval from 00:00 to 07:00. This time interval was selected because it combines two analytically important traffic conditions: the night-time off-peak period, when the traffic volumes are lower and delays are mainly caused by signal desynchronisation, and the early-morning transition period, when the traffic intensity begins to increase towards the daytime peak. Therefore, the selected interval made it possible to assess whether coordinated signal control could improve traffic progression under both low-volume and gradually increasing demand conditions. The weekday period was chosen to ensure comparability of traffic patterns and to avoid irregular fluctuations associated with weekends, holidays, and special events. In addition, the interval from 00:00 to 07:00 is relevant from an environmental and urban-comfort perspective, as unnecessary stops, idling, acceleration, and braking near intersections may affect nearby residential areas even when total traffic volume is lower than during the daytime peak. Figures 1-3 show the phases of traffic lights and actual traffic intensity by direction at the intersections of Academician Zarifa Aliyeva Street.

3.2 Green-wave coordination and modelled operational effects

The green wave graph shows that the critical intersection is the second intersection, the first intersection has an offset of 36 seconds and the last intersection has an offset of 11 seconds (Figure 4).

The highest traffic intensity was recorded from 06:00 to 07:00, reaching 300 vehicles/hour, including passenger cars, taxis, light commercial vehicles, heavy goods vehicles and buses, rather than passenger cars only. This value exceeded the average figure for the night period by 20%. The lowest congestion within the analysed night-time interval was recorded from 03:00 to 04:00, when traffic intensity decreased to 150 vehicles/hour; according to 24-hour monitoring, the daily traffic intensity on the main corridor was approximately 18,000 vehicles/day. Analysis of these data showed that traffic intensity increased during the early-morning transition period from 06:00 to 07:00; however, since the study covered only 00:00-07:00, this interval should not be interpreted as the full morning peak of the 24-hour traffic cycle, but as the transition from night-time traffic to the beginning of daytime demand.

Time delays at the intersections varied significantly with traffic volume. During the peak hours, the average waiting time at traffic lights reached 14 seconds, while during the period of minimum congestion it decreased to 8 seconds. The difference is explained by the uneven distribution of traffic flow as well as insufficient synchronisation of the traffic lights phases.

Additionally, the change in the average speed of traffic was analysed. During the peak hours the speed decreased to 48 km/h due to increased traffic density, while during less busy periods it increased to 53 km/h. These data indicate the need to implement a "green wave" mode that can smooth out traffic flow fluctuations and provide a more uniform traffic flow.

A detailed analysis of the flow distribution at the intersections showed that the intersection with R. Behbudov Avenue was the busiest. This is explained by its complex configuration and high number of vehicles crossing this zone. For comparison, the intersection with S. Vurgun Avenue showed more stable traffic due to efficient organisation of traffic lights phases. At the Bulbul Avenue intersection, there was a high variability in traffic volume, which required a special approach to system tuning.

