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Methodological principles for forming a simulation model of road-traffic management with dynamic redistribution of traffic flows

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Abstract. The aim of the study was to develop a conceptual model of two-level road-traffic management in urban transport networks. The methodology was based on structural-functional analysis and the application of a multi-level approach to managing transport flows. It was found that the initial stage of forming a simulation model involved formalising the street-road network and selecting a system of variables to describe its state over time. The state of the traffic flow was specified by indicators of density, traffic intensity, average speed, queue lengths and waiting time. In the proposed formulation, the road-traffic management system had two levels: routing and local traffic-signal control. Dynamic flow assignment was considered as a mechanism for adjusting routes for each origin-destination pair and setting traffic-signal phases, whereas local control was interpreted as regulating green-signal durations and coordinating the operation of traffic signals at intersections. Optimal control was oriented towards reducing delays and uneven network loading, taking into account the specified constraints. The control algorithm combining local and network regulation was interpreted as an approach aimed at improving network efficiency, ensuring optimal use of resources under variable demand and driver behaviour. The proposed architecture of a discrete-event simulation model for dynamic redistribution of transport flows was based on a stochastic dynamical system with discrete time. It integrated two control levels: local traffic-signal control and network control of routes for origin-destination pairs. The model specified an approach to adaptive flow distribution based on the current network state (queues, delays, traffic intensity) and made it possible to study the impact of route changes and traffic-signal control parameters on delays and network loading under stochastic demand fluctuations. The practical significance lies in the possibility of using the results by local authorities and road services as a methodological basis for designing and implementing simulation models of urban transport systems

Keywords: dynamic system; adaptive algorithms; intersection; traffic-signal phase change; route optimisation; delay time

Introduction

The increasing number of vehicles and urbanisation lead to significant problems in urban road traffic, such as congestion, high delays and uneven network loading. Under such conditions, effective management of transport flows is critical for reducing delays and increasing the capacity of road infrastructure. In this regard, the active development of simulation models for traffic management, in particular with dynamic flow redistribution, has become a key tool in modern intelligent transport systems of the twenty-first century. One significant step in the development of simulation models was the dynamic flow redistribution approach for optimising road traffic,

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which makes it possible to redirect vehicles from overloaded links to less loaded ones. In the study by Z. Hu *et al.* (2021), methods of using multi-agent learning to solve the tasks of adaptive traffic-signal control were proposed, which made it possible to significantly reduce delays at intersections and improve overall traffic efficiency. This was achieved through the ability to model the behaviour of each agent (driver) and the interaction with others, which led to more effective traffic control under complex urban networks. In the work by S. Mostafi *et al.* (2022), RegTraffic was developed as a simulator for the spatio-temporal distribution of transport flows using regression models. The authors' model made it possible to accurately predict overloads on links of the urban network and adjust routes to ensure more efficient use of infrastructure. This model was able to adapt to real urban traffic conditions, taking into account various factors such as time and space, which made it very flexible and suitable for real scenarios. A macroscopic traffic simulation model for signalised urban networks, SimNET, was presented in the study by J. Liu *et al.* (2025). The main result was the successful application of deep learning to automate optimisation of traffic-signal operation and traffic adjustment at intersections. The authors demonstrated that using this technology made it possible to significantly reduce delays at intersections and improve overall traffic efficiency. In the work by M. Ashfaq *et al.* (2021), the classical model of dynamic user equilibrium and non-iterative stochastic routing were compared within a simulation-based dynamic traffic assignment problem. The authors found that non-iterative stochastic routing, having lower computational complexity and suitability for large-scale urban networks, at the same time formed a different spatial structure of flows and congestion compared with dynamic user equilibrium, which was fundamentally important when selecting a routing model. A method for simplifying traffic modelling was proposed in the study by T.S. Khan *et al.* (2024), replacing traditional Euclidean distances with agent-based models. Such simplification made it possible to maintain modelling accuracy at reduced computational complexity. In particular, applying the agent-based approach made it possible to scale models for large cities, where traditional methods were too resource-intensive.

In the work by T.V. Le *et al.* (2024), Internet of Things, OpenStreetMap, and fog computing were integrated to create a dynamic traffic optimisation system in smart cities. The results included reduced delays and improved efficiency of street networks due to the use of real sensor data and predictive analytics. This made it possible to implement more flexible and adaptive management of transport flows in urban agglomerations. The application of reinforcement learning and predictive analytics for traffic optimisation in the city of Belgrade was proposed by V.N. Skoropad *et al.* (2025). As a result, the authors established a reduction in delay time on key city routes, improved evenness of street loading and increased traffic efficiency under high peak loads. This approach envisaged the implementation of adaptive algorithms that made it possible to optimise traffic during peak loads, increasing the evenness of street loading and improving urban mobility. The study by Y. Zhao *et al.* (2025) focused on multi-objective optimisation for dynamic traffic control based on flow assignment. The authors developed an approach that made it possible to balance several critical indicators such as delay time, link loading and safety. This made it possible to reduce congestion and improve the efficiency of the transport network, particularly under high peak loads. In the work by A.A. Korchevska *et al.* (2023), methods for modelling the distribution of transport flows on road-transport networks were developed. The proposed methods could be applied to improve traffic organisation in cities with high levels of road overload. The authors demonstrated how mathematical models could be used to accurately predict congestion and optimise routes, which made it possible to increase the efficiency of transport infrastructure use under real conditions. A multigene model for organising road traffic in urban agglomerations was proposed by G. Weigang & K. Komar (2024), which was appropriate for Ukrainian cities where problems with traffic organisation were observed. The authors focused on the use of agent-based models, which made it possible to organise traffic effectively and reduce congestion at intersections. This approach could be used in Ukraine to improve urban mobility.

