Analysis effectiveness functioning urban transport system based on the duration of the movement

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Abstract. The article deals with the analysis of the effectiveness of the functioning of the urban transport system based on the dependence of the duration of movement. An important characteristic of the quality of the system is the reliability and comfortable conditions of movement. In turn, such indicators as travel time and «buffer» indices, «buffer» time are used to assess the degree of reliability. To calculate the indicators, it is necessary to conduct studies of the modes of movement of public transport and the car-laboratory in the context of varying load on the road network. Based on the available data, functional dependencies have been established that allow determining the duration of movement of public transport depending on the duration of the car-laboratory movement. The result of the study is a developed methodology for assessing the functioning of the transport system.

1. Introduction
In the conditions of high competition, urban public passenger transport should have high reliability and provide comfortable conditions for movement, which will enhance its attractiveness as compared to individual road transport. In practice, the reliability of the transport network is assessed by compliance with the timetable and regularity of traffic, for which the normalization of speeds on routes is carried out. In this case, the greatest difficulty is the prediction of reliability with an increase in the load level of the road networks, which does not always allow us to obtain an estimate of the required accuracy.

Research into the reliability of transport systems is limited by the lack of data that is not always possible to obtain, without using modern technologies. An alternative method of collection is to conduct field surveys that are costly and time-consuming projects. With the development of geoinformation technologies, there are opportunities to obtain data on the characteristics of traffic flow in real time. To assess the reliability of the functioning of urban transport systems, GLONASS and GPS equipment tracks can be used [1].

As part of the analysis of the effectiveness of the functioning of the urban transport system based on the dependence of the duration of movement: we single out the criteria for evaluating the reliability of operation; establish the relationship between the duration of the movement of the car-laboratory and the duration of movement of the rolling stock. If you don’t wish to use the Word template provided, please use the following page setup measurements.

2. Theoretical basis
To assess the degree of reliability of the functioning of the urban transport system based on the duration of the movement, the following indicators are used [2, 3, 4]:
• **Travel Time Index (TTI)** allows to evaluate the impact of load on traffic conditions and is determined by the ratio of the average duration of the movement (\(TT_{50\%}\)) at a certain time of day to the duration of movement under free flow conditions (\(TT_{15\%}\)):

\[
TTI = \frac{TT_{50\%}}{TT_{15\%}},
\]

where \(T_{50\%}\) – average time of movement on a certain site, min; \(T_{15\%}\) – time of movement in conditions of free flow, min;

• **«Buffer» Time (BT)** estimated as the additional time required to reach the destination with a given reliability, for example, with a reliability of 90% or 95%. Accordingly, \(BT\) is defined as:

\[
BT = TT_{90\%}/95\% - \bar{T},
\]

where \(TT_{90\%}/95\%)\) – duration of movement with a reliability of 90% / 95%, min; \(\bar{T}\) – average duration of movement, min.

• **«Buffer» Index (BI)** relative indicator, expressed as a percentage and its value increases with decreasing reliability and is determined by:

\[
BI = \frac{BT}{\bar{T}} \times 100%,
\]

Figure 1 shows the main parameters of the reliability of the functioning of urban passenger transport using the indices presented above. The parameters for assessing the reliability include: a set of statistical data (minimum, average values), «buffer» time, 95% coverage of the duration of movement.

![Figure 1. The main parameters for estimating the travel time index TTI, «buffer» time BT, and «buffer» index BI.](image)

3. **Experimental studies traffic flow simulation**

The method of data collection is as follows: experimental studies are performed using individual vehicles equipped with a GPS navigator [5]. The resulting tracks of the car include information about time and speed of movement on the route geographically referenced to the terrain. In the course of further data processing, a variational set of durations of movement along the route under investigation was found at various periods. The total travel time on the route is affected by the change in travel time at the site in. The variation is proportional to the time of arrival at the stopping points length of the route (Figure 2). Thus, the assessment of reliability using geo-information technologies is based on the analysis of variations in the duration of movements [6, 7, 8].
Figure 2. Variation of the duration of the route.

The purpose of processing each track was to obtain the parameters: the length of the route (km); total driving time (min), which includes time in motion and downtime; maximum and average speeds; as a result, a database on the duration of movement was formed [9]. Two methods for collecting information on the duration of the route:

- data collection from public transport equipped with on-board satellite equipment;
- data collection using the car-laboratory using GPS-navigator.

