

The formalization of the process of coordinating the operation of different modes of urban passenger transport based on a network-dynamic model

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Abstract. Problem. The quality of transport services for the urban population largely depends on the coordination of the operation of different modes of urban passenger transport (UPT) at transfer nodes and on common sections of the route network. As a result of excessive route duplication, uneven transport supply, and operational constraints in urban electric transport, disruptions in service regularity, rolling stock accumulation, and additional passenger time losses occur. **Goal.** The aim of this paper is to develop a formalized approach to the adaptive coordination of UPT operations across different modes based on a network-dynamic model. **Methodology.** The study combines a literature review of coordination in UPT, transfer node operation, service headway regularity, and synchronization models with the adaptation of the Kuramoto model of coupled oscillators to coordinate inter-route interactions in the UPT system. Each route is represented as a phase oscillator. The coupling matrix is constrained by the structure of the route network graph; that is, route interactions are considered only on common sections and at transfer nodes. **Results.** A network-dynamic model for coordinating the operation of different UPT modes is proposed. The Kuramoto order parameter is shown to be an indicator of the coordination component of transport service quality. The role of urban electric transport as a backbone oscillator with a fixed phase, relative to which the coordination of intermodal interaction of UPT is proposed to be carried out, is formalized. Three phase states of the system are distinguished: phase drift, chimera state, and phase locking. **Originality.** Unlike the classical Kuramoto model, the proposed approach accounts for the topological constraints of the route network via spatial-technological coupling and the specific features of intermodal coordination in UPT. It is substantiated that the target state of the system is not complete synchronization, but phase locking with regular service headways. **Practical value.** The model can be used to form an integrated system of adaptive dispatching control, allowing control actions to be differentiated by the system's current phase state, coordinating the arrival of rolling stock at transfer nodes, and reducing passenger time losses.

Keywords: urban passenger transport; intermodal interaction; coordination; Kuramoto model; order parameter; dispatching control; network-dynamic model; transfer node; backbone phase; urban electric transport.

Introduction and Analysis of publications

The urban population is determined by the ability of the transport system to ensure the coordinated, regular, and accessible operation of different modes of urban passenger transport (UPT) under conditions of variable demand and limited resources. In this context, technological

interaction among different UPT modes is a key factor in improving the quality of transport services, as it ensures coordination of traffic regimes, service headways, and the arrival times of rolling stock at transfer nodes. The consequences of uneven transport supply are most clearly manifested at transfer nodes, where

passenger flows are concentrated, and vehicles of different UPT modes and ownership forms interact. Under conditions of excessive route duplication, when several routes of different modes of UPT have common sections of movement and stopping points, the regularity of service headways is disrupted, the probability of simultaneous or closely timed vehicle arrivals increases, and the phenomenon of rolling stock accumulation (“bunching”) is formed [1], which causes passenger time losses, overloading of transfer nodes, and a decline in the quality of transport services.

Existing approaches to solving the problem of route operation coordination and the interaction of different modes of UPT can be divided into two main areas: static or tactical timetable optimization [2–5] and dynamic real-time traffic control [6, 7–9]. In addition, researchers have paid considerable attention to the problem of transfer coordination in public transport systems [10]. Transfer coordination at the tactical planning level primarily aims to increase connectivity within the route network, reduce passenger waiting time, and ensure more seamless trips. At the same time, the authors of the systematic review note that most of the approaches considered are focused on planned parameters of transport system operation: timetables, standard headways, predetermined transfer connections, and stable demand characteristics. This limits their application in a dynamic urban transport network, where actual vehicle movements often deviate from planned schedules, and interactions among different modes of transport require operational adjustments.

In [11], the main emphasis is placed on the organization of technological interaction in transport within transfer nodes, the concept of the functional stability of infrastructure facilities is substantiated, and slot coordination of the timetable and the permissible duration of vehicle stay at nodes are proposed. This approach ensures coordination through static planning of resource characteristics, but it does not account for the dynamic interactions among routes in real time. Further development of the problem of coordinating transport operations at transfer nodes is presented in [12], which focuses on timetable synchronization and the minimization of passenger transfer time. The analyzed approaches make an important contribution to the study of improving the quality of transport services; however, they do not fully take into account the conditions of simultaneous operation of different modes of urban passenger transport, the degree of route duplication, and the

accessibility of different modes of transport, as well as the need for operational adjustment of rolling stock interaction in real time.

