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Research paper

Economic and Mathematical Modeling of the Quality of Services Provided by the Urban Passenger Transport Infrastructure Using Nonfinancial Indicators

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Abstract

The article reviews the issues of justifying the expediency of using financial indicators to assess the quality of passenger transportation and identification of the main factors that influence the quality of transportation. An economic and mathematical model of the passenger transportation quality using nonfinancial indicators was developed in the study.
It was proposed to use a mathematical toolkit of the theory of queuing systems (QS) to study the operation of the route of the urban passenger transport system (UPTS).

Keywords: *economic and mathematical modeling, economic and mathematical model, urban passenger transport system, vehicle unit, integrated indicator of the service quality, nonfinancial indicators.*

1. Introduction

The breakeven and high-quality operation of transport enterprises should rely on constant monitoring of the appropriate satisfaction of demand for transportation. The quality of passenger service depends on the arrangement of the transport process, operational characteristics of the rolling stock, condition of the road and route networks, urban planning, and other factors, which has a direct impact on the travel time, convenience and comfort of the trip and the level of fares.
The analysis of the studies indicates the imperfection and labor intensity of a comprehensive assessment of indicators related to the passenger service quality and the possibility of their constant control, as well as the lack of quantitative assessment approaches to quality violations with respect to each stopping point and time ranges [1, 2, 3].
The issues of rational arrangement of the route operation that would consider for interests of both carriers and passengers, which would ensure the quality of passenger transportation and the opportunity to influence and control it, have not been studied sufficiently and are a priority area of the scientific research.
At the same time, the existing approaches to quality management and its normative evaluation do not give an idea of the elements of the transportation service, which is complex and consists of the following options: time and comfort of waiting at the stop, compliance with the law and the rights of commissionary passengers when boarding a vehicle unit (VU), comfortable accommodation conditions in the vehicle on the route legs, road safety, economically justified fare (tariff value), creation of an enabling environment for people with special needs, availability of information about the route at the stop and during the trip, service culture, etc.
The goal of the study is to develop a scientifically based approach to the establishment and use of a cost estimate of the quality deviation from the target at the route of the urban passenger transport system (UPTS) based on nonfinancial indicators.

2. Theoretical Justification of the Model of the UPTS Service Quality

The Balanced Scorecard (BSC) concept developed by Robert Kaplan and David Norton expanded the criteria in the analysis by adding nonfinancial indicators [4, 5]. In practice, this approach allows to expand the volume of information underlying managerial decision-making.
This study will cover the following list of nonfinancial indicators, which further serve as the basis for calculating an integrated value aimed at reflecting the service quality:
– increase in the waiting time for the vehicle unit (VU) by passengers at the stops along the route, depending on the adjustment in the traffic interval relative to the target, pass.×hour;
– passenger-kilometers of the route legs in uncomfortable conditions (when the occupancy factor exceeded the target), pass.×km;
– increase in the travel time of passengers due to deceleration of the VU operation (for example, due to difficult road conditions), pass.×hour;
– denial in boarding the VU at the stop along the route due to its overfilling, pass.; and

– replacement of the VU model serving a certain route for another VU with a lower passenger capacity.

The analysis of the UPTS route operation indicates that it is a complex QS, the characteristics of which in dynamics can be reproduced only in simulation modeling. In the QS terminology, passengers are transactions arriving to stops (queuing), and the passenger vehicle is a service device (or a server) with a number of channels equal to passenger capacity. The vehicle moves sequentially from the first stop to the last, ensuring the processes of embarking and disembarking passengers according to the existing parameters of the passenger traffic at stops, which depend on the season, the day of the week (business day or weekend), and the time of the day. The key managed characteristic of the VU movement is a traffic interval. The traffic interval, along with the factory passenger capacity of the VU, its occupancy at the time of arrival to the next stop, and the parameters of the passenger flow of that stop describe the quality of passenger service at the stop.

The quality of passenger transportation is better satisfied when the traffic interval is reduced. As such, the interests of the carrier and passengers in relation to the VU traffic interval are opposite. The carrier increases its revenue when the interval increases, while the rights of passengers are more fully satisfied when the traffic interval is reduced.

To harmonize the interests of the carrier and passengers, the optimal interval for the movement of the VU of a certain brand, which operates on a certain route in a certain time of the day and at which the carrier gives up some share of its revenues in order to reduce the economic losses of passengers associated with the waiting for VU, should be found so that their total losses in monetary terms have been the least. The optimal traffic interval of the VU should be found in the $I_{\min} \div I_{\max}$ range. The interval $I_{\min}$ is the smallest interval where the economic interests of the carrier are still met. The interval $I_{\max}$ is the maximum traffic interval where the rights of passengers are still met.

3. The Model of the UPTS Service Quality using Nonfinancial Indicators

The optimal interval among many possible VU traffic intervals on the urban passenger route in the time of the day range is found using the criterion for choosing the optimal interval:

$$Q_{\Sigma}(I) = Q_{car}(I) + Q_{pas}(I) \to \min, I \to I_{opt}, \tag{1}$$

where $Q_{car}(I)$ is the dependence of the carrier's loss of the excess inclusion income from the operation of a certain brand of the VU, which operates on a certain route in a certain range of time of the day from the traffic interval; $Q_{pas}(I)$ is the dependence of the cost estimate of passengers' losses from waiting for boarding the VU from the traffic interval; and $Q_{\Sigma}(I)$ is the total cost of losses of the carrier and passengers.