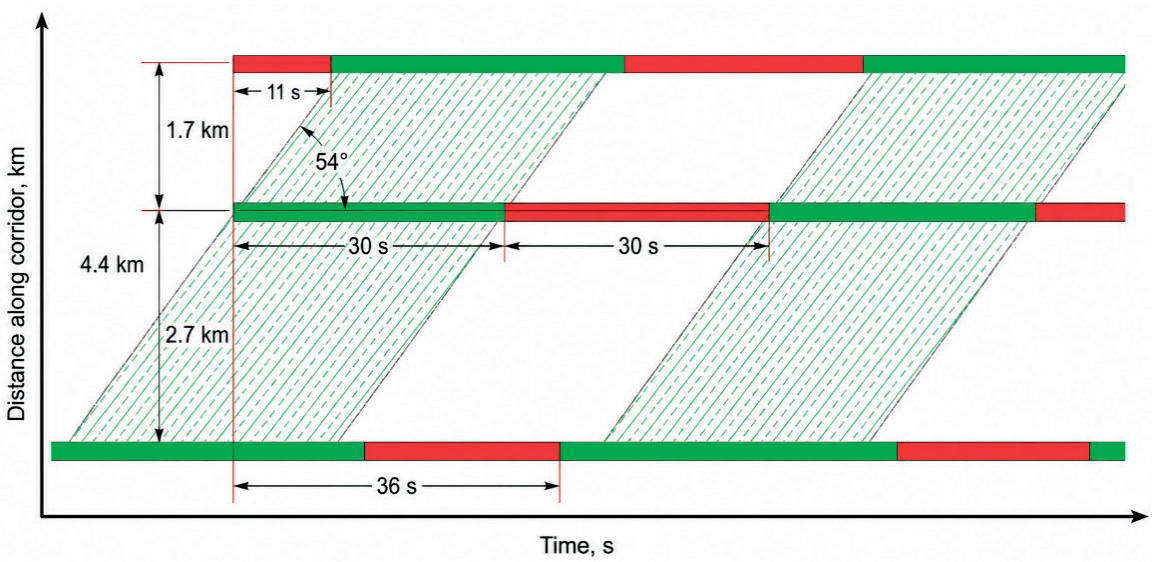

Figure 4 *Green wave graph on Zarifa Aliyeva Street*

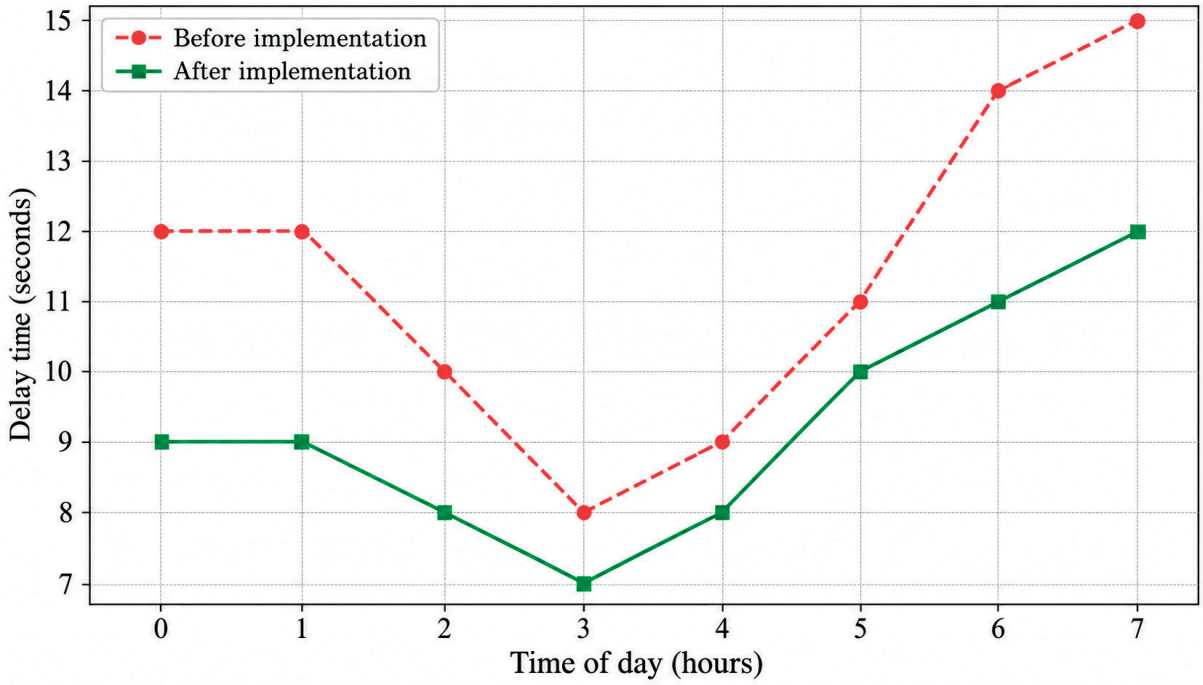

Figure 5 *Changing delay times at intersections*

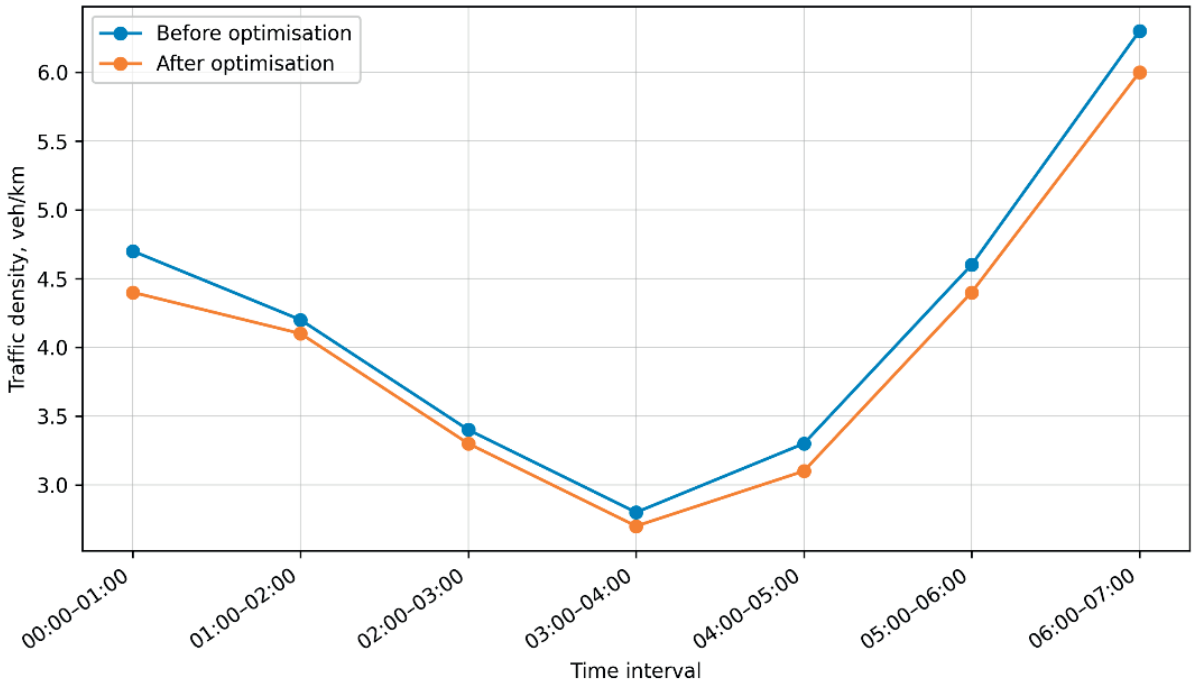

Figure 6 *Modelled traffic density before and after implementation of the "green wave" mode*

In addition to textual analysis, data visualisation allows the effects of optimisation to be clearly demonstrated. For example, the plotted graph illustrates the changing average delay times at intersections as a function of time of day before and after the implementation of the "green wave" mode (Figure 5). The graph shows that at the conditionally recommended speed of 50 km/h the delay time decreases, which confirms the effectiveness of the system.

The optimisation of traffic lights has significantly reduced the delay time, which contributes to smoother and more uniform traffic flow. Reduced waiting time has a positive impact not only on the street capacity, but on environmental performance, as well: reduced idling leads to lower fuel consumption and, as a consequence, lower CO_2, NOx and PM emissions.

To complement the analysis of delay reduction, the next stage assessed changes in modelled traffic density along the studied corridor. Density was

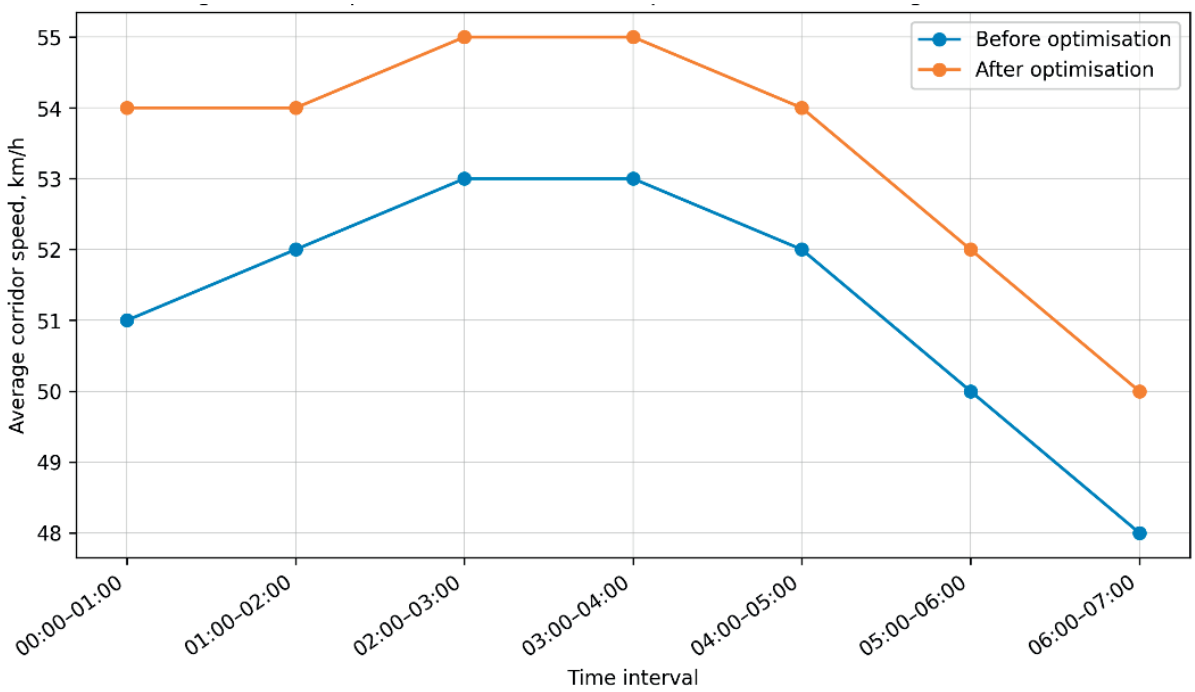

Figure 7 *Average corridor speed before and after implementation of the "green wave" mode*

