https://doi.org/10.33271/nvngu/2022-1/158

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AUTOMATION OF THE COORDINATED ROAD TRAFFIC CONTROL PROCESS

Purpose. To increase output of traffic network while deriving new dependencies of transport flow characteristics upon control law parameters and using them to develop an algorithm to automate a process of the transport flow coordinated regulation within towns and cities.

Methodology. The aggregated simulation model, describing processes of road traffic formation within a local section of urban traffic system, is used for the analysis of dependencies to assess quality of transport flow control upon correcting conditions being parameters of traffic cycles within intersections. The abovementioned should involve a PID controller as well as a negative feedback idea to automate control of the road traffic process. In this context, control criterion is applied to determine critical flow intensity if a traffic jam occurs. The criterion makes it possible to identify changes in the road traffic nature. To determine the optimal settings of the PID controller for different stocks of the stability control system, the standard deviation of the controlled variable from the set value and the mean static control error are defined.

The derived dependencies of control quality criteria upon a law of flow regulation have helped develop a new algorithm of the coordinated automated road traffic control within a local section of urban traffic section using standard control action. Simulation experiments made it possible to assess efficiency of the proposed algorithm of control compared with available ones applied in terms of different road conditions.

Findings. As a part of the studies, algorithm of the coordinated automated road traffic has been developed. It helps support maximum output of road systems while monitoring changes in the traffic environment characteristics.

Originality. For the first time, dependencies of assessment criteria of traffic flow control upon the parameters of a law of flow intensity regulation have been identified if maximum output of road systems is provided. The dependencies have helped substantiate optimum control criteria for different road conditions while automating a process of coordinated traffic flow regulation within local section of urban traffic network.

Practical value. The proposed dependencies of assessment criteria of traffic flow control upon the parameters of a law of flow intensity regulation as well as the algorithm of automated coordinated control are the theoretical foundations to solve such an important applied scientific problem as automation of a process of urban traffic flow regulation.

Keywords: *traffic flows*, *coordinated control, simulation modeling*

Introduction. Poor traffic capacity is the problem being common for all cities; especially, it concerns their central areas [1]. The fact can be explained by the following: the current road urban infrastructure was developed in a long time for traffic flows [2] which were less intensive to compare with the present ones. The World Bank has published a forecast according to which the number of vehicles will double up to the year of 2050; thus, their quantity will move beyond 2 billion ones. In addition, it is expected that future population growth will change traffic conditions of metropolitan cities for the worse [3]. The problem needs its comprehensive solution being both adaptation to the significant traffic environment and pedestrian flows of street and road infrastructure (i.e. road widening, construction of multi-level road junctions, interchanges [4] and so on), and implementation of smart coordinated management of urban traffic flows [5]. The latter involves analysis of traffic streams in terms of all their urban routes to form the unified control strategy. It should be mentioned that the strategy development is among the mandatory functions of such intelligent systems as a 'Smart City' [6]. Currently, the problem is topical and remains unsolved.

Unsolved problem. According to the 'Smart City' concept, modern intellectual systems to manage road traffic involve complex multilevel structure with numerous spatially distributed elements and significant degree of centralization [7, 8]. Hence, on-line processing of data concerning traffic situation in a city as well as its control formation based on it needs both rapid and reliable (and thus expensive) information transmission channels. Moreover, increase in the area of sections of urban traffic scheme within which traffic flows are controlled in the coordinated manner factors into substantial growth in data to be analyzed in real time. The abovementioned influences negatively both efficiency of the data processing algorithms and formation of the strategy to control the road traffic.

Decentralized management system is alternative to the intellectual systems of traffic control with a high centralization degree [9, 10]. The system consists of an aggregate of relatively independent local networks controlling traffic flows within small areas of urban traffic scheme. In the context of certain road conditions, such local networks may use simple algorithms of automated control of basic parameters of traffic flows commonly applied for controllers at a lower level of the automated control systems. Moreover, development and maintenance of such a decentralized system are cheaper since its step-by-step implementation is possible. Hence, a fewer number of hardware resources as well as data ones are required for functioning.

Literature review. Traffic jams exert downward pressure on travel time, fuel consumption, and environment. Despite the responsiveness, the tailored solutions are developed and implemented (the strategies depend upon housing density and features of the built environment), activities in the field are in constant progress. However, up to now no universal approach to be applied for any agglomeration has been devised.

