Analysis of Efficiency of Toll Road Network Development

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Abstract. The article analyzes the experience of Russian cities that provide toll roads charging. Based on the analysis, rates for toll roads were proposed depending on the category of vehicles, corresponding to the volume and quality of services provided to the user of the toll road. Based on the data obtained and the methodology for calculating the rate for vehicles on toll roads, the calculation of the amount of savings received by users when driving a toll road, compared with an alternative free route, was made. The calculation included determining the cost of operating a vehicle when driving through a toll road facility by reducing the consumption of fuel and lubricants, tire wear, repair costs, and other items of operating costs. The advantage for users of toll roads was determined by saving time for delivery of goods and passengers, increasing comfort and traffic safety. Additional attraction of funds through placement of gas stations and advertising is considered. The payback period of the toll road has been determined. The conclusion is made about the need for further research on the problems of development of the network of toll roads.

1. Introduction
A toll road is a road or a section of a road where traffic is carried out at the expense of charging a certain fee set in accordance with approved tariffs. The purpose of collecting funds is to pay for the construction, reconstruction, and maintenance of the road.

The experience of operating toll roads in Russia is small in comparison with world practice [1, 2, 3]. The first section, 20 km long, of the reconstructed Don highway was opened in 1999 in the Lipetsk region. Paid sections of highways operate in 13 subjects of the Russian Federation: Voronezh, Kaluga, Novgorod, Leningrad, Lipetsk, Moscow, Pskov, Rostov, Ryazan, Tver, Tula regions, Udmurtia and St. Petersburg. The sections open to traffic on a paid basis are divided by the following highways: M-1 “Belarus”, M-4 “Don”, M-11 “Moscow - St. Petersburg”, M-3 “Ukraine” [2].
The passage of a vehicle on a toll road or a toll road section is carried out on the basis of a contract (concession agreement) with the owner of the road (with a concessionaire).

Electronic means of travel registration include a transponder and a contactless smart card. A transponder is a transmitting-receiving device installed on the windshield of a vehicle and which enables non-stop high-speed travel at toll collection points. Vehicles using a transponder save up to 20% on travel through the toll section.

Also, to reduce costs on toll roads, the Free Flow system is being introduced, which allows to pay for travel at speed without standing in traffic jams in front of the barriers. The principle of operation is to recognize the state number of the vehicle, determine the category. After that, the car owner receives a receipt for payment or the payment is debited from the transponder’s personal account.

2. Calculation process
The amount of a toll collection on a road is determined by the formula:

\[ A_{i,N} = P_{0i,N} \cdot L \cdot A \cdot B \cdot C, \]  

where \( P_{0i,N} \) – the cost of one kilometer of a toll road or a toll section for the vehicle of the corresponding category, set by the operator;

\( L \) – the length of a toll road or the length of a toll section, km;

\( A, B, C \) – coefficients that take into account the differentiation of the amount of payment for a vehicle on a toll road, depending on the time of day, day of the week / month of the year.

The amount of payment established by the operator for one kilometer of a toll road or a toll road section for the passage of vehicles of the corresponding category shall not exceed the maximum amount of payment for the passage of vehicles of the corresponding category on toll roads, toll road sections in the \( i \)-th year (rubles per kilometer). The toll on a toll road is differentiated depending on the category and carrying capacity of vehicles. The classification is based on the number of axles and the height of the user’s vehicle.

The toll calculation process consists of the following steps:
1) collection and preparation of source data;
2) calculation of the amount of savings received by users when driving on a toll road and road object in comparison with an alternative free route;
3) determination of consumer demand for toll road services;
4) determining the optimal value of the fare;
5) drawing up a price list.

**Stage 1.** Preparation of initial data.

In the Perm Krai territory, the construction of toll roads is expected to be carried out in the long term [4]. Currently, projects are being prepared for the construction of two highways on the territory of the region: Perm Northern bypass and Kunya - Gubakha [5].

**Table 1.** Tariffs for travel on the road "Northern Bypass".

| Road section | Travel time | Vehicle classification |
|--------------|-------------|------------------------|
|              |             | I category of vehicles | II category of vehicles | III category of vehicles | IV category of vehicles |
| Payment method |             |                        |                        |                        |                        |
| Start of the crossroads | 10.0 | 8.0 | 16.0 | 13.0 | 23.0 | 18.0 | 33.0 | 26.0 |
| Intersection | 7.5 | 6.0 | 12.0 | 9.5 | 17.0 | 14.0 | 25.0 | 20.0 |
| end of route | 30.0 | 24.0 | 48.0 | 38.0 | 69.0 | 55.0 | 99.0 | 79.0 |
| The whole road | 22.5 | 18.0 | 36.0 | 29.0 | 52.0 | 42.0 | 74.0 | 59.0 |
|               | 40.0 | 32.0 | 64.0 | 51.0 | 92.0 | 74.0 | 132.0 | 106.0 |
|               | 30.0 | 24.0 | 48.0 | 38.0 | 69.0 | 55.0 | 99.0 | 79.0 |
In the daytime, the fare is calculated taking into account a correction factor of 1.0, at night - 0.75. The calculation results are shown in Table 1.

