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Utilizing multi-source real data for traffic flow optimization in CTraf

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The problem of optimal control of traffic flow in an urban road network is considered. The control is carried out by varying the duration of the working phases of traffic lights at controlled intersections. A description of the control system developed is given. The control system enables the use of three types of control: open-loop, feedback and manual. In feedback control, road infrastructure detectors, video cameras, inductive loop and radar detectors are used to determine the quantitative characteristics of current traffic flow state. The quantitative characteristics of the traffic flows are fed into a mathematical model of the traffic flow, implemented in the computer environment of an automatic traffic flow control system, in order to determine the moments for switching the working phases of the traffic lights. The model is a system of finite-difference recurrent equations and describes the change in traffic flow on each road section at each time step, based on retrived data on traffic flow characteristics in the network, capacity of maneuvers and flow distribution through alternative maneuvers at intersections. The model has scaling and aggregation properties. The structure of the model depends on the structure of the graph of the controlled road network. The number of nodes in the graph is equal to the number of road sections in the considered network. The simulation of traffic flow changes in real time makes it possible to optimally determine the duration of traffic light operating phases and to provide traffic flow control with feedback based on its current state. The system of automatic collection and processing of input data for the model is presented. In order to model the states of traffic flow in the network and to solve the problem of optimal traffic flow control, the CTraf software package has been developed, a brief description of which is given in the paper. An example of the solution of the optimal control problem of traffic flows on the basis of real data in the road network of Moscow is given.

Keywords: traffic flow control, optimal control, traffic flow simulation, evolutionary computation, heterogeneous data processing

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СПЕЦИАЛЬНЫЙ ВЫПУСК

УДК: 519.876.5, 519.179.2

Использование реальных данных из нескольких источников для оптимизации транспортных потоков в пакете CTraf

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Рассмотрена задача оптимального управления транспортным потоком в сети городских дорог. Управление осуществляется изменением длительностей рабочих фаз светофоров на регулируемых перекрестках. Приведено описание разработанной системы управления. В системе управления предусмотрено использование трех видов управлений: программного, с обратной связью и ручного. При управлении с обратной связью для определения количественных характеристик транспортного потока используются детекторы дорожной инфраструктуры, видеокамеры, индуктивные петлевые и радиолокационные датчики. Обработка сигналов с детекторов позволяет определить состояние транспортного потока в каждый текущий момент времени. Для определения моментов переключения рабочих фаз светофоров количественные характеристики транспортных потоков поступают в математическую модель транспортного потока, реализованную в вычислительной среде системы автоматического управления транспортными потоками. Модель представляет собой систему конечно-разностных рекуррентных уравнений и описывает изменение транспортного потока на каждом участке дороги в каждый такт времени на основе рассчитанных данных по характеристикам транспортного потока в сети, пропускным способностям маневров и распределению потока на перекрестках с альтернативными направлениями движения. Модель обладает свойствами масштабирования и агрегирования. Структура модели зависит от структуры графа управляемой сети дорог, а количество узлов в графе равно количеству рассматриваемых участков дорог сети. Моделирование изменений транспортного потока в режиме реального времени позволяет оптимально определять длительности рабочих фаз светофоров и обеспечивать управление транспортным потоком с обратной связью по его текущему состоянию. В работе рассмотрена система автоматического сбора и обработки данных, поступающих в модель. Для моделирования состояний транспортного потока в сети и решения задачи оптимального управления транспортным потоком разработан программный комплекс CTraf, краткое описание которого представлено в работе. Приведен пример решения задачи оптимального управления транспортным потокам в сети дорог города Москва на основе реальных данных.

Ключевые слова: управление транспортными потоками, оптимальное управление, моделирование транспортных потоков, эволюционные вычисления, обработка гетерогенных данных

Работа выполнялась с использованием инфраструктуры Центра коллективного пользования «Высокопроизводительные вычисления и большие данные» (ЦКП «Информатика») ФИЦ ИУ РАН (г. Москва).

Introduction

Dense traffic remains one of the main problems of traffic control in large cities. Every year the number of vehicles and their time spent on the roads increase. It affects economic, environmental and psychological indicators: costs, environmental pollution, safety and stress.

A review of existing traffic management systems showed that there is no common approach to solving these problems, and, moreover, the level of automation of transport systems remains low. Currently, specialized information systems have been developed that can simulate and manage traffic flows in urban networks, for example, TRANSYT-7F [TRANSYT-7F], Synchro [Frost, 2019], SUMO [Krajzewicz et al., 2002], TransNet [Aliev et al., 2005]. Along with the systems being developed, there is also a manual control mode, when the operator switches traffic light coordination plans in accordance with the current situation online using cameras located at intersections. However, it cannot be argued that the problem of traffic flow control in cities has been solved.

This work is aimed at creating an automated system for traffic flows control using real multi-source data and universal recurrent traffic flow model (URTFM). The traffic flow control problem is considered as a mathematical problem of dynamic object control.

