Prospects of Development and Design Features of Toll Roads in the Russian Far East

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Abstract. The article considers the issues of the efficiency of location and operation of toll points on highways and provides the assessment of the development of the network of highways in the Far East with the prospects for the organization of toll city bypasses. The calculation of the efficiency of the toll point was carried out based on the example of the highway «Eastern bypass of Khabarovsk».

1. Introduction
The implementation of investment projects for the creation of toll roads in Russia, developed in recent years, imposes increased requirements on their feasibility study, but the domestic experience in commercial construction and operation of road structures is still not sufficient. The construction of toll roads requires the formation of new regulations and recommendations and adaptation of existing ones for the placement of transport facilities and related transport infrastructure: toll points for vehicles and their elements.

The geographical peculiarities of the Russian Far East as a bridge between Europe and Asia determine the development of transport communications of international through traffic and the investment attractiveness of the region.

The issues of the specifics of the region are of significant interest in the construction of toll roads in the Far East (Bypass of the city of Khabarovsk), in the development of regional recommendations for the construction of toll points and improving the efficiency of the road network. Therefore it is necessary to analyze the features of the formation of regional traffic flows that affect the technical standards of toll road infrastructure. This includes, among other things, the issues of creating of transport corridors and increasing their efficiency, considering economic ties with the countries of the Asia-Pacific region [1,2].

2. Features of the formation of traffic flow
The development of the Far East and the integration of Russia into the economies of the Asia-Pacific region creates the conditions for the implementation of the transit potential of the Far East. Increasing throughput of transport corridors solves the problem of increasing the efficiency of transport
communication, reducing risks and transport costs, ensuring the safety of cargo, and meeting delivery times. This can be achieved only on condition of development, renovation and modernization of infrastructure, optimization of cargo transportation, development of modern logistics centers, elimination of administrative barriers [3].

Currently, the road density in the Far East is about 5.6 times less than the average for Russia [4]. The length of roads increases insignificantly; the length of highways in the Far Eastern Federal District also lags behind all districts (figure 1).

![Figure 1. Length of public roads.](image)

President Vladimir Putin's Address to the Federal Assembly speaks of the need to "increase the quality and volume of road construction, use new technologies and solutions, infrastructure mortgage, life cycle contracts for this" and "to relieve cities from transit traffic flows by building bypasses" [5].

Khabarovsk is located in the center of international and domestic road, rail and air transport routes (figure 2) [6]. Since the commissioning of the federal highway "Amur" Chita - Khabarovsk (2010), the flow of road transport through the center of Khabarovsk has grown by more than 2.5 times, which has led to a serious deficit in the capacity of the road network.

The ratio of light and freight vehicles in the flow in 2015 was 91% - light vehicles and 9% - freight vehicles, and in 2019 it was 48% and 52%, respectively.

The characteristics of the traffic density on individual sections of federal roads such as Khabarovsk-Nakhodka "Vostok", Chita-Khabarovsk "Amur", Petropavlovsk-Kamchatsky - seaport, entrance to the airport from Petropavlovsk-Kamchatsky, Khabarovsk-Vladivostok "Ussuri" is given in Table 1 [7].
Table 1. Analysis of the amount of traffic on the federal roads of the Far East.

| Name and length of roads (from km to km)                                      | Average density, vehicles / day |
|-------------------------------------------------------------------------------|---------------------------------|
| Khabarovsk-Nakhodka "Vostok" at the 5-246 km section                          | 18076                           |
| Chita-Khabarovsk "Amur" at the 1811-2161 km section                           | 31624                           |
| Entrance to the airport from Anadyr at the 0-30.5 km section                 | 6651                            |
| Petropavlovsk-Kamchatsky - seaport, entrance to the airport from Petropavlovsk-Kamchatsky | 32238                           |
| Khabarovsk-Vladivostok "Ussuri" at the 14-752 km section                     | 14464                           |
| Entrance to the seaport, airport from the worker's settlement Palana at the 9.5 km section | 5712                            |

3. Determination of the features of the traffic condition
The data on vehicles registered in the Khabarovsk Krai were analyzed to determine the ratio of the number of RHD and LHD vehicles. The average size of vehicles for each brand and model has been determined, taking into account the dimensions of the body and the average vehicle of a particular manufacturer, and the number of cars present in the Khabarovsk Krai. Information on models and manufacturers is given in Table 2 and figure 3.
Figure 3. Number of RHD vehicles in the total sample.