Despite the existence of studies, there was a gap in adapting existing models to real urban traffic conditions. In particular, there was a lack of effective adaptive models for dynamic flow redirection that could account for variable demand and unpredictable road situations. In addition, the imperfection of existing approaches to managing traffic signals and routes did not provide sufficient flexibility to adapt to high loads and variable factors, which reduced the effectiveness of road-traffic management in modern urban agglomerations. Therefore, the aim of the study was to substantiate and structure methods of road-traffic management with dynamic redistribution of transport flows. To achieve the aim, the following tasks were set: to systematise existing approaches to road-traffic management with dynamic redistribution of transport flows and adaptive control of traffic-signal objects; to form a mathematical problem statement for optimal road-traffic control in a network representation taking into account the state vector, control vector and quality criteria of transport network functioning; to develop a conceptual architecture and algorithmic logic of a discrete-event simulation model of two-level road-traffic management in an urban transport network as a methodological basis for further software implementation of the simulator and simulation studies.

Materials and Methods

The study was based on a theoretical-analytical and mathematical-simulation approach to describing a road-traffic management system with dynamic flow redistribution, which was used for structural-functional analysis of the urban transport network, formalisation of key variables and control parameters, and formation of a conceptual two-level management model. The study included 3 stages. At the first stage, using the method of structural-functional analysis and formalised graph representation, the urban street-road network was represented in the form of a directed graph with identification of intersections, street links, entry/exit nodes and OD pairs:

$$G = (V, E), \quad (1)$$

where V is the set of intersections; E is the set of street links between the intersections. Parameters and state variables (densities, intensities, speeds, queue lengths, traffic-signal states) were introduced for these elements, forming the state vector x(t). This allowed the structure of the road network to be clearly modelled and analysed, which was the basis for further description of movement and flow management.

Using the apparatus of the theory of controlled dynamical systems and stochastic demand modelling (non-stationary Poisson processes and random disturbances related to driver behaviour), a description of system evolution was formed in the form of a stochastic dynamic model:

$$x_{k+1} = F(x_k, u_k, \xi_k), \quad (2)$$

where: x_{k+1} is the state of the same system at the next simulation step; x_k is the state vector at discretisation moment k; F is the state-transition function (operator); u_k is the control (route distribution and traffic-signal control parameters); ξ_k are random disturbances reflecting the stochastic nature of demand and the micro-dynamics of movement. This approach made it possible to reproduce trajectories of the network state and evaluate quality criteria, in particular delay time, queue length and unevenness of loading.

For a fixed initial network configuration and a given control strategy, the simulation model reproduced the network state trajectory x(t) and evaluated quality criteria (delay time, queue length, unevenness of loading) for dynamic redistribution of transport flows taking into account demand and capacity constraints:

$$J(u) = E[\int_0^T L(x(t), u(t))dt] \to \min, \quad (3)$$

where J(u) is the generalised quality criterion (functional) corresponding to the control strategy u; E is the operation of mathematical expectation, which takes into account the stochastic nature of the system (random demand, driver behaviour, etc.) and gives the average value of the criterion over all possible realisations of randomness; $\int_0^T$ dt is integration over time from 0 to the control / simulation horizon T; x(t) is the state vector of the transport system at time t (densities and intensities on links, queue lengths, traffic-signal phases); u(t) is the control vector at time t (route distribution of flows among paths for OD pairs and traffic-signal control parameters at intersections); L(x(t),u(t)) is the instantaneous cost/quality function, which at each time t is computed from the current network state x(t) and control u(t) and includes separate metrics (time spent, delays, queue length, unevenness of loading); →min means that the problem is to find such a control strategy u for which the value of the criterion J(u) is minimal among all admissible strategies.

Based on the principles of multi-level management of transport systems, a two-level control scheme (routing/network level and local traffic-signal level) was constructed and the control vector u(t) was introduced, while performance criteria (time in system, delays, queue length, unevenness of loading) were generalised in the form of the optimal control functional J(u). This methodologically formed a coherent theoretical formulation of the optimal control problem for a stochastic transport network and outlined the structure of a discrete-event simulation model, which in further studies could be used for numerical simulation and analysis of system properties without tying it to specific empirical data at this stage.

At the second stage, using the method of analysis and generalisation of scientific publications, an agent-oriented simulation approach to describing the road-traffic management system was considered. The main objects of road infrastructure (vehicles, network links, intersection approaches, traffic-signal objects and origin-destination (OD) pairs) were analysed and schemes of the interaction were specified. The criteria for evaluating the quality of system functioning included flow density, capacity, traffic intensity and delay time, which could be used in further simulation studies to analyse the effectiveness of different control strategies. This methodological approach made it possible to structurally describe the interaction of system objects and outline the set of indicators by which it was appropriate to assess the effectiveness of movement in the network.

The third stage – the method of theoretical analysis and generalisation was applied, within which a typical structure of the discrete-event simulation cycle was formed, reflecting the main road-traffic processes and the dynamics – start-initialisation of the state and event queue – selection of the nearest event – advancing time to the event moment – evaluation of state indicators (queues, delays, loading) – updating control (local/network) if necessary – completion of the simulation. Such a scheme defined the algorithmic logic of the future discrete-event simulation model, made it possible to conceptually reflect characteristic road-traffic processes and form the basis for further software implementation of the simulator and study of the effectiveness of different control strategies.