Statistical data processing allowed to obtain the following indicators, reflected in Table 1.

Table 1. Statistical characteristics of the duration of the route.

| Statistics                       | Car-laboratory | Public transport |
|----------------------------------|----------------|-----------------|
| Sample size, number of tracks    | 80             | 354             |
| Minimum value, min               | 30.28          | 43.17           |
| Maximum value, min               | 42.05          | 58.52           |
| Variation range, min             | 11.77          | 15.35           |
| Average value, min               | 34.26          | 48.32           |
| Coefficient of variation, %      | 6.97           | 4.54            |
| Standard deviation, min          | 2.39           | 2.19            |
| Error estimating average, min    | 0.27           | 0.12            |

Data collection on the duration of public transport was carried out using the system of satellite monitoring and control of transport «POTOK», which was tested in the city of Angarsk [10]. With the help of equipment information about the duration of movement along the route, the time of staying at stopping points was obtained.

Figure 3 shows the distribution of values of the variation range of the duration of movement by the hour of the day. The values of the variations in the duration of the movement suggest that the survey covers a wide range of traffic flow conditions.
The next step is to establish the relationship between the duration of the movement of the public transport and the automobile laboratory. Among the dependencies considered are linear, power, and exponential (Table 2).

Table 2. The dependence of the duration of the movement of the car-laboratory and public transport.

| Period                        | Car-laboratory – Public transport | Car-laboratory in free flow conditions – Public transport | Car-laboratory – Public transport | Car-laboratory in free flow conditions – Public transport |
|-------------------------------|-----------------------------------|----------------------------------------------------------|-----------------------------------|----------------------------------------------------------|
| Weekdays peak period         |                                   |                                                          |                                   |                                                          |
| Linear dependence            | $y = 0.9833 + 1.1663x$            | $y = 5.1722e^{0.0669x}$                                  | $y = 1.7157x^{0.87}$              |                                                          |
| Exponential dependence       | $R^2 = 0.9650$                    | $R^2 = 0.8747$                                          | $R^2 = 0.9542$                    |                                                          |
| Power dependence             |                                   |                                                          |                                   |                                                          |
| Weekdays off-peak period     |                                   |                                                          |                                   |                                                          |
| Linear dependence            | $y = 0.2609 + 1.5242x$            | $y = 4.9704e^{0.0873x}$                                  | $y = 1.6284x^{0.98}$              |                                                          |
| Exponential dependence       | $R^2 = 0.9280$                    | $R^2 = 0.8705$                                          | $R^2 = 0.9091$                    |                                                          |
| Power dependence             |                                   |                                                          |                                   |                                                          |
| Weekend                       |                                   |                                                          |                                   |                                                          |
| Linear dependence            | $y = 0.9078 + 1.1967x$            | $y = 4.5499e^{0.0752x}$                                  | $y = 1.3828x^{0.97}$              |                                                          |
| Exponential dependence       | $R^2 = 0.9662$                    | $R^2 = 0.8562$                                          | $R^2 = 0.9468$                    |                                                          |
| Power dependence             |                                   |                                                          |                                   |                                                          |
| Car-laboratory – Public transport | $y = -0.2463 + 1.4831x$       | $y = 4.2392e^{0.0931x}$                                  | $y = 1.2709x^{1.05}$              |                                                          |
| Car-laboratory in free flow conditions – Public transport | $R^2 = 0.9871$                  | $R^2 = 0.8723$                                          | $R^2 = 0.9725$                    |                                                          |

The high quality of linear regression models, for which the calculated coefficients of determination ($R^2$) exceed the value of 0.9 for all cases, have been experimentally confirmed. The final choice of the results of experimental studies was made in favor of a linear function, based on a higher value of the coefficient of determination.

The obtained linear equations for peak and inter-peak periods of weekdays (Formulas (4, 5)) and for weekends (Formula (6)) have a high approximation quality, the coefficients of determination $R^2 > 0.9$ (Figure 4).
Figure 4. Graphs of the duration of the movement of public transport and the car-laboratory.

The dependences of the duration of the movement of public transport ($T_{bus}$) and car-laboratory ($T_a$):

- on weekdays peak period (Figure 4, a):
  $$T_{bus} = 0.7891 + 1.1741 T_a, R^2 = 0.9701;$$  
  \( (4) \)

- on weekdays off-peak period (Figure 4, b):
  $$T_{bus} = 0.7307 + 1.2043 T_a, R^2 = 0.9711;$$  
  \( (5) \)

- at the weekend (Figure 4, c):
  $$T_{bus} = 0.9705 + 1.1493 T_a, R^2 = 0.9705.$$  
  \( (6) \)

Based on the obtained statistics on the duration of the movement, an estimate of the travel time index in the daily interval was made (Figure 5).
Figure 5. The values of the travel time index in the daily interval.