The traffic flow on urban road networks is described by a universal system of recurrent finite-difference equations. The network includes a group of intersections of various topologies, traffic lights and road infrastructure. Data on the network configuration, parameters and operating modes of traffic lights, as well as data from detectors and video cameras are combined in a database. Next, the problem of optimal traffic flow control is formulated. Optimization criteria are chosen and the problem of optimal control is solved taking into account the existing constraints. As a result, a Pareto set of optimal solutions (coordination plans) is formed depending on the amount of transport on road sections and conditions.

This approach will automate the process of traffic light control and thereby reduce the load on operators of traffic management centers, solve the optimization problem and improve the quality of control in accordance with the selected criteria, ensure consistent control on the networks under consideration, and increase the level of safety by reducing congestion.

Optimal control system

In this study, control of traffic flows at neighboring intersections is performed by coordination of traffic lights phases using data from inductive loop detectors, radar detectors and video cameras. The current coordination plan at intersections is taken as a basic solution, and then it is improved by evolutionary methods, taking into account the data on traffic flows observed over a certain time interval. The resulting coordination plan can be automatically corrected, that is, the feedback principle is implemented. In the case of emergency situations, for example, traffic accidents, etc. the deviation between the expected "historical" parameters and real-time data is received from detectors in the current mode.

Figure 1 shows a flowchart of the developed control system. The control unit includes the control object model and control mode selection unit. The control action $\mathbf{u}(k)$ can be generated using three modes: program control; control with feedback on the current state of the traffic flow, most commonly by a human-operator with an expert system or based on data received from detectors, or control based on solving the optimal control problem. The system also provides the possibility of adjusting some parameters of the model ($\mathbf{p}$) in order to update it under external disturbing influences.

The developed control system uses the universal recurrent traffic flow model built on the basis of the theory of controlled networks [Diveev, 2008]. The model is discrete in time and space, and in general, is a system of recurrent finite-difference equations

$$\mathbf{x}(k+1) = \mathbf{x}(k) + \mathbf{f}(\mathbf{x}(k),\ \mathbf{A}(\mathbf{u}(k))) + \delta(k), \tag{1}$$

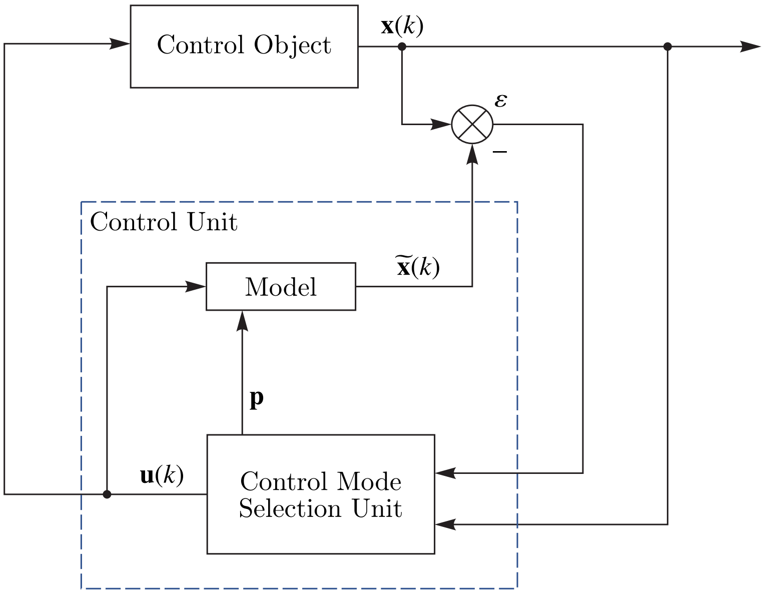

Figure 1. Control system of traffic flow

where $\mathbf{x}(k)$ is a state vector of traffic flow at control step k, $k = \overline{1, K}$, $\mathbf{x}(k) = [x_1(k) \dots x_L(k)]^T$, L is the number of road sections, $\mathbf{f}(\mathbf{x}(k), \mathbf{A}(\mathbf{u}(k)))$ is the change of traffic flow in one control step, $\mathbf{A}(\mathbf{u}(k))$ is a configuration matrix that is an adjacency matrix of network graph with maneuvers that are allowed at a given control step, $\mathbf{u}(k)$ is a control vector, $\mathbf{u}(k) = [u_1(k) \dots u_M(k)]^T$, M is the number of regulated intersections, and $\delta(k)$ is the input flow, $\delta(k) = [\delta_1(k) \dots \delta_L(k)]^T$. The model, its properties, and a methodological example are given in [Sofronova, Diveev, 2022].

Among possible control modes the optimal control mode with feedback on the current state of the traffic flow is implemented as follows. The order of phases is given as

$$\mathrm{S}_i = \left(0,\ 1,\ \dots,\ u_i^+\right), \quad i = \overline{1, M}, \tag{2}$$

where u_i^+ is the last phase in a phase cycle.