Paper [11] confirms that UAVs (drones) will be essential for the development of urban traffic networks from the viewpoint

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of traffic safety and monitoring as well as from the viewpoint of road infrastructure control. Papamichail, et al. [12] represented a set of new challenges and associated developments concerning simulation, evaluation, and traffic management in the highways. Nevertheless, the majority of the authors adhere to classical ideas as for the problem solving and consider procedures of the centralized approach and decentralized approach to control traffic within the urban networks. Paper [7] deals with an approach in terms of which the centralized system of traffic control calculates routes of each vehicle. Routing is analyzed basing upon the shortest way within a time-dependent static network, and influence of traffic rerouting procedure on the total way time. Grüner and co-workers [8] believe that optimum road network distribution is that very promising approach to prevent traffic jams. The abovementioned can be computed with the help of the centralized system of traffic management and formulated in the form of routing recommendations. To define optimum vehicle routes in Birmingham (Great Britain) and Turin (Italy), paper [13] proposes a new dynamic simulation-based centralized approach with the use of a cost function. The following has been selected as the criteria: average traffic speed; vehicle density; road width and length; and availability of traffic light regulation. Using a system of optimal control, based on kinematic wave model by Hamilton-Jakobi, study [14] develops and analyzes traffic control procedures in London (Great Britain). Test scenarios rely upon actual road conditions. Specific attention is paid to compare efficiency increase and computational efforts of two strategies (i. e. centralized and decentralized) under different conditions.

Paper [15] considers the decentralized approach, being an alternative for the centralized one, in terms of which certain crossings are able to shape asynchronously their own control policies. The authors prove that the abovementioned helps improve and stabilize the whole control system even if congestion takes place. The above is the substantial advance in the process of adaptive control system development with the use of the decentralized optimization methods. Study [15] is the most important among those ones keeping off the connected cars [16] and distributing to adaptive control of network traffic with uncertainty using the advanced simulation and optimization techniques. Study [17] represents the decentralized system to control traffic; it incorporates dynamic traffic routing and traffic control at the crossroads without traffic lights for the connected vehicles. Thorough research by Yao and Li [18] proves that the decentralized control system, requiring less technical maturity and infrastructural investment, may be more advantageous to compare with the centralized one in the context of critical and congested traffic. Wang, et al. [19] provide incentive-based strategy of the decentralized routing. Moreover, they think it helps bring the network efficiency closer to a system optimum. Sun and Yin, authors of paper [20], substantiate theoretically and numerically that the decentralized system may be flexible and scaled; in addition, it may be implemented in real time.

Hence, an approach to develop the decentralized traffic control was selected in the research as a basic one.

Unsolved aspects of the problem. Paper [21] has laid the foundations for the automated coordinated control of traffic flows within a local section of an urban traffic network. However, lack of an integrating component in the control algorithm, proposed by [21], results in nonavailability of a mechanism of the static error compensation in terms of control. It is particularly significant if complex perturbing effects (i. e. changes in characteristics of external traffic flows or road networks themselves) vary a dependence of traffic flow intensity upon the basic control influence (i. e. the number of vehicles passing through along the major routes per unit of time). Hence, it is impossible for the control algorithm to involve the assigned certain constant value of a control signal which will always have corresponding critical value of traffic flow intensity.

We support the idea by means of a simulation model of a traffic network described in [21]. The model makes it possible to monitor the basic characteristics of traffic flows in real time taking into consideration the parameters of road networks influencing capacity of the routes. Input data of the model correspond to actual characteristics of traffic flows as well as parameters of highway networks in the city of Almaty (Kazakhstan).

Disadvantage of the algorithm proposed by [21] is as follows. Intensity of the major traffic, being critical from the viewpoint of jams, is assumed as an invariable value.

What actually happens is that it depends upon road conditions being variables (i. e. characteristics of traffic flows during rush hours and capacity of the main route). Fig. 1 demonstrates traffic flow dynamics calculated with the help of the algorithm, proposed by [21]. The dynamics involves other road conditions, i. e. when critical intensity of the flow is 1.5 unit/s.

Fig. 1 explains that the system of the automated coordinated control of a traffic flow cannot support the specified intensity at 1.5 unit/s level. First of all, it depends upon the fact that changes in road conditions vary *critical traffic flow intensity-the system stimulus* dependence (i. e. the number of vehicles passing through along the major route per unit of time).

