Implementation of the mathematical model of interaction of passenger transport modes for sustainable economic development

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Abstract. As part of a research, the study of the level of solving the scientific problem of transport flow management in large cities was carried out as a component of the integrated information-intelligent transport system of the city. A significant amount of research on a number of important components of the problem has been identified, including the application of new approaches, methods and information technologies for planning and forecasting traffic flows, optimization of bimodal urban networks. The software implementation of a mathematical model to optimize the interaction of urban passenger transport, passenger transfer points and urban trains in major transportation hubs in terms of sustainable development and digitalization was proposed. A toolkit for the integrated interaction of city train, urban passenger transport and passenger transfer points in major cities has been implemented. As a result of the study, a high level of versatility of the proposed model and the possibility of its active practical application was determined.
Keywords: Queue, Vehicle, Transport Flow Management, Information-Intelligent Transport System, City Network.

1 Introduction

Urban networks are becoming more complex, cities are expanding, and the number of vehicles is increasing, which certainly requires new approaches to solving the congestion issue. There is also the problem of interaction between urban modes of transport and mainline transport, mainly aviation, in providing transport mobility of the population over long distances. Ensuring the creation and implementation of an integrated urban information-intelligent system is impossible without a quality content of the traffic management system cluster.

The complexity of urban logistics is due, among other things, to the need to ensure the interaction of a large number of participants and the diversity of their interests. To a large extent, these interests contradict each other, and therefore a compromise must be found to satisfy all stakeholders. In addition, there are significant issues in the separation of freight and passenger flows in cities, which will create an opportunity for better management. On the one hand, the passenger flow in the city should be transported as effectively as possible, taking into account the orientation of the passenger clientele towards certain key parameters, in particular, speed, price, comfort, and on the other hand, it should not impede the effective development of the city, its environment, development plan, etc. This is the balance of interests of society, the city, passenger carriers and other participants in the process of passenger service in the city.

It should be noted that urban logistics varies significantly from city to city across the globe. Undoubtedly, the best practices for implementing urban innovations are implemented in developed countries. The positive experience of the United States, the United Kingdom, France, Germany, Japan, South Korea, Norway, Sweden, Italy, Denmark, and China is particularly noteworthy.

In general, sustainable economic development of a city is now defined as one of the key aspects of its overall success. Of course, there are many examples of the fastest possible global implementation of revolutionary innovations in cities, but this is rather an exception to the general rule, and most cities in the world are focused on progressive development within the framework of the sustainable development concept.

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2 Literature review and defining the problem

The study of the transport system sustainability of cities by Zope et al. [1] highlighted the need for constant analysis of the macro-level transport system with subsequent monitoring of changes in the micro-level system. An attempt to benchmark the urban transport system was made, showing that cities with the large modal share of the sustainable regime have a higher index of transport sustainability. The relative significance of each indicator in the overall stability of the city transport system using the system of monitoring and modelling of index values was detailed.

Zhang et al. dealt with the problem of assessing the priority indicators of urban transport and noted the exceptional priority effectiveness of urban passenger transport for congestion mitigation [2]. The application of the structural entropy model TOPSIS allowed to ensure the priority of public transport in Wuhan, China from bad to excellent in 10 analyzed years (from 2006 to 2015). It should be agreed with the authors that, despite significant advances in practice, the indicators of infrastructure efficiency, the level of public transport services and policy support need to be further improved.

To ensure sustainable and energy efficient urban transport the priority of policies and measures is essential as noted by Letnik et al. [3]. The authors implemented a methodology for comprehensive mapping and comparative analysis of strategic policy documents and measures in more than 100 European cities. It revealed the heterogeneity of transport-logistics policy, mobility and accessibility planning. It is clear that the problem identified by the authors in this study is insufficiently studied and requires, in particular, further development and implementation of comprehensive mechanisms to ensure transport mobility and accessibility.

The task of ensuring the last mile delivery is becoming extremely important to reduce congestion in cities. A mathematical model for calculating the cost of transporting the last mile in the supply chain with small and fragmented volumes was proposed by Kin et al. [4]. Active use of such tools by logistics operators will significantly reduce congestion in cities and remove heavy vehicles from city streets.

Problems of transport modelling were considered in particular by Antonova et al. [5; 6], Yakushenko [7] and Shevchuk [8].