Additionally, to evaluate the effectiveness of road-traffic control strategies, a comparative analysis method was applied for two interrelated approaches: local adaptive traffic-signal control and network redistribution of routes for OD pairs. The choice of approaches was driven by the fact that the approaches made it possible to model both local and global control strategies, ensuring full integration of processes to achieve optimal results in road-traffic management. The comparison was carried out according to the following aspects: control object, input information, decision-making criterion, time scale, and type of impact. This made it possible to select an optimal control strategy based on a detailed comparison of the effectiveness of each approach according to key parameters, and to build a theoretical model that integrated both control levels to ensure maximum efficiency of the transport network. Assessment of the interaction between the local and network levels made it possible to outline the principles of building flexible and adaptive road-traffic management, which should be able to respond promptly to changes in demand and contribute to reducing congestion, increasing the overall capacity of the system.

Results and Discussion

Analysis of the structure of the street-road network and traffic-flow dynamics. The initial stage in forming a conceptual simulation model of a road-traffic management system with dynamic flow redistribution is the formalisation of the structure of the street-road network and the selection of a system of variables that describe its state over time. Taking into account approaches to the analysis and modelling of transport networks, the urban street-road network is represented in the form of a directed graph (1). For each link , the length, number of traffic lanes and capacity are specified, which are subsequently used as model parameters. Entry and exit nodes of the network are identified separately, as well as the set of (OD) pairs for which transport demand is specified over time (Mehrabani *et al.*, 2023; Qi, 2024). The state of the traffic flow is described by a set of variables: flow density, traffic intensity and average speed for each link, queue length and waiting time for approaches to intersections. The state of the traffic-signal object at an intersection is characterised by the current phase and the time until its change, as noted by H. Xie *et al.* (2025). Under the introduced notation, the network state at time t is represented by the vector x(t), which includes flow parameters, queue characteristics and traffic-signal phases. The system dynamics are interpreted as the evolution of this state vector within a controlled dynamical system (Bouadi *et al.*, 2022; Boyles *et al.*, 2025). Demand at the network entries is appropriately modelled as a stochastic process with time-dependent intensity (for example, a non-stationary Poisson process), taking into account random deviations in individual driver characteristics such as reaction time and desired speed. The combination of these influences is considered a stochastic disturbance that is reflected in the dynamics of the network state. Dynamic flow assignment and adaptive infrastructure control are key instruments for reducing delays and increasing network efficiency (Agarwal *et al.*, 2024; Ma *et al.*, 2024). Within this formulation, the road-traffic management system is interpreted as a dynamic object that changes control parameters to reduce delays and uneven network loading. Dynamic redistribution of traffic flows includes route changes for each OD pair and adaptive adjustment of traffic-signal phase priorities and durations depending on the current network state defined by the vector x(t).

Taking into account the practice of multi-level management of transport systems, two control levels are distinguished. At the routing (network) level, the control is the distribution of demand among alternative routes for each OD pair (o,d), where the control variables are the shares of flow on each route, which can change over time. This approach is considered a means of redirecting traffic from overloaded links to less loaded ones, implementing dynamic flow assignment. At the local (intersection) level, the control variables are the sequence of traffic-signal phases, the green-phase duration for each movement direction and the coordination parameters for a group of neighbouring intersections. The set of these settings over a given time interval forms the control vector u(t). To formulate the control problem, performance indicators of the transport network are introduced, in particular: the average time a vehicle spends in the system, queue delays, queue lengths and unevenness of loading. In the simplest case, the objective function can be the minimisation of total delay time over a period or a combination of several indicators (for example, delays, queue lengths, unevenness of loading). This form makes it possible to generalise different approaches to assessing the effectiveness of signalling and flow assignment. Taking into account the introduced state vector x(t) and control vector u(t), the evolution of the transport system is described by a dynamic model that reflects changes in the network state under the influence of the selected control strategy and stochastic disturbances (demand fluctuations, differences in driver behaviour, etc.). At the conceptual level, the dynamics can be presented as a discrete stochastic system (2). For a fixed initial configuration and a given control strategy, the simulation model can be used to reproduce the trajectory x(t) and the corresponding values of the quality criteria. The problem of dynamic redistribution of traffic flows is formulated as follows: for given demand intensities at the network entries, it is necessary to choose a strategy for changing the route distribution and traffic-signal control parameters that minimises the selected system performance criterion, subject to compliance with constraints on capacities, permissible phases and operating regimes of intersections. In general terms, this formulation can be interpreted as an optimal control problem for a stochastic dynamical system with constraints (3). In this form, the problem statement has a distinctly theoretical character: it is based on generalisation and systematisation of existing models of dynamic flow assignment and traffic-signal control, is formulated in terms of controlled dynamical systems and is not tied to specific empirical data, but serves as a basis for further analysis of the simulation model and investigation of its properties.

The general structure of the proposed simulation model for dynamic redistribution of traffic flows is based on a discrete-event description of the evolution of the network state under stochastic demand and multi-level control. Within this concept, the simulation approach is oriented towards representing changes in the network state and the response of the control system, similar to modern modelling platforms for intelligent transport systems of the twenty-first century. The simulation process is considered in a discrete-event mode: the system state changes only at the moments when events occur (vehicle arrival, traffic-signal change, departure from a queue, etc.), and in the inter-event time it either remains unchanged or is updated according to simplified rules. In the conceptual description, the system dynamics are interpreted as a discrete-event stochastic system, with two variants of time representation: event time, where the model's internal "clock" moves from event to event, and a hybrid mode, where event time is combined with fixed discretisation for periodic updating of aggregated indicators and implementation of algorithms at the network level (Ma *et al.*, 2024). The main evolution of the simulation model at the conceptual level is specified by a sequence of events that change the state of the transport network, while time discretisation with a fixed step is used only for computing aggregated indicators and implementing optimisation or control-adaptation procedures at a higher level. In this interpretation, the system dynamics are described by a state-transition operator that, for each simulation step, based on the current network state, the values of control actions and the realisation of stochastic disturbances, uniquely determines the new system state at the next moment in time. Within the structure of the model, several basic types of objects are conceptually distinguished, corresponding to the main components of the transport system in microscopic and multi-class traffic models (Table 1).