Therefore, the synchronization of rolling stock arrival times should be considered not as an isolated task of transfer optimization, but as a component of a unified system for coordinating the operation of different modes of urban passenger transport, capable of adapting to real disturbances in the transport system.

The problem of route duplication is often analyzed separately from transfer synchronization, although in real urban networks these processes are interconnected [13–15].

To address UPT route duplication, the authors of [13] demonstrate that duplication can have both positive effects, such as increased coverage and reliability, and negative effects, including increased operating costs, network complexity, and inefficient resource use. For Ukrainian cities, this problem is of particular importance, since route duplication often arises not as a result of planned capacity redundancy, but as a consequence of the fragmented organization of transport services, the operation of transport service market participants with different forms of ownership, namely municipal and private carriers, and the absence of a centralized system for managing transport supply. Closely related to route duplication is the problem of its perception by passengers in the context of interactions among different transport modes in multimodal networks. The authors of [14] study passenger route-choice models and emphasize that route duplication affects not only the spatial characteristics of the transport network but also passenger behavior, the distribution of origin–destination flows, and the assessment of trip alternatives due to the added complexity of choice.

This indicates that excessive duplication cannot be assessed solely by the length of common sections or the number of routes. It should be related to traffic intensity, passenger demand, service headways, transport mode, and the quality of transfer connections.

In [15], the authors propose a combined bus scheduling approach that includes both all-stop and stop-skipping services. This approach allows for the consideration of passenger flow imbalances between stops and overlapping intervals. However, its application to urban electric transport is limited, since trolleybus routes offer less flexibility for route changes, skipped stops, or redistribution of operational work. Therefore, for the coordination of trolleybus and bus transport, a model is needed

that accounts not only for route duplication but also for the operational differences between the transport modes.

A separate research area is formed by real-time transfer synchronization models. The authors of [6] systematize operational control tools, including vehicle holding at a stopping point, speed regulation, stop skipping, short-turning, operational rescheduling, route changes, and boarding restriction. These methods are important for improving transfer reliability; however, they are primarily considered in the context of bus routes or transport networks operated by a single operator. For urban networks in which municipal buses and electric transport operate alongside buses of private carriers, this assumption is simplified, since different modes of transport have distinct operational constraints, levels of controllability, and economic motivations for operators.

The problem of operational traffic regulation is also considered in the study by the authors of [9], who proposed a holding model for UPT vehicles with short service headways that accounts for system dynamics. This approach has practical significance for stabilizing service headways and reducing bunching. At the same time, such operational control cannot always be directly applied across different modes of urban transport, since the control actions for trolleybuses, buses, and fixed-route taxis differ in terms of their technological and organizational nature. In addition, vehicle holding at a stopping point, by itself, does not solve the problem of excessive duplication of transport supply on common sections of the network, since this tool affects only the local coordination of arrival times.

Instead, overcoming the consequences of excessive route duplication requires adaptive coordination of service headways, distribution of transport work across modes, determination of the priority of backbone routes, and application of mechanisms to regulate carriers' participation in the transportation process.

One such mechanism is economic motivation and contractual relations. Under conditions in which private carriers are economically interested in maintaining passenger flow and high service frequency on profitable sections of routes, even if such supply duplicates municipal transport operations, contractual models of interaction between transport authorities and private operators may create a conflict of interest [16].

Therefore, an important aspect of coordinating the operation of different modes of UPT, in addition to technical or mathematical

algorithms, is a mechanism for aligning the interests of all participants in the service process through the introduction of a mechanism for compensating carriers for the transport work actually performed [17] and for ensuring carriers' compliance with contractual obligations regarding the established level of transport service quality and environmental standards.

The authors of [18] emphasize the need to determine compensation for the provision of socially important transport services in integrated passenger transport systems, thereby providing a methodological basis for including a compensation mechanism in the transport supply management system.