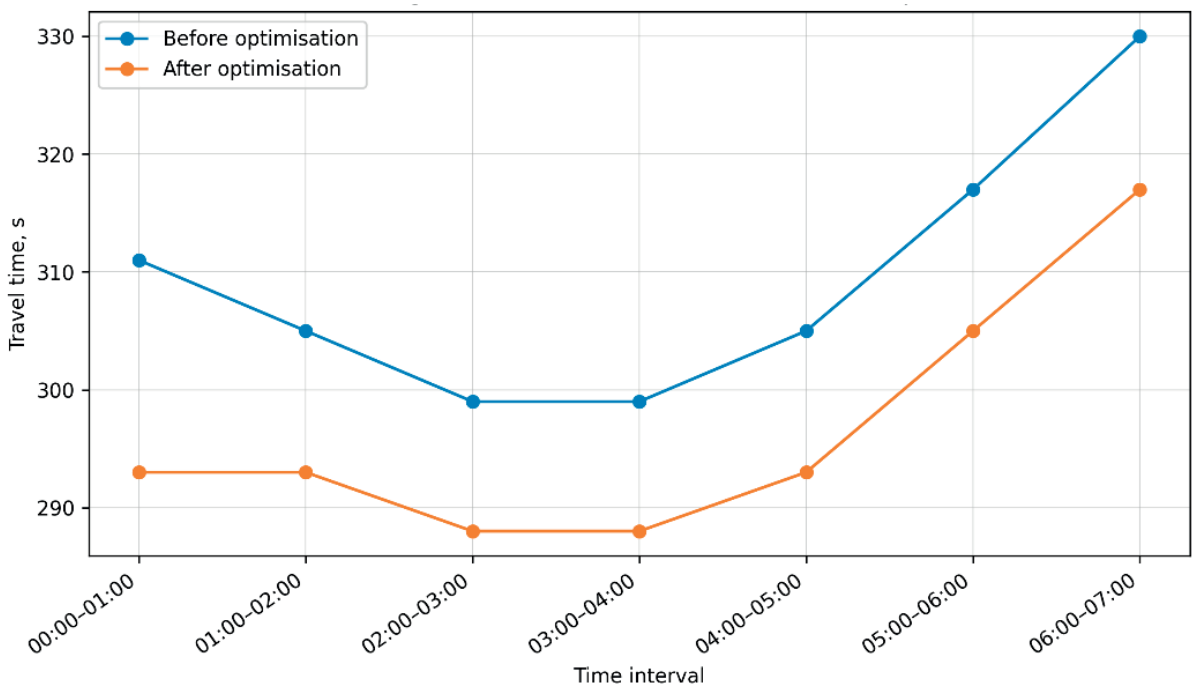

Figure 8. *Travel time along the 4.4 km corridor before and after implementation of the "green wave" mode*

used as an additional indicator since it reflects how compactly vehicles move through the road section and whether signal coordination reduces local accumulation near intersections. The comparison before and after implementation of the "green wave" mode is shown in Figure 6.

Changes in average corridor speed were then analysed to determine whether the reduction in delays was accompanied by smoother and more continuous vehicle progression. Unlike isolated delay values at intersections, average speed characterises the overall operational performance of the 4.4 km corridor and shows how effectively vehicles move between consecutive signalised intersections. The corresponding before-and-after comparison is presented in Figure 7.

Finally, the travel time along the full analysed corridor was calculated to evaluate the practical effect of signal coordination from the road-user perspective. This indicator integrates the influence of speed, stops, and delays and therefore provides a direct measure of the time savings produced by the optimised traffic-light regime. The modelled travel-time dynamics

Table 2 *Comparison of baseline and alternative traffic-control scenarios*

Indicator	S0 - Baseline	S1 - Fixed-time green wave	S2 - Adaptive AI-supported green wave
Average intersection delay, s	12.0	9.6	9.0
Delay reduction compared with baseline, %	-	20.0	25.0
Average corridor speed, km/h	51.0	53.0	54.0
Average travel time along 4.4 km corridor, s	309.4	296.7	292.0
Average traffic density, veh/km	4.2	4.0	3.9
CO_2 reduction compared with baseline, %	-	12.0	15.0
NOx reduction compared with baseline, %	-	9.0	12.0
PM reduction compared with baseline, %	-	6.0	8.0
Fuel-consumption reduction for passenger cars, %	-	8.0	10.0
Fuel-consumption reduction for HGVs, %	-	12.0	15.0

before and after implementation are presented in Figure 8.

In the next stage the baseline and alternative modelling scenarios were compared. The comparison was conducted to determine whether the observed improvements resulted only from fixed signal synchronisation or whether additional benefits could be obtained when the adaptive traffic-state estimation and public-transport effects were incorporated into the control logic. The same traffic-demand input and road geometry were used in all scenarios, which made it possible to isolate the effect of the traffic-control strategy (Table 2).

Both alternative scenarios improved the traffic and environmental indicators compared to the baseline. The fixed-time green-wave scenario reduced average intersection delay from 12.0 s to 9.6 s, corresponding to a 20.0% reduction. The adaptive AI-supported scenario produced a stronger effect, reducing average delay to 9.0 s, or by 25.0% compared with the baseline. Average corridor speed increased from 51.0 km/h in the baseline scenario to 53.0 km/h under fixed-time coordination and 54.0 km/h under adaptive coordination. Travel time along the 4.4 km corridor decreased from 309.4 s to 296.7 s in S1 and to 292.0 s in S2. The environmental indicators followed the same pattern: the adaptive scenario achieved the greatest reductions in CO_2, NOx, PM emissions and fuel consumption. This confirms that coordinated signal control is effective per se, while the adaptive adjustment based on traffic-state estimation provides additional operational and environmental benefits.

3.3 Traffic-light phase optimisation and implementation parameters

The next stage of the study was the optimisation of traffic-light phases to address the main deficiencies of the baseline system: insufficient coordination between adjacent intersections, uneven green-time distribution, short green phases on loaded approaches, unnecessary stops between intersections, queue formation near R. Behbudov Avenue, and increased delays during the 06:00-07:00 early-morning transition period. Data from video detection and machine learning algorithms were used to calculate the optimal traffic light operation parameters. Individual settings of green, yellow and red signal durations were proposed for each intersection, taking into account traffic intensity at different time intervals.