Table 1. Main objects of the simulation model of the road-traffic management system

Object	Role in the model	Main variables/parameters
Vehicle (agent)	Carrier of flow moving through the network along a specified route	Network position, route, desired speed, reaction time, minimum headway
Network link	Street segment between intersections	Flow density, traffic intensity, average speed, capacity
Intersection approach	Queue of vehicles before a controlled node	Queue length, waiting time, service regime (movement permitted/prohibited)
Traffic-signal object	Tool of local control of movement priorities at an intersection	Active phase, time to phase change, set of permissible phases, duration constraints
OD-pair (origin-destination)	Source and destination of transport demand	Demand intensity, time profile, set of permissible routes

Source: compiled by the author on the basis of M. Bouadi *et al.* (2022), B. Mehrabani *et al.* (2023), H. Qi (2024), J. Ma *et al.* (2024)

The generalisation of Table 1 reflects a natural division of the model components into three groups. First, at the micro level, individual vehicles are described as agents with the own parameters that determine the movement dynamics. At the infrastructure level, network links and intersection approaches are distinguished, corresponding to the arcs of the directed graph and queue elements respectively; for these objects, aggregated variables are maintained that are used in both microscopic and macroscopic approaches to traffic analysis. Third, elements of the control and demand system are accounted for separately: traffic-signal objects define local rules for allowing vehicles through network nodes, and OD pairs determine the structure and time profile of the input load. This division makes it possible to explicitly separate flow carriers, infrastructure elements and control components, which conceptually simplifies the construction of the simulation algorithm and creates prerequisites for further theoretical analysis of the model's properties. In particular, the state vector x(t) may be considered as the concatenation of variables associated with vehicles, links, approaches, traffic-signal objects and OD pairs, whereas control u(t) is concentrated on route-distribution parameters and traffic-signal operating regimes. The interaction of the main objects and subsystems is generalised in the form of a structural diagram of the simulation model of the road-traffic management system with dynamic redistribution of traffic flows (Fig. 1).

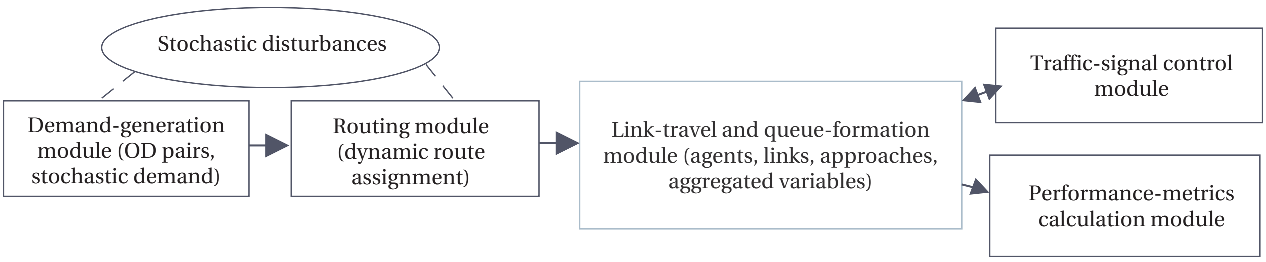

Figure 1. Structural diagram of the simulation model of the road-traffic management system with dynamic redistribution of traffic flows

Source: compiled by the author on the basis of M. Bouadi *et al.* (2022), B. Mehrabani *et al.* (2023), H. Qi (2024), J. Ma *et al.* (2024), H. Xie *et al.* (2025), S.D. Boyles *et al.* (2025)

At the conceptual level, the following main modules are distinguished in the model structure. The demand-generation module, which, based on the parameters of OD pairs, generates vehicle arrival flows at the network entries, taking into account the stochastic nature of intensity and temporal demand fluctuations (Smelyakov *et al.*, 2023). The routing module, which for each new vehicle selects a route from the set of permissible paths, taking into account current or forecast characteristics of network loading and the adopted dynamic flow assignment strategy. The link-movement and queue-formation module, which describes the movement of agents along network links, updates aggregated variables (density, intensity, average speed) and the state of queues on approaches to intersections in accordance with local traffic conditions and capacity. The traffic-signal control module, which implements local algorithms for changing phases and signal durations at signalised intersections based on the selected control strategy, infrastructure parameters and current loading indicators (Hu *et al.*, 2022; Jia *et al.*, 2024). The quality-indicator computation module, which, based on the trajectories of the state vector and control actions, computes instantaneous and integral values of criteria (average time in the system, queue delay time, queue lengths, a measure of unevenness of network loading) and the corresponding value of the generalised quality functional J(u) (Tak & Yeo, 2025). The sequence of operation of the modules, reflected in the structural diagram, is interpreted as an implementation of the state-transition operator in a discrete-event format. Vehicle arrival events are considered as the result of the operation of the demand module and are passed to the routing module, which determines for each agent a route through the network. Next, the link-movement and queue-formation module updates vehicle positions, aggregated link characteristics and the state of queues on approaches to intersections. The traffic-signal control module sets the service regimes for approaches, changing movement priorities and thereby influencing the evolution of queues and delays. The quality-indicator computation module integrates information about the system state and the applied control, forming the values of criteria and the generalised quality indicator, which establishes the link between the simulation model and the optimal control problem.