Table 2. Dimensions of light vehicles.

| Manufacturer | Dimensions, mm | Wheelbase, mm | Sample size | Percentage, % |
|--------------|----------------|---------------|-------------|---------------|
| HONDA        | Length 4397   | Width 1708    | Height 1437 | 2627          | 5307          | 3.4          |
| ISUZU        | Length 4428   | Width 1716    | Height 1745 | 2537          | 1852          | 1.2          |
| KIA          | Length 4357   | Width 1796    | Height 1682 | 2627          | 489           | 0.3          |
| MAZDA        | Length 4290   | Width 1666    | Height 1734 | 2339          | 5844          | 3.7          |
| Mitsubishi   | Length 4445   | Width 1728    | Height 1733 | 2592          | 10683         | 6.8          |
| Nissan       | Length 4489   | Width 1711    | Height 1598 | 2603          | 26206         | 16.6         |
| Subaru       | Length 4214   | Width 1628    | Height 1523 | 2411          | 1655          | 1.1          |
| Suzuki       | Length 3817   | Width 1638    | Height 1630 | 2322          | 1965          | 1.2          |
| Toyota       | Length 4504   | Width 1714    | Height 1556 | 2559          | 102928        | 65.3         |
| Daihatsu     | Length 3812   | Width 1565    | Height 1653 | 2363          | 601           | 0.4          |

The limiting parameters of the vehicle necessary for the design of the road were established based on the analyzed sample. The vehicles with high cross-country ability prevail among light vehicles, and the maximum width and length of a light vehicle are 1.796 and 4.504 m, respectively [8, 9]. Japanese freight vehicles have strict size and performance limits, and comply with existing road design standards in width and length.

The drivers have to go much further into the oncoming lane for vision by passing. In order to solve this problem, some drivers use a mirror system, which avoids blind spots by passing [10].

In order to identify the differences in the position of RHD and LHD vehicles, a study was carried out to determine the position of the car in the lane, relative to the right edge of the roadway markings (Table 3).
The study was carried out using video monitoring, photographic recording of vehicles moving in a forward direction at a section with markings at 7 intersections in Khabarovsk. As a result, the average displacement of the RHD vehicle was determined, which is 0.36 m, which is 2.2 times less than the displacement of the LHD vehicle relative to the right edge of the lane.

Left-hand and right-hand steering affects the distribution of blind spots. The combination of RHD and LHD vehicles in the lane in places with a large number of conflicts affects the traffic safety, the displacement of the dynamic corridor relative to the center of the lane.

Blind spots in combination with the displacement of vehicles relative to the axis of the lane in the flow indicates the need to determine the width of the traffic, considering the complexity of maneuvers with a mixed traffic flow.

4. Features of the design of toll points for vehicles

Advantages for the user of toll road are the following: speed - 120 km/h, high transport and operational performance, saving travel time. The time savings are greater the less time the user spends at toll points. The admissible waiting time of any potential user of toll road services at the toll point of the highway is estimated based on the benefits for the consumer of these services. In this case, the limiting situation (associated with the refusal to use a toll road structure) can take place when the user's savings from traveling on it is equal to zero [11, 12, 13].

In mathematical form, this condition can be represented in the following form:

$$C_dT_w = hC_oT_o,$$  \(1\)

where \(C_d\) – is the average cost of 1 hour of vehicle downtime, rubles; \(T_w\) – is the average waiting time of the vehicle for service, h; \(C_o\) – is the average cost of 1 hour of vehicle operation, rubles; \(T_o\) – is the average travel time along a toll road, h; \(h\) – is the share of savings from reducing the cost of traffic on a toll road in comparison with an alternative one (free).

Table 3. Displacement of vehicle in the lane.

