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SERGIY POSONSKIY

Khmelnytskyi National University

<https://orcid.org/0000-0002-4697-7699>

e-mail: p.s.f@ukr.net

ANDRII NICHEPORUK

Khmelnytskyi National University

<https://orcid.org/0000-0002-7230-9475>

e-mail: andrey.nicheporuk@gmail.com

OLEKSANDR DYKHA

Khmelnytskyi National University

<https://orcid.org/0000-0003-3020-9625>

e-mail: tribosenator@gmail.com

MODELING OF THE URBAN ROAD FREIGHT TRANSPORTATION PROCESS USING DESIGN OF EXPERIMENTS (A CASE STUDY OF KHMELNYTSKYI)

The paper investigates the influence of key organizational factors on the productivity of urban road freight transportation using the city of Khmelnytskyi (Ukraine) as a case study. Improving the efficiency of freight transport is an important task in modern urban logistics due to increasing traffic intensity, growing freight demand, limited road network capacity, and the necessity to reduce transportation costs while maintaining a high level of service quality.

To describe the transportation process, a response surface methodology based on a central composite experimental design was applied. Three independent variables were selected for the study: the average technical vehicle speed, the route length, and the average service time at a delivery point. The investigated ranges of the factors were determined according to the actual operating conditions of urban freight transportation in Khmelnytskyi.

A second-order regression model was developed to describe the relationship between vehicle productivity and the selected factors. The adequacy of the model was confirmed using statistical analysis, while the significance of the linear, quadratic, and interaction effects was evaluated. The obtained results demonstrate that the average technical speed has the greatest influence on transportation productivity, whereas the route length and the average service time at delivery points also have a statistically significant effect. The significance of the quadratic speed term indicates the nonlinear character of the transportation process and confirms the suitability of using a second-order regression model.

Based on the response surface analysis and the desirability function, the rational operating conditions for urban freight transportation were determined. The optimal productivity is achieved at an average technical speed of approximately 35–38 km/h, a route length of 10–12 km, and an average service time of 8–10 minutes per delivery point. Under these conditions, the predicted vehicle productivity reaches approximately 31–32 tons per shift.

The proposed mathematical model can be used by freight transport operators to optimize urban delivery routes, reduce vehicle idle time, improve fleet utilization efficiency, and support managerial decision-making in the organization of urban freight transportation. The developed methodology can also be adapted for similar transportation systems in other cities with comparable traffic and logistics conditions.

Keywords: urban freight transportation, road transport, freight transport productivity, mathematical modeling, design of experiments; central composite design, response surface methodology, regression analysis, transportation process optimization.

ПОСОНСЬКИЙ СЕРГІЙ, НІЧЕПОРУК АНДРІЙ, ДИХА ОЛЕКСАНДР

Хмельницький національний університет

МОДЕЛЮВАННЯ ПРОЦЕСУ МІСЬКИХ ВАНТАЖНИХ АВТОМОБІЛЬНИХ ПЕРЕВЕЗЕНЬ МЕТОДОМ ПЛАНУВАННЯ ЕКСПЕРИМЕНТУ (НА ПРИКЛАДІ М. ХМЕЛЬНИЦЬКОГО)

У статті досліджено вплив організаційних факторів на продуктивність міських вантажних автомобільних перевезень на прикладі м. Хмельницького. Для математичного опису транспортного процесу використано метод планування експерименту – центральний композиційний план. Як основні фактори дослідження обрано середню технічну швидкість руху автомобіля, довжину маршруту перевезення та середній час обслуговування однієї точки доставки. Побудовано квадратичну регресійну модель, що описує залежність продуктивності перевезень від досліджуваних факторів, та виконано оцінювання статистичної значущості їх лінійних, квадратичних ефектів і взаємодій. За результатами аналізу встановлено, що найбільший вплив на продуктивність транспортного процесу має середня технічна швидкість руху автомобіля, тоді як довжина маршруту та час обслуговування точки доставки також істотно впливають на ефективність перевезень. На основі побудованих поверхонь відгуку та функцій бажаності визначено раціональні параметри організації міських вантажних перевезень, що забезпечують максимальну продуктивність автомобіля в умовах експлуатації міста Хмельницького. Отримані результати можуть бути використані транспортними підприємствами для оптимізації маршрутів, скорочення непродуктивних витрат часу та підвищення ефективності використання рухомого складу.