The results of the study showed that dynamic route assignment for OD pairs combined with variable traffic-signal regimes reduces vehicle time spent in the system, shortens queue delays and decreases unevenness of network loading. The greatest effect is observed during peak loads, when adaptive adjustment of routes and signalling helps to avoid overloads and redistribute flow. This is consistent with the results of X. Song *et al.* (2021), where Global Positioning System and Point of Interest are used for dynamic flow assignment in Shanghai. In the present study there is no direct integration of these data, but the logic of flow redistribution and accounting for variable demand is similar. The results of X. Song *et al.* indicate that adding spatial information increases the accuracy of Dynamic Traffic Assignment models, so the effects of reducing delays can be improved through integrating such data into the proposed simulation model. In the study by R. Rahman & S. Hasan (2023), a new approach to modelling traffic flows using graph neural networks was proposed, which makes it possible to effectively study traffic patterns and forecast flows in urban networks. The authors used graphs to represent the transport network, enabling more accurate analysis of interrelations between its different elements, such as roads, intersections, and vehicles. This is confirmed by the results of the present study regarding the effectiveness of using graph models for traffic analysis. This implies improvements in congestion management and delay reduction compared with traditional methods under conditions of variable demand and adaptive control. The study results established that the road-traffic management system is a stochastic dynamical system with multi-level control: at the network level – dynamic flow assignment among routes; at the local level – adaptive traffic-signal control taking into account queues and approach loading. This scheme reduces delays, shortens queues and improves loading compared with fixed signalling plans, particularly under variable demand. This is consistent with the conclusions of Y. Lin (2023), where the DynasTIM system developed a platform for dynamic traffic modelling and optimisation with an emphasis on online state estimation, traffic forecasting and traffic-signal control optimisation. Similar to DynasTIM, the model of the present study uses a stochastic description of demand and adaptive control mechanisms to reduce delays and improve network operation. Unlike the approach of Y. Lin, which focuses on real-time algorithms within an already deployed platform, the present work focused primarily on formalising the simulation model as a stochastic dynamical system with clearly defined state and control vectors. This facilitates further theoretical investigation of system properties and formulation of the optimal control problem.

Z. Grujić & B. Grujić (2025) focused on the optimal route in urban road networks using Dijkstra's algorithm. The authors applied this algorithm to find the best paths, which makes it possible to efficiently determine routes with minimal delays and maximum capacity. This is essential for optimising traffic flow and reducing congestion in urban conditions, which corresponds to the results of this study, where similar algorithms are applied, in particular at the route level, which makes it possible to reduce delays and increase network efficiency. Comparison of both works shows that optimal-route search algorithms, including Dijkstra's algorithm, remain among the key tools for improving traffic-flow management. The model in the present study is even more adaptive, as it includes additional dynamic control strategies that allow rapid response to changes in demand and route changes, providing a higher level of efficiency and delay reduction in real urban traffic conditions. The results of the study revealed that the use of dynamic routing and adaptive traffic-signal control makes it possible to significantly reduce the average vehicle delay time, decrease queue lengths on approaches to intersections and load the transport network more evenly. Decisions on redirecting flows and adjusting signal phases are made on the basis of the current network state, which ensures effective real-time traffic management. Similar conclusions were reached by Z.C. Su *et al.* (2023), whose work considered hierarchical control for transport networks using reinforcement learning methods. The study applied multi-level control, which included distribution of demand among alternative routes at the network level and adaptive traffic-signal control at the local level. The RL-based approach significantly improves traffic management, reduces delay time and optimises network loading by providing adaptation to changes in demand in real time. Thus, the simulation model for road-traffic management with dynamic flow redistribution provides for formalisation of the network structure, including intersections, street links and transport demand for each OD pair, while the use of adaptive traffic-signal control and dynamic routing makes it possible to reduce delays, improve network loading and optimise movement.

Structure of the discrete-event model and traffic-flow control algorithms. Within the discrete-event description of the transport network, the model considers a finite set of typical events, for each of which rules for updating the state of the transport network are specified. One of the basic types is the event of a vehicle arriving in the network: it is modelled at one of the entry nodes according to a specified stochastic demand process for the corresponding OD pair (Smelyakov *et al.*, 2023). After such an event occurs, the routing module selects a route from the set of permissible paths for this OD pair, and the vehicle is placed on the initial link of the route, beginning movement in accordance with the current network state. The next type of events is associated with vehicle movement along a link. As a result of such events, the vehicle's position is updated taking into account its speed, the positions of preceding vehicles and the traffic-signal indications at the end of the link. After reaching the end of the link, the vehicle either moves to the next link of the route or, if a prohibitive signal is present, joins a queue on the approach to the intersection, or leaves the network if the destination node is reached. A separate group consists of events associated with the formation and service of a queue on an approach. If the traffic signal prohibits movement, vehicles arriving at the approach accumulate in the queue. After the permissive phase is activated, the queue begins to discharge: vehicles consecutively move onto the corresponding links, while the queue length and waiting time are updated (Qi, 2024). Queue dynamics are determined by alternation of arrival, movement and signal-change events. Another type is traffic-signal phase switching events. These events are initiated according to the rules of the selected control algorithm (in particular, a fixed cycle, the maximum-load principle, or reinforcement-learning-based approaches) (Hu *et al.*, 2022; Agarwal *et al.*, 2024). During such an event, the set of permitted movement directions at the intersection is updated, as well as the corresponding time counters in the controllers, which determine the duration of the current and subsequent phases.