However, in most studies, the compensation mechanism is considered mainly a financial and organizational tool rather than a component of adaptive real-time coordination of transport operations, which complicates its use based on transport service quality indicators.

Therefore, it is relevant to address the issue of ensuring effective interaction among different modes of transport on routes by integrating adaptive models to coordinate UPT mode operations and a carrier compensation mechanism within contractual obligations, thereby developing an integrated adaptive system to coordinate UPT mode operations.

Purpose and Tasks

The purpose of this study is to develop a formalized approach to the adaptive coordination of the operation of different modes of urban passenger transport based on a network-dynamic model, with the aim of improving the quality of transport services for the urban population under conditions of excessive route duplication. To achieve this aim, it is necessary to analyze scientific approaches to the coordination of urban passenger transport and synchronization models; to adapt the Kuramoto model to the task of coordinating inter-route interaction; to formalize routes as phase oscillators; to substantiate the Kuramoto order parameter as an indicator of the coordination component of transport service quality; and to determine the phase states of the system.

Methodology for coordinating the operation of different modes of urban passenger transport based on a network-dynamic model

The integrated adaptive coordination system (IACS) for the operation of different UPT modes should be based on principles of self-regulation

and synchronization of vehicle arrivals at transfer nodes through operational responses to external disturbances, using current GPS data in a centralized dispatching system.

The formalization of coordination processes, especially in dynamic management tasks under conditions of excessive route duplication on common sections of the route network [11] and vehicle accumulation at transfer nodes [1, 19], requires a specific mathematical apparatus that makes it possible to simultaneously take into account the structural characteristics of the route network and the dynamics of temporal parameters of route operation. The mathematical apparatus of the theory of synchronization of coupled oscillators in complex networks [20], adapted in this study to the specifics of inter-route interactions at transfer nodes, is used to solve this task. This interaction involves temporal and spatial events, including the simultaneous or sequential presence of vehicles from different routes at common points along the route network. To provide a mathematical description of the adaptive coordination system, the study proposes integrating a dynamic approach based on the Kuramoto model with spectral analysis [21].

Based on the conducted analysis of publications, the parameters for assessing inter-route interaction can be grouped into three characteristic groups: structural parameters that characterize the spatial configuration of interaction, such as the number of routes passing through a transfer node and the number of route pairs with a significant intensity of transfer passenger flow; flow parameters that characterize the intensity of interaction during peak-load periods, such as the hourly intensity of transfer passenger flow between pairs of routes and the total hourly transfer passenger flow at the node; and temporal parameters that characterize the dynamics of interaction, such as headways between the arrivals of vehicles of different routes, actual service headways on routes, and their coefficients of variation.

The structure of inter-route interaction at a transfer node is formalized as a weighted undirected graph

$$G = (M, E, W), \quad (1)$$

where M – the set of vertices (routes passing through the transfer node), $M = \{1, 2, \dots, m\}$; E – the set of edges (pairs of routes $i-j$ with a significant intensity of transfer passenger flow), $E = \{(i, j) : i, j \in M, i \neq j, p_{ij} > 0\}$; W – the edge

weight function, determined by the intensity of transfer passenger flow between pairs of routes, $w(e) > 0$.

Unlike the traditional approach, in which the vertices of the graph are stopping points, and the edges are route sections, in the proposed model, the vertices are route oscillators, while the edges are pairs of routes interacting at the transfer node.

The proposed interpretation of the graph corresponds to the Kuramoto model [19], in which interactions between route oscillators are described, and the graph's structure determines the model's coupling matrix.

The inter-route interaction graph G should be algebraically represented by an adjacency matrix of size $m \times m$, the elements of which are defined as a normalized matrix of the total transfer passenger flow

$$A = [a_{ij}], a_{ij} = \frac{p_{ij} + p_{ji}}{p_{\max}}, a_{ii} = 0, \quad (2)$$

where p_{ij}, p_{ji} – transfer intensity between pairs of routes $i-j$, pass. per hour; p_{\max} – the maximum value of the total transfer passenger flow among all route pairs at the transfer node, pass. per hour.

