Methodical approach in determining the reliability and efficiency of urban cargo transportation taking into account the congestion of street networks

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Abstract. A methodical approach has been developed in order to assess the reliability and efficiency of urban cargo traffic, taking into account the congestion of street networks. Modelling the transportation process is carried out online and allows one to determine the parameters of the transportation process, which take into account the presence of traffic jams on the city streets. A criterion for assessing the reliability of the logistics system of cargo urban transportation has been proposed — the reliability coefficient and the integral criterion of efficiency. The criteria take into account the travel time of the vehicle along the route and the time of delays in accepting the applications for services at the logistics centre (LC), as well as the time of delays at the transport company. It has been shown that in the absence of delays in the logistic chains, the reliability coefficient is equal to one, and the efficiency criterion tends to a minimum. The role of the LC capacity in the unit costs of transport services has been determined. Insufficient capacity of the LC increases the processing time of one application, which leads to an increase in the total unit costs.

1. Introduction

The urgency of the task of forming the routes of the urban transport network of cargo transportation is confirmed by the fact that at this stage there are Internet resources that allow the collection of information on the needs of cargo transportation. At the same time, for modelling and forecasting the cargo flows in the city transport network, it is necessary to have special modules of dynamic modelling of the real-time movement of cargo volumes taking into account the load (congestion) on transportation routes. Such modelling modules for urban cargo transportation should complement the existing Internet resources, and work on their basis, using the systems of information collection, the selection of the shortest distances, and the determination of congestion of highways and the presence of traffic jams on the routes.

Based on the above, the main argument of such scientific research is the search for solutions to improve the efficiency of cargo transportation in the city. The ways of such a search are the application of the mathematical model which interacts with the modern Internet resources and allows choosing a rational route taking into account the congestion of highways and streets of the city at different hours of the working day. The practical significance of such research is to increase the reliability and reduce the cost of transport services within the city.

2. Analysis of literature data and the problem statement

The authors of the work [1] the analysis of tendencies of development of city freight transportations is
executed and the criterion of economic efficiency is offered. By means of the developed criterion the method of an estimation of cargo transportations of the city on the basis of the information on cargo flows is presented. Through the creation of an information matrix, tariffs for urban freight transportation are justified.

Analysis of works [2, 3] allows us to draw a conclusion about the prospects of the logistics approach in the development of freight models. In work [2] the results of formalization of the process of functioning of various production and transport systems are presented. In work [3] presents a mathematical model of the logistics system, which allows to rationalize the technology of interconnected enterprises based on the development of a set of technological and management solutions. In work [4] the analysis of the process of functioning of the transport and storage complex is carried out and the criterion of efficiency is formalized. This indicator represents the specific costs of cargo handling and takes into account the costs of the cargo owner associated with the downtime of cars waiting to be serviced.

Authors of works [5, 6] the results of forecasting the delivery time of goods in the city network are presented. The prospects of using IT systems for monitoring vehicles on the route are noted, which is substantiated in the work [7]. It is proved that this approach increases the informativeness of monitoring and allows to perform the forecast for transport services. This direction was further developed in the work [8], where an information model was developed, which was created on the basis of artificial neural networks. The simulation results show that the availability of information and communication systems is an important component of urban freight transport. A similar conclusion was made in the work [9], where it is emphasized that the exchange of information on the density and intensity of traffic on the streets of the city will increase the level of transport services.

Works [10, 11] devoted to assessing the reliability of transport services. Based on the analysis of transport networks, the authors concluded that it is advisable to evaluate them by comparing the criterion of reliability. Works are devoted to modelling of city motor traffic flows [12, 13]. They used the concept – “resistance to movement” on a separate section of the street. This approach allows you to develop a mathematical model of reducing the speed of vehicles in some parts of the city streets where there are traffic jams.

Methods of modelling dynamic traffic flows of urban freight traffic taking into account the congestion of streets in real time based on the use of available Internet resources need further development and improvement. The received forecast will allow to substantiate a rational route of delivery of cargo in real time thereby to increase reliability and efficiency of delivery.