In this respect, a new approach is proposed as for the development of an algorithm of the coordinated control of traffic flows based upon typical laws of the automated control in terms of actual low intensity deviation from the specified critical level.

Methods. The aggregated simulation model, describing processes of road traffic formation within a local traffic network section, was used to obtain both static and dynamic characteristics of each flow for the section. The research concerning dependencies of stimulus (being parameters of light cycles at the junctions) upon traffic flow characteristics if PID controller and negative feedback principle are applied to automate road traffic control. In this context, a control criterion was applied to determine critical flow intensity if a traffic jam occurs. The criterion helps identify changes in the road traffic behaviour. Standard deviation of the controlled quantity from the specified value as well as average static control value was determined to identify optimum PID controller settings for different margins of the control system in terms of its sustainability. Computational experiments were used to assess efficiency of the proposed algorithm in comparison with the available control algorithms.

Purpose. The purpose is to improve capacity of road networks while deriving new dependencies of light cycle parameters at the junction upon characteristics of road traffic and using them to develop an algorithm to automate a process of the coordinated control of urban traffic flows.

Results. Specific features of the traffic system described by [21], used as the research tool, are as follows. It has the branched structure; its components have non-stationary characteristics; and signals between elements are complex and variable. Hence, from the viewpoint of the automated control theory, a traffic system is quite a complicated nonlinear non-stationary control object with a discrete-time signal. The traditional method of synthesis of the automated control systems is not applicable for such

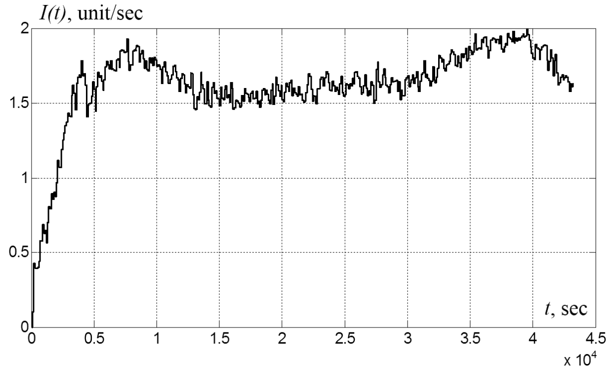

Fig. 1. Time variation of average intensity of a traffic flow in terms of the major route and the known control algorithm

objects. Thus, the simplified dynamic model of control objects will be used instead of the complicated simulation model of a traffic network. For the purpose, in the light of nonavailability of apparent changes in the intensity dynamics of a traffic flow as well as availability of transport delay due to the flow intensity control at a distance from a junction, a structure of the simplified model of a control object is proposed in the form of two aperiodic series-connected links and a link of transport delay (Fig. 2).

The purpose built app *Control and Estimation Tools Manager* of mathematical package MATLAB was applied to identify parametrically the simplified model of the traffic system. While optimizing in terms of the identification results, local optimum was achieved according to which the normalized standard deviation of temporal change in graphs of the traffic flow intensity, obtained using both simplified and complicated simulation models, was 0.91 (the unit corresponds to absolute coincidence of the graphs). In this context, both time constants of aperiodic links were 22.075 s; gain factor was 1.355; transport delay time was 179.37 s.

Consideration of the results of parametric identification of a dynamic model of a traffic network made it possible to develop the simplified dynamic model of the automated control of traffic flow intensity in terms of the major route (Fig. 3).

The flow control algorithm is implemented in the block simulating PID controller operation (*PID Controller* in Fig. 3) in the form of a proportional-integral-derivative (PID) control law. The control is exercised in terms of a traffic actual intensity deviation from the specified critical level being 1.5 unit/s (*Constant* block in Fig. 3).

The customized *pidtool* app of MATLAB package was applied to adjust the PID controller (to synthesize the automated control system). The app demonstrates qualitative results as for the control system synthesis in the context of linear and simple dynamic models of the control objects. However, it operates incorrectly if the control object is highly nonlinear with the impulse shaped signals. Hence, it turned out to be inapplicable while synthesizing the system on the basis of the complicated simulation model of a traffic system.