At the same time, typical violations of the traffic timetables are the following: nonarrival of the VU to the route, withdrawal of the VU from the route, and arrival of the VU to a stop earlier or later than planned. The former two violations are recorded as violations only if the deviation from the planned time of the VU arrival to a stop exceeds a certain time interval (for example, ±2 minutes). The specified permissible deviation Δ from the traffic timetable should be found along with the calculation of the optimal interval for each of the time of the day ranges on the route according to the following expression:

$$\Delta i_{m,k} = \frac{i_{m,k,\max} - i_{m,k,opt}}{2} \tag{2}$$

where: $i_{m,k}$ is a given acceptable deviation of the traffic interval for each k-th time of the day range on the route m; $i_{m,k,max}$ is the maximum value of the traffic interval for the k-th time of the day range on the route m which lacks violations of the passenger rights; and $i_{m,k,opt}$ is the optimal value of the traffic interval for the k-th time of the day range on the route m.

The physical content of the indicator $\Delta i_{m,k}$ must be emphasized. The specified acceptable deviation from the planned traffic interval is a deviation which lacks violations of passenger rights and economic interests of the carrier in relation to the current and next runs on the route. As such, this indicator limits adjustments in the start of the current run, indicating that these adjustments violate two optimal intervals: of the current and the next runs. In this case, this pair of intervals will always be adjusted in such a way that one of them will increase and the other will decrease by the value $\Delta i_{m,k}$. The economic interests of the carrier will not suffer, because the revenue from the run with a smaller interval will decrease by the same amount that it will increase for a run with a larger interval. As for the passenger rights, they will not be violated either: the quality of passenger transportation will increase for a run with a smaller interval and decrease for a run with a longer interval. But this decrease in the service quality lies within the acceptable range (passenger rights are not violated).

It must be noted that all factors of the negative impact on quality are normally manifested through adjustments in the planned timetable for the VU operation on the route. For example, the no-navailability of a VU on the route due to a technical malfunction leads to the exclusion of all runs of that VU from the planned timetable, and the violation of the start time of the run adjusts the traffic interval of the VU that performs the next run. The adjusted start of runs on the route results in the violation of the passenger rights due to the increase in the number of passengers at the stops and due to the increase in the number of passengers in the VU cabin on the route legs. If an increase in the number of passengers at the stops increases the waiting time for the VU by passengers, an increase in the number of passengers in the VU cabin worsens the comfort of their transportation on the route legs.

The reasons for the timetable violations may differ, but all of them result in violations of the passenger rights.

Now let us define indicators reflecting the quality of the UPTS route runs operation in case of violation of the planned timetable.

It is proposed to use three nonfinancial indicators for the quantitative assessment of passenger rights violations caused by the timetable violation, namely: the total number of passengers who were denied boarding the VUs that operated on the route over the day due to their overfilling; the total waiting time for the VUs by passengers associated with the timetable violations; and total passenger-kilometers of the route legs in uncomfortable conditions (when the occupancy factor for the VU cabin exceeded the target).

The total number of passengers boarding the VUs that operated on the route over the day due to their overfilling Pmdenial can be found using the following expression:

$$P_m denial = \sum_{j=1}^{N^A} \sum_{i=1}^{K} P_{i,j} denial, \tag{3}$$

where N^A is the number of actually performed runs on the route over the day; K is the number of stops on the route, and $P_{j,i} denial$ is the number of passengers who were denied boarding the VU due to its overfilling at the stop I during the run J.

The total waiting time of VUs by passengers ΔQ_{nar} associated with violations of the traffic timetable for all runs on the route over the day is found using the following formula:

$$\Delta Q_{viol} = Q_{actual} - Q_{target}, \tag{4}$$

where Q_{actual} is the total waiting time for the VU by passengers over the day relative to the actual traffic timetable for the route, which differs from the target timetable, pass.×hour; Q_{target} is the total waiting time for the VU by passengers over the day at the stops along the route when the traffic is as scheduled, pass.×hour.

The following expression is used to find Q_{target}:

$$Q_{target} = \sum_{j=1}^{N^T}\sum_{i=1}^{K}\left(\frac{t^T_{j+1,i} - t^T_{j,i}}{2}\right)P^T_{j+1,i}, \quad (5)$$

where NT is the number of scheduled runs on the route over the day; $t^T_{j+1,i}$ is a target arrival time of the VU operating $j+1$ run, for the i stop, hour; $t^T_{j,i}$ is a target arrival time of the VU operating run j,i stop, hour; $P^T_{j+1,i}$ is the average number of passengers arriving at stop i in the time interval $t^T_{j+1,i} - t^T_{j,i}$, people.
The following expression is used to find Q_{actual}:

$$Q_{actual} = \sum_{j=1}^{N^A}\sum_{i=1}^{K}\left(\frac{t^A_{j+1,i} - t^A_{j,i}}{2}\right)P^A_{j+1,i} + \sum_{j=1}^{N^A}\sum_{i=1}^{K}\left(\frac{t^A_{j+1,i} - t^A_{j,i}}{2}\right)P_{j,i}denial, \quad (6)$$

where $t^A_{j+1,i}$ is the actual arrival time of the VU operating $j+1$ actual turnaround run, for the i stop, hour, $t^A_{j,i}$ is the actual arrival time of the VU operating j actual turnaround run, for the i stop, hour; and $P^A_{j+1,i}$, is the average number of passengers arriving at the stop i in the time interval $t^A_{j+1,i} - t^A_{j,i}$, people.
The cost estimate of the time spent by passengers on waiting for the VU due to a violation of the traffic timetable on the route over the day can be found using the following formula:

$$S_1 = C_{tar} \cdot \Delta Q_{viol}, \quad (7)$$

where C_{tar} is the hourly tariff rate of the passenger waiting for transport, rub./hour.
The total passenger-kilometers on the route legs with violation of the comfort of the trip K_{viol} are found using the following formula:

$$K_{viol} = \sum_{j=1}^{N^A}\sum_{i=1}^{K} P^a_{j,i} I_{i,i+1} \quad (8)$$

$$P^a_{j,i} = \begin{cases} P^a_{j,i}, Y_{target} < Y_{j,i} \le Y_{\max} \\ 0, Y_{j,i} \le Y_{target} \end{cases}$$

where $P^a_{j,i}$ is the number of passengers in the VU that departed from the i stop on the route during the j actual run, pass.; $I_{i.i+1}$ is a distance between stops i and $i+1$, km; Y_{target} is the static occupancy rate, or the maximum value at which comfortable travel of passengers is ensured, $Y_{j,i}$ is a static rate of the VU occupancy after departure from the i stop when performing the j actual run; and $Y_{\max}$ is the maximum value of the static rate of the VU occupancy, at which new passengers cannot embark.
The cost estimate of the violation of passenger rights during the VU transportation along the route with the excess of the static rate of the VU occupancy S_2 is found using the following formula:

$$S_2 = \frac{C_{pas} \cdot K_{pas} \cdot K_{viol}}{L_{t.d.}}, \quad (9)$$

where C_{pas} is the fare for transportation of 1 passenger on the route, rub./pass; $L_{t.d.}$ is an average distance traveled by passengers on the route, km; and K_{pas} is the rate of fare usage for transportation of 1 passenger on the route.
As such, the total cost estimate of violations of the rights of passengers on the route per day is found using the following formula:

$$S_{sum} = S_1 + S_2. \quad (10)$$

It must be emphasized that the assessment of the passenger transportation quality on the urban passenger transport route is only possible when the actual operation of the VU on the UPTS route is compared with the optimal traffic timetable that serves as a standard, where there are no violations of passenger rights.
The introduction of the proposed indicators allows to schedule optimal runs of the urban passenger transport route and to assess the quality of passenger transportation during the route operation.
Finding the cost estimate of the level of poor-quality transport services (10) allows to propose the following ratio as a measure of the transport service efficiency:

$$K_{ef} = \frac{1}{1 + \frac{S_{sum}}{C + T + I - R_I}}, \quad (11)$$

where C is a full cost price of transportations of all categories of passengers by the corresponding transport enterprise (rub.); T is target revenues (rubles); I is an investment component used to finance the upgrading of passenger vehicles in accordance with the adopted local transport development programs under the established procedure at the expense of enterprises involved in carrying passengers by public transport (bus, trolley, tram, subway) and on principles of the capital return; and R_I is revenues from other operational activities net of the target financing associated with operational activity (rub.).
If the passenger rights are not violated, the factor of the transport service efficiency is equal to one; otherwise, if there are any violations, it takes values from 0 to 1.

4. Conclusion

The concept of the passenger transportation quality in the case of the optimal route organization focuses on the elimination of passenger rights' violations as a resultant indicator, which serves as a generalization of the grounds for the provision of services, namely: the total number of passengers who were denied boarding the VUs operating on the route over the day due to their overfilling, the total waiting time for the VUs by passengers associated with violations of the timetable, and total passenger-kilometers of the route legs in uncomfortable conditions (when the rate of the VU occupancy exceeded the target).
The concept of the transport service efficiency factor is the ratio of the result and costs in the implementation of the transportation process and allows to quantify its efficiency.
The conducted study resulted in the generalization of the developed methodological approaches to the assessment of the passenger transportation quality through the introduction of an integral indicator of the passenger service quality, which is the sum of the cost estimates of such nonfinancial indicators as the total waiting time for the VUs by passengers at the route stops and total passenger-kilometers of the route legs in uncomfortable conditions for traveling passengers.
This allows to solve the following tasks: reconciling the economic interests of carriers and the social interests of passengers, developing tariffs, determining the amount of compensation for carriers of communal ownership for transporting commissionary passengers, reducing subsidies to the communal carrier for the reduced quality of transportation of commissionary passengers, etc.

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