3. The purpose and tasks of the study
The purpose of the study is to develop a methodical approach to assessing the reliability and efficiency of urban cargo transportation, taking into account the congestion of streets, online.

4. The methodical approach in conducting the research of urban cargo transportation
The mathematical models in the form of the second-order differential equations were chosen as a methodical approach in conducting the research. Such equations have proved themselves well in technical fields and have a well-founded apparatus of solution. The chosen method allows us to study the processes that are functions of time.

The target function of choosing rational routes for the urban cargo transportation is to increase the reliability of cargo delivery (in the exact time) and to reduce transportation costs. The factor that changes in the decision-making process is the congestion of the city streets, which will be taken into account by the parameter – the resistance of the route $R_r$. The method of calculating the resistance of the route is given in work [14, 15].

The difficulties in choosing rational urban routes taking into account the real congestion of city highways are stipulated by the fact that such tasks do not currently have formal methods of solution. For example, the classic transport problem allows one to determine the shortest route. However, in the city, the shortest route is not always rational owing to the uneven congestion of highways. There may
be traffic jams on the shortest route, which will reduce the speed of vehicles and increase delivery time and delivery costs.

The process of “manual” route selection from those options that are considered and analysed in the logistics centre by the way of search and comparison, takes into account the quantitative rather than qualitative side of the process. Therefore, for the implementation of modelling, forecasting and quality management of urban transportation, the problem should be formalized in the form of developing a dynamic mathematical model.

5. The results of the research on transport processes of urban cargo transportations

The procedure of the methodical approach during the choice of rational routes of urban cargo transportations with the maximum reliability and the minimum expenses for transportation can be broken down into the following stages.

The first stage of modelling allows choosing a route with minimal resistance and determine the time of delivery \( t_d \), i.e. the time of following the route, as well as the quality factor of the route \( Q_r \). The physical content of the quality factor of the route and the formula for calculation are given in works [14, 15].

This allows choosing from several possible routes, using the Internet resource videoprobki.ua, the optimal value of \( Q_r \rightarrow \max \). The value of the quality factor of the route \( Q_r \) can serve as a criterion for choosing the optimal route of cargo traffic in the city network, as it takes into account the material, information and energy flows. The route is chosen on the basis of information from the Internet resources Google Maps and videoprobki.ua. The peculiarity of the proposed criterion \( Q_r \), in comparison with the known ones is that it is determined online.

The second stage of modelling takes into account the inertia of the system in decision-making and the process of following the route, which allows determining the time of delays in the logistics system (LS).

The sum of delivery time and delay time determines the total time of executing the order for the transport service:

\[
t_{\Sigma} = t_{dc} + t_d,
\]

where \( t_L \) is the order execution time (hour); \( t_{dc} \) is the time of cargo delivery (hour); \( t_d \) is the time of delays in the LS (hour).

The author of work [14] obtained a second-order differential equation, which allows representing the transition process in the logistics system of urban cargo transportation from the moment of receipt of the application for transport services to the moment of the delivery of goods to the customer:

\[
T_L \frac{d^2m}{dt^2} + 2d_L \cdot Q_r \cdot T_L \frac{dm}{dt} + m \cdot \frac{[K_{LC} \cdot K_{TC}]}{1} + m \cdot K_{LS} = J,
\]

The time constant of the logistics system \( T_{LS} \), which characterizes the inertia of the system, is determined by the expression:

\[
T_{LS} = (T_{LC} \cdot T_{TC})^{1/2} \cdot (K_{LC} \cdot K_{TC})^{1/2},
\]

where \( T_{LC} \) is the time constant of the logistics centre (LC), which takes into account the inertia (delay) in the processing of applications (hour); \( T_{TC} \) is the time constant of the transport company (TC), which takes into account the inertia (delay) in accepting applications for transport services (hour); \( K_{LC} \) is the coefficient of sensitivity of the logistics centre to the receipt of applications; \( K_{TC} \) is the coefficient of sensitivity of the transport company to the receipt of applications for transport services from the logistics centre; \( d_L \) is the coefficient that characterizes the absence or presence of an oscillatory process in the LS.