Finally, the model includes network events of flow redistribution. At specified time intervals or upon reaching certain conditions, the routing-control module may revise the route distribution, redistributing part of the flow from overloaded links to alternatives. Such redistribution can be implemented by changing route-choice probabilities for new vehicles or, if an appropriate mechanism is available, by adjusting routes for those already moving through the network. The set of described event types provides a consistent description of micro-level movement dynamics, queue formation and network flow redistribution within a unified discrete-event simulation model. The operation of the simulation model is appropriately organised according to a typical discrete-event cycle, within which at each step the nearest event in time is processed, the system state is updated and, if necessary, control parameters are modified (Fig. 2).

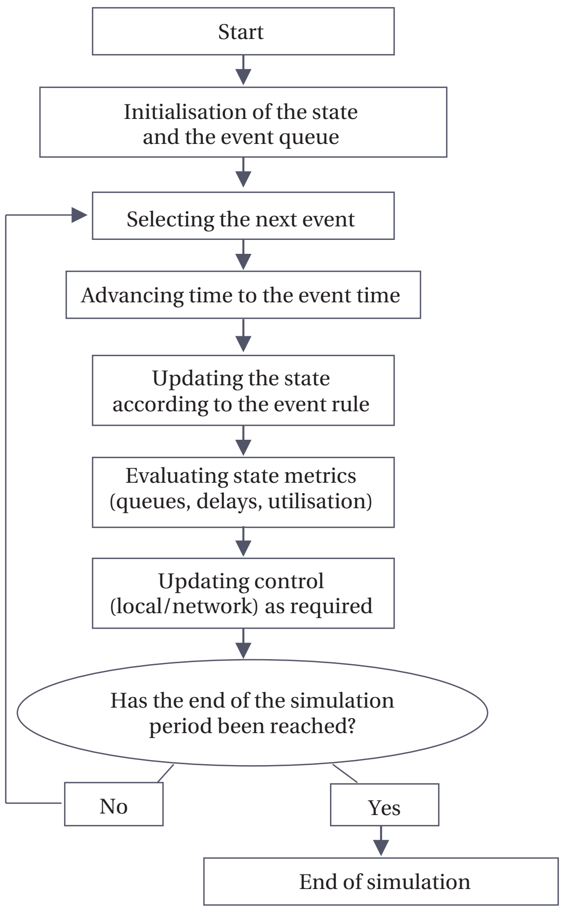

Figure 2. Flowchart of the simulation event-processing cycle in the model of the road-traffic management system

Source: compiled by the author on the basis of B. Mehrabani *et al.* (2023), H. Qi (2024), H. Xie *et al.* (2025)

Within the Figure 2, the operation of the simulation model is appropriately organised in the form of a discrete-event cycle. At each step, the event closest in time is selected from the event queue (vehicle arrival, traffic-signal change, completion of queue service, flow redistribution event, etc.), after which model time is advanced to the moment of its occurrence. Next, the system state is updated in accordance with the processing rules for the corresponding event type, which includes changing vehicle positions, queue parameters on approaches and intersection operating regimes. Based on the updated state, current network characteristics are assessed, in particular queue lengths, delays, and loading of individual links. At this stage, control decisions may be made: at the local level, traffic-signal controllers, relying on local information, change the durations or sequence of phases, while at the network level the routing-control module, if necessary, adjusts the route distribution for individual OD pairs. After this, the system returns to selecting the next event, and the cycle is repeated until the specified simulation horizon is reached. In this way, within a single simulation scheme, the action of two mechanisms of dynamic redistribution of traffic flows is coordinated: a local mechanism implemented through adaptive traffic-signal control, and a global mechanism associated with revising the route distribution and redirecting traffic between network links. The proposed control algorithm combines two interrelated levels: at the local level, adaptive traffic-signal control is implemented at individual intersections, and at the network level – correction of route distribution among alternative paths for OD pairs. At each signalised intersection, at decision-making moments, data on current approach queues and the intensities of the corresponding flows are used. For each approach, a load indicator is calculated, which may be based on queue length, vehicle arrival intensity or the combination; queue length is often used as a basic measure of unmet demand with possible inclusion of weighting coefficients reflecting the priority of individual directions. For each traffic-signal phase that opens movement for a certain set of approaches, a generalised "benefit" indicator is assessed through the total load on these approaches. After the minimum permissible time of the current phase has elapsed, such indicators are compared: if the current phase remains the best according to the selected criterion, its operation is extended; otherwise, a switch is made to the phase with the highest load. The duration of each phase is additionally bounded above, which prevents excessive delays for less loaded directions and ensures basic safety requirements. Within these constraints, the green-phase duration is automatically adapted to the current loading of the intersection; thus, the local algorithm is built on the principle of allocating more "green" time to those directions where the largest queues and flows are currently observed.

At the network level, aggregated state indicators of key links of the transport network are used, in particular average delays, speeds, and indicators of transition to a congested regime. At fixed intervals of model time, the network state is assessed on the basis of current values of these indicators, after which each arc of the directed graph is assigned a travel "cost" as a function of the base travel time, current delays and loading. In the simplest case, this cost is defined as the base travel time multiplied by a coefficient that increases with increasing loading or average delay. Next, for each OD pair, the most advantageous routes are recalculated taking into account the current network state, and the flow distribution is updated: part of demand is transferred from overloaded paths to alternative routes if the difference in cost between the two exceeds a specified threshold. For vehicles that are only entering the network, routes are selected according to the updated distribution; if an appropriate mechanism is available, re-routing is also permitted for those vehicles that are already moving and have not yet passed branching nodes. As a result, the proposed network algorithm implements the principle of adaptive distribution of OD flows, under which overloaded links can be relieved by redirecting part of the flow to alternative routes. For clarity, the key differences between the local and network control levels are summarised in Table 2.

