Evaluation of the efficiency of the road network functioning

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Abstract. Road transport has an impact to one degree or another on the life of every person. The article discusses approaches to assessing the costs caused by the deterioration of traffic conditions, which are subdivided into individual and social ones. Assessment of total costs should be carried out when adopting traffic management measures. The proposed approaches made it possible to estimate the individual costs caused by traffic management measures using the city of Irkutsk as an example.

1. Introduction.
Traffic management, its analysis and assessment are relevant research topics for the past years [1-9]. Intensive growth in the level of motorization in the context of the little-changing capacity of the existing road network, especially in the areas of historical development, leads to a decrease in the speed of communication in certain sections of road network, which is associated with the emergence of the concept of “transport congestion”.

The term Congestion itself is borrowed from medicine and is used mainly in foreign specialized literature on the problems of urban road network functioning. Moreover, it is used in relation to both transport and the elements of transport infrastructure.

From the point of view of transport issues, the translation of the term Congestion into Russian is complicated, since this term refers to the set of states of the road network. The Joint Transport Research Center [10] provides the following definitions of the term “transport congestion” as:

1. The situation of excess demands for road space over supply.
2. Interference caused by vehicles against each other, in accordance with the dependence “speed-intensity” in conditions when the load on the road network approaches the value of its throughput.
3. The difference between the expected quality of the road network functioning and its real state.

Given the many formulations of the term, we can summarize them to the fact that the transport congestion is a load state of the road network, in which the volume of traffic approaches or exceeds the traffic capacity. [11]

The issue of the economic assessment of transport congestion is very important, since such an assessment will help in deciding on the need to introduce changes in the traffic organization on the city air traffic control and their consequences.

The term “transport congestion” describes the situation if the number of cars exceeds the capacity of the road. However, deterioration is possible not only in the case of such an excess, but also at a lower
traffic intensity, as well as in case of changing the parameters of the road network functioning (changes in speed growth regime, placement of artificial irregularities, etc.). In the framework of the study, not only transport congestion was considered, but generally the deterioration of traffic conditions and the costs due to them was considered.

2. Materials and methods.
The costs incurred because of a decrease in the speed of communication are the sum of the costs of traveling in free conditions and the additional costs caused by the deterioration of traffic conditions. The costs in this study are understood as additional costs. Costs are borne by both road users and other people, companies and the environment.

Costs are divided into individual costs incurred by the participants in the movement, and social costs or negative impacts incurred by enterprises, the environment and other persons not involved in road traffic. The cost structure is given in table 1. It should be understood that some types of impacts can not always and not in full be compensated. Costs (financial losses) can also include lost revenue, for example, transport and logistics companies, taxi services and other organizations whose performance is reduced due to the deterioration of traffic conditions in urban road network.

| Table 1. The structure of individual and public costs |
|------------------------------------------------------|
| Individual expenses | Public expenses |
| 1. The time spent on movement; | 1. The cost of maintaining roads; |
| 2. Direct travel costs (fuel, etc.); | 2. Environmental impact; |
| 3. Indirect travel expenses (wear of parts, deterioration of clothing, etc.); | 3. Impact on the psychophysical state of others (noise, dust, dirt, etc.); |
| 4. Psychophysical costs; | 4. Probability costs (for example, the risk of an accident, etc.); |
| 5. Probable costs (for example, the risk of being late, the risk of pickpocketing in public transport, etc.); | 5. Financial losses. |

Cost estimation can be carried out both for each participant in the movement, and for road network as a whole, and the total individual and social costs can be determined according to (1, 2).

\[
C_{\text{ind}} = C_{\text{time}} + C_{\text{dir}} + C_{\text{indr}} + C_{\text{indpph}} + R_{\text{ind}} + LR_{\text{ind}} \quad (1)
\]

\[
C_{\text{pub}} = C_{\text{road}} + C_{\text{eco}} + C_{\text{pubpph}} + R_{\text{pub}} + LR_{\text{pub}} \quad (2)
\]

Each of the presented indicators can be determined on the basis of different approaches and have its individual dimension, for example, time costs are more easily estimated in seconds (minutes, hours), while direct costs are in rubles, and environmental impact can be estimated in m³ of pollutants.