Therefore, all this suggests that there is a practical need to set the task of creating applied mathematical tools for the interaction of passenger modes of transport in terms of sustainable economic development, taking into account the modern processes of digitalization. The software implementation of the proposed mathematical model should also be provided.

The choice of research methods is due to the processes taking place in the transport and logistics systems of major cities, as well as countries as a whole. In the framework of the study, when solving the problems, the authors found that the set of selected methods provides a generalization and clarification of transport and logistics processes of interaction of passenger modes of transport in terms of sustainable economic development, as well as the credibility of the conclusions made. In the study, an attempt to systematize the basic approaches and principles to the origin and features of the development of urban transport flows is made. Scientific literature was thoroughly researched, methods of scientific observation, probability theory and mathematical statistics, systematization, comparison, expert estimates, correlation-regression analysis, deduction, synthesis, trend estimation, etc. were used. Thus, it determines the relevance of the study.

Diao noted the extremely acute problems for large cities of business centres on the example of Singapore, namely a significant shortage of land resources, the dynamics of economic growth and population density [9]. Based on official statistics, the impact of transport policy on the mobility model of Singapore residents has been assessed. The author emphasized the extremely successful experience and appropriateness of focusing on three key areas of transport policy evolution: reasonableness, inclusiveness and environmental friendliness. Singapore's successful and best practices should definitely be adopted by other cities around the world.

A set of criteria for the organizers of the urban transport system was developed by Oviedo Hernandez and Dávila [10], which can help identify sound principles of transport provision and practice for socially vulnerable groups of the population in satellite cities of large ones. The importance of this issue is due to the inability to provide the necessary transport access to the work place from the place of residence in conditions of limited financial resources of the country.

Emerson et al. investigated an extremely interesting aspect of the problem concerning the regimes of doing business in the public transport organization [11]. In particular, the existing regimes are compared with the regime of community franchise with individual property on the line of urban public transport. The benefits of using mixed regimes and the community franchise regime allows to achieve additional flexibility. Such positive practices, after detailed calculations, should be widely implemented on the principles of public-private partnership.

The application of the macroscopic fundamental diagram allows to control the traffic flow in cities with inhomogeneous congestion on the perimeter in order to control congestion as was determined by Aalipour et al. [12]. The sliding mode control and linear quadratic regulator as types of system controllers were proposed. Performance evaluation was carried out by simulation. It is worth noting that the authors conducted a large original study and achieved relevant results that should be used in the development of an integrated transport system of the city.

In order to analyze the flow of urban transport in relation to different modes, the optimization of the network measurement system which takes into account the topological characteristics and geometric properties of the road network was proposed by Zhao et al. [13]. This study provided a better understanding of the urban transport flow by different modes in terms of complex networks. Due to the importance of the presented results, they should be used to solve relevant issues in the perspective.

As was noted by Wen et al. [14], a ranking algorithm to study traffic requirements, taking into account the attractiveness of street segments and the complexity of traffic flow based on probability, can be applied. In practical calculations, the authors identified the most congested segments of the city and identified their characteristics. These developments can be used to further understand the distribution of congestion.

Yang et al. outlined that comprehensive transport infrastructure planning can give a systematic look at the urban transport problems [15]. Transport infrastructure, public space and behavioural factors, integration of urban design and computer modelling are necessary elements of integrated planning. The value of this study lies in its systematic nature, which aims to provide an integrated set of tools for designers and developers of projects and models, as well as decision makers.

Richter et al. conducted the study of integrated urban development taking into account the new intelligent transport systems [16]. The authors attempted to implement solutions for rapid adaptation and use of modern technologies and methodologies for urban modelling. In order to meet the requirements of various stakeholders in the representation of roads and road infrastructure, the authors proposed a kind of compromise management system.

Mastalerz et al. defined the urban transport system as a complex formation with numerous elements characterized by the nonlinear nature of the main transport processes [17]. A method of selection and substantiation of various alternatives in the transport system development through the use of a mathematical model formed by a digital model of city street and road network and public transport routes, a system of nonlinear dynamic models of transport and economic system of the region, as well as special tools for forecasting and processing, were offered.