Normalization of the matrix by the maximum value of the total transfer passenger flow ensures the range $a_{ij} \in [0; 1]$, which meets the requirements of the Kuramoto model with the standard coupling coefficient K . The need to transform the asymmetric matrix of transfer passenger flow data into a symmetric form is substantiated by the fact that the coordination effect between routes is realized regardless of the direction of transfers.

To assess the structural properties of the inter-route interaction graph, it is necessary to use the Laplacian matrix [21]

$$L = D - A, \quad (3)$$

where D – the diagonal matrix of vertex degrees of the graph $d_{ij} = \sum_j a_{ij}$.

The second smallest eigenvalue $\lambda_2(L)$ known as the spectral gap or the Fiedler value, characterizes the algebraic connectivity of the interaction graph, determines the system's ability to achieve phase locking [22], and serves as a criterion for the rate of coherence attainment in cases of strong coupling $K \geq 1$. The determination of algebraic connectivity λ_2 for a transfer node is carried out by numerically

computing the spectrum of the Laplacian matrix using standard linear algebra libraries, such as *NumPy* for *Python*, *MATLAB*, or *R*. According to synchronization theory and within the application of the Kuramoto-type model, a higher value of λ_2 indicates a high degree of system connectivity and its greater ability to reach a synchronous state under a fixed level of noise and dispersion of natural frequencies, whereas lower values correspond to partially coordinated or uncoordinated interaction.

Each i -th route ($i=1,2,\dots,m$) is modeled as a phase oscillator with its natural frequency ω_i , rad/s

$$\omega_i = \frac{2\pi}{h_i}, \quad (4)$$

where h_i – the scheduled service headway on the i -th route, min. For consistency of measurement units, minutes should be converted into seconds.

The time elapsed since the last arrival of a vehicle on the i -th route at the transfer node is converted to a phase angle within the range of the trigonometric circle $[0; 2\pi)$. Accordingly, the current phase of the i -th route is determined by the formula, rad/s

$$\theta_i(t) = \frac{2\pi(\Delta t_i)}{h_i(\bmod 2\pi)}, \quad \theta_i(t) \in (0; 2\pi], \quad (5)$$

where Δt_i – the time elapsed from the last arrival of a vehicle of the i -th route to the current moment, min.

The phase describes the vehicle's position on the i -th route in the current operating cycle and is automatically updated at the frequency of GPS data updates to the vehicle's current coordinates, namely every 30 s in the centralized dispatching system. If GPS data for the i -th route is not updated in the system within the specified time interval, its phase is extrapolated based on the vehicle's last recorded position on the route and the average travel speed along the section from the control point to the transfer node.

The proposed formalization of the current phase parameter builds on the general idea of representing periodic processes via a phase variable [19] and is consistent with the approach in [23], which uses bus arrival times at stopping points to describe the synchronization dynamics of routes.

When developing the model, it is proposed to coordinate the interaction around the electric transport route with the maximum intensity of transfer passenger flow as a backbone oscillator

with a fixed phase. Taking into account the operational constraints on the maneuverability of rolling stock, the trolleybus route is adopted as the reference phase of synchronization

$$\theta(t) = \omega_0 \cdot t + \varphi_0, \quad (6)$$

where $\theta(t)$ – the phase of the electric transport route (trolleybus route), rad/s; ω_0 – the own frequency of the trolleybus route, rad/s; φ_0 – the initial phase, rad/s.

The coordination effect is implemented by adjusting the phases of bus routes relative to the trolleybus phase $\theta(t)$. This approach fully corresponds to the priority of environmentally friendly electric transport within the modern concept of sustainable urban mobility and integrated urban development. This hierarchy fully corresponds to the idea of system synchronization in the presence of a leading oscillator. Under such a configuration, urban surface electric transport routes act as leading oscillators that, owing to their higher passenger capacity and movement stability, impose the target dynamic rhythm on the entire transfer node. The entire bus segment aligns with the electric transport timetable: high-capacity municipal buses provide synchronized support for main corridors, while the flexible phase trajectories of bus routes operated by private operators are aligned with the feeder network principle. This will enable more even distribution of resources, reduce vehicle accumulation at the transfer node, and minimize passenger transfer time.