The calculation of total costs is possible in case of their economic evaluation by bringing all indicators to a single dimension – rubles.

Since in this study, costs are understood as additional costs caused by the deterioration of traffic conditions, such additional costs are the difference between the actual costs incurred and the potential costs that could be incurred in case of better conditions for the operation of the road network, for example, in the case of cars moving in free conditions.

\[
C_{\text{add}} = C_{\text{fact}} - C_{\text{ff}} \quad (3)
\]
For example, the time spent on traveling in the investigated road network section, caused by the deterioration of traffic conditions, is the difference between the actual duration of movement and the duration of movement in free conditions, can be graphically represented by a hatched figure, Figure 1.

\[
\text{Figure 1. Time costs of traffic participants caused by difficulty in traffic conditions}
\]

Despite the apparent simplicity, the assessment of each of the indicators is very labor-intensive, since it requires the collection and processing of a large amount of data, individual indicators may be excluded from the estimated total costs, for example, the collection of data that is impossible or time-consuming and can be carried out in terms of aggregate and in terms of individual indicators.

3. Results and discussion.

The total costs incurred when traveling by road network by all participants for each type of cost represent the sum of the costs incurred by each participant in the road traffic and the amount of costs attributable to social impact, and can be represented graphically (Figure 2), where \(N\) is the traffic intensity vehicles in the road network section during the day \(T\), and \(i\) is the unit cost per vehicle, and it is assumed that the peak unit costs occur during peak periods of intensity.

Since the process of moving cars is continuous, the total costs will be determined by the volume of the figure shown in Figure 2, which is defined as:

\[
C_{tm} = \iiint dC dN dT
\]

(4)

In discrete form, total costs can be defined as a sum of individual and public costs (5). Such data can be obtained on the basis of geographic information received from road users.

\[
C_{tm} = \sum_i C_{ind_i} + \sum_i C_{pub_i}
\]

(5)
If it is necessary to calculate the total costs attributable to one road user, a number of questions arises when dividing public costs, since each participant has a different effect. It implies that the procedure for calculating the share of public expenses per 1 road user, requires a detailed analysis based on research and may be the subject of a separate study.

The assessment of individual costs is intuitively made by each participant in the road traffic and affects the choice of time for the start of movement, and the assessment of public costs in existing sections of the CDS should be carried out by state and municipal authorities responsible for the SDE, and design organizations at the stage of designing new sections of the CDS.

An integrated assessment of some indicators can be carried out analytically based on regulatory or tabular data. Actual assessment can be applied on the basis of geoinformation data received from participants in the movement, for example, on the basis of data from the Avtodata platform project.

The deterioration of the conditions of movements, first of all, affects the time costs, their monetary value is complex and can be carried out on the basis of average specific earnings.

\[ C_{\text{time}_i} = \Delta T_i \cdot Sal_{i,\text{as}} \]  

In addition, it is possible to assess the impact, both in the context of persons involved in road traffic, and in the context of vehicles, while the total costs of each road user can vary even in a single vehicle. When assessing costs, you should also pay attention to the fact that the value of some costs can take zero or negative values, for example, a passenger who rested during the trip will have a negative value of the psychophysical costs of \( C_{\text{pph}} \), and those who did not pay for travel in public transport will not have direct costs.

Reducing specific public costs can be achieved using public transport. Public expenses are partially redistributed to the participants in the movement and are compensated by the state as taxes and other fees paid. Nevertheless, the psychophysical and environmental impact on the population remains uncompensated, so people who are not involved in road traffic are forced to bear the costs of road traffic on their own.

Since most of the movement to and from work falls on peak hours, a significant impact on the psychophysical state of people, as well as on the duration of rest, affects the duration of the trip.

Considering the described approach, it is possible to carry out an integrated assessment of the costs of movement, given below.