It is assumed that the initial state is

$$\mathbf{x}(0) = \mathbf{x}^0 = \left[x_1^0 \dots x_L^0\right]^T, \tag{3}$$

$$\mathbf{u}(0) = \mathbf{u}^0 = \left[u_1^0 \dots u_M^0\right]^T, \tag{4}$$

where $u_i \in \mathrm{U}_i$, $i = \overline{1, M}$, and the current state at any control step is available from various detectors. Optimizer searches for control in the form of traffic signal timing at each control cycle, which is called the coordination plan,

$$\widetilde{\mathbf{u}}(\cdot) = (\widetilde{\mathbf{u}}(0),\ \dots,\ \widetilde{\mathbf{u}}(K)), \tag{5}$$

$$\widetilde{\mathbf{u}}(k) = [\widetilde{u}_1(k) \dots \widetilde{u}_M(k)]^T, \tag{6}$$

where $\widetilde{u}_i(k) \in \{0,\ 1\}$, $i = \overline{1, M}$.

The resulting control determines the moments of phase switching

$$u_i(k) = \begin{cases} (u_i(k-1) + 1) \bmod u_i^+, & \text{if } \widetilde{u}_i(k) = 1, \\ u_i(k-1) & \text{otherwise.} \end{cases} \tag{7}$$

The duration of phases is within minimum and maximum possible values given by documentation on particular intersection in the considered network.

Control should minimize the given quality criteria

$$J_i = \sum_{k=1}^{K} f_{0,i}(\mathbf{x}(k),\ \mathbf{A}(\mathbf{u}(k))) \to \min, \quad i = \overline{1,\ r}. \tag{8}$$

CTraf software package

CTraf software package [Sofronova, Diveev, 2020] was developed for simulation and optimal control of traffic flows. CTraf is designed for a comprehensive analysis of traffic flows and scientific substantiation of the choice of traffic light phase durations at regulated intersections, as well as the configuration of network sections in order to optimize traffic and eliminate congestion.

The core of the software package is a URTFM unit. CTraf implements both simulation and the search for the optimal coordination plan for groups of traffic lights. It is assumed that information about the state of the road network is obtained from video stream processing unit and detector data. Restrictions on the capacity of vehicles on road sections, on the duration of traffic light phases are stored in the network configuration database. Optimization strategy as a quality criterion is determined by the operator.

A generalized block diagram of the developed software package is shown in Fig. 2.

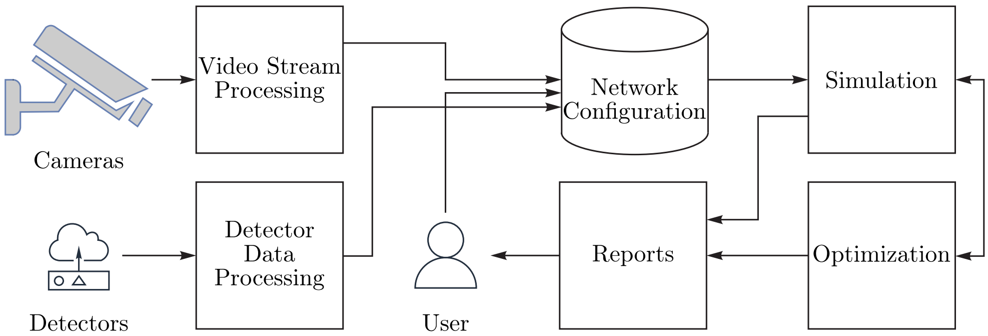

Figure 2. CTraf structure

Verified parameters of the model

The mathematical structure of the model includes a description of the road network graph in the form of an adjacency matrix and parameters that determine the flow distribution on road sections [Sofronova, Diveev, 2022]. It is necessary to know its main parameters: the capacity of maneuvers, the distribution of traffic at the intersection in alternative directions, the quantitative characteristics of input flows and the initial state of the traffic flow.

The capacity of maneuvers depends on the geometry of the intersection, which can be determined by the duration of the movement of the first car, on the number of lanes and on the duration of the traffic light phase that allows this maneuver. The flow distribution depends on the routes taken by the drivers and can be determined from preliminary observations. The assessment of input flows is determined by the amount of transport entering the network along the input roads. The initial state of the traffic flow is determined by the number of vehicles on all road sections. If there are no congestions in the network at the moment, then the initial state can be determined by assessing the input flows. In the presence of congestion, additional sources of information should be used.

Let us consider the process of obtaining flow distribution and input flow parameters using detectors and cameras located at intersections.

Data sources

The integrated development of the transport infrastructure in the cities makes it possible, in one form or another, to obtain various information about the movement of traffic flows in almost any section of the road network. The sources of data from the road infrastructure are: radar detectors of traffic flows, inductive loop detectors, and complexes of road cameras (see Fig. 3). Other sources of data are not considered here.