Digital technologies are significantly transforming the transport and logistics system, and may also have different effects on energy consumption and the environment as was highlighted by Noussan and Tagliapietra [18]. One must agree with the authors in their emphasis on the development of "responsible" digitalization as part of the implementation of the EU policy on joint mobility. Creutzig et al. noted the inseparability of digitalization and public policy as a successful symbiosis of sustainable urban transport [19]. Serious threats to environmental sustainability in the implementation of these processes are also identified. As was determined by Pernestål et al., digitalization has the potential to change the business ecosystem of transport, providing the opportunity to increase flows with the same initial input data [20].

Davidsson et al. proposed an interesting study examining the fourth wave of digitalization in relation to urban modes of transport and their role in supporting sustainable development [21]. One should agree with the approach of the authors regarding the gradation of opportunities for the participants of urban transport and logistics markets – operators, organizers, passengers, as well as in the highlighting importance of automation, digitalization, as important factors in improving effectiveness. Singh et al. devoted the study to the introduction of digital technologies on roads [22]. It was pointed out that digitalization provides a wide range of opportunities for road users to improve reliability and intelligence. The most interesting of the components proposed by the authors is the traffic management system, in particular using the forecasting traffic flow models.

The development of intelligent transport systems of cities is multidirectional and a large number of participants of transport and logistics markets are interested in. One should agree with the concept of applying an integrated intelligent city system through simulation modelling and application noted by Richter et al. [16].

The increasing complexity of transport planning has led to the emergence of the transport coordinator. Lechtenberg and Hellingrath pointed out that there is a dramatic increase in the number of orders in e-commerce, so there is a need for reactive planning, which led to the digitalization of the process and the implementation of platform-oriented business models [23]. Various transport problems are studied in [24-28].

Consequently, as a result of the implementation of the methodological basis of the study, it is necessary to note the correctness of the choice of the initially defined methods and move on to the solution of the set tasks.

3 Research aim and objectives

A mathematical model of interaction of passenger transport modes for sustainable economic development should become one of the effective tools, and therefore this research is devoted to solving this problem, which determines its purpose.

To achieve this goal, a number of scientific tasks have been solved: the conceptual foundations of the integrated information-intelligent transport system of the city have been developed, its scheme has been implemented; a mathematical model for optimising the interaction of the system of urban passenger transport, passenger transfer points and urban train in large transport hubs has been formalised; the essence and conditions of the model and constraints have been characterised;

The optimal ratio of urban passenger transport and urban train for different scenarios of optimisation of interaction of urban passenger transport system, passenger transfer points and city train in Kyiv, Ukraine was analyzed. The practical importance of the proposed mathematical model and the possibility of its use to determine the optimal interaction of urban passenger transport, passenger transfer points and city train system in major cities of Ukraine and other countries were confirmed.

4 Overview key findings

The digitalization of the world economy is becoming more widespread. The gaps between developed and developing countries are deepening. The COVID-19 pandemic has given a significant impetus to the development of information systems, which has led to a drastic reduction in the transport mobility of the population and the desire for satisfaction due to the consumption of more goods and services. All this led to transport collapses on certain modes of transport, especially the maritime transport, which proved unprepared for such a radical change in consumer orientations and the resulting imbalance of cargo flows.

At the same time, the example of Turkey shows that it is possible to successfully promote innovations in the transport and logistics sector in a rapidly developing economy. Moreover, revolutionary projects related to both passenger and freight traffic can be observed. It was obviously the right decision to create logistics hubs with a key centre at the new Istanbul airport, develop a system for the production of aircraft spare parts, implement maritime transport projects, expand railway connections, and continue gas and oil pipeline construction projects. The compromise here is the reorientation of the country's resources from consumption to production, infrastructure development and transport provision. Time will tell whether such steps are appropriate or not, but it is already clear that Turkey is becoming a key player in transport and logistics between Europe and Asia, which opens up enormous opportunities for the economy.

Urban development should obviously be based on the successful transport and logistics practices of other countries, but it should be remembered that integration into the transport and logistics sector of any country is a crucial factor for successful development. There are sometimes exceptions to this rule, and they occur when a country focuses on the successful development of one or more major cities. This is most common in developing countries. To a certain extent, this rule can be seen in the example of China, which invests incomparably more in the successful development of key cities such as Shanghai, Beijing, Tianjin, Shenzhen, while Aksu, Urumqi, and Hami are clearly lagging behind in terms of transport and logistics.