Table 2. Comparison of local and network-level control

Aspect	Local level (traffic-signal control)	Network level (route redistribution)
Control object	Signal phases at individual intersections	Distribution of OD flows across alternative routes
Input information	Queue lengths, approach flow rates	Average delays, speeds, link utilisation
Decision criterion	Maximum "load"/"pressure" on movement directions	Minimisation of route "cost" based on link costs
Time scale	Frequent updates at the level of individual phases or cycles	Periodic updates at intervals ΔT of model time
Type of intervention	Change of the active phase and its duration	Change in the distribution of flows between routes; possible re-routing

Note: ΔT is a fixed time interval between each update or simulation step, enabling regular evaluation and adjustment of transport network parameters such as delays, travel speed, or link utilisation

Source: summarised on the basis of T. Hu *et al.* (2022), B. Mehrabani *et al.* (2023), A. Agarwal *et al.* (2024), S.D. Boyles *et al.* (2025)

Both control levels can be represented as a single control action comprising local and network components: the local component is responsible for configuring traffic signals at intersections (selection of active phases and the durations), whereas the network component determines the distribution of routes across alternative paths for individual OD pairs. Within the previously introduced description of transport-system dynamics, the evolution of the state vector is interpreted as the outcome of the action of a transition operator, which at each simulation step uses the current network state, the parameters of local and network control, and the realisation of stochastic disturbances. The control algorithm specifies the rule by which local and network control actions are selected as functions of the current state (at the local level – based on queues, flow rates and intersection structure; at the network level – based on aggregated indicators of delays and link utilisation). Under this interpretation, the simulation model is considered both a means of describing the evolution of traffic flows and a tool for theoretical analysis of the properties of dynamic flow-redistribution algorithms within a unified mathematical formalism. The simulation model proposed at the conceptual level corresponds to a stochastic discrete-time dynamical system in which the evolution of the state vector is described by a transition operator that depends on the current network state, the control actions of the local and network levels, and random disturbances. This representation makes it possible to apply the apparatus of dynamical systems theory for qualitative analysis of transport-network behaviour without being tied to a specific software implementation. Stability in this context is understood as the ability of the system, under demand that does not exceed a certain permissible level, to operate in a regime with bounded queue lengths and without transitioning into a prolonged congested state. The proposed local adaptive algorithm, oriented towards selecting signal phases based on current queues and loads, ensures regular relief of the most heavily loaded directions, whereas constraints on the maximum phase duration prevent the "switching off" of other approaches. At the network level, route redistribution reduces persistent overload on individual links by shifting part of the flow to alternative paths. Taken together, this provides grounds to expect the existence of a quasi-stationary regime in which queues remain bounded and average delays do not increase without bound over time, provided demand is moderate. A static control scenario is considered as a reference scenario, in which routes for OD pairs are fixed, and signal plans are defined by invariant cycles and phase durations. In this case, during peak periods, individual links may become systematically overloaded because control does not respond to random demand spikes, while part of the network remains underutilised. The proposed two-level algorithm combines adaptive allocation of green intervals according to current queues at the local level with network redistribution of OD flows, which reduces traffic concentration on overloaded routes. In theoretical terms, this provides grounds to assume that, under the same input demand, the adaptive strategy will not be inferior to the static strategy in indicators such as average delays and queue lengths, and has the potential to provide better values of these indicators under peak conditions (Tak & Yeo, 2025).

The stochastic nature of demand and driver behaviour necessitates an analysis of the robustness of the proposed algorithm. Local control relies on directly measurable characteristics of the state (queues, flow rates, intersection operating regimes), which increases the system's ability to adapt to short-term random deviations without relying on precise forecasts. At the network level, decisions are based on averaged indicators of delays and link utilisation, which smooths small-scale fluctuations at the level of individual vehicles. As a result, the proposed two-level algorithm, which combines adaptive selection of signal phases based on current queues with network redistribution of routes, is considered an approach that may contribute to limiting queue growth, reducing delays and increasing the uniformity of network utilisation compared with static control schemes, while maintaining acceptable resilience to stochastic influences. The results of the study established that a discrete-event model of two-level road-traffic control can contribute to reducing delays and balancing network utilisation through adaptive traffic-signal control and dynamic route assignment for OD pairs. This corresponds to the study by F. Condette *et al.* (2024), which also confirmed the use of discrete-event models to analyse vehicle traffic in urban conditions. The authors described events such as vehicle arrival, movement along a link and queue formation on approaches to intersections, and the researchers also examined traffic-signal control in detail, including analysis of queue lengths and waiting times, which confirmed the conclusions of the present study regarding the importance of adaptive traffic-signal control for reducing delays and improving network functioning. This confirmed the effectiveness of using discrete-event simulation for real traffic management and adaptive signal control to improve transport-system performance indicators. The study by Z. Meng *et al.* (2023) confirmed the concept of using discrete-event simulation for modelling road traffic, which forms the basis of the present study, where a finite set of typical events for each control stage was described. The authors noted the significance of aggregated control interfaces, which allow not only regulation of vehicle movements but also effective response to changes in traffic flow in real time. This aligns with the concept of dynamic route assignment for different OD pairs in the present study, where the route-choice module selects an optimal path depending on the network state. The significance of discrete-event models for analysing traffic flows was also noted by C. Calistus *et al.* (2023). In the authors' model, events such as vehicle arrivals, movement along a link and queue formation were taken into account, which is analogous to the approach of the present study. In addition, the simulation results of C. Calistus *et al.*, which included synchronised traffic signals, confirmed the effectiveness of adaptive control for reducing delays. Adaptive control is effective for regulating signal phases, where signal-change events are initiated according to current queues and traffic intensity.