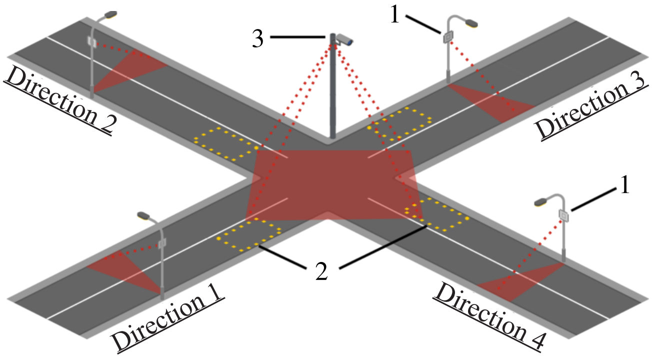

Figure 3. Sample road infrastructure: 1 — radar detectors, 2 — inductive loop detectors, 3 — road cameras

Radar detectors of traffic flows are placed on sections of the road network and allow collecting statistical data on the traffic intensity of vehicles in lanes and directions, as well as classifying vehicles by size and speed. The data package is transmitted in specified time intervals. Generally the package consists of timestamp, the number of vehicles passing in a specified time interval separately for each lane, the number of vehicles moving at a certain speed, grouped into speed ranges in increments of 10 km/h, the number of vehicles classified by length into small (< 3 m), average (from 3 m to 7.5 m) and big (> 7.5 m) vehicles.

Among the considered sources of information, this type of detector is the cheapest and easiest to install and maintain. At the same time, radar detectors have a number of disadvantages, the main of which is the average reliability of measurements. Depending on the detector model and taking into account possible shortcomings during its installation, the measurement error can reach 20 %.

Inductive loop detectors are placed at intersections just before the stop line in each lane. This type of detectors transmits the number of passing vehicles every minute. They have the highest accuracy in measuring the number of vehicles entering the intersection. At the same time, they do not allow determining the distribution of traffic flows along the exit directions of the intersection nor the traffic speed and length of vehicles. The complexity and cost of installing induction loop detectors is very high due to the need to place them under the roadway.

Among the complexes of road cameras, for the purpose of assessing the characteristics of traffic flows, the cameras for monitoring the traffic situation located directly at intersections are the most suitable. Data from road cameras, with appropriate installation of cameras and processing of the video stream, provides ample opportunities for assessing the characteristics of traffic flows, but they are highly susceptible to noise, for example, due to weather conditions or poor lighting at night.

When implementing the data input block of the CTraf software package, it was necessary to automate the receipt of all the necessary parameters of the mathematical model for describing the movement of vehicles along sections of the road network (1) using the available data from different types of detectors and road cameras. Preliminary analysis showed that the data obtained from radar detectors and inductive loop detectors is not enough to accurately determine the distribution of traffic flows at intersections and build an appropriate flow distribution matrix. For these purposes, it was decided to use data from road cameras and implement a video data processing unit based on neural network technologies for object recognition and their tracking algorithms within the CTraf software package.

Data from radar and inductive loop detectors are used to determine the incoming traffic flow $\delta(k)$ for each direction (see Fig. 3), as well as to validate the model as a whole. Moreover, for intersections equipped with inductive loop detectors, preference is given to the data obtained from these detectors as the most reliable. Statistical data from the detectors are received in raw form for a certain time interval, then they are subjected to preliminary verification and processing, and the average value of the density of traffic flows is calculated for each astronomical hour during the day.

In the process of implementing the data input block, we had to face the problem of heterogeneity of data from radar detectors from different manufacturers and the problem of an insufficient number of detectors in some directions of the sections of the road network under consideration. The first problem was solved by taking into account the type and manufacturer of the detector at the data preprocessing stage. To solve the second problem, a special technique is used, based on the simulation of output traffic flows at adjacent intersections.

Video stream data processing unit

To model real intersections, data on the distribution of traffic flows between directions of traffic at intersections are needed. A method has been developed to determine the flow distribution parameters. On each frame of the video, the YOLOv8 neural network [Jiang et al., 2022] is applied, which solves the problem of detecting objects in the image. The core component of YOLOv8 is a convolutional neural network that is used to extract features from an input image. After extracting features using a convolutional neural network, YOLOv8 uses a fully connected neural network (DNN) to process these features and predict the coordinates and classes of objects in the image. For each video frame, the BoT-SORT algorithm [Aharon, Orfaig, Bobrovsky, 2022] selects objects using the YOLOv8 object detector and tracks their movement in subsequent frames using the Kalman filter. For each trajectory, the points of the first and last appearance of the car on the frame are stored. After that, the points of the first and last appearance of each car on the frame are clustered using the k-means algorithm [Lloyd, 2022].

All points of first appearance in the frame are clustered into k_1 clusters, all points of last appearance in the frame are clustered into k_2 clusters. For each unique vehicle identifier obtained in the BoT-SORT algorithm, the cluster number to which the point of its first appearance belongs and the cluster number to which the point of its last appearance belongs are determined. Thus, we have a table of vehicle movement distribution between clusters (see the example for a T-shaped intersection in Table 1). If we normalize the table by rows (divide by the total number of cars that have left the input cluster), we get the values of flow distribution in alternative directions.