Synthesis of the automated control of a traffic flow based upon the simplified dynamic model of a control model made it possible to derive such controller adjustments providing monotonic transition process with up to 500 s duration being reasonable in view of the fact that temporal changes in deterministic component of characteristics of traffic flows are tenfold slower. In addition, quite sufficient sustainability of the control system is provided in terms of amplitude (9.74 dB) and phase (60 degrees). The abovementioned is rather important requirement from the viewpoint of nonstationary nature of traffic flow characteristics.

After the algorithm of traffic flow intensity, reflecting approximately characteristics of the transport network, was developed using the simplified dynamic model of a control object, check up its efficiency in regard to a more complex simulation model being closer to the actual traffic system in terms of its characteristics from the viewpoint of the vehicle flow formation. For the purpose, combine the simulation results under the conditions of the available algorithm controlling traffic flow, described by [21], and the proposed algorithm (Fig. 4).

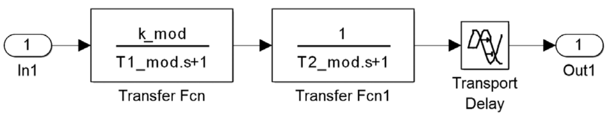

Fig. 2. Structural patterns of the simplified dynamic model of a traffic network

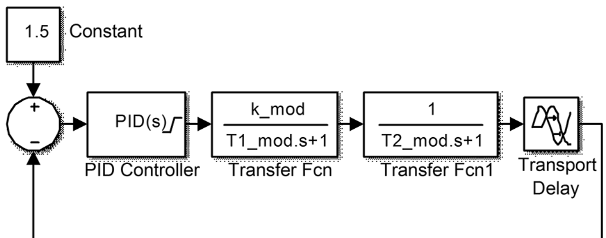

Fig. 3. Structural pattern of the system of the automated traffic control

Fig. 4 explains that the system of the automated control of traffic flow intensity, implementing the proposed PID controller-based algorithm, operates correctly in contrast with the control system implementing an algorithm described by [21]. If a PID controller is applied (the dotted line in Fig. 4), then during the whole simulation period, the traffic flow intensity is around the specified 1.5 unit/s level with minor deviations from it. The abovementioned depends upon availability of a dynamic random component within the characteristics of traffic flows which cannot be compensated. In turn, if an algorithm, proposed by [21] is used (the solid line in Fig. 4), then rush hours demonstrate heavy deviations of the flow intensity from the specified critical level; hence, the control system is a poor one. It is inadmissible that intensity exceeds significantly its critical level resulting in congestion.

It is seen in Fig. 4 that in terms of the major route, average intensity of traffic flow intensity after diffusion of groups of vehicles demonstrates availability of a random component. Under the conditions, relative standard deviation σ and static error Δ are the classic criteria to evaluate the control quality.

To analyze efficiency of the proposed algorithm for the coordinated automated control of traffic flows in terms of different road conditions, determine dependence of the designated criteria of control quality (i.e. σ and Δ) upon PID law of intensity control of the major traffic flow. In this regard, taking into consideration the nonstationary nature of characteristics of traffic flows, sustainability reserves of the control system in terms of amplitude and phase have been selected as the basic parameters of a control law since they identify the system robustness level. The mentioned dependencies were obtained using the aggregated simulation model of a traffic system [21] and they are shown in Figs. 5 and 6.

Analysis of Figs. 5 and 6 helps conclude that there are optimum adjustments of the PID controller of traffic flow intensity in terms of the major route which correspond to minimum extrema in the Figures. In this regard, the conclusion is true relative to the standard deviation of the actual traffic flow intensity from its critical level as well as to the static control error. Optimum adjustments of the PID controller of traffic flow intensity follow the control system sustainability in terms of amplitude (14 dB) and phase (69 degrees).

Then, let us study the efficiency of PID control law of intensity of the major traffic flow with optimum adjustment for different road conditions.