Ключові слова: міські вантажні перевезення, автомобільний транспорт, продуктивність перевезень, математичне моделювання, планування експерименту, центральний композиційний план, поверхня відгуку, оптимізація транспортного процесу.

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Statement of the problem

Road transport is one of the key components of the transport system of a modern city, ensuring the timely delivery of goods to enterprises, retail networks, and end consumers. The increasing volume of urban freight transportation, the rapid development of e-commerce, and the growing demand for faster product delivery necessitate the improvement of transport process organization and the enhancement of vehicle fleet utilization efficiency [1–3].

For medium-sized cities in Ukraine, including Khmelnytskyi, increasing traffic load on the urban road network is accompanied by a decrease in the average technical speed of vehicles, longer delivery times, and higher operating costs. Under such conditions, freight transport productivity is determined not only by the technical characteristics of vehicles but also by organizational parameters of the transport process, among which route length, average technical speed, and service time at delivery points play a significant role [3–6].

One of the most effective approaches to investigating multifactor transport systems is the application of mathematical modeling and design of experiments (DoE), which makes it possible to assess the simultaneous influence of several factors, identify their interactions, and determine rational operating conditions for the transport process [7, 8].

Despite the considerable number of studies in the field of transport logistics, the mathematical modeling of urban freight transport productivity using a central composite experimental design for the conditions of medium-sized Ukrainian cities remains insufficiently investigated [4–12].

Forming article's objective

The purpose of this study is to develop a mathematical model of the urban freight transportation process using the design of experiments methodology, to evaluate the influence of organizational factors on transport productivity, and to determine their rational values for the conditions of Khmelnytskyi.

Analysis of recent publications

Improving the efficiency of urban freight road transportation is among the most relevant research directions in transport technologies, logistics, and transportation management. The continuous growth of traffic intensity, rapid expansion of e-commerce, increasing requirements for delivery speed, and the need to reduce operating costs have stimulated the extensive application of mathematical methods for analyzing transport processes and optimizing road freight transportation [1–3].

One of the leading research directions is the development of the City Logistics concept, which aims at the comprehensive optimization of urban freight distribution while considering economic, transport, and environmental factors. The studies of E. Taniguchi, R. Thompson, and T. Yamada established the theoretical foundations of urban logistics, proposed models of transport network operation, and substantiated approaches to improving the efficiency of urban freight transportation [3]. Further development of this research area is reflected in recent studies devoted to evaluating urban logistics performance, the operation of urban consolidation centers, last-mile delivery optimization, and the implementation of intelligent transport systems [4–10].

Another important research area concerns the mathematical modeling of transport processes. Modern approaches are based on regression analysis, simulation modeling, operations research methods, multicriteria optimization, and digital decision-support technologies. The application of mathematical models enables the quantitative assessment of the influence of technical, organizational, and operational factors on transport system performance and the determination of rational operating conditions [6, 8, 11, 12].

Among contemporary mathematical modeling techniques, the Design of Experiments (DoE) method occupies a prominent place. Its main advantage lies in the possibility of simultaneously investigating the influence of several factors, identifying interaction effects, and constructing adequate mathematical models of complex processes. The theoretical foundations of central composite designs, regression coefficient estimation, model adequacy testing, and optimization procedures are comprehensively presented in the fundamental work of D. Montgomery [7]. Operations research methods widely applied to transport optimization problems are thoroughly described by H. Taha [8].

Despite the substantial body of scientific literature, most studies focus on vehicle routing optimization, urban logistics systems, or traffic flow analysis. Considerably less attention has been devoted to the mathematical modeling of urban freight transport productivity using Design of Experiments techniques, which enable the simultaneous consideration of several organizational factors and the determination of their optimal values. Studies employing a central composite design to develop mathematical models of urban freight transport productivity under the conditions of medium-sized Ukrainian cities, particularly Khmelnytskyi, are practically absent [4–12].

The conducted review demonstrates that the majority of current research is aimed at solving routing problems, optimizing logistics networks, and implementing digital technologies in urban logistics. At the same time, insufficient attention has been paid to the quantitative assessment of the influence of organizational parameters of the transport process on freight transport productivity using statistical experimental design methods. Addressing this scientific gap constitutes the basis of the present study.

Therefore, an important scientific and practical task is the development of a mathematical model of the urban freight transportation process based on the Design of Experiments methodology, the evaluation of the influence of organizational factors on transport productivity, and the determination of their rational values for the operating conditions of the transport system of the city of Khmelnytskyi.