Table 1. Table of vehicle distribution between input and output nodes of a T-shaped intersection

	$k_2^{(3)}$	$k_2^{(4)}$	$k_2^{(5)}$
$k_1^{(0)}$	$P_{0,0}$	$P_{0,1}$	$P_{0,2}$
$k_1^{(1)}$	$P_{1,0}$	$P_{1,1}$	$P_{1,2}$
$k_1^{(2)}$	$P_{2,0}$	$P_{2,1}$	$P_{2,2}$

An example of the implementation of the developed video stream processing method is shown in Figs. 4, 5. In Fig. 5, the sign “×” indicates the entrance sections, the sign “⋆” indicates the exit sections, and the colored dots indicate objects and vehicles.

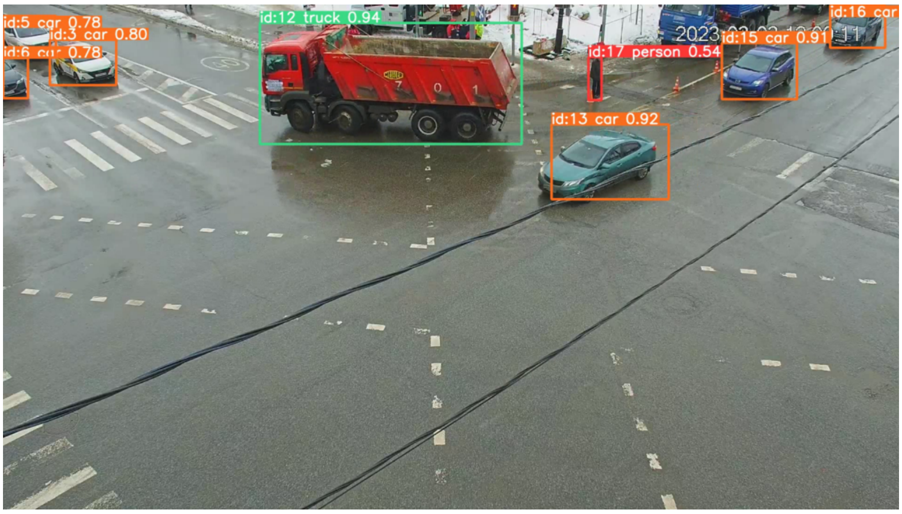

Figure 4. An example of vehicles identification in video stream

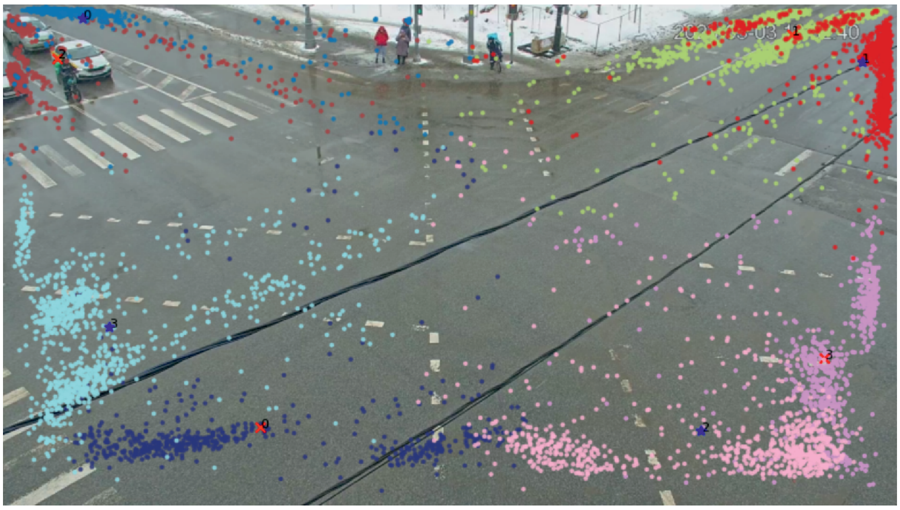

Figure 5. An example of a processed video stream

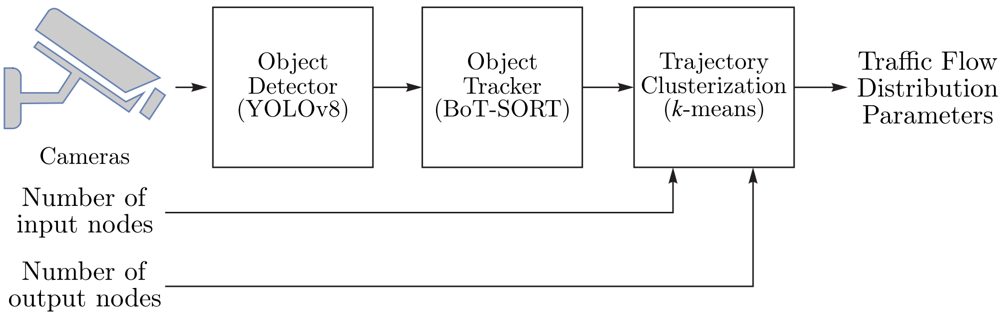

Figure 6. Video stream processing scheme

Thus, the process of preparing data on the distribution of transport flows for model (1) is reduced to the video stream processing procedure shown in Fig. 6.