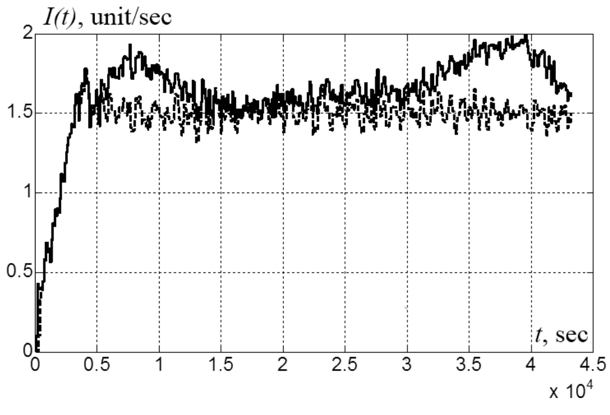

Fig. 4. Temporal changes in average traffic flow intensity according to its major route in terms of the known control algorithm (solid line) and the proposed one (dotted line)

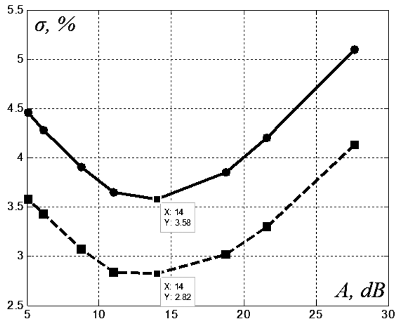

Fig. 5. Dependence of standard deviation of the controlled value upon the specified value (solid line) and that of average static control error (dotted line) upon the system sustainability in terms of amplitude

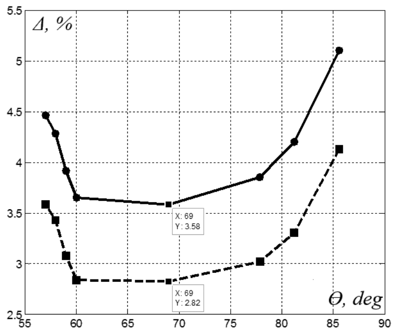

Fig. 6. Dependence of the standard deviation of the controlled value upon the specified value as well as average static control error (solid line) and that of average static control error (dotted line) upon the system sustainability in terms of a phase

Fig. 7 demonstrates simulation results of the coordinated automated control of traffic flows depending upon substantial changes in the velocity the traffic flow is crossing a junction which generates significant changes in the intensification coefficient in terms of a control channel.

Analysis of Fig. 7 helps conclude that for the significantly increased velocity as well as for the significantly decreased velocity of a junction crossing by the major traffic flow, the automated control system provides efficient stabilization of the actual traffic flow intensity at the specified critical level being 1.5 unit/s. It is understood that if acceleration is available during a junction crossing by the major traffic flow, then the control object has more complicated characteristics due to which heavier deviations of actual flow intensity from the specified level take place. However, the deviations are short-time ones being no more than 15 %.

Fig. 8 shows simulation results of the coordinated automated control of traffic flows in terms of significant changes in spatial velocity of the major flow of traffic between junction and control point of the flow intensity; the abovementioned gives rise to substantial changes in the traffic delay in terms of a control channel.

Analysis of Fig. 8 helps conclude that for significantly increased spatial velocity as well as for significantly decreased spatial velocity of a junction crossing by the major traffic flow, the automated control system also provides efficient stabilization of actual traffic flow intensity at the specified critical level being 1.5 unit/s. Also, the analysis makes it possible to conclude that if the increased spatial velocity of the major traffic flow between a junction and a control point of the flow intensity takes place, then the control object has more complex characteristics due to which greater variations in the actual flow intensity happen. However, their amplitude is not more than 20 %. Moreover, variations in flow intensity, involving significant amplitudes (i. e. up to 20 %) are short-term ones and rare.

In addition, to support efficiency of the proposed algorithm of the coordinated automated control of a traffic flow, the experiment, based upon a simulation model of a traffic system, quality control criteria was derived for other flow characteristics which experienced significant variations. Hence, average standard deviation σ is 3.7 % and relative error Δ is 2.94 % for 30 % acceleration of the major traffic flow crossing a junction while for 30 % decrease σ is 1.85 % and Δ is 1.49 % in terms of deceleration.

In turn, for spatial velocity of the major traffic flow between a junction and control point of the flow intensity, increased by 30 %, average standard σ deviation is 4.34 % and relative Δ error is 3.42 %. Average standard σ deviation is 3.58 % and relative Δ error is 2.82 % if the spatial velocity decreases by 30 %.