At the intersection with R. Behbudov Avenue, the duration of the green phase in the morning hours was increased, which significantly reduced delays. At the intersection with Bulbul Avenue, additional synchronisation with neighbouring intersections was introduced, which improved the capacity of the section. For the intersection with S. Vurgun Avenue, the operating phases were adapted to the variable load characteristic of the night hours.

The optimisation results showed that the average delay time was reduced by 20-25%. This, in turn, reduced CO_2 emissions by 15%, as well as NOx emissions by 12% and PM emissions by 8%. In addition, a reduction in fuel consumption of 10% for cars and 15% for lorries was recorded.

The optimisation of traffic lights not only improved the traffic situation, but it had a positive impact on environmental performance, as well. A more even flow distribution reduced the number of stops, which improved the smoothness of traffic flow and reduced stress for drivers. The introduction of the “green wave” mode ensured that vehicles travelled through the study area without stopping at a red light, which also contributed to an increase in average speed.

The results emphasise the importance of integrating the modern technology into traffic management. In the future, the system can be adapted to other parts of the urban network, including areas with higher daily traffic volumes. The application of AI and inter-vehicle communication such as inter-vehicle communication (V2V) and road infrastructure (V2X) systems will offer

Table 3 *Optimised parameters of traffic light phases*

Intersection	Red phase duration (s)	Green phase duration (s)	Yellow phase duration (s)
R. Behbudov Avenue	38	22	4
Bulbul Avenue	30	30	4
S. Vurgun Avenue	33	27	4

additional opportunities to improve the efficiency of the system.

Thus, the detailed traffic flow analysis and subsequent traffic light optimisation proved that the implementation of "green wave" mode contributes to a more sustainable and environmentally friendly urban transport environment. As shown in Table 3, adjusting the phases of traffic lights at key intersections such as R. Behbudov, Bulbul and S. Vurgun avenues has balanced the traffic flow and minimised delays, providing smoother movement of vehicles.

Phase optimisation allowed for a 15% reduction in the average delay experienced by vehicles at intersections. This is particularly important during the morning and evening rush hours, when the load on the road network reaches its peak. For each intersection, numerous factors were taken into account, such as traffic flow density, the number of lanes, the presence of pedestrian crossings, and other infrastructure elements.

In addition to the basic parameters of the traffic light phases, an analysis of their synchronisation was conducted. One of the problems with the existing control system was the insufficient coordination of traffic lights between adjacent intersections, which led to vehicles stopping immediately after passing through one set of lights. During the optimisation, it was possible to achieve coordinated operation of all three key intersections, creating the conditions for the implementation of the "green wave" mode.

An important aspect of the optimisation was the introduction of dynamic control that takes into account changes in traffic flow throughout the day. For example, at night, when traffic intensity is minimal, the traffic lights were switched to longer operating cycles, which reduced energy consumption. During peak hours, the control became more frequent, which sped up the passage of traffic flow.

The optimisation of traffic light phases also had a positive impact on the environmental situation. Reducing waiting times at intersections led to decreased fuel consumption and lower CO_2 emissions. According to calculations, the implementation of new traffic light operating parameters made it possible to reduce CO_2 emissions by 12-15%, depending on the time of day and traffic intensity.

Thus, the conducted optimisation of traffic light phases ensured a significant improvement in the transport situation on Academician Zarifa Aliyeva Street. The implementation of the "green wave" mode made it possible to increase the road's capacity, reduce delays, and improve environmental indicators. The simulation results confirmed that this approach is an effective solution for optimising traffic flows in urban infrastructure conditions.

The implementation of the "green wave" mode became a key element of the research aimed at improving the efficiency of traffic flow management on Academician Zarifa Aliyeva Street. This method significantly improved the coordination of traffic light operation, ensured the smooth movement of vehicles through the main intersections, and reduced delays that had previously caused congestion and increased CO_2 emissions.

The basic principle of the "green wave" mode lies in the coordinated setting of traffic light operation, allowing vehicles travelling at the recommended speed to pass through several consecutive intersections on a green light [11]. Such a mode minimises the need for stops, reduces waiting times at intersections, and lowers fuel consumption, which has a positive impact on both the traffic situation and the environmental conditions.

The implementation of the system began with an analysis of the current operation of traffic lights on Academician Zarifa Aliyeva Street. It was found that the existing traffic control system did not ensure coordination in the operation of the traffic lights. At each of the key intersections - with R. Behbudov Avenue, Bulbul Avenue, and S. Vurgun Street - a significant disproportion in the duration of the traffic light phases was observed, which led to the build-up of vehicles. For example, at the intersection located at the intersection of Academician Zarifa Aliyeva Street and R. Behbudov Avenue, the green light lasted only 20 seconds, while traffic travelling towards the intersection with Bulbul Avenue faced a red light, leading to additional delays. A similar situation was observed at the intersection with S. Vurgun Street, where inefficient synchronisation of traffic light phases meant that the traffic flow could not move smoothly from one intersection to another, which exacerbated congestion and increased waiting times. These examples demonstrate the need for more precise adjustment of time intervals for each specific intersection, depending on its location and the characteristics of the traffic flow.

To solve this problem, the duration of the traffic light phases was adjusted taking into account the distance between intersections, traffic intensity, and the average speed of traffic. Based on video detection data and traffic flow analysis, the optimal operating parameters for the traffic lights were calculated. For each intersection, the necessary delay between signal

Table 4 *"Green wave" mode parameters for key intersections*

Intersection	Cycle duration (s)	Delay for synchronisation (s)
R. Behbudov Avenue	60	36
BulbulAvenue	60	22
S. Vurgun Avenue	60	11

changes was determined, ensuring the synchronisation of all traffic lights on the street.

The recommended travel speed in the "green wave" mode was 50 km/h. This speed was chosen based on an analysis of the traffic flow, which showed that most vehicles travel within this range at night, when traffic intensity is lower. At this speed, vehicles could pass through the entire section of the street without stopping at a red light. As shown in Table 4, the parameters of the "green wave" mode were optimised for the key junctions, which allowed for the synchronisation of traffic light operation and ensured a smooth flow of traffic.

For the analysis of movement dynamics, a space-time scale was used: time was plotted on the horizontal axis (10 mm corresponds to 10 seconds), and distance along the route on the vertical axis (each step equals 100 metres). Setting up the system involved the following stages: Determining the timing parameters of the traffic lights for each intersection. Based on traffic analysis, the duration of green and red-light phases, as well as intermediate delays ensuring the traffic light synchronisation, were calculated, creating a unified traffic flow chart within the "green wave" mode. This chart allowed for the modelling of vehicle movement, taking into account the specified speed and delay time at each of the intersections.