Figure 2. The total cost of movement on the road network
The effect of increasing the duration of movement on the mode of work and rest

Assuming an 8-hour working day with lunch, lasting 1 hour, as well as sleep, lasting 8 hours, the employee has 7 hours (420 minutes) per day to rest, carry out personal affairs and other activities. An increase in the duration of movement of only 10 minutes to and from work reduces the duration of the specified personal time by 4.7%, and the annual costs will be 4940 minutes or 82.3 hours, i.e. more than 3 days.

Using a similar valuation approach to commercial transportation, taking into account an 8-hour working day (480 minutes), reducing the duration of movement by 5 minutes will increase the efficiency of using working time by 1%.

Effect of 1 second delay

The traffic intensity in the sections of the road network changes during the day, for a more effective functioning, the traffic cycle of the traffic light object should be adjusted depending on the traffic intensity. Not on all traffic light objects, various cycles have been worked out in detail, depending on the time of day and the day of the week. In addition, in order to increase the efficiency of traffic management, it should be possible to temporarily change the regulation cycles in connection with a change in traffic intensity, for example, for the period of repair work, or in connection with a significant decrease in the intensity of both automobile and pedestrian traffic, for example the period of self-isolation of citizens for the reason caused by COVID-19.

The incorrect operation cycles of traffic lights can have a negligible effect on every road user. However, even a slight effect can be significant in cities. The population of the city of Irkutsk is about 623.5 thousand people. Daily average additional travel costs of only 1 second per city resident lead to a total time cost of more than 173 hours a day or more than 63 thousand hours (7.2 years) per year.

Environmental impact assessment

In accordance with GOST R 56162-2014 [12], in calculating of the mileage emissions of pollutants by road, a coefficient is used that takes into account the change in the amount of pollutants emitted depending on the average speed. When driving speed decreases from 60 to 30 km/h, this coefficient increases from 0.3 to 1, that is, emissions (excluding NxO) increase by 3.3 times, that is, there is more than 3-fold increase in environmental load per account of pollutants emitted, and when the speed decreases to 5 km/h from 0.3 to 1.4, that is, more than 4.6 times.

Thus, congestion not only increases the duration of movement, but also significantly increases the load on the environment.

Direct cost estimate

Direct costs incurred by road users can be divided into fare (taxi or public transport) and their individual direct costs in the case of using your own car. The change in travel costs in the case of a fixed fare, calculated not according to the duration of travel, does not change in the case of an increase in travel time, however, these costs will be borne by the carrier and either already taken into account in the fare, or their cost will be transferred to the fare in future. A consolidated estimate of direct costs may be based on fuel consumption.

Fuel consumption largely depends on the type and condition of the engines of vehicles involved in the movement. At the first stage, in order to calculate the averaged minimum additional costs, the specific idle fuel consumption can be used. As shown in [13] the average fuel consumption on cars with a maximum carrying capacity of up to 3.5 tons is about 0.85-1.2 liters/hour or an average of 2.86 \cdot 10^{-4} liters/second. At a cost of 1 liter of AI-92 fuel in the city of Irkutsk, about 42 rubles per liter, the minimum cost per car will be 0.012 rubles per second or 43.2 rubles/hour.

To calculate the unit costs per person it is necessary to determine the average number of people per car. In many respects, this will depend on the availability of public transport in the road network surveyed area. For example, in Moscow, on average, from 1 to 1.7 people fall on 1 passenger car traveling along the road network, while taking into account the developed metro network and public transport.
transport in Moscow, which suggests that in cities where public transport is less developed, the number of people per 1 car traveling on CDS will be higher.

In addition, in some cases, for example, when calculating time costs, it is necessary to consider passengers of public transport. For our calculations of direct costs, we take the average value of 1.5 people per car. Thus, the unit cost per person will be 0.008 rubles per second, or 28.8 rubles/hour.