Conclusions. Efficiency of the use of standard control law in the context of the automated control theory has been proved to set the coordinated automated control of traffic flows within a local section of urban traffic network. It has been proved that the abovementioned is possible if transition takes place to the simplified dynamic model of a traffic system as a control object while adjusting PID controller of flow intensity. It has been identified that optimum values of flow control parameters are available in terms of which minimum standard deviations of actual flow intensity from its critical level are observed as well as static control error. It has been proved that PID law of a traffic flow intensity control is also efficient in terms of significant changes in characteristics of traffic flows and road conditions. The results are foundations to developed so-called *lower level* of smart decentralized control of urban traffic. The level is required to solve a problem of implementing commands as for the data provision at *higher level* of characteristics of traffic flows.

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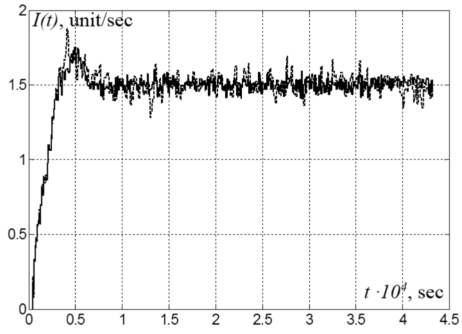

Fig. 7. Temporal changes in average intensity of a traffic flow if velocity of a junction crossing by the major transport flow experiences 30 % acceleration (dotted line) and 30 % deceleration (solid line)

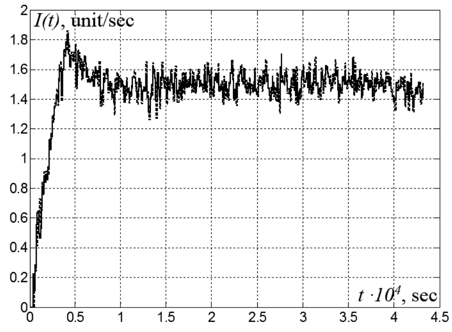

Fig. 8. Temporal changes in average intensity of a traffic flow if either 30 % spatial velocity increase (dotted line) or 30 % spatial velocity decrease (solid line) happens between a junction and control point of the flow intensity

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Автоматизація процесу координованого керування дорожнім трафіком

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Мета. Збільшення пропускної здатності дорожніх мереж за рахунок отримання нових залежностей характеристик транспортних потоків від параметрів закону керування, створення на їх основі алгоритму для автоматизації процесу координованого керування транспортними потоками в містах.

Методика. За допомогою агрегованої імітаційної моделі, що описує процеси формування дорожнього трафіку на локальній ділянці міської транспортної схеми, проведені дослідження залежностей критеріїв оцінювання якості керування транспортними потоками від керуючих впливів, якими є параметри світлофорних циклів на перехрестях, за умови використання ПІД-регулятора та принципу зворотного від'ємного зв'язку для автоматизації процесу керування дорожнім трафіком. При цьому, в якості уставки для системи керування, з урахуванням поставленої мети, задана критична інтенсивність потоку за виникнення заторів, для визначення якої використаний критерій керування, що дозволяє ідентифікувати зміну характеру дорожнього трафіку. Для визначення оптимальних налаштувань ПІД-регулятора для різних запасів системи керування за стійкістю встановлені середньоквадратичне відхилення керованої величини від заданого значення та середня статична помилка керування. За допомогою обчислювальних експериментів оцінена ефективність запропонованого алгоритму в порівнянні з існуючими алгоритмами керування за різних дорожніх умов.

Результати. У ході досліджень розроблено алгоритм координованого автоматичного керування дорожнім трафіком, що дозволяє за рахунок відстеження змін характеристик транспортних потоків підтримувати максимальну пропускну здатність дорожніх мереж.

Наукова новизна. Уперше визначені залежності критеріїв оцінювання якості керування транспортними потоками від параметрів закону керування інтенсивністю потоків за умови забезпечення максимальної пропускної здатності дорожніх мереж. Встановлені залежності дозволили обґрунтувати оптимальний закон керування для різних дорожніх умов і за рахунок цього автоматизувати процес координованого керування транспортними потоками на локальній ділянці транспортної схеми міста.

Практична значимість. Запропоновані в роботі залежності критеріїв якості керування транспортними потоками від параметрів закону керування дорожнім трафіком, а також алгоритм автоматичного координованого керування ним є теоретичною основою для розв'язання важливої науково-прикладної задачі автоматизації процесу координованого керування транспортними потоками в місті.

Ключові слова: *транспортні потоки, координоване керування, імітаційне моделювання*

The manuscript was submitted 13.05.21.