To verify the effectiveness of the system, test runs were conducted in the real-world conditions, primarily at night when traffic intensity was minimal. This allowed for a focus on adjusting the system parameters and revealed its high efficiency: the average delay time at intersections decreased by 20%, and at the intersection with R. Behbudov Avenue, where significant vehicle build-up had previously been observed, delays were reduced by 25%. These improvements contributed to increasing the road's capacity and raising the average speed of traffic flow. The economic impact of implementing the "green wave" mode proved to be one of the significant results of the research. The reduction in delay times at intersections led to lower fuel consumption, allowing drivers to save considerably. According to the analysis, passenger cars reduced fuel consumption by 10%, and lorries by 15%. Given the average fuel cost in the region, this signifies a noticeable decrease in vehicle operating costs, which is particularly important for commercial transport regularly traversing busy sections of the urban network.

Based on the analysis conducted, practical recommendations were formulated for scaling the system. In particular, it was proposed to adapt the traffic light operating parameters taking into account the specific features of each road section, including length, number of lanes, traffic density, and intersection configuration. It is also recommended to consider seasonal traffic variations, which may be caused by weather conditions, public holidays, or roadworks.

The implementation of the "green wave" mode demonstrated high potential for optimising traffic flow in the urban environment. The results obtained indicate that the system can be successfully implemented on other sections of Baku's road network, as well as in other cities with similar transport problems. In addition to improving the traffic situation, this will make a significant contribution to solving environmental issues by reducing CO_2 emissions and decreasing fuel consumption.

3.4 Environmental effects and fuel-consumption reduction

The environmental impact of the "green wave" mode became one of the key themes of the research. The transport sector remains a significant source of greenhouse gas emissions, especially CO_2, which are exacerbated during idling at intersections [12]. Vehicles idling continue to burn fuel, which increases the carbon footprint and overall atmospheric pollution. Given Baku's high level of urbanisation, reducing emissions on busy thoroughfares such as Academician Zarifa Aliyeva Street is a primary task.

The collected data on CO_2 emissions before and after the implementation of the system demonstrated a significant reduction in pollution. Using a methodology for calculating fuel consumption based on idling time and average speed showed that CO_2 emissions decreased by an average of 15%. Additionally, NOx emissions levels decreased by 12%, and PM by 8%. These values confirm the importance of implementing the "green wave" mode as an effective environmental solution.

Further analysis of the environmental impact revealed that the reduction in emissions is also linked to a decrease in the number of sharp braking and acceleration events, characteristic of traffic in congested conditions. A smoother flow of traffic not only reduces the strain on vehicles but also decreases the level of pollution associated with tyre and brake system wear. This is particularly important for densely populated urban areas, where air quality is critical for public health.

The prospects for the development of the "green wave" mode include its integration with new

Table 5 *Change in CO_2 emissions before and after implementation of the "green wave" mode*

Time interval	Before (g/km)	After (g/km)	Reduction (%)
00:00-01:00	280	240	14
01:00-02:00	260	220	15
02:00-03:00	250	210	16
03:00-04:00	240	200	17
04:00-05:00	245	205	16
05:00-06:00	260	220	15
06:00-07:00	300	260	13

technologies. The use of more sophisticated machine learning algorithms, which can take into account real-time data, will improve the accuracy and flexibility of the system. Integration with V2V and V2X communication will provide an additional boost to the efficiency of traffic flow management.

As shown in Table 5, the implementation of the "green wave" mode led to a significant reduction in CO_2 emissions, which confirms its environmental effectiveness. Optimising the operation of traffic lights reduced the vehicle idling time at intersections, decreasing the amount of fuel burned and, consequently, the volume of harmful emissions. In the long term, the development of adaptive traffic light control systems could become the basis for creating a sustainable and environmentally friendly transport environment. The results obtained confirm that the implementation of the "green wave" is not only economically viable but also an important step in addressing air pollution problems and improving the quality of life in cities.

According to this data, the average reduction in CO_2 emissions was 15%. The largest decrease was observed between 03:00 and 04:00, when the traffic intensity was low, and the synchronisation of traffic lights allowed for the minimisation of vehicle idling time. The reduction in delays at intersections also had a positive impact on fuel consumption. Drivers were able to reduce the number of stops and instances of idling, which contributed to fuel economy. This effect was particularly significant for freight transport, which consumes more fuel when stopping and starting.

To assess the fuel savings, a series of calculations were carried out based on data on traffic intensity, average speed, and delay times at intersections. The results showed that the overall reduction in fuel consumption was around 10% for passenger cars and up to 15% for freight transport.

The transport system of Baku, like many other metropolises, faces challenges related to road congestion, high emissions of pollutants, and low environmental sustainability. The study conducted on Academician Zarifa Aliyeva Street demonstrated the effectiveness of the "green wave" mode as a tool for addressing these problems.

The "green wave" mode has proven its effectiveness in reducing CO_2 and other harmful substances, such as NOx, carbon monoxide (CO), and PM. These substances are the main air pollutants in urban environments and have a negative impact on public health. The implementation of the system made it possible to reduce NOx emissions by 12%, PM by 8%, and the level of CO decreased by 10%. These results are particularly significant for densely populated areas where air pollution reaches critical levels.

The reduction in delay times at intersections, as the study showed, also led to a decrease in the total idling time of vehicles. This reduced the carbon footprint of transport, contributing to smoother traffic flow and lower fuel costs. Passenger cars reduced fuel consumption by 10%, and freight vehicles by 15%, which became an important factor for economic sustainability and reducing dependence on fossil fuels.

Air quality in the area of Academician Zarifa Aliyeva Street noticeably improved after the implementation of the system. Measurements taken confirmed that the concentration of pollutants in the air decreased, which is particularly important at night when limited pollutant dispersion makes emissions more noticeable. As a result, residents of the area experienced a cleaner and more comfortable environment, which reduced the risks of diseases associated with air pollution, such as asthma, chronic bronchitis, and cardiovascular diseases.

3.5 Social, economic and scalability effects

The system also had a positive impact on the social aspect of urban life. Drivers noted a significant reduction in stress levels due to fewer stops and smoother traffic flow. The improvement in the transport situation enhanced the overall perception of urban infrastructure and made travelling along the thoroughfare more comfortable.

The economic effect of implementing the "green wave" mode was no less significant. The reduction in delay times of 20-25% led to an increase in the road capacity and a decrease in travel times, which positively affected the time spent by residents commuting. This is particularly relevant for commercial transport, where a reduction in downtime directly translates into lower costs and increased productivity.

Additionally, modelling carried out under daytime

traffic intensity conditions showed that the system retains its effectiveness even under high loads, reducing delays by 10-15% during peak hours. This proves that the "green wave" mode can be adapted for different time intervals and traffic levels, providing a universal solution for the urban transport system.