Presentation of the main material

To investigate the process of urban freight road transportation, a mathematical modeling approach based on the Design of Experiments (DoE) methodology was employed. The application of this approach makes it possible to establish an analytical relationship between transport productivity and the main organizational factors, evaluate their individual and combined effects, and determine rational operating conditions for the vehicle fleet. The methodological basis of the study is a second-order Central Composite Design (CCD), which enables the development of an adequate quadratic regression model and is widely used in the investigation of multifactor engineering systems [7].

The object of the study is the process of urban freight road transportation within the transport network of the city of Khmelnytskyi. The subject of the study is the relationship between freight transport productivity and the organizational parameters of the transportation process.

The optimization criterion adopted in this study is the daily (shift) vehicle productivity, i.e., the amount of freight transported during one 8-hour working shift, W (t/shift). This indicator comprehensively characterizes the efficiency of vehicle utilization in urban freight transportation while accounting for the combined influence of operating conditions.

Based on the analysis of previous studies [1–6] and considering the specific characteristics of urban freight transportation in Khmelnytskyi, three independent factors were selected for investigation.

1. Average technical speed (V), km/h. This parameter characterizes road conditions, traffic congestion, and vehicle operating conditions, directly determining the duration of the transportation cycle. Under the urban conditions of Khmelnytskyi, the average technical speed of freight vehicles typically ranges from 25 to 35 km/h depending on the time of day, traffic intensity, and route configuration.

2. Route length (L), km. This factor represents the distance between the depot and delivery points within a single transportation cycle. As the route length increases, the trip duration becomes longer; however, the relative impact of preparatory and finishing operations decreases, which may positively influence productivity up to a certain optimum value.

3. Average service time per delivery point (t), min. This parameter includes vehicle maneuvering, preparation of accompanying documentation, loading and unloading operations, and vehicle preparation for subsequent movement. In urban freight transportation, this factor is often one of the most influential because it directly determines the duration of the transportation cycle.

Under the operating conditions of Khmelnytskyi, the average technical speed of light-duty freight vehicles involved in urban transportation generally ranges from 25 to 35 km/h, depending on the time of day and traffic congestion. Typical delivery routes are 8–20 km long, covering the city center, industrial districts, and commercial areas, while the average service time at a delivery point is 10–15 minutes.

Thus, the selected factors characterize the three principal components of the urban freight transportation process: the vehicle operating regime, the spatial characteristics of the route, and the time required to perform transportation operations. Their combination provides a sufficiently comprehensive description of the organizational conditions of freight transportation and enables the development of an adequate mathematical model of transport productivity.

To investigate the influence of organizational factors on urban freight transportation productivity, a mathematical modeling approach based on the Design of Experiments methodology was applied. This approach makes it possible to establish quantitative relationships between the investigated factors and the response variable, evaluate their individual and interaction effects, and determine the optimal parameters of the transportation process while minimizing the number of required experiments [7, 8].

Unlike a conventional full factorial experiment, which allows only a linear regression model to be obtained, the Central Composite Design (CCD) enables the construction of a quadratic regression model that more adequately describes real transportation processes, where the relationship between the influencing factors and transport productivity is inherently nonlinear [7].

In this study, a second-order rotatable Central Composite Design for three factors was employed. The experimental design consisted of eight factorial points corresponding to a full factorial (2^3) design, six axial (star) points, and two center-point experiments. Consequently, the total number of experimental runs was 16, providing sufficient statistical accuracy for estimating linear, quadratic, and interaction effects and for developing an adequate mathematical model.

To construct the mathematical model, the natural values of the investigated factors were transformed into a dimensionless coded space. The natural and coded factor levels are presented in Table 1.

According to the selected Central Composite Design (CCD), an experimental matrix consisting of factorial, axial (star), and center points was constructed. Such a design structure makes it possible to estimate the linear effects, interaction effects, and quadratic terms of the regression model, while also providing the basis for assessing the adequacy of the developed mathematical model of the transportation process [7].

Table 1

Factor levels and variation intervals

Factors	Levels				
	– 1,68	– 1	0	+ 1	+ 1,68
V – average technical speed, km/h	16,6	22	30	38	43,4
L – route length, km	5,9	10	16	22	26,1
t – average service time of one point, min	3,9	8	14	20	24,1

The experimental design matrix includes eight factorial points corresponding to the full factorial (2^3) design, six axial points located at a distance of ($\alpha = 1,68$) from the design center, and two replicated experiments at the center point. This combination ensures the statistical efficiency and rotatability of the design, enabling reliable estimation of second-order regression coefficients over the investigated factor space.