The evening peak period (from 16 to 17 o’clock) is pronounced, in which the value of the TTI for the car-laboratory reaches 1.16, and for the public transport – 1.14, i.e. peak travel time is 14-16% longer than in free flow conditions. The value of the travel time index in the morning peak period varies in the range from 1.10 to 1.11. The minimum value of the travel time index (1.02 – 1.03) of the automobile laboratory is typical for the inter-peak period in the morning for 10 o’clock, in the evening from 19 o’clock to 21 o’clock. The minimum value of the travel time index (1.05 – 1.06) of the public transport at 8 and 15 o’clock.

On the basis of the obtained data on the duration of movement, the travel time, «buffer» indices and the «buffer» time were also estimated in the weekly interval (Table 3).

Table 3. The values of reliability criteria based on the results of surveys on weekdays and weekends.

| Day of the week | Car-laboratory | Public transport |
|-----------------|----------------|-----------------|
|                 | TTI  | BT  | BI  | TTI  | BT  | BI  |
| Mon             | 1.05 | 5.3 min | 11.34% |
| Tue             | 1.04 | 4.8 min | 10.41% |
| Weekdays Wed    | 1.07 | 4.57 min | 13.40% |
| Thu             | 1.04 | 7.1 min | 15.17% |
| Fri             | 1.03 | 5.5 min | 11.89% |
| Weekend Sat     | 1.09 | 3.43 min | 10.04% |
| Sun             | 1.03 | 3.1 min | 6.57% |

| Main statistical indicators |        |
|-----------------------------|--------|
| Dispersion                  | 0.01   |
| Standard deviation          | 0.03   |
| Average grade error         | 0.01   |

As part of our study, we used methods of mathematical statistics and methods for constructing interval estimates using \( q \)-quantiles. The level quantile \( q \) of a continuous random variable with a continuous distribution function is the possible value of a random variable for which the probability of an event is equal to a given value of \( q \).

Due to the representativeness of the studied samples based on the data obtained, a classification of the reliability of the public transport operation based on quantiles of 25, 50 and 75% distributions, which are the limits of the reliability levels (Figure 6) of the considered indicators (Table 4), is substantiated.

Figure 6. Estimated scale of reliability of the route, based on quantiles of distribution of 25, 50 and 75%.

The reliability levels of the operation of the public transport route are presented in table 4. They are divided into 4 levels of reliability A, B, C, D, depending on the values of the travel time and buffer indices. Level A – during peak periods, there is no deterioration in driving conditions; level B – during peak periods there is a slight deterioration in traffic conditions; level C – during peak periods, there is a deterioration of traffic conditions; the D level – during peak periods of the public transport is not functioning reliably. Thus, level A corresponds to the best traffic conditions on the city’s road networks, and level D corresponds to congestion.
Table 4. Reliability levels of the operation of the public transport route.

| Reliability level | Value travel time index $TTI$ | Value «buffer» index $BI$ | Driving conditions |
|-------------------|-------------------------------|--------------------------|--------------------|
| A                 | $<1.03$                       | $<8\%$                   | during peak periods, there is no deterioration in driving conditions |
| B                 | $1.03–1.05$                   | $8–11\%$                 | during peak periods, there is a slight deterioration in driving conditions |
| C                 | $1.05–1.07$                   | $11–15\%$                | during peak periods, there is a worsening of traffic conditions |
| D                 | $>1.07$                       | $>15\%$                  | during peak periods, the public transport is not functioning reliably |

4. Conclusion

As part of the survey, a methodology for assessing the functioning of the urban transport system using geo-information technologies was formulated, which consists of the following steps: collecting tracks about the duration of movement in the surveyed route sections; exporting track characteristics to a database; analysis of motion characteristics with the identification of dependencies «distance – time»; assessment of the duration and changes in the speed of movement with the use of statistical data processing.

The obtained dependences between the characteristics of the tracks of the car-laboratory and the public transport (Formulas (4–6), Figure 4) prove the possibility of practical use of the proposed methodology for assessing the functioning of the transport system.

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