**Stage 2.** Calculation of the amount of savings that can be achieved when driving on a toll road, compared to an alternative free route.

The economic assessment of the total benefits (effect) of the toll road user includes [6, 7, 8, 9]:

$$E_{\text{sum}} = E_{\text{oc}} + E_{\text{dg}} + E_{\text{tt}} + E_{\text{ra}},$$  

(2)

where $E_{\text{oc}}$ - savings in operating costs of a vehicle when driving through a toll road facility in comparison with an alternative passage;

$E_{\text{dg}}$ - savings from accelerating the delivery of goods;

$E_{\text{tt}}$ - savings from reducing travel time (saving time); $E_{\text{ra}}$ - savings from reducing the risk of road accidents are estimated based on a comparison of accident statistics for a specific or similar road (toll and alternative).

The cost savings for operating a vehicle when driving on a toll road object ($E_{\text{oc}}$) include: fuel and lubricants costs, tire repair and replacement costs, and other operating costs (maintenance and repair, depreciation, drivers' wages, overhead costs). It includes both fixed and variable expenses that depend on mileage. To determine the costs of operating a vehicle, we take the tariff for each group of vehicles as the arithmetic mean of the tariffs used by motor transport companies in the area of gravity of a toll road or toll facility, as a rule, approved for 1 hour of work and 1 km of run. Then:

$$E_{\text{oc}} = T_{\text{tv}} (L_a - L_{\text{tr}}),$$  

(3)

where, $T_{\text{tv}}$ - tariff for each group of vehicles;

$L_a$ - the length of the alternative section;

$L_{\text{tr}}$ - the length of the toll road.

Savings from accelerated delivery of goods ($E_{\text{dg}}$) is expressed in the speed of transportation of goods - a larger volume of transportation per unit of time. Based on this, it is possible to increase the profit of a freight carrier that uses a toll road. In addition, the shipper also benefits from the acceleration of the turnover of goods and capital. For this calculation, the following formula is used:

$$\Delta E_{\text{dg}} = (C_{\text{tg}} \cdot \Delta t/(365 \cdot 24)) \cdot (B_r/100),$$  

(4)

where $C_{\text{tg}}$ - the average cost of transported goods (100,000 rubles);

$\Delta t$ - time saving, hour;

$B_r$ - the rate of a bank loan,% (the rate of the Savings Bank of the Russian Federation + 12% is used in the calculations);

365 and 24 - the number of days in a year and hours in a day, respectively.

The calculation of the time savings ($E_{\text{tt}}$) is that the delivery of the transported cargo will be delivered in a shorter period of time compared to the alternative road. The cost of $V_oT$ time is determined using the “economic activity” method:

$$V_oT = \text{GDP} / (P \cdot 24 \cdot 365),$$  

(5)

where $V_oT$ is the cost of one hour of time;

GDP - gross domestic product (103 trillion 626.6 billion rubles in 2018);

$P$ - the number of employed population (71.8 million for 2018).

In this way $V_oT = 7159.06$ rubles.

To account number of passengers, a correction factor $K_p = 1.0–1.5$ is introduced.

The calculation of the cost of saving time is taken into account only for the first and fourth groups of vehicles, then:

$$E_{\text{tt}} = K_p \cdot \Delta t \cdot V_oT,$$  

(6)

The time savings calculation results are presented in Table 2.

An assessment of the economic effect (total benefit) of using a toll road is presented in Table 3.

**Stage 3.** Determination of consumer demand for travel services on toll road objects.

A survey is used as a method for determining consumer demand. The main objectives of the survey are: determination of users' perception of the most acceptable amount of payment for toll roads; determination of the optimal value of the size of the fare for each category of vehicles; study and formation of public opinion on the issue of collection of fares; identification of factors affecting the
willingness of users to pay for travel; identification of the significance of saving factors for various categories of users; preparation of recommendations for the operating organization on the introduction of various discounts, on conducting an advertising campaign in the media, etc.