The adaptation of the model consists of selecting the moment of arrival, specifically at the transfer node, as the phase reference point, which reflects the coordination task: the phases of routes of different transport modes are aligned with respect to their presence at the point of interaction of vehicles of different routes, where passenger transfers take place.

To describe the dynamics of inter-route interaction, it is proposed to use an extended classical Kuramoto model [19–23], adapted to the specifics of inter-route interaction at transfer nodes with a phase shift in the interaction function

$$\frac{d\theta(t)}{dt} = \omega_i + \frac{K}{m} \cdot \sum_j^m a_{ij} \times \left[\sin(\theta_j - \theta_i - \delta) \right] + \xi_i(t), \quad (7)$$

where δ – the phase shift parameter, which specifies the target phase difference between neighboring route oscillators in the phase-locking

state. For a transfer node with m routes, the optimal value of the phase shift $\delta = 2\pi / m$, rad/s, corresponds to the uniform distribution of route phases along the phase circle and ensures uniform time headways between vehicle arrivals at the transfer node; K – the coupling coefficient, which characterizes the strength of mutual influence between routes through the control actions of the dispatching system; $\xi_i(t)$ – random fluctuations that model variations in service headways and fluctuations in passenger flows, making it possible to take into account the real operating conditions of UPT.

Numerical integration is performed using the Euler method with a fixed step size \min , corresponding to the GPS data update frequency in the system.

The adaptation of the Kuramoto model consists in replacing the classical form, in which all oscillators are connected by a complete graph with equal weights, with a coupling matrix a_{ij} determined by the intensity of passenger flows between pairs of routes. This defines the network-dynamic type of the model, in which phase dynamics are constrained by the structure of the inter-route interaction graph constructed from empirical or simulated parameters of transfer passenger flows.

For graphs with a symmetric structure and a uniform distribution of frequencies, the critical value of the coupling coefficient is determined on the basis of the spectral characteristics of the graph [21]

$$K \approx \frac{2 \cdot \Delta\omega}{\lambda_2}, \quad (8)$$

where $\Delta\omega$ – the width of the range of natural frequencies of route oscillators, defined as the difference between the maximum (ω_{\max}) and minimum (ω_{\min}) frequencies of the routes at the transfer node.

The ability of the system to reach the state of synchronization, or phase locking, is determined by the relationship between the coupling coefficient K and the critical value of the coupling strength K_c . However, the operating mode of the UPT system is determined not only by the ratio of coupling strength but also by the controllability structure of the route network, which arises when a share of bus routes operated by private operators is not integrated into the centralized dispatching system. The combination of these two factors determines three qualitatively different states of the UPT system: the state of phase drift – when

$K < K_c$ the system is in a state of low coordination or absence of coordination; the chimera state [24], which is characterized by the corresponding ratio for the subset of controlled routes ($M_c \subset M$), which is characterized by the corresponding ratio for the subset of controlled routes, which includes municipal passenger transport routes, namely electric transport and high-capacity buses, as well as bus routes of private operators integrated with the centralized dispatching system through the GPS monitoring system, and $K \approx 0$ by another ratio for the subset of uncontrolled routes operated by private operators; and $K \geq K_c$, the state of phase locking, when the entire set of m routes forms a global dynamic structure with regular phase shifts between adjacent elements. In the mathematical description of this mode, a phase-shift parameter is introduced that specifies the target phase difference between neighboring route oscillators in the phase-locking state. This is the target state of adaptive control, characterized by a sharp increase in the order parameter [21]. Thus, the coupling strength determines the minimum level of coherence and control influence of the dispatching system at which stable stabilization of service headways is possible.

An increase in the spectral gap λ_2 reduces the required coupling strength K_c , thus, in strongly connected networks, synchronization is achieved with smaller dispatcher control actions. An increase in the frequency range $\Delta\omega$, on the contrary, raises the required coupling strength, since different degrees of route controllability according to scheduled service headways complicate their coordination.