Video processing setup and results

In the experimental setup, we utilized a video recording of a crossroad spanning a duration of 2 hours, captured at a rate of 25 frames per second. This resulted in a total of approximately 180,000 frames. To optimize computational efficiency, we processed every 5th frame, effectively utilizing around 36,000 frames for analysis. The crossroad under investigation is depicted in Fig. 4.

We employed the YOLOv8 object detection system to identify vehicles in each selected frame. Post detection, every vehicle was tracked throughout the sequence of frames to monitor its movement and direction.

To analyze the traffic flow, we set four input and four output nodes at the crossroad, see Fig. 7. This setup required us to run the k-means clustering algorithm twice, each time with k set to 4. This approach allowed us to effectively categorize the traffic flow into distinct clusters, representing different traffic patterns at the crossroad.

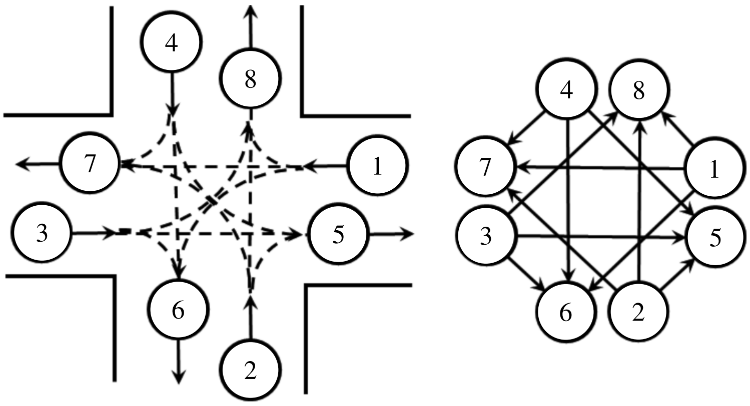

Figure 7. X-shaped intersection and its graph

The results of the analysis are summarized in Table 2, where k_1 represents the input nodes (rows) and k_2 represents the output nodes (columns). The distribution values have been rounded to the third decimal point for clarity.

Table 2. Discrete distribution of traffic flow from each input node (k_1) to each output node (k_2)

	$k_2^{(5)}$	$k_2^{(6)}$	$k_2^{(7)}$	$k_2^{(8)}$
$k_1^{(1)}$	—	0.21	0.575	0.215
$k_1^{(2)}$	0.233	—	0.337	0.43
$k_1^{(3)}$	0.501	0.191	—	0.308
$k_1^{(4)}$	0.165	0.465	0.37	—

The table provides the discrete distribution of traffic flow from each input node to each output node. For instance, from input node 1, approximately 21 % of traffic flows to output node 6. This detailed analysis of traffic flow distribution serves as a foundation for further optimization using the URTFM and the CTraf software package.

The current version of the CTraf software package is designed for internal scientific research only. However, further plans for the development of this scientific project include the development of a new version of the CTraf software with extended functionality, which will be available for non-commercial use upon request.

Optimization method

The multi-criteria variational genetic algorithm with nondominated sorting (VarNSGA-II) [Deb et al., 2002] is used to solve the optimal control problem. The method uses the principle of small variations of the basic solution [Sofronova, Diveev, 2021]. According to this principle, one basic solution is given, and the other possible solutions are defined by the set of codes of small variations of the basic solution. For the problem of optimal traffic flow control, the existing coordination plan is used as a basic solution. The small variations change the durations of the working phases of the traffic lights without changing their sequence. The algorithm maintains diversity in the set of solutions by applying nondominated sorting [Deb et al., 2002]. In the space of quality criteria values, a special metric is used to keep in the population of solutions whose quality criteria values are far enough away from solutions of the same rank on the Pareto front. As a result, we obtain a set of Pareto optimal solutions.

Computational experiment

The computational experiment was carried out for X-type intersection at 800-letiya Moskvi street and Beskudnikovski boulevard using CTraf. Traffic flow data as well as the current coordination plan for rush hours on a working day (10.00–16.30) were experimentally obtained.

A graph of road network is presented in Fig. 7. Entrance road sections are 1–4, and exit sections are 5–8. To shorten the presentation of networks and its parameters, let us use lists instead of matrices. A list is an ordered set of ordered sets. Each element of the list corresponds to a row of the matrix and contains the indices of the matrix columns that contain nonzero elements. If a matrix row contains only zero elements, then it corresponds to the empty set in the list element. Parameters of the model used in the experiment are given in Table 3.