**Impact assessment calming traffic on roads is used to increase safety**

The adoption of measures to decelerate the movement is of a serious ethical nature, since it is assumed that, for the sake of the life and health of several people, others must sacrifice their time and health. For this reason, the choice of such measures must be approached reasonably. Measures of sedation include the installation of artificial irregularities and the reduction of speed limits on the sections of the road network, an assessment of the costs incurred by which will be given below.

**Temporary loss on artificial bumps**

In accordance with GOST R 52605-2006 [14], the speed of movement on artificial bumps should be reduced to 20 km/h. Assuming the maximum permissible speed \( V_0 = 60 \) km/h and acceleration during braking and acceleration \( a = 1.5 \) m/s\(^2\), the travel time during braking to \( V = 20 \) km/h will be:

\[
T = \frac{V - V_0}{a} = \frac{20}{3.6} - \frac{20}{1.5} = 7.4s
\]

A similar time will be required to accelerate to 60 km/h with the same acceleration, that is, the total cost of time will be about 14.8 seconds. In this case, the path \( l_1 \) traveled with a decrease in speed and the path \( l_2 \) traveled during its set will be 164.5 m:

\[
l_1 = V_0 \cdot t + \frac{a \cdot t^2}{2} = \frac{60}{3.6} \cdot 7.4 + \frac{-1.5 \cdot 7.4^2}{2} = 82.3m
\]

\[
l_2 = V_0 \cdot t + \frac{a \cdot t^2}{2} = \frac{20}{3.6} \cdot 7.4 + \frac{1.5 \cdot 7.4^2}{2} = 82.2m
\]

The same section of the track, in the absence of artificial irregularities, can be covered at a speed of 60 km/h in 9.9 seconds:

\[
t_{60} = \frac{l_1 + l_2}{V_0} = \frac{82.3 + 82.2}{60} = 9.9s
\]

Thus, the difference in the duration of the passage of the same section of passenger cars will be 4.9 seconds or about 0.5 hours per year. In the case of installing two artificial irregularities in a row, for example, as is done at pedestrian crossings with two-way traffic, in accordance with [14], the duration of movement will be longer.

**Exceeding the maximum allowed speed**

The maximum permitted speed on the roads of the Russian Federation is set in accordance with the traffic laws. Nevertheless, the technical capabilities of modern cars allow you to move at speeds higher than the established ones, and liability arises only when the permissible speed is exceeded by more than 20 km/h (non-fines), which many road users use, exceeding the maximum permitted speed is up to 20 km/h.
In connection with the discussed possibility of reducing the non-fined threshold, we can evaluate the effect of such a decrease on the duration of movement. A decrease in the non-fine amount of speeding will have a greater effect on the duration of movement in areas with a lower maximum permissible speed, Figure 3. Data on the change in the duration of movement for the most frequently set speeds on urban road network (40 and 60 km/h) are given in table 2.

![Figure 3. The dependence of the additional time spent on reducing non-fines over speed](image)

| Maximum permissible speed, km/h | Non-standard excess, km/h | Actual speed of movement, km/h | Duration of movement in a section with a length of 1 km, s | Increase in duration of movement, s |
|---------------------------------|---------------------------|-------------------------------|----------------------------------------------------------|-----------------------------------|
| 40                              | 20                        | 55                            | 65,5                                                     | 0                                 |
|                                 | 10                        | 45                            | 80                                                       | 14,5                              |
|                                 | 0                         | 35                            | 102,9                                                    | 37,4                              |
| 60                              | 20                        | 75                            | 48                                                       | 0                                 |
|                                 | 10                        | 65                            | 55,4                                                     | 7,4                               |
|                                 | 0                         | 55                            | 65,5                                                     | 17,5                              |

Lowering the non-fine threshold to 10 km/h will increase the duration of travel at a maximum speed of 40 km/h by 14.5 s/km, and at a speed of 60 km/h by 7.4 s/km.