The experimental design matrix used in this study is presented in Table 2.

Table 2

Matrix of the central compositional plan and test results

№	V, average technical speed, km/h		L, route length, km		t, average service time of one point, min		W, tons/shift
1	-1,00000	22	-1,00000	10	-1,00000	8	25,72
2	-1,00000	22	-1,00000	10	1,00000	20	20,78
3	-1,00000	22	1,00000	22	-1,00000	8	22,02
4	-1,00000	22	1,00000	22	1,00000	20	16,18
5	1,00000	38	-1,00000	10	-1,00000	8	31,61
6	1,00000	38	-1,00000	10	1,00000	20	28,04
7	1,00000	38	1,00000	22	-1,00000	8	28,86
8	1,00000	38	1,00000	22	1,00000	20	23,87
9	-1,68179	16,6	0,00000	16	0,00000	14	19,1
10	1,68179	43,4	0,00000	16	0,00000	14	29,44
11	0,00000	30	-1,68179	5,9	0,00000	14	29,95
12	0,00000	30	1,68179	26,1	0,00000	14	22,83
13	0,00000	30	0,00000	16	-1,68179	3,9	30,42
14	0,00000	30	0,00000	16	1,68179	24,1	21,62
15	0,00000	30	0,00000	16	0,00000	14	28,09
16	0,00000	30	0,00000	16	0,00000	14	27,94

Based on the results obtained from the second-order Central Composite Design (CCD), the experimental data were statistically processed, and the coefficients of the quadratic regression model were determined. The calculations were performed using the STATISTICA software package, which provides estimation of regression coefficients by the least squares method, assessment of their statistical significance, and verification of the adequacy of the developed mathematical model.

To describe the urban freight transportation process, a second-order quadratic regression model of the general form was adopted:

$$W = b_0 + b_1V + b_2L + b_3t + b_{12}VL + b_{13}Vt + b_{23}Lt + b_{11}V^2 + b_{22}L^2 + b_{33}t^2. \quad (1)$$

The estimated regression coefficients are presented in Fig. 1.

Taking into account the estimated regression coefficients and the results of their statistical significance analysis, the final quadratic regression equation describing the dependence of transport productivity on the investigated organizational factors was obtained. Insignificant coefficients were excluded from the model, resulting in a statistically adequate regression equation that can be used to analyze the transportation process and determine rational operating conditions.

The resulting regression equation describing the relationship between freight transport productivity and the investigated factors is given as follows:

$$W = 28,09 + 3,31V - 1,99L - 2,50t - 1,52V^2 - 0,75L^2 - 0,88t^2. \quad (2)$$

The statistical evaluation of the developed regression model was performed using analysis of variance (ANOVA). The results are presented in Table 3.

The analysis indicates that all three investigated organizational factors have a statistically significant influence on the productivity of urban freight road transportation ($p < 0,05$). The largest contribution to the variation of the response variable is provided by the average technical speed of the vehicle, which exhibits the highest Fisher statistic ($F = 336,43$, $p < 0,001$). A slightly smaller, yet still highly significant, effect is observed for the average service time per delivery point ($F = 193,00$, $p < 0,001$) and the route length ($F = 122,46$, $p < 0,001$).

The analysis of the quadratic effects demonstrated that all second-order terms of the regression model are statistically significant ($p < 0,05$), confirming the nonlinear relationship between transport productivity and the investigated factors. This result justifies the application of a second-order Central Composite Design for modeling the transportation process. The most pronounced nonlinear effect was observed for the average technical speed factor.

At the same time, the interaction effects between the investigated factors were found to be statistically insignificant ($p > 0,05$), indicating that within the studied ranges each organizational factor affects vehicle productivity predominantly independently of the others.

The developed regression model demonstrates a high level of predictive accuracy. The coefficient of determination is $R^2 = 0,9916$, while the adjusted coefficient of determination is $R^2_{adj} = 0,9789$, indicating that the model explains more than 99 % of the variation in the response variable. Furthermore, the relatively small residual mean square (MS Residual

= 0,4422) confirms the adequacy of the regression model and its suitability for subsequent response surface analysis and the determination of optimal operating parameters of the urban freight transportation process.