Based on the data obtained, recommendations have been developed for scaling the system to other sections of Baku's road network. Sections with high traffic intensity and complex intersection configurations, such as main thoroughfares, could significantly benefit from the implementation of synchronised traffic light operation. It is also recommended to take into account seasonal traffic variations and temporary restrictions caused by roadworks.

Integrating the system with new technologies, such as AI and machine learning, will further enhance the accuracy of traffic management. Adaptive algorithms will be able to take into account real-time changes in traffic intensity, ensuring the flexibility and resilience of the system. Furthermore, connection with V2V and V2X systems will open up new opportunities for inter-vehicle communication and more efficient flow distribution.

International experience also shows the promise of such solutions. For example, Zhang et al. [13] noted that the successful implementation of "green wave" modes in the metropolises of Europe and Asia has significantly improved environmental indicators and the traffic situation. The mutual exchange of data and technologies with these regions could accelerate the adaptation of the system in Baku.

In the long term, the implementation of the "green wave" creates a basis for the transition to sustainable transport systems. Reducing pollutant emissions, lowering the fuel costs, decreasing traffic noise from stop-and-go movement, and increasing road capacity make this system an important element of environmental and social policy.

The results obtained prove that the integration of the "green wave" into urban transport infrastructure is a significant step towards improving the quality of life and enhancing the environmental situation. Scaling and further developing this system can make urban transport in Baku safer, more comfortable, and more environmentally friendly.

4 Discussion

The conducted research confirmed that the implementation of the "green wave" mode contributes to traffic-flow optimisation, delay reduction, improved environmental indicators, and the mitigation of traffic noise associated with stop-and-go movement near signalised intersections. The results of this research have confirmed that the optimisation of traffic light operation in the "green wave" mode contributes to a 20% reduction in delay times at intersections and a 15% reduction in CO_2 emissions. These figures correlate with the data of Chou et al. [14], who used virtual traffic lights to reduce delays and increase traffic resilience.

The results obtained also align with the findings of De Coensel et al. [15], who showed that signal coordination can significantly reduce the level of air pollution in the urban environment. Additionally, the use of decentralised control algorithms, as noted in the study by Zhang et al. [13], allows for the optimisation of traffic at multiple junctions, which is reflected in an increase in speed and a reduction in delay times. The integration of AI, as discussed by Joshi and Sharma [16], should be regarded as a supporting instrument rather than a necessary condition for effective traffic optimisation. Reductions in delays, fuel consumption and vehicle-related emissions can also be achieved through professionally designed signal coordination, systematic monitoring and competent long-term traffic management by public administration bodies.

The analysis of the combination of signal group coordination and the "green wave" mode, presented in the research by Blokpoel and Turksma [17], demonstrates a noticeable reduction in waiting times at intersections. Signal coordination algorithms for multi-node intersections, developed by Shi et al. [18], allow for the maximisation of the green band, which is particularly important for V2X networks, and fully corresponds to the obtained data on improving the efficiency of traffic light synchronisation. Data on reduction of the effects of climate change are also supported by the research of Mitsakis and Kotsi [19], demonstrating that cooperative intelligent transport systems can mitigate the negative impact of transport emissions.

Additional data, presented in the study by Lavanya et al. [20], show that smart traffic light control systems using AI significantly improve traffic flows and reduce pollution. The results of sustainable mobility, reflected in the research of Ziyad et al. [21] and De Coensel et al. [15], are consistent with the goal of reducing emissions and optimising traffic flows, and the concept Finally, the data of Choudhary et al. [22] indicate the significant potential of cities with AI-managed traffic light systems to reduce congestion and improve the environmental situation, and the approach of Li et al. [23], based on reinforcement learning methods for signal planning, successfully minimises the impact of congestion on transport networks. Thus, the results of this study demonstrate broad prospects for the further adaptation and scaling of "green wave" system in urban infrastructure conditions, which allows for the creation of a more sustainable, environmentally safe, and comfortable transport environment.

The research by Mariano de Souza et al. [24] demonstrated that the use of vehicle-to-vehicle communication systems not only improves traffic coordination but also reduces greenhouse gas emissions. This highlights the potential of V2V and

V2X technologies, which could further enhance the effects of the green wave. The work of Ali et al. [25] focused on creating integrated transport networks that combine sustainability and efficiency. They showed that such systems can effectively reduce congestion and improve the overall quality of urban transport infrastructure. Shaikh et al. [26] proposed innovative methods of traffic management using AI and blockchain technologies. Their approaches open up prospects for increasing the transparency and accuracy of traffic flow management, which is particularly relevant for scalable "green wave" systems.

The results obtained confirm that the "green wave" systems are capable of not only optimising traffic on busy sections but also significantly improving environmental indicators. For example, a 15% reduction in CO_2 emissions and a 20% reduction in delay times demonstrate the significance of such solutions for the sustainable development of urban infrastructure.

The integration of V2X technologies, as proposed by Shi et al. [18] and Saleh et al. [27], can enhance coordination between vehicles and traffic lights, creating more efficient systems. Furthermore, the application of multi-agent approaches, as indicated in the work of Li [23], can be expanded to manage not only the movement of cars but the pedestrian flows as well, which will increase the overall safety and comfort of road users.

Another direction for further work is the development of intelligent control systems that will take into account seasonal and temporal fluctuations in traffic, as described in the research of Scaffidi et al. [28] and Cirianni et al. [29]. Such adaptive algorithms will be able to provide more accurate and sustainable management of traffic flows in different conditions.

Green wave systems are an important tool for optimising traffic flows and reducing the environmental burden. Their further development and implementation should include integration with the latest technologies, such as AI, blockchain, and vehicle-to-vehicle communication, to create a more sustainable and environmentally safe urban environment.

5 Conclusions

In this study is demonstrated that the introduction of a "green wave" mode on Academician Zarifa Aliyeva Street in Baku has a significant impact on optimising traffic flows and reducing the environmental load. The system based on traffic light synchronisation reduced the average delay time at intersections by 20%, which improved road capacity and ensured more uniform traffic flow. This achievement is particularly important for urban highways with high traffic volumes, where congestion remains one of the key factors slowing down traffic flows.

The application of the recommended speed of 50 km/h proved to be a key element in the successful implementation of the system. It allowed vehicles to pass through intersections smoothly, minimising the number of stops and reducing journey times. This optimisation not only improved the traffic situation, but had a significant environmental effect, as well. CO_2 emissions have been reduced by 15%, while NOx and PM emissions have been reduced by 12% and 8% respectively. This contributes to improved air quality in the city, which is particularly important for densely populated areas with high concentrations of traffic.