The formulas for calculating the above time constants and coefficients are presented in work [14].
The right part of equation (2) is the order for the required productivity of the logistics system, t/h. The left part of the equation is the reaction of the LS to the order J.

The increase of the time constants of $T_{LC}$ and $T_{TC}$ makes the process less sensitive (less susceptible) to the order for transport service $J$. The process of processing the applications and the delivery of goods increases in time.

The gain coefficients of $K_{LC}$ and $K_{TC}$ characterize the sensitivity of $LC$ and the transport company to the receipt of applications.

The solution for the above stated differential equation (2) is the expression:

$$m(t) = m \cdot \left(1 - \exp\left(-d_{LS} \cdot Q \cdot T_{LC}^{-1} \cdot t\right)\right) \cdot \cos f \cdot t + A \cdot \sin f \cdot t,$$

where $m(t)$ is the function of the delivery of a given weight of cargo in time; $t$ is the current time (hour); $f$ is the oscillation frequency, dimension (1/hour), is determined by the expression given in work [14]; $A$ is the amplitude of oscillations, measureless value, is determined by the expression given in work [14].

The big value of the time constant $T_{LC}$ suggests that the logistics centre and the transport company have a great inertia in accepting applications for processing, and, as a consequence, will have a big delay time.

The dynamic model (3) allows determining the total time of the transport service taking into account various factors. The model works online and interacts with Google Maps and videoprobki.ua resources. This is the difference between the developed model and the previously known ones. The results of the dynamic modelling of the process of cargo delivery on urban routes, formula (4), with changing the weight of the cargo and the presence of congestion on the route, are presented in work [14].

The value of the total transport service time $t_2$ is given by the joint use of the developed models.

The first allows one to determine the time of the vehicle on the route $t_{dc}$, taking into account the quality factor of the route $Q_r$. The second allows one to determine the delays in making decisions on the service $t_d$.

The values of $t_{dc}$, $t_d$, $t_2$ obtained above allow determining the reliability of the logistics system of urban cargo transportation. According to works [10, 11], it can be stated that the reliability of the LS of cargo transportation is evaluated as the ratio of the following indicators of the process. In the numerator – of the mathematical expectation of the time spent on the delivery of goods along the route. In the denominator – of the mathematical expectation of the total time spent on the delivery of goods along the route and the time for delays that occurred during the delivery of goods along the route.

In accordance with the conclusions of work [15] let us write an expression for assessing the reliability of the LS when executing $n$ applications that were performed in the LS:

$$K_R = \left(\sum_{i=1}^{n} t_{dc,i} + \sum_{i=1}^{n} t_{d,i}\right)^{-1} \cdot \sum_{i=1}^{n} t_{dc,i},$$

where $K_R$ is the coefficient of reliability of the LS, a measureless value; $n$ is the number of applications for transport services.

Based on expression (5), the reliability coefficient is less than one and becomes equal to one only when the total delays are zero. In the presence of even insignificant delays $K_R$ is less than one. The obtained measureless parameter of the $K_R$, which has the physical content of the part of the execution of the application in the exact time, can be a criterion that assesses the reliability of the logistics system functioning. The present criterion will be used while determining the expenses for the urban transportation.

An important indicator of the work of the logistics system of urban cargo transportation is the value of expenses. The expenses characterize the effectiveness of the LS, and include the following components.
Based on works [1-4], which are devoted to the economic criteria, one can conclude that it is more appropriate to apply specific criteria or parameters that take into account the expenses per ton of the cargo transported, the measure of UAH/t.

The first component of the expenses is the operating costs, which are formed by the adopted tariff for the transportation of goods. This tariff is determined by the market and has a measure of UAH/km.

The expression using which one can determine the unit costs associated with the market value of the tariff, can be represented as follows:

$$B_1 = l_r^2 \cdot T_r \cdot \omega \cdot \left[ m \cdot \nu_{tech} \cdot K_R \right]^{-1},$$  \hspace{1cm} (6)

where \(B_1\) is the expenses for transport services, which depend on the tariff (UAH/t); \(l_r\) is the length of the route (km); \(T_r\) is the tariff for transportation (UAH/km); \(\omega\) is the frequency of the receipt of applications for service in the logistics centre (LC) (1/hour); \(m\) is the weight of goods, t; \(\nu_{tech}\) is the technical speed of the vehicle on the route (km/hour); \(K_R\) is the reliability factor, formula (5).