Effect Estimates; Var.: W, tons/shift; R-sqr=,99156; Adj.:97889 (Spreadsheet1) 3 factors, 1 Blocks, 16 Runs; MS Residual=,4422091 DV: W, tons/shift										
Factor	Effect	Std. Err.	t(6)	p	-95, % Cnf. Limit	+95, % Cnf. Limit	Coeff.	Std. Err.	-95, % Cnf. Limit	+95, % Cnf. Limit
Mean/Interc.	28,09084	0,468770	59,9246	0,000000	26,94380	29,23788	28,09084	0,468770	26,94380	29,23788
(1)V, average technical speed, km/h(L)	6,61210	0,360491	18,3419	0,000002	5,73001	7,49419	3,30605	0,180246	2,86501	3,74710
V, average technical speed, km/h(Q)	-3,03330	0,439833	-6,8965	0,000459	-4,10953	-1,95707	-1,51665	0,219916	-2,05476	-0,97853
(2)L, route length, km(L)	-3,98111	0,359752	-11,0662	0,000032	-4,86139	-3,10082	-1,99055	0,179876	-2,43069	-1,55041
L, route length, km(Q)	-1,50399	0,436077	-3,4489	0,013651	-2,57103	-0,43695	-0,75199	0,218039	-1,28552	-0,21847
(3)t, average service time of one point, min(L)	-4,99785	0,359752	-13,8925	0,000009	-5,87813	-4,11756	-2,49892	0,179876	-2,93906	-2,05878
t, average service time of one point, min(Q)	-1,76514	0,436077	-4,0478	0,006743	-2,83218	-0,69810	-0,88257	0,218039	-1,41609	-0,34905
1L by 2L	0,34500	0,470218	0,7337	0,490794	-0,80558	1,49558	0,17250	0,235109	-0,40279	0,74779
1L by 3L	0,55500	0,470218	1,1803	0,282547	-0,59558	1,70558	0,27750	0,235109	-0,29779	0,85279
2L by 3L	-0,58000	0,470218	-1,2335	0,263526	-1,73058	0,57058	-0,29000	0,235109	-0,86529	0,28529

Fig. 1. Fragment of determining regression coefficients.

Table 3

Results of the analysis of variance (ANOVA) of the regression model of urban freight road transport productivity

Factor	SS	df	MS	F	p
Average technical speed (linear effect)	148,77	1	148,77	336,43	<0,001
Average technical speed (quadratic effect)	21,03	1	21,03	47,56	<0,001
Route length (linear effect)	54,15	1	54,15	122,46	<0,001
Route length (quadratic effect)	5,26	1	5,26	11,89	0,0137
Service time (linear effect)	85,35	1	85,35	193,00	<0,001
Service time (quadratic effect)	7,25	1	7,25	16,38	0,0067
(V\times L)	0,24	1	0,24	0,54	0,4908
(V\times t)	0,62	1	0,62	1,39	0,2825
(L\times t)	0,67	1	0,67	1,52	0,2635
Error	2,65	6	0,44	—	—

Also, based on the results of statistical processing of experimental data, a Pareto diagram of standardized effects was constructed (Fig. 2), which reflects the influence of the studied factors and their interactions on the productivity of urban freight transportation.

The analysis of the obtained results showed that the average technical speed of the vehicle (V) has the greatest statistically significant influence on transport productivity. The standardized effect of this factor is 18,34, which considerably exceeds the critical value at the significance level of $p = 0,05$. This indicates that vehicle speed is the dominant factor determining the productivity of the transportation process. An increase in the average technical speed reduces the duration of the transportation cycle, increases the number of trips completed during a working shift, and consequently improves vehicle productivity.

The second most influential factor is the average service time per delivery point (t), with a standardized effect of 13,89. This result confirms that reducing the time required for loading, unloading, and processing accompanying documentation is one of the most effective ways to improve the productivity of urban freight transportation.

The third statistically significant factor is the route length (L), with a standardized effect of 11,07. As the route length increases, the transportation cycle becomes longer, reducing the number of trips that can be completed during a working shift and, consequently, decreasing overall transport productivity.