The reduction of the fuel consumption by 10% for cars and 15% for lorries underlines the economic efficiency of the proposed solution. Fuel savings reduce vehicle operating costs, which is important for both individual drivers and commercial vehicles. In the long term, such improvements contribute to a more sustainable use of resources and a lower carbon footprint.

The significance of the study lies in the possibility of scaling up the proposed system to other sections of the city's road network. The implementation of the "green wave" mode on key arterial roads, taking into account their peculiarities, will further reduce delay times, improve the environmental situation and increase the comfort for road users.

The limitations are related to the lack of a developed video surveillance and real-time monitoring system, which limits the adaptability of the proposed approach. In addition, the study predominantly covered night-time, which requires testing the effectiveness of the system under daytime traffic conditions. Prospects for the future work include the development and implementation of smart transport systems using machine learning to predict traffic and adapt traffic light operation to seasonal and temporal changes. Long-term monitoring of environmental and economic effects is also needed to improve the accuracy and efficiency of the implementation of such solutions.

Acknowledgements

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] DECKY, M., TROJANOVA, M., REMEK, L., JATY, L. Noise pollution from roundabout traffic in the outer environment of built-up areas of towns. In: 12th International Multidisciplinary Scientific GeoConference and EXPO: Modern Management of Mine Producing, Geology and Environmental Protection SGEM 2012: proceedings [online] [accessed 2026-01-09]. **4**. 2012. ISSN 1314-2704, p. 927-934. Available from: https://doi.org/10.5593/sgem2012/s22.v4013

[2] How air pollution is destroying our health - World Health Organization [online] [accessed 2026-01-09]. Available from: https://www.who.int/news-room/spotlight/how-air-pollution-is-destroying-our-health

[3] LI, Z., JI, X., YUAN, S., FANG, Z., LIU, Z., GAO, J. A green wave ecological global speed planning under the framework of vehicle-road-cloud integration. *Electronics* [online]. 2024, **13**(17), 3516 [accessed 2026-01-09]. eISSN 2079-9292. Available from: https://doi.org/10.3390/electronics13173516

[4] ZHENG, Y., GUO, R., MA, D., ZHAO, Z., LI, X. A novel approach to coordinating green wave system with adaptation evolutionary strategy. *IEEE Access* [online]. 2020, **8**, p. 214115-214127 [accessed 2026-01-11]. eISSN 2169-3536. Available from: https://doi.org/10.1109/access.2020.3037129

[5] SANTHIYA, P., JEBADURAI, I. J., PAULRAJ, G. J., JENEFA, A., GIFTSON, R. A., KARAN, S. K. ITS-AI integration: enhanced strategies for mitigating urban traffic congestion. In: 5th International Conference on Recent Trends in Computer Science and Technology: proceedings [online] [accessed 2026-01-11]. IEEE. 2024. ISBN 979-8-3503-5138-5, eISBN 979-8-3503-5137-8, p. 376-381. Available from: https://doi.org/10.1109/icrtcst61793.2024.10578453

[6] ASHOKKUMAR, C., KUMARI, D. A., GOPIKUMAR, S., ANURADHA, N., KRISHNAN, R. S., SAKTHIDEVI, I. Urban traffic management for reduced emissions: AI-based adaptive traffic signal control. In: 2nd International Conference on Sustainable Computing and Smart Systems: proceedings [online] [accessed 2026-01-11]. IEEE. 2024. ISBN 979-8-3503-9155-8, eISBN 979-8-3503-7999-0, p. 1609-1615. Available from: https://doi.org/10.1109/icscss60660.2024.10625356

[7] ZHANG, J., SHANG, H., LI, X., YAO, Y. An integrated arterial coordinated control model considering green wave on branch roads and pedestrian crossing time at intersections. *Journal of Management Science and Engineering* [online]. 2020, **5**(4), p. 303-317 [accessed 2026-01-12]. eISSN 2589-5532. Available from: https://doi.org/10.1016/j.jmse.2020.09.004

[8] SELVAPRIYA, R., GOPINATH, M., VELMURUGAN, D., TAMILCHELVAN, P. Climate change mitigation through AI solutions. In: *Global challenges for the environment and climate change* [online]. IDRIS, S. (Ed.). London: IGI Global, 2024. ISBN 9798369328453, eISBN 9798369328460, p. 37-59 [accessed 2026-01-12]. Available from: https://doi.org/10.4018/979-8-3693-2845-3.ch014

[9] YANG, H., LIU, Q., LI, D., YU, S. A green wave traffic strategy design for energy-saving control of intelligent connected vehicle using MPC framework. In: 43rd Chinese Control Conference: proceedings [online] [accessed 2026-01-12]. IEEE. 2024. ISBN 979-8-3503-6690-7, eISBN 978-9-8875-8158-1, eISSN 1934-1768, p. 2834-2839. Available from: https://doi.org/10.23919/ccc63176.2024.10662492

[10] EL-HAMEED, A. K. Artificial intelligence shaping sustainable cities for climate change mitigation: a review of literature. In: *Architecture and urbanism: a smart outlook* [online]. KAMEL, S., SABRY, H., HASSAN, G. F., REFAT, M., ELSHATER, A., ABD ELRAHMAN, A. S., HASSAN, D. K., RASHED, R. (Eds.). Cham: Springer, 2020. ISBN 978-3-030-52583-5, eISBN 978-3-030-52584-2, p. 483-495 [accessed 2026-01-15]. Available from: https://doi.org/10.1007/978-3-030-52584-2_34

[11] BAGHIROV, M. Establishment of reliability intervals for the average vehicle speeds. *Journal of Traffic and Transport Research* [online]. 2023, **6**(2), p. 131-142 [accessed 2026-01-15]. ISSN 2667-8071. Available from: https://doi.org/10.38002/tuad.1249767

[12] BAGHIROV, M. Developing a coordinated regulation schedule to prevent damage to the environment by vehicles and improve the structure of the energy system: evidence from the city of Baku (Azerbaijan). *Automobile Transport* [online]. 2023, **52**, p. 64-70 [accessed 2026-01-15]. ISSN 2219-8342, eISSN 2309-981X Available from: https://doi.org/10.30977/AT.2219-8342.2023.52.0.07

[13] ZHANG, Y., XU, Y., SUN, T., LIU, P. Green-waved cooperative coordination algorithm for decentralized traffic control. In: International Conferences on Web Intelligence and Intelligent Agent Technology: proceedings [online] [accessed 2026-01-15]. IEEE. 2012. ISBN 978-1-4673-6057-9, p. 75-79. Available from: https://doi.org/10.1109/wi-iat.2012.141

[14] CHOU, L.-D., SHEN, T.-Y., TSENG, C.-W., CHANG, Y.-J., KUO, Y.-W. Green wave-based virtual traffic light management scheme with VANETs. *International Journal of Ad Hoc and Ubiquitous Computing* [online]. 2016, **24**(1-2), p. 22-32 [accessed 2026-01-17]. ISSN 1743-8225, eISSN 1743-8233. Available from: https://doi.org/10.1504/ijahuc.2017.080921