The implementation of the integrated information-intelligent transport system of the city should be based on the modelling of its transport flow. This modelling should include both theoretical assumptions and developments formed by designing new effective algorithms for solving problems, making statements, developing new and improving existing methods, proving theorems, and practical implementation of specific problems using modern information systems.

In general, the problem of creating an integrated information-intelligent transport system of the city is extremely complex and approaches to its solution can differ significantly. It does not mean that some approaches are initially correct and other ones are initially incorrect, just the complexity of the problem involves a variety of approaches to solving it. The complexity of solving this issue requires a step-by-step solution of its individual components.

Moreover, the successful solution of these components of problems is possible only after their theoretical development. It is also very important to consider the importance of adequate implementation of such innovations in the conditions of sustainable development of the city and the country's economy as a whole. The implementation of modern information systems in urban logistics should become an integral part of the overall policy of digitalization of the city and country. It is obvious that such projects cannot be of a purely commercial nature and must be components of the social development of the city in terms of transport mobility and accessibility for its residents.

Traffic management was identified as an important component of solving the general problem of creating an integrated information-intelligent transport system of the city. Some theoretical components of traffic management have been studied. However, this task is just one of the most urgent, by far not the sole one. Nevertheless, such alternative solutions must also be part of the integrated development of urban logistics, which means that the interaction of city trains, urban passenger transport, and passenger transfer points in major transport hubs should be systemic in nature.

Such a systemic effect can be achieved by using the appropriate mathematical apparatus. It should also be said that the problem of interaction between passenger transport modes has been successfully solved in most major cities of the world's leading countries, but it often uses expensive in financial terms technologies and solutions. A striking example is the use of hybrid modes of urban transport, that is, the rolling stock of which can be transformed, even while moving along the route.

The cost of such vehicles is several times higher than the cost of similar vehicles for one mode of transport, not to mention the fact that such vehicles for one mode of transport themselves are much more expensive than those used in cities in less wealthy countries. That is, a theoretical justification and mathematical apparatus for solving the problem of interaction of passenger modes of transport just for cities that are located in countries with low or middle-income levels is proposed.

The results of studying the features of transport flows in large cities must be taken into account when determining the loading of vehicles of urban passenger transport and the duration of passenger transportation to their destinations.

The mathematical model for optimizing the interaction of the system of urban passenger transport, passenger transfer points and city train in large transportation hubs will look as follows:

$$\begin{cases} F_{ct} = Nl \cdot e_{train-km} + At \cdot e_{pass-h} \to \min, \\ F_{UPT} = \sum_{i=1}^{n} e_{km}^{i} \cdot \sum_{j=1}^{m} L_{tot}^{j} + e_{pass-h} \cdot \sum_{j=1}^{n} A_j \cdot t_j \to \min, \end{cases} \quad (1)$$

where Nl – total train-kilometres run for the period in one direction, train-km; $e_{train\text{-}km}$ – rate per train-km, UAH; At – total passenger-hours of waiting time, pass-hours; $e_{pass\text{-}h}$ – rate for passenger-hours of waiting for a city train; i – mode of urban passenger transport (i=1,2, 3, … , n); j – particular vehicle of a certain mode of urban passenger transport (j=1,2, 3,… , m); L_{tot} – total distance run of a particular mode of urban passenger transport; e_{km}^{i} – cost per kilometre of a particular mode of urban passenger transport; e_{pass-h}^{i} – the cost of one pass-hour of waiting for urban passenger transport.

After transformations this mathematical model will be as follows:

$$F_{tot} = Nl \cdot e_{pass-km} + e_{pass-h}\left(\sum_{i=1}^{d} A_i t_i + \sum_{j=1}^{n} A_j t_j\right) + \\ + \sum_{i=1}^{n} e_{km}^{i} \cdot \sum_{j=1}^{m} L_{tot}^{j} \to \min, \quad (2)$$

The following restrictions will apply:

$$n_{eCT}^{s} \geq a_{pass}^{i\ UPT}, i = 1...m \quad (3)$$

$$\sum_{i=1}^{m} n_{eUPT}^{s} \geq A_{CT}, \quad (4)$$

$$\sum_{i=1}^{m} a_{pass}^{UPT} \leq a, \quad (5)$$

where n_{eCT}^{s} – number of empty seats in the city train; a_{CT}^{iUPT} – capacity of urban passenger transport; n_{eUPT}^{s} – number of empty seats in urban passenger transport; A_{CT} – capacity of the city train; a – occupied seats of the city train.