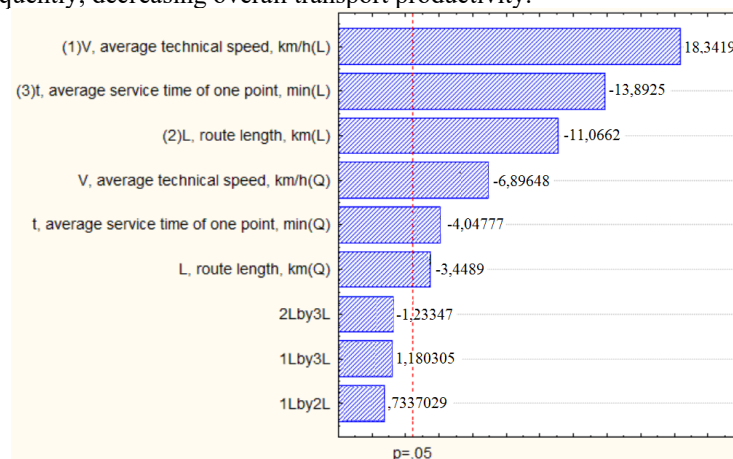


Fig. 2. Pareto diagram of standardized effects.

A notable feature of the obtained results is that the quadratic effect of the average technical speed (V^2) also exceeds the critical level of statistical significance, with a standardized effect of 6,89. This confirms the existence of a nonlinear relationship between average technical speed and transport productivity. From a practical perspective, this indicates that once a certain speed level is reached, further increases in speed no longer result in proportional improvements in productivity. Such behavior can be explained by the specific operating conditions of urban transportation, including traffic signal regulation, traffic congestion, speed limits, vehicle maneuvering, and other factors that restrict the effectiveness of further speed increases.

In contrast, the quadratic effects of route length (L^2) and service time (t^2) exhibit considerably smaller standardized effects (approximately 3,45–4,05) and do not reach the threshold of statistical significance. This suggests that, within the investigated ranges, the influence of these factors on transport productivity can be considered predominantly linear.

The interaction effects between the investigated factors are relatively small and do not exceed the critical significance level. This indicates that the influence of each organizational factor on transport productivity is manifested largely independently of the levels of the other factors.

From a practical standpoint, these findings suggest that the transportation process can be optimized by improving each factor individually, without the need to account for substantial interaction effects between them.

Based on the developed quadratic regression model, the optimization of the transportation process parameters was performed using the desirability function approach. The optimization results are presented in Fig. 3 in the form of predicted productivity profiles and the corresponding desirability function. The response surface plots illustrating the relationships between the investigated factors and transport productivity under the optimal operating conditions are presented in Fig. 4.

The analysis of the optimization profiles indicates that the average technical speed of the vehicle has the greatest influence on the productivity of urban freight transportation. As the speed increases from 16,6 km/h to approximately 35–38 km/h, the predicted productivity rises rapidly. Beyond this range, further increases in speed result in only marginal improvements in productivity, confirming the nonlinear nature of this relationship and agreeing with the significance of the quadratic term identified in the Pareto chart analysis.

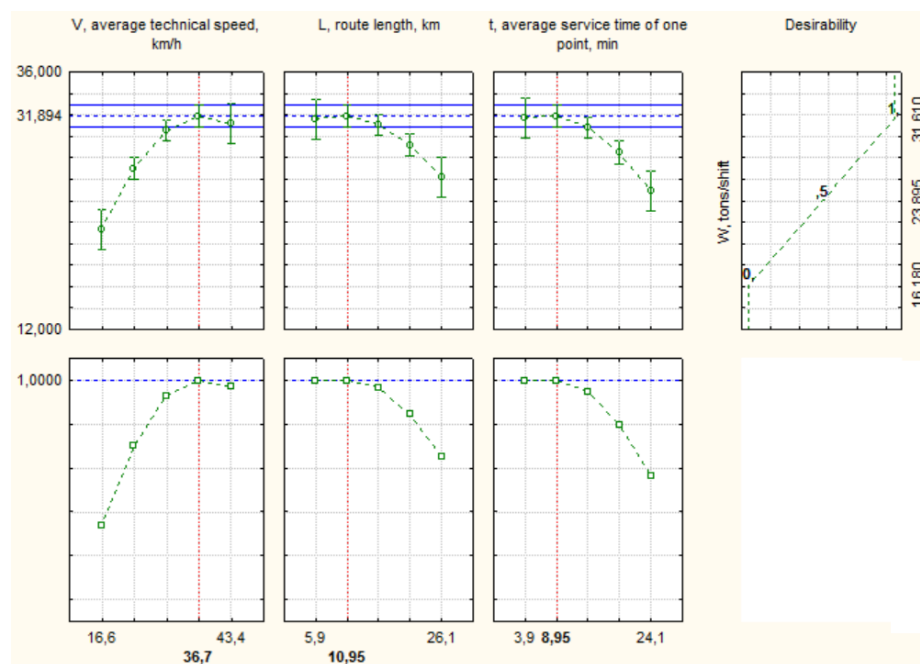


Fig. 3. Profiles for predicted values and desirability.