Setting the maximum allowed speed

Another way to calm the movement is to reduce the maximum permitted speed in individual sections of the road network. Speed reduction is carried out, as a rule, in the emergency sections of the road network to increase safety. An assessment of such a regulatory impact is possible at the planning stage. As an example, we can evaluate the changes in the speed regime adopted in the fall of 2019 in the city of Irkutsk at the dam of a hydroelectric power station with a length of 2.5 km, where the maximum permitted speed was reduced from 60 to 40 km/h.

The traffic intensity at the dam of a hydroelectric power station can exceed 4,000 aut./h in peak periods, table 3.
Table 3. Traffic intensity on the dam of the hydroelectric power station in the city of Irkutsk, vehicle/hour

| Measurement Period              | Direction to st. Baikalskaya | General Intensity |
|---------------------------------|------------------------------|-------------------|
| in the morning rush hour        | 2370                         | 3234              |
| during the inter-peak period    | 1699                         | 2736              |
| in the evening rush hour        | 2124                         | 4074              |

By extrapolating the data on the intensity, it is possible to obtain estimated data on the daily intensity of movement at the dam of the hydroelectric station, table 4.

Table 4. Estimated data of the daily dynamics of traffic intensity at the hydroelectric station dam, in the city of Irkutsk

| Day period | 0:00-6:00 | 6:00-7:00 | 7:00-8:00 | 8:00-9:00 | 9:00-10:00 | 10:00-17:00 | 17:00-18:00 | 18:00-19:00 |
|------------|-----------|-----------|-----------|-----------|------------|-------------|-------------|-------------|
| Intensity  | 684       | 1492      | 2985      | 3234      | 2985       | 2736        | 3405        | 4074        |

There are no artificial irregularities, unregulated pedestrian crossings, or other objects affecting the speed of vehicles at the dam. Speed control is carried out using cameras that take into account both temporal and spatial speeds, which gives reason to believe that most of the participants in the movement observe the speed regime, taking into account the excess of speed by a non-punishable value.

Assuming that the previously mentioned speed reduction from 60 to 40 km/h will affect only 60% of cars, taking into account the average number of people per car in the amount of at least 3 people, since there is active public transport on the dam of the hydroelectric power station, we get the average daily amount people P, which were affected by a decrease in speed in an amount of more than 90 thousand people/day:

\[ P = 50308 \cdot 60\% \cdot = 90554 \text{ people/day} \]  \( (11) \)

The change in the duration of movement at a given speed and the total loss of time are shown in table 5.

Table 5. Estimation of time costs caused by a decrease in speed at the dam in Irkutsk

| Indicators          | Duration of movement, sec | Including excess by a non-fine amount, sec |
|---------------------|---------------------------|------------------------------------------|
| At a speed of 60 km/h| 150                       | 120                                      |
| At a speed of 40 km/h| 225                       | 164                                      |
| Deviation           | 75                        | 54                                       |
| Quantity of people  |                           | 90554                                    |
| Additional expenses |                           |                                          |
| sec/day             | 6791550                   | 4889916                                  |
| h/day               | 1886.5                    | 1358.3                                   |
| day per day         | 78.6                      | 56.6                                     |

The analysis showed that a decrease in speed from 60 to 40 km/h leads to additional time costs incurred by road users in the amount of more than 56.6 years each year, which is comparable to the duration of a human life. In addition, a decrease in the speed of movement, as has been shown earlier, significantly increases the environmental impact.
The obtained values of additional time costs can be estimated in monetary terms. One of the options for such an assessment is the assessment based on average earnings.

The average salary in Irkutsk is about 45 thousand rubles, while in 2020, according to the production calendar, there will be 1971 working hours at a 40-hour working week, which gives an average cost of 1 hour of work of about 274 rubles/hour (excluding holidays, taxes, contributions and other expenses related to remuneration) or 7.61 kopecks per second.

Estimated time and direct costs in monetary terms are given in tables 6.7.