Consequently, the essence of conditions (1) is that the high level of interaction of all modes of urban passenger transport in a particular passenger transfer point will be provided when there is a balance of available free seats in the vehicle and the actual number of passengers transferring from one mode of urban passenger transport to the vehicle of another mode. However, ideally, due to the real complexities in the functioning of intracity passenger transportation system, achieving conditions (1) is quite difficult, because a number of restrictions (3)-(5) apply.

To better illustrate the role of the mathematical modelling the interaction of the system of urban passenger transport, passenger transfer points and city train, the scheme of the integrated information-intelligent transport system of the city was offered (Figure 1).

The optimal ratio of urban passenger transport and city train for different scenarios of optimizing the interaction of urban passenger transport system, passenger transfer points and city train in Kyiv, Ukraine was analyzed. All this confirmed the practical importance of the proposed mathematical model and the possibility of its use to determine the optimal interaction of urban passenger transport, passenger transfer points and city train system in major cities of Ukraine and other countries. The degree of versatility of the proposed model is also determined by the possibility of its adaptation to a wide range of practical tasks related to the interaction of passenger transport in cities with different levels of development, varying sizes and other operating conditions.

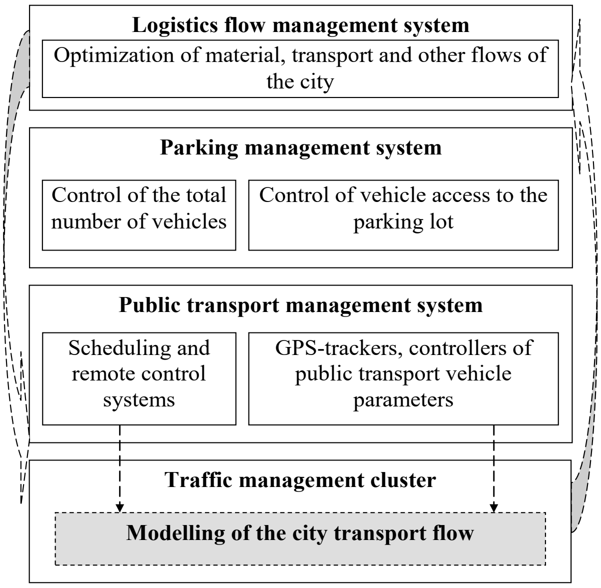

Fig. 1: Scheme of the integrated information-intelligent transport system of the city

5 Conclusions

The need to create an applied mathematical toolkit of interaction of passenger modes of transport in terms of sustainable economic development, taking into account the modern processes of digitalization, as well as software implementation of these innovations was determined. The methods of scientific observation, probability theory and mathematical statistics, systematization, comparison, expert estimates, correlation-regression analysis, deduction, synthesis, trend estimation, etc. were used, which in aggregate provided a systematic study of the processes of the interaction of passenger transport modes in the conditions of sustainable economic development and the reliability of the conclusions drawn.

It was determined that the implementation of an integrated urban information-intelligent transport system should be based on the modelling of its transport flows, including the provision of interaction between urban transport modes in terms of sustainable development of the city and national economy in general. The proposed toolkit should reflect the principles of compromise management of transport mobility of the population and economic principles in operation of transport enterprises and the city.

The proposed mathematical model of interaction between passenger transport modes should become part of the integrated development of urban logistics. Moreover, a toolkit of interaction between city train, urban passenger transport and passenger transfer points in large transport hubs was offered. The scientific novelty of the proposed model is determined by the fact that a high level of interaction between all modes of urban passenger transport at a particular passenger transfer point will be provided when there is a balance between the available free seats in the vehicle and the actual number of passengers transferring from one mode of urban passenger transport to the vehicle of another type of transport. The optimum parameters of interaction of passenger transport modes in Kyiv were analyzed. Also universality of the offered model and possibility of its practical application for calculation of similar interaction for large cities of Ukraine and other countries were determined.

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