As expression (1) shows, the increase in the weight of the transported cargo \(m\), the technical speed on the route \(\nu_{tech}\) and the reliability factor \(K_R\) will help to reduce the unit costs of the transportation.

The second component of the expenses is the operating costs associated with the consumption of fuel by vehicles during the execution of the order. Based on works [1-4], we can write the expression:

$$B_2 = N_v \cdot \nu_{tech} \cdot t_{Σ} \cdot C_f \cdot 0.01 \cdot G_f \cdot \left[ m \cdot K_R \cdot \beta \cdot \gamma \right]^{-1},$$ \hspace{1cm} (7)

where \(N_v\) is the number of vehicles which are on duty; \(t_{Σ}\) – the total time of the order execution taking into account delays (hour); \(C_f\) is the cost of one litre of fuel (UAH/l); \(G_f\) is the fuel consumption by the vehicle in the city movement cycle (l/100 km); \(\beta\) is the coefficient that takes into account the presence of idling (the coefficient of the mileage utilization); \(\gamma\) is the coefficient of utilization of the loading capacity of the vehicle.

The third component of the expenses is the expenses that take into account the drivers' salaries, the vehicle maintenance costs and the amortization, which depend on the initial cost of the vehicle.

The expression for the calculations of the third component of the expenses can be represented as follows:

$$B_3 = N_v \cdot K_{L-Unl} \cdot t_{Σ} \cdot R_{dr} \cdot \left[ m \cdot K_R \right]^{-1} + 0.00041 \cdot C_v \cdot N_v \cdot \left[ m \cdot K_R \right]^{-1},$$ \hspace{1cm} (8)

where \(K_{L-Unl}\) is the coefficient that takes into account the increase in the total delivery time of cargo for loading and unloading operations, \(K_{L-Unl} = 1.15 - 1.3\); \(R_{dr}\) is the hourly rate of the driver’s salary (UAH/hour); \(C_v\) is the initial cost of the vehicle (UAH).

The coefficient of 0.00041 takes into account the expenses for the vehicle maintenance, which are equal to 5% of the initial cost of the vehicle \(C_v\) and the amortization costs, which are equal to 10% of \(C_v\) per year, attributed to one day of operation. The total, integrated unit costs for urban cargo transportation will be expressed by the following formula:

$$B = B_1 + B_2 + B_3,$$ \hspace{1cm} (9)

The analysis of the obtained formulas (6) – (9) allows concluding that the unit costs of urban transport services depend on the distance of the transportation, the cargo weight, the reliability factors, the mileage and load capacity utilization, the total time spent on duty, the tariff for the transportation, and fuel use. The presented integral value of unit costs, formula (9), can act as an economic criterion of urban cargo transportation in the process of solving optimization problems for the choice of routes. This criterion should be kept to a minimum.

6. The research results

We will model the impact of various parameters of the transport process on the total unit costs, which reflect the efficiency of urban cargo transportation.
The role of the LC in the general part of unit costs for transport services is represented by the dependencies in the figures 1–2.

The analysis of the dependencies presented in figure 1 allows estimating the degree of influence of the weight of the transported cargo and the time required to process one application in the LC, \( t_{LC} \). With the increase of \( t_{LC} \) unit costs increase by 1.16-1.52 times, and the change in the weight of the transported cargo has an optimum that corresponds to \( m = 10 \) t and occurs at higher values of \( t_{LC} \) (low capacity of the LC).

**Figure 1.** The dependencies of the change of the value of unit costs \( B \) of the logistic system at various weight of the transported cargo \( m \) and the time of registration of one application in the LC, \( t_{LC} \)

![Figure 1](image1)

**Figure 2.** The dependencies of the change of the value of unit costs \( B \) of the logistic system at various length of the route \( l_r \) and the time of registration of one application in the LC, \( t_{LC} \)

![Figure 2](image2)

**Figure 3.** The dependencies of the change of the value of unit costs \( B \) of the logistic system at various weight of the transported cargo \( m \) and the frequency of receipt of applications in the LC, \( \omega \)

![Figure 3](image3)
The nature of the influence on unit costs of the route length \( l \) and time \( t_{LC} \) is presented in figure 2. From the dependencies it follows that the degree of the influence of \( t_{LC} \) on the value \( B \) is similar to the above dependencies, and the length of the route increases unit costs by 2.3-2.55 times.