Unlike the classical Kuramoto model with a fully connected topology, the matrix a_{ij} in the proposed adaptation of the model is determined by the structure of the transport network: inter-route interactions occur only on common sections and at transfer nodes. The degree of route synchronization is quantitatively assessed using the Kuramoto order parameter

$$R(t) = \frac{1}{M} \cdot \sum_j^M e_i^{\theta_j(t)}, \quad (9)$$

The order parameter $R(t)$ integrates three established aspects of the coordination component of transport service quality (service regularity, passenger waiting time, and the absence of vehicle accumulation at stopping points) into a single quantitative indicator with an analytically defined range of values $R(t) \in [0; 1]$. It is proposed to consider the order parameter $R(t)$ as an indicator of the

coordination component of transport service quality, characterizing the system's ability to form a coordinated operating mode across common sections of the route network and at transfer nodes. Unlike aggregated quality criteria based on passenger time-loss assessments, the parameter $R(t)$ directly describes the internal consistency of route-oscillator operation and enables detection of coordination disruptions before they manifest as passenger time losses while waiting at a transfer node.

Based on the formulated indicator for the coordination component of transport service quality, the objective function of the dispatching control loop of the IACS for different UPT modes is formalized. Its mathematical task is to minimize the deviation of the current state of system coherence from the optimal value R^* and to stably maintain the phase trajectory within the admissible region of the phase-locking state

$$\min_{v_i} \int_0^T (R_\delta(t) - R^*)^2 dt, \quad (10)$$

under the constraints of the system state space and operational constraints

$$\begin{cases} v_{\min} \leq v_i^*(t) \leq v_{\max} \\ R_{\min} \leq R_\delta(t) \leq R_{\max} \\ C(t) \leq N_{\max} \\ I_\Sigma(t) = \sum_{k \in M_{et}} I_k(t) \leq I_{\max} \end{cases} \quad (11)$$

where v_{\min}, v_{\max} – the maximum permissible speeds of specific modes of UPT on the route section from the control point to the transfer node, km per hour; T – the total simulation time, namely the duration of the calculation period for assessing the states of the UPT system, s; $C(t)$ – the actual number of vehicles simultaneously present at the stopping point, units; N_{\max} – the number of bays in the bus stop lay-by, units; $I_\Sigma(t)$ – the total load current on the feeder section of the overhead contact network, A; $I_k(t)$ – the current consumed by trolleybus k at time t , A; I_{\max} – the maximum permissible total current of the traction substation protection setting, A; $I_{\max} \approx 800 - 1200$ A at the nominal network voltage of 600 V.

It should be noted that, when solving the

problem of UPT coordination, the tendency of the classical Kuramoto order parameter toward unity ($R \rightarrow 1$) is a critically inadmissible condition. This means complete synchronization and complete “merging” of phases, leading to the accumulation of vehicles at the transfer node and along common sections of routes, known as the bunching effect.

In order to prevent phase “merging” and ensure stable clock-based separation of trips, the target mode of adaptive control for a system with mmm routes is assessed using the modified order parameter $R(t)$, adapted to a fixed shift step (5).

The proposed network-dynamic model for coordinating the operation of different modes of UPT has the following limitations: 1) the model does not take into account unplanned closures of route sections and road traffic accidents as random external disturbances; 2) the model is intended to be applied under peak-load conditions; its application during the off-peak period is a subject of further research; 3) the model assumes the possibility of controlling the phases of bus routes through the dispatching system, provided that a “dispatcher–driver” communication channel is available; in the absence of such a communication channel, in particular for private operators not integrated into the centralized dispatching system, the corresponding routes are modelled as uncontrolled oscillators, which forms the conditions for the emergence of the chimera state described in the study.