Actual tariffs should be set slightly higher than the values identified during the survey, since users give a real assessment of all the advantages of paid travel only during operation. Therefore, the base value should be increased by 20%, provided that the new value does not exceed the \( E_{\text{sum}} \) savings value.

| Vehicle category | Length, km (paid / alternative) | Average travel speed, km / h (paid / alternative) | Travel time, h (paid / alternative) | Save time |
|------------------|---------------------------------|-----------------------------------------------|-----------------------------------|-----------|
| I                | 40 / 50                         | 100 / 65                                      | 0.4 / 0.76                        | 0.36      |
| II               | 70 / 45                         | 0.57 / 1.1                                    | 0.53                              |
| III              | 60 / 35                         | 0.66 / 1.43                                   | 0.77                              |
| IV               | 60 / 35                         | 0.66 / 1.43                                   | 0.77                              |

Table 2. Saving time when driving along the Northern Bypass road.

| Vehicle category | Saving the cost of operating vehicles, rubles | Savings from accelerating cargo delivery, rubles | Saving time, Total benefit, rubles |
|------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|
| I                | 10                                            | 0.49                                          | 74.14                             |
| II               | 15                                            | 0.72                                          | -                                 |
| III              | 20                                            | 1.05                                          | -                                 |
| IV               | 30                                            | 1.05                                          | 158.58                           |

Table 3. The total benefits of using the Northern Bypass road.

Stage 4. Determination of the optimal value of the size of the fare.

The recommended amount of toll on toll roads should bring the potential concessionaire maximum income, taking into account the different behavior of road users at different tariff levels. To determine the point of maximum income, it is necessary to calculate the income elasticity. Several scenarios are simulated sequentially when the tariff level is increased in increments of 0.5 rubles per kilometer, while the intensity and income are calculated in each scenario. As the tariff level increases, the intensity decreases. At the same time, at first, incomes grow to a certain level, after which they also begin to decline. The tariff corresponding to the maximum income (extreme point) is the optimal tariff from the point of view of the concessionaire.

Stage 5. Drawing up a price list, which indicates the cost of travel for the entire paid facility, for tariff sections, as well as the unit cost of travel.

Specific values are used to calculate fares for tariff sections. Tariff sections are road sections between toll collection points.

The fare must correspond to the volume and quality of services provided to the user of the toll road, and take into account the need for full, and when this is not possible, partial coverage of the costs of construction (reconstruction) of the road and the costs of its operation, as well as profit from the organization operating the toll road. Thus, the introduction of toll roads on the existing transport network will have an impact on the country's economic development. An alternative source of funding will emerge through toll collection and the use of roadside service facilities.

To assess the efficiency of projects of highways and road structures, the following main indicators are used, based on the commensuration of the costs of their implementation and the results from implementation: the integral effect or net discounted income, the investment return index, the internal rate of return and the payback period [10, 11, 12, 13, 14]. If the net discounted income (NDI) is positive, the project is effective (at a given discount rate) and can be accepted for implementation. If NDI is negative, then the profitability of the project is below the specified discount rate (rate of return) and should be abandoned. The net present value of a road is defined as the difference between the
present value of income and expenses during the analyzed period. The payback period, after which the net present value becomes positive, can be determined by the formula:

$$\sum_{t=1}^{n} \frac{R_t}{(1+r)^t} \geq \sum_{t=1}^{n} \frac{C_t}{(1+r)^t},$$

(7)

where n - analyzed time period, years;

\(t\) - the number of years between the year of profit or expenditure and the starting year;

\(R_t/(1+r)^t\) - profit from the sale of paid services in the \(t\)-th year;

\(C_t/(1+r)^t\) - road maintenance costs in the \(t\)-th year;

\(r\) - discount rate, in fractions of units.

The average value of the annual income received when paying for travel on a toll road is determined by the formula:

$$D_t = d \cdot N_t \cdot 365,$$

(8)

where \(d\) is the average toll on the road for 10 km (18.75 rubles);

\(N_t\) - traffic intensity in the \(t\)-th year.

An assessment of the commercial and budgetary effectiveness of a road project should take into account its economic environment, including: forecasts of the general inflation index and price change indices throughout the entire estimated period of the project; the current taxation system (tax bases, rates, payment terms, tax benefits, distribution of tax payments between the budgets of the corresponding levels).

The inflation index is determined by the formula based on the monthly inflation rate:

$$I_r = \sum_{m=12}^{m=1} \left(1 + \frac{I_m}{100}\right)^{m-1},$$

(9)

where \(I_m\) inflation index within a month in relative values:

$$I_m = \left(\frac{I_{Ct} - I_{Cn}}{I_{Cn}}\right) \cdot 100\%,$$

(10)

where \(I_{Ct}\) is the consumer price index of the current period;

\(I_{Cn}\) - consumer price index of the previous period;

\(I_m = (100.2 - 100.0) / 100.0 \cdot 100\% = 0.2\%\);

\(m\) - serial number of the month from the moment of the calculation. \(I_0 = 0.93\).

The inflation index during the transition from the first year to the second, from the second to the third, etc. determined by the formula, taking into account monthly inflation of 0.2%:

$$I_t = I_2 \left(1 + \frac{I_m}{100}\right)^{12(t-1)},$$

(11)

where \(t\) is the year for which the calculation is performed.

Based on the calculations performed and the data obtained, a payback period for the toll road was built (Figure 1).

3. Conclusion
As a result of the research and calculations carried out, it can be concluded that further analysis of toll roads network and toll sections is necessary and consider the development prospects.
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