The influence of the frequency of requests \( \omega \) for service in the \( LC \), which is represented by the dependencies in figure 3, allows concluding that when changing the weight of the transported cargo there is an optimum, which is characteristic of \( m=10t \). The increase of the number of service requests per unit time increases \( B \), because it requires an increase in the capacity of the \( LC \).

The provided results of modelling the degree of influence of the \( LC \) on unit costs, Figures 1–3, suggest that the capacity of the logistics centre must be managed. The increase of the capacity of the \( LC \) will reduce the service time of one application \( t_{LC} \), which will reduce unit costs for the transport services. In this case, the increase of the length of the route clearly increases unit costs, and the weight of the transported cargo has an optimum.

The degree of the influence on the value of unit costs of the coefficients of the mileage utilization \( \beta \) and the coefficient of the carrying capacity utilization \( \gamma \), the change of which takes place during urban cargo transportation, is represented by the dependencies in the figures 4–5.

The decrease of the mileage utilization coefficient from the value of Figures 1–2 \( \beta=1 \) to \( \beta=0.5 \) increases unit costs by 1.13-1.22 times. Thus, the influence of the weight of the transported cargo, Figure 4, has an optimum. It should be noted that the optimum exists for \( \beta < 1 \).

![Figure 4](image1.png)

**Figure 4.** The dependencies of the change of the value of unit costs \( B \) of the logistic system at various weight of the transported cargo \( m \) and the mileage utilization coefficient \( \beta \)

![Figure 5](image2.png)

**Figure 5.** The dependencies of the change of the value of unit costs \( B \) of the logistic system at various weight of the transported cargo \( m \) and the coefficient of the carrying capacity utilization of the vehicle \( \gamma \)

The dependencies that characterize the degree of the influence of the carrying capacity coefficient on unit costs, Figure 5, are similar. The decrease of the value of \( \gamma \) from 1 to 0.5 increases the unit costs by 1.17-1.36 times. In this case, the increase in the weight of the transported cargo has an optimum,
which is clearly expressed at $\gamma=1$ and becomes less expressed with the decrease of $\gamma$ from 1 to 0.5, figure 5.

7. The analysis of research results
The dependencies given above allow one to estimate the degree of the influence of the weight of the transported cargo and the time required to service one application in the $LC$. With the increase of $t_{LC}$ unit costs increase by 1.16-1.52 times, and the change in weight of the transported cargo has an optimum.

The nature of the influence on unit costs of the length of the route $l$, suggests that the length of the route increases unit costs by 2.3-2.55 times.

The influence of the frequency of the receipt of service requests $\omega$ in the $LC$ allows one to conclude that when changing the weight of the transported cargo there is an optimum.

The decrease of the mileage utilization coefficient from the value of $\beta=1$ to $\beta=0.5$ increases unit costs by 1.13-1.22 times. In this case, the influence of the weight of the transported cargo has an optimum.

The decrease of the value $\gamma$ from 1 to 0.5 increases the specific unit costs by 1.17-1.36 times. In this case, the increase in the weight of the transported cargo has an optimum, which is clearly expressed at $\gamma = 1$.

8. Conclusions
The modelling of the influence of various factors and operating parameters of the transport process of urban cargo transportation within the accepted restrictions suggests that unit costs of transport services $B$, UAH/t, clearly increase with the increase of the route length, however, in this case, they have an optimum when changing the weight of the transported cargo.

It has been established that the existence of the optimum is influenced by the mileage utilization coefficient and the vehicle carrying capacity utilization coefficient.

The influence of the logistics centre (logistics centre capacity) on unit costs of transport services has been shown. The insufficient capacity of the $LC$ increases the time of registration of one application, which leads to the increase in total unit costs.

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