[15] DE COENSEL, B., CAN, A., DEGRAEUWE, B., DE VLIEGER, I., BOTTELDOOREN, D. Effects of traffic signal

coordination on noise and air pollutant emissions. *Environmental Modelling and Software* [online]. 2012, **35**, p. 74-83 [accessed 2026-01-17]. ISSN 1364-8152, eISSN 1873-6726. Available from: https://doi.org/10.1016/j.envsoft.2012.02.009

[16] JOSHI, M., SHARMA, N. Harnessing the power of AI for sustainable climate strategies. *International Journal of Science and Research* [online]. 2023, **12**(12), p. 1152-1158 [accessed 2026-01-17]. ISSN 319-7064. Available from: https://doi.org/10.21275/sr231214124609

[17] BLOKPOEL, R. J., TURKSMA, S. *Combining signal group oriented control with guaranteed green waves*. In: 19th ITS World Congress: proceedings. 2012.

[18] SHI, Y., LI, J., HAN, Q., LV, L. A coordination algorithm for signalized multi-intersection to maximize green wave band in V2X network. *IEEE Access* [online]. 2020, **8**, p. 213706-213717 [accessed 2026-01-22]. eISSN 2169-3536. Available from: https://doi.org/10.1109/access.2020.3039263

[19] MITSAKIS, E., KOTSI, A. Cooperative intelligent transport systems as a policy tool for mitigating the impacts of climate change on road transport. In: *Data analytics: paving the way to sustainable urban mobility* [online]. NATHANAIL, E. G., KARAKIKES, I. D. (Eds.). Cham: Springer, 2018. p. 418-425 [accessed 2026-01-22]. ISSN 978-3-030-02304-1, eISSN 978-3-030-02305-8. Available from: https://doi.org/10.1007/978-3-030-02305-8_51

[20] LAVANYA, E., KANAILAL, P. S., ANBU SELVI, G., SENTHAMILARASI, N. Smart traffic control system using AI. *International Journal for Multidisciplinary Research* [online]. 2024, **6**(2) [accessed 2026-01-22]. eISSN 2582-2160. Available from: https://doi.org/10.36948/ijfmr.2024.v06i02.14871

[21] ZIYAD, M., NARANJE, V., SURESH, S., MISHRA, V. P., SALUNKHE, S. Intelligent traffic system for sustainable mobility. In: International Conference on Computational Intelligence and Knowledge Economy: proceedings [online] [accessed 2026-01-22]. IEEE. 2021. ISBN 978-1-6654-2922-1, eISBN 978-1-6654-2921-4, p. 504-507. Available from: https://doi.org/10.1109/iccike51210.2021.9410725

[22] CHOUDHARY, S., ALI, S. S., BABU, N. R., SHARMA, H., KALIRAMAN, B., DHANKHAR, Y. A more efficient way to control traffic lights through AI-led smart city management. In: 3rd International Conference on Technological Advancements in Computational Sciences: proceedings [online] [accessed 2026-01-22]. IEEE. 2023. ISBN 979-8-3503-4234-5, eISBN 979-8-3503-4233-8, p. 1133-1138. Available from: https://doi.org/10.1109/ictacs59847.2023.10390336

[23] LI, Y., NIU, W., TIAN, Y., CHEN, T., XIE, Z., WU, Y., XIANG, Y., TONG, E., BAKER, T., LIU, J. Multiagent reinforcement learning-based signal planning for resisting congestion attack in green transportation. *IEEE Transactions on Green Communications and Networking* [online]. 2022, **6**(3), p. 1448-1458 [accessed 2026-01-25]. eISSN 2473-2400. Available from: https://doi.org/10.1109/tgcn.2022.3162649

[24] MARIANO DE SOUZA, A., BOUKERCHE, A., GUILHERME, M., MENEGUETTE, R. I., LOUREIRO, A. A., VILLAS, L. A. Decreasing greenhouse emissions through an intelligent traffic information system based on inter-vehicle communication. In: 12th ACM International Symposium on Mobility Management and Wireless Access: proceedings [online] [accessed 2026-01-25]. 2014. ISBN 978-1-4503-3026-8, p. 91-98. Available from: https://doi.org/10.1145/2642668.2642677

[25] ALI, S. M., AHMADI, S., AMANI, A. M., JALILI, M. Urban integrated sustainable transportation networks. In: *Interconnected modern multi-energy networks and intelligent transportation systems: towards a green economy and sustainable development* [online]. DANESHVAR, M., MOHAMMADI-IVATLOO, B., ANVARI-MOGHADDAM, A., RAZZAGHI, R. (Eds.). Piscataway: IEEE, 2024. ISBN 9781394188758, eISBN 9781394188789, p. 59-91 [accessed 2026-01-25]. ISBN unavailable. Available from: https://doi.org/10.1002/9781394188789.ch4

[26] SHAIKH, M. K., LIAQUAT, S. F., SIDDIQUI, F. A., ABDUL MOID KHAN, JAVEED, M., AHMED, M. Enhancing traffic control with AI blockchain and dynamic computation techniques. *VFAST Transactions on Software Engineering* [online]. 2024, **12**(3), p. 55-67 [accessed 2026-01-25]. ISSN 2309-3978. Available from: https://doi.org/10.21015/vtse.v12i3.1866

[27] SALEH, K. T., MUSA, A. A., MALAMI, S. I., LEVENT, Y. S., DULAWAT, S. AI-based green transportation: a sustainable approach. In: *Artificial intelligence for future intelligent transportation: smarter and greener infrastructure design* [online]. DHANARAJ, R. K., KAMILA, N. K., PANI, S. K., BALUSAMY, B., RAJASEKAR, V. (Eds.). New York: Apple Academic Press, 2023. ISBN 9781003408468, p. 269-302 [accessed 2026-01-25]. Available from: https://doi.org/10.1201/9781003408468-11

[28] SCAFFIDI, C., TRICOMI, G., DISTEFANO, S., PULIAFITO, A. Continuous green2 waves for surfing smart cities. In: International Conference on Smart Computing: proceedings [online] [accessed 2026-01-25]. IEEE. 2020. ISBN 978-1-7281-6998-9, eISBN 978-1-7281-6997-2, p. 404-409. Available from: https://doi.org/10.1109/SMARTCOMP50058.2020.00085

[29] CIRIANNI, F. M., COMI, A., QUATTRONE, A. Mobility control centre and artificial intelligence for sustainable urban districts. *Information* [online]. 2023, **14**(10), 581 [accessed 2026-01-25]. eISSN 2078-2489. Available from: https://doi.org/10.3390/info14100581