The study results showed that dynamic route assignment for OD pairs defines a mechanism for controlling vehicle flows, within which traffic can be redirected from overloaded links to less loaded paths, which is consistent with the conclusions of H. Zhu *et al.* (2024). The authors demonstrated that the use of digital twin technology allows traffic signals to be adaptively configured. Adaptive control helps to reduce delays and redirect traffic flow, contributing to more even network utilisation. The approaches applied in both studies demonstrated the effectiveness of adaptive control and dynamic flow redistribution in improving the operation of transport systems. The work by Y. Chen & C.G. Cassandras (2025) described a method of adaptive traffic-signal control that accounts for turning movements, approach delays and intersection blocking, which correlates with the description of mechanisms for adjusting signal phases depending on traffic intensity and queue lengths in the present study. The authors also indicated the appropriateness of dynamically adapting signal phases to reduce delays and improve traffic flow, which directly corresponds to the concept of adaptive control in the present study, which is oriented towards optimising green time for directions with high flows. This confirms the effectiveness of redirecting flows to alternative routes to reduce overload. Thus, in the discrete-event conceptual model of the transport network, events are described that determine the evolution of the system state, in particular vehicle arrivals, the movement, queue formation on approaches and switching of signal phases. The model is characterised by accounting for the stochastic nature of demand and the embedded possibility of adaptively changing routes and signal-phase parameters through dynamic redistribution of traffic flows. The proposed approach is conceptual and methodological in nature and serves as a basis for further software implementation of a simulator and quantitative assessment of the impact of different control strategies on delays and network utilisation.

Conclusions

The results of the study established that, within the proposed conceptual model, the choice of a control strategy was appropriately represented as a combination of adaptive adjustment of traffic-signal phases and redirection of traffic flows in order to reduce the level of congestion. Stochastic disturbances were taken into account through modelling fluctuations in transport demand and driver behaviour. The optimisation problem was formulated as minimisation of the system performance criterion in the presence of constraints on capacity and permissible operating regimes at intersections, and the modelling problem was presented as estimation of the mathematical expectation of quality indicators under random values of demand and driver behaviour. The distribution of demand across routes was described on the basis of network control, which accounts for delays and utilisation on different links, while dynamic flow redistribution reconciles local and global strategies in order to form more balanced routes. Local traffic-signal control at individual intersections was considered as an instrument for reducing the probability of excessive queue accumulation and the emergence of congestion. The stochastic nature of demand and unpredictable driver behaviour were taken into account as factors that can substantially affect the effectiveness of the selected control strategies. The proposed conceptual simulation model of dynamic redistribution of traffic flows was based on representing the urban transport network as a stochastic discrete-time dynamical system and provided for two control levels: local control of traffic-signal objects and network-level control of routes for OD pairs. Within the model, an approach to adaptive flow allocation was formalised with account taken of changes in queues, delays and traffic intensity, which created theoretical prerequisites for further software implementation of a simulator and evaluation of response effectiveness to fluctuations in transport demand. This structure was used as a scheme within which it was possible to analyse how changing routes and traffic-signal control parameters affects delays and network utilisation. Comparison of the results of adaptive and static control showed the advantage of the adaptive approach under peak loads and reduced delays. In the prospects for further research, practical application of systematised approaches to developing transport models for specific urban networks was appropriate, as well as integration of new factors and technologies (intelligent transport systems, monitoring tools, decision-support systems) into the structure of transport systems.

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Conflict of Interest

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Методологічні засади формування імітаційної моделі управління дорожнім рухом із динамічним перерозподілом транспортних потоків

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Анотація. Метою дослідження було формування концептуальної моделі дворівневого управління дорожнім рухом у міських транспортних мережах. Методологія базувалась на структурно-функціональному аналізі та застосуванні багаторівневого підходу в управлінні транспортними потоками. Виявлено, що початковий етап формування імітаційної моделі передбачає формалізацію вулично-дорожньої мережі та вибір системи змінних для опису її стану в часі. Стан транспортного потоку задається показниками щільності, інтенсивності руху, середньої швидкості, довжини черг та часу очікування. У запропонованій постановці система управління дорожнім рухом має два рівні: маршрутизацію та локальне світлофорне керування. Динамічне призначення потоків розглядається як механізм коригування маршрутів для кожної origin-destination-пари та налаштування світлофорних фаз, тоді як локальне керування трактується як регулювання тривалості зелених сигналів і координація роботи світлофорів на перехрестях. Оптимальне керування орієнтоване на зменшення затримок і нерівномірності завантаження мережі з урахуванням заданих обмежень. Алгоритм керування, що поєднує локальне і мережеве регулювання, інтерпретується як підхід, орієнтований на покращення ефективності мережі, забезпечуючи оптимальне використання ресурсів при змінному попиті та поведінці водіїв. Запропонована архітектура дискретно-подійної імітаційної моделі для динамічного перерозподілу транспортних потоків базується на стохастичній динамічній системі з дискретним часом. Вона інтегрує два рівні управління: локальне керування світлофорами та мережеве керування маршрутами для origin-destination-пар. Модель задає підхід до адаптивного розподілу потоків на основі поточного стану мережі (черги, затримки, інтенсивність руху) і дає змогу досліджувати вплив змін маршрутів та параметрів світлофорного керування на затримки й завантаження мережі за умов стохастичних коливань попиту. Практична значимість полягає у можливості використання результатів органами місцевого самоврядування та дорожніми службами як методичної основи для проектування і реалізації імітаційних моделей міських транспортних систем

Ключові слова: динамічна система; адаптивні алгоритми; перехрестя; зміна фаз світлофора; оптимізація маршрутів; час затримки