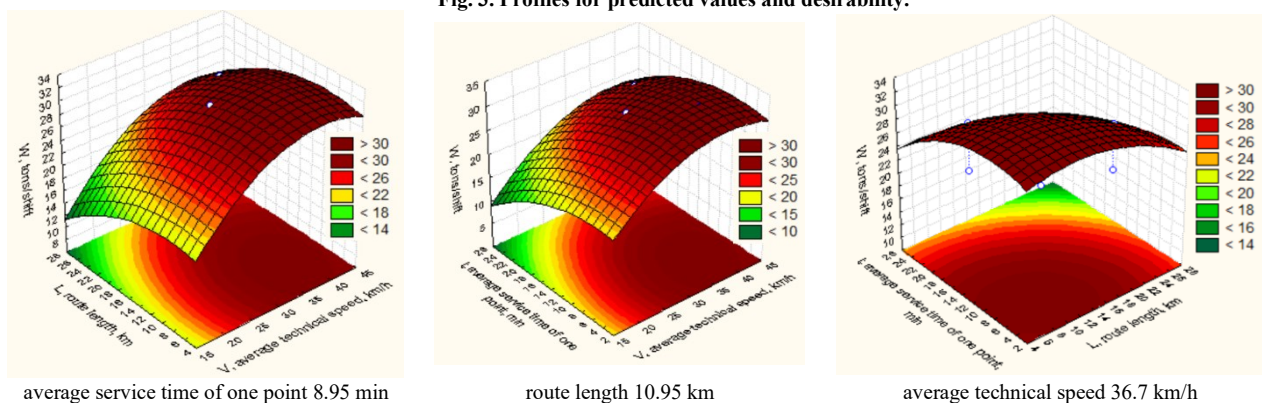


Fig. 4. Transportation performance surfaces at optimal factor values.

The influence of route length is negative. As the route length exceeds approximately 16–18 km, transport productivity gradually decreases because the transportation cycle becomes longer, reducing the number of trips that can be completed during a working shift.

A similar trend is observed for the average service time per delivery point. As the duration of loading, unloading, and related service operations increases, transport productivity decreases almost linearly. This behavior can be explained by the fact that unproductive vehicle downtime occupies an increasingly larger proportion of the available working time.

The desirability function, shown on the right-hand side of Fig. 3, demonstrates that the maximum desirability value is achieved under conditions of high predicted transport productivity. A desirability value approaching 1,0 indicates the optimal combination of the investigated organizational factors.

The optimization results indicate that the most efficient operating conditions for urban freight transportation correspond to the following parameter values:

1. Average technical speed of the vehicle: approximately 35–38 km/h.
2. Route length: 10–12 km.
3. Average service time per delivery point: 8–10 min.

Under these conditions, the predicted transport productivity reaches approximately 31–32 t/shift, corresponding to the maximum value of the desirability function.

Conclusions

Using a second-order Central Composite Design, the influence of the average technical speed of the vehicle, route length, and average service time per delivery point on the productivity of urban freight transportation in the city of Khmelnytskyi was investigated. A quadratic mathematical model adequately describing the transportation process was developed.

The study demonstrated that the average technical speed has the greatest influence on transport productivity, followed by the average service time per delivery point and route length. A statistically significant quadratic effect of vehicle speed was identified, confirming the nonlinear relationship between speed and transport productivity.

Based on the analysis of the response surfaces and the desirability function, the optimal transportation parameters were determined as follows: an average technical speed of 35–38 km/h, a route length of 10–12 km, and an average service time per delivery point of 8–10 min. Under these operating conditions, the predicted transport productivity reaches approximately 31–32 t/shift.

The developed mathematical model can be applied by transport enterprises to support decision-making regarding vehicle operating conditions, optimize urban freight transportation routes, and improve the overall efficiency of the transportation process.

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