### Table 6. Estimation of time costs in monetary terms

| Estimated indicator | Time costs | Unit cost, rub. | Cash Valuation of Time Costs |
|---------------------|------------|----------------|-------------------------------|
|                     | Unit of measurement | Value | Unit of measurement | Value |
| The impact of an additional 10 minutes of travel costs per person | hour/year | 82,3 | 274 | rubles/year | 22 550 |
| The effect of 1 second delay in Irkutsk | hour/year | 63145 | 274 | rubles/year | 17 301 730 |
| Losses on artificial irregularities (1 car passage) | seconds | 4,9 | 0,0761 | rubles/artificial roughness | 0,3729 |
| Reduction of non-fines to 10km/h at 40 km/h | seconds/km | 14,5 | 0,0761 | rubles/km | 1,1 |
| Reduction of non-fines to 10km/h at 60 km/h | seconds/km | 7,4 | 0,0761 | rubles/km | 0,56 |
| Decrease in the maximum allowed speed at Dam in Irkutsk | hour/year | 495 816 | 274 | rubles/year | 135 853 584 |

### Table 7. Assessment of direct costs in monetary terms

| Estimated indicator | Time costs | Unit cost, rub. | Cash valuation direct costs |
|---------------------|------------|----------------|-------------------------------|
|                     | Unit of measurement | Value | Unit of measurement | Value |
| The impact of an additional 10 minutes of travel costs per person | hour/year | 82,3 | 28,8 | rubles/year | 2 370 |
| The effect of 1 second delay in Irkutsk | hour/year | 63145 | 28,8 | rubles/year | 1 818 576 |
| Losses on artificial irregularities (1 car passage) | seconds | 4,9 | 0,008 | rubles/artificial roughness | 0,04 |
| Reduction of non-fines to 10km/h at 40 km/h | seconds/km | 14,5 | 0,008 | rubles/km | 0,12 |
| Reduction of non-fines to 10km/h at 60 km/h | seconds/km | 7,4 | 0,008 | rubles/km | 0,06 |
| Decrease in the maximum allowed speed at Dam in Irkutsk | hour/year | 495 816 | 28,8 | rubles/year | 14 279 501 |
As can be seen from tables 6.7, direct costs in value terms amount to 10% of the time. An enlarged economic assessment shows that an increase in the duration of movement to and from work by 10 minutes is comparable to costs (temporary + direct) of about 25 thousand rubles per year for each person, which corresponds to half the average monthly wage, which will lead to colossal costs, because, as shown in the study, a one-second delay per day for each resident of Irkutsk corresponds to costs of more than 19 million rubles per year.

A single passage of a car of a single artificial roughness increases the time by 4.9 s, which corresponds to costs of about 41.2 kopecks. In the case of daily traffic intensity of 10,000 cars/day, the additional costs caused by the daily passage of artificial bumps will exceed 2.25 million rubles per year.

A decrease in the size of the non-fine amount of speeding from 20 to 10 km/h means an increase in costs of 62 to 122 kopecks/km, which corresponds to 6-11% of the unit cost of operating a car, countries will lead to annual costs of billions of rubles.

An insignificant amount of costs, measured in kopecks, gives impressive amounts when converted to all participants in the movement. As it was shown, the decrease in the maximum permitted speed at the dam of the hydroelectric power station in the city of Irkutsk from 60 to 40 km/h corresponds to the cumulative increase in costs for the movement of participants in more than 56 years/year, which in monetary terms corresponds to more than 150 million. rubles/year.

The similar amounts of additional costs, calculated in the hundreds of millions of rubles on the road network section of a small length (about 2.5 km), confirm the need for an economic assessment when making decisions on the organization of road traffic.

Accounting for other types of costs indicated in table 1 will give an even greater total value of additional costs.

4. Conclusion.
Despite the enormous importance of economic costs, it should be emphasized that the issue of safety is a key issue in the organization of traffic. However, the most economically efficient improvements in road safety that can be achieved by various methods should be made taking into account the additional costs incurred, both individual and public.

Further research should be aimed at studying each of the types of costs, both individual and public, approaches to their assessment, as well as the development of a multifactor model of economic assessment of travel difficulties (congestion).

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