Table 3. Parameters of the model

Parameter / Value
Adjacency matrix $\mathbf{A} = ((6, 7, 8), (5, 7, 8), (5, 6, 8), (5, 6, 7), (\ ), (\ ), (\ ), (\ ))$
Control matrix $\mathbf{C} = ((1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1), (\ ), (\ ), (\ ), (\ ))$
Matrix of admissible phases $\mathbf{F} = ((\{2, 2, 2\}), (\{1, 1, 1\}, \{3, 3, 3\}, \{1, 1, 1\}), (\ ), (\ ), (\ ), (\ ))$
Capacity matrix $\mathbf{B} = ((0.111, 0.748, 0.08), (0.106, 0.295, 0.454), (0.414, 0.21, 0.365),$ $(0.044, 0.295, 0.101), (\ ), (\ ), (\ ), (\ ))$
Distribution matrix $\mathbf{D} = ((0.118, 0.797, 0.085), (0.124, 0.345, 0.531), (0.418, 0.212, 0.369),$ $(0.13, 0.623, 0.247), (\ ), (\ ), (\ ), (\ ))$
Initial state of traffic flow at each section (veh) $\mathbf{x}^0 = [759\ 616\ 1500\ 679\ 0\ 0\ 0\ 0]^T$
Increments to the entrance road sections at each control step (veh/sec) $\Delta = [0.085\ 0.069\ 0.168\ 0.076\ 0\ 0\ 0\ 0]^T$
Traffic light phase constraints (sec) $\widetilde{\mathbf{u}}_1^- = [12\ 12\ 12\ 29]^T$ $\widetilde{\mathbf{u}}_1^+ = [57\ 57\ 57\ 40]^T$

As a quality criterion we have chosen the maximization of the number of vehicles on all exit sections of the intersection

$$J_1 = -\sum_{i \in \mathrm{I}_1} x_i(K) \to \min \tag{9}$$

and the minimization of traffic at the input sections as an average value for all cycles from the difference of the maximum and minimum number of cars at the input sections

$$J_2 = \frac{1}{C} \sum_{i \neq j,\ k \bmod T_c = 0} \left(x_i^{\max}(k) - x_j^{\min}(k) \right) \to \min, \quad i,\ j \in \mathrm{I}_0, \tag{10}$$

where C is the number of control cycles and T_c is the duration of the control cycle. The maximization of the number of vehicles on all exit sections of the intersection at the final control step K means the efficiency of using the capacity of intersection.

The basic coordination plan (CP_{bas}) is presented in Table 4. It consists of four phases that change sequentially and repeat cyclically. Phases 1–3 allow certain maneuvers and are effective in terms of traffic flow throughput. Phase 4 is not effective since it serves for pedestrians crossing the road while the traffic is waiting.

Table 4. Basic and optimal coordination plans

Phase	CP_{bas}	CP_{24}^{opt}
1	37	42
2	24	12
3	50	57
4	29	29
J_1	−2381	−2441
J_2	849	815

When simulating the basic coordination plan (CP_{bas}), the following values of the quality criteria were obtained $J_1 = -2381$ and $J_2 = 849$. The execution time for simulation was less than 1 min. The simulation was performed for $K = 2800$ control steps. In this experiment one control step equals one second.

Optimization was carried out by VarNSGA-II with the parameters given in Table 3. The type of optimization was chosen within a fixed control cycle. The resulting Pareto set of optimal solutions is presented in Fig. 8. One chosen solution $\widetilde{\mathbf{u}}(\cdot)$ #24 had the values of the quality criteria $J_1^* = -2441$ and $J_2^* = 815$ that were 2.5 % and 4 % better than the basic solution. The optimal coordination plan for the solution obtained is CP_{24}^{opt} (see Table 4). Note that the constraints on the duration of the phases and cycle length were not violated, and the basic solution was chosen by experts in city traffic management.

The computational experiment was performed on Intel Core i7-6700, 3.40 GHz, RAM 16 Gb. The execution time depends on the size of the network, the number of control steps, and the parameters of the evolutionary algorithm. For the given example, the size of population is $H = 128$, the number of generations is $G = 32$, the size of archive is $H = 128$, and the depth of variations is $d = 8$. The execution time for one optimization run is approximately 7 min.

Conclusion

The research presents an innovative approach to urban traffic flow control, utilizing a combination of data sources and the universal recurrent traffic flow model (URTFM) for traffic light coordination optimization. Despite inherent limitations in data collection methods, the study demonstrates their effective application in real-time traffic flow control.