Promising directions for further research include: conducting experimental studies to substantiate the boundaries of admissible regions of the order parameter $R(t)$ values using the developed model for different states of the UPT system and different types of inter-route connections at a transfer node; developing a control algorithm for the integrated adaptive system for coordinating the operation of different modes of transport according to the criterion of the order parameter $R(t)$ as the boundary of the passenger-acceptable level of coordination of the UPT system, below which the parameter value will indicate deterioration of the coordination component of quality and may be interpreted as an indicator of an increased risk of passengers refusing to use public transport services [1]. Solving these tasks will enable the dispatching control loop to differentiate its control actions based on whether the system's current phase state lies within the defined regions.

Conclusions

An approach to coordinating the operation of different modes of urban passenger transport under conditions of excessive route duplication on common sections of the route network and at transfer nodes has been substantiated. The proposed network-dynamic model is an adaptation of the classical Kuramoto model for route coordination, in which each route is represented as a phase oscillator and interactions between routes are constrained by the route network graph. This allows consideration not only of the temporal consistency of rolling stock arrivals but also of the spatial structure of route interactions at common points in the transport network.

The Kuramoto order parameter is proposed as an indicator of the coordination component of transport service quality, characterizing the level of consistency in system operation. The model proposes that urban electric transport serves as a backbone oscillator with a fixed phase, relative to which adaptive coordination of bus routes and fixed-route taxis can be carried out, while accounting for the operational constraints of electric transport.

The classification of phase states of coupled oscillators has been adopted to coordinate the operation of urban passenger transport, and three states have been distinguished: phase drift, chimera state, and phase locking. It is substantiated that the target state of the system is not complete synchronization, but phase locking, which ensures regular service headways, coordinated arrivals at transfer nodes, reduced passenger time losses, and improved transport service quality. The objective function of the dispatching control loop of the UPT coordination system has been formalized, enabling differentiation of control actions based on the system's current phase state and directing its dynamics toward the phase-locking region.

Conflict of interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Формалізація процесу координації роботи різних видів міського пасажирського транспорту на основі мережево-динамічної моделі

Анотація. Проблема. Якість транспортного обслуговування населення міст значною мірою залежить від узгодженості роботи різних видів міського пасажирського транспорту (МПТ) у пересадочних вузлах і на спільних ділянках маршрутної мережі. Наслідками надмірного дублювання маршрутів, нерівномірності транспортної пропозиції та експлуатаційних обмежень міського електротранспорту виникають порушення регулярності руху, скупчення рухомого складу й додаткові часові втрати пасажирів. **Мета.** Розробка формалізованого підходу до адаптивної координації роботи різних видів МПТ на основі мережево-динамічної моделі. **Методологія.** Методологічною основою дослідження є адаптація моделі Курамото зв'язаних осциляторів до задачі координації міжмаршрутної взаємодії у системі МПТ. Кожен маршрут представлено як фазовий осцилятор, фаза якого визначається моментами прибуття транспортних засобів до спільних точок мережі. Матрицю зв'язку обмежено структурою графа маршрутної мережі. **Результати.** Запропоновано мережево-динамічну модель координації роботи різних видів МПТ. Параметр порядку Курамото обґрунтовано як індикатор координаційної складової якості транспортного обслуговування. Формалізовано роль міського електротранспорту як опорного осцилятора з фіксованою фазою, відносно якого запропоновано здійснювати координацію міжвидової взаємодії МПТ. Виокремлено три фазові стани системи: фазовий

дрейф, стан химери та фазове захоплення. **Оригінальність.** На відміну від класичної моделі Курамото, запропонований підхід враховує топологічні обмеження маршрутної мережі через просторово-технологічний зв'язок та специфіку міжвидової координації МПТ. Обґрунтовано, що цільовим станом системи є не повна синхронізація, а фазове захоплення з регулярними інтервалами руху. **Практичне значення.** Модель може бути використана для формування інтегрованої системи адаптивного диспетчерського управління, що дозволить диференціювати керуючі впливи залежно від поточного фазового стану системи, узгоджувати прибуття рухомого складу до пересадочних вузлів і зменшувати часові втрати пасажирів.

Ключові слова: міський пасажирський транспорт; міжвидова взаємодія; координація; модель Курамото; параметр порядку; диспетчерське управління; мережево-динамічна модель; пересадочний вузол; опорна фаза, міський електротранспорт

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