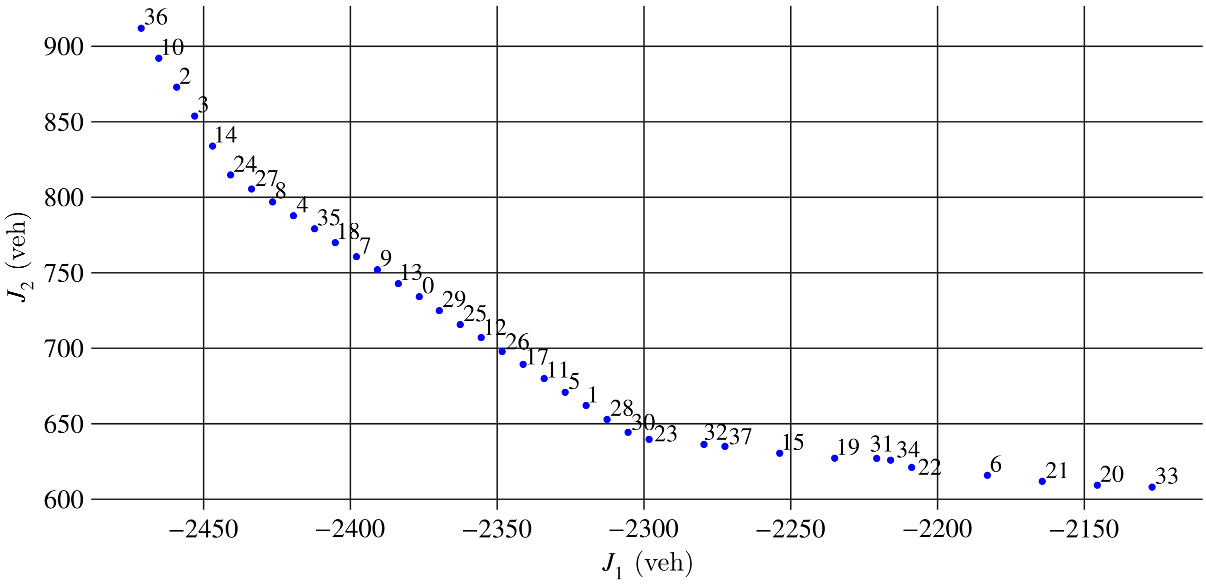

Figure 8. Pareto set

Key findings underscore the significance of real-time data and feedback mechanisms in traffic control, enabling dynamic response to changing conditions. However, the study also identifies potential areas for further research, including enhancing data reliability, expanding data sources, and improving real-time data analysis and predictive modeling techniques. The findings and the developed CTraf software package offer valuable resources for traffic management authorities and researchers alike.

References

Aharon N., Orfaig R., Bobrovsky B.-Z. BoT-SORT: robust associations multi-pedestrian tracking // arXiv:2206.14651 [cs.CV]. — 2022. — https://arxiv.org/abs/2206.14651 (accessed: 08.10.2023).

Aliev A. S., Strel'nikov A. I., Shvetsov V. I., Shershevskii Yu. Z. Modeling of the city transport flows as applied to the Moscow agglomeration // Automation and Remote Control. — 2005. — Vol. 66, No. 11. — P. 1805–1815. — DOI: 10.1007/s10513-005-0214-y

Deb K., Pratap A., Agarwal S., Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II // IEEE Transactions on Evolutionary Computation. — 2002. — Vol. 6, No. 2. — P. 182–197. — DOI: 10.1109/4235.996017

Diveev A. I. Controlled networks and their applications // Computational Mathematics and Mathematical Physics. — 2008. — Vol. 48, No. 8. — P. 1428–1442. — DOI: 10.1134/S0965542508080125

Frost A. Cubic's trafficware releases version 11 of Synchro software suite. — [Electronic resource]. — https://www.traffictechnologytoday.com/news/data/cubics-trafficware-releases-version-11-of-synchro-software-suite.html (accessed: 08.10.2023).

Jiang P., Ergu D., Liu F., Cai Y., Ma B. A review of Yolo algorithm developments // Procedia Computer Science. — 2022. — Vol. 199. — P. 1066–1073. — DOI: 10.1016/j.procs.2022.01.135

Krajzewicz D., Hertkorn G., Rössel C., Wagner P. An example of microscopic car models validation using the open source traffic simulation (SUMO) // Proceedings of Simulation in Industry, 14th European Simulation Symposium, 2002. — P. 318–322.

Lloyd S. P. Least squares quantization in PCM // IEEE Transactions on Information Theory. — 1982. — Vol. 28, No 2. — P. 129–137.

Sofronova E., Diveev A. Controlled networks to solve traffic flows problem // 2022 International Conference on Modern Network Technologies (MoNeTec), Moscow, Russian Federation, 2022. — P. 1–8. — DOI: 10.1109/MoNeTec55448.2022.9960764

Sofronova E., Diveev A. Software package for simulation and search of optimal control program of traffic lights by variational genetic algorithm. — Certificate on state registration No. 2020619911, 25.08.2020.

Sofronova E., Diveev A. Universal approach to solution of optimization problems by symbolic regression // Applied Sciences. — 2021. — Vol. 11, No. 11. — P. 5081. — DOI: 10.3390/app11115081

TRANSYT-7F. — [Electronic resource]. — https://mctrans.ce.ufl.edu/highway-capacity-software-hcs/transyt-7f (accessed: 08.10.2023).