| Lanes under investigation | Sample size | Lane width, m | Displacement of vehicle from the right edge of the lane, m | Average number |
|---------------------------|-------------|---------------|----------------------------------------------------------|---------------|
|                           |             |               | Interval boundary | Average number | Steering | Steering |
|                           |             |               | LHD | RHD | LHD | RHD |
| Karl Marx st. – Pushkin st. | 530 | 3.5 | 0.44-0.87 | 0.2-0.37 | 0.69 | 0.33 |
| Karl Marx st. – Promyshlennaya st. | 158 | 3 | 0.5-1.3 | 0.16-0.4 | 0.88 | 0.31 |
| Lenin st. – Dikopoltsev st. | 80 | 3 | 0.32-1.04 | 0.05-0.4 | 0.74 | 0.31 |
| Leningradskaya st. – Stantsionnaya st. | 466 | 3 | 0.57-0.7 | 0.17-0.3 | 0.61 | 0.24 |
| Seryshev st. – Kalilin st. | 163 | 3 | 0.64-1.04 | 0.29-0.42 | 0.76 | 0.38 |
| Karl Marx st. – Dikopoltsev st. | 335 | 3 | 0.58-1.0 | 0.23-0.45 | 0.82 | 0.38 |
| Bolshaya st. – Vyazemskaya st. | 1255 | 3.5 | 0.82-1.24 | 0.45-0.68 | 1.09 | 0.60 |
| Average | | | | | 0.79 | 0.36 |
Assuming that the ratio $C_o/C_d$ for the traffic flow under consideration is constant and taken equal to $b$, the ratio of the waiting time of the vehicle in this flow to the travel time was expressed as follows:

$$\frac{T_w}{T_o} = h \frac{C_o}{C_d} = hb.$$  \hspace{1cm} (2)

Provided that the share of time savings from reducing the cost of traffic on a toll road «Eastern bypass of Khabarovsk» is 4.5% ($h = 0.045$), and $b = 3$, then the maximum waiting time of the vehicle for service should not exceed 13.5% of travel time on a toll road ($T_w = 0.135 T_o$).

The waiting time of the vehicle for service depends on the type of toll point, its structure and the geometry of the service area. The service area of the toll point can be divided into separation area, holding area, exit area and merging area (figure 4). Vehicles line up to pay in the holding area and wait in line to pay a toll at a toll booth or try to leave the service area, creating hindrance to traffic for others waiting. In the separation zone, the driver selects a specific tollbooth and the time spent on approaching the pay window depends on the length of the holding zone and the separation zone and geometry [14-17].

![Figure 4. Toll point service zone.](image)

The delay at the toll point differs for different types of payment acceptance; these losses can be optimized with the introduction of automatic toll collection systems (Table 4). After passing the toll point, the number of lanes is reduced from the number of toll booths to the original width of the carriageway. A vehicle passing a toll point in the exit area and merging area must wait or slow down in order to allow another vehicle moving in the adjacent lane.

| Table 4. Average values of vehicle service time depending on the accepted payment system. |
|-----------------------------------------------|------------------|------------------|------------------|------------------|
| Type of toll collection system               | Payment acceptance                                      | Payment is made                     | Toll point capacity, vehicles /min |
| Manual                                        | Carried out by the operator of the toll point             | In cash                            | 6                |
|                                                |                                                              | Only by payment cards               | 8                |
| Automated                                     | Carried out through a machine with a bill acceptor       | Only in bills or coins of a certain denomination | 8                |
|                                                |                                                              | Bills or coins, credit cards, chip cards | 10               |
| EFC                                           | Carried out in the automatic service lane using the communication technology | With a stop in a portal with a barrier | 20               |
|                                                |                                                              | Non-stop                           | 30               |
Loss of time in the service area is the loss of time in the queue and it can be calculated based on the queuing theory [18, 19]. The probability of presence of vehicles in the toll system at each transport junction of the highway «Eastern bypass of Khabarovsk» was determined based on the algorithm for modeling the operation of the toll point (figure 5).

**Figure 5.** Probability of vehicles arriving in the toll system as a multichannel queuing system for the flow of vehicles with waiting.

Taking into account the intensity of the arrival of cars at the toll point, as well as the time of car servicing at the toll points, it is possible to calculate the efficiency (values of total discounted costs) for each transport junction of the highway and determine the length of each zone. According to the Road industrial methodical document «Methodological recommendations for the construction and placement of toll points», the size of the site for the placement of toll points is determined depending on the number of transit lanes, toll booths determined on the basis of the estimated traffic density, as well as the layout and size of other buildings and structures, included in the toll point. At the same time, the entry and exit sites must be at least 150 m long.

5. **Conclusion**

The regional feature of traffic flow is the predominance of RHD vehicles, for light vehicles the share of RHD vehicles is 70%, for freight vehicles - 50% (from 42% to 84% in regions). There is a tendency to an increase in the number of freight vehicles in the traffic flow on the main transit routes.

The mixed traffic flow and the placement of «blind spots» make necessary increasing the width of the traffic lane (when the traffic flow is moving at a speed of 20 km/h - up to 4.5 m) and distribute the traffic among the lanes in accordance with the position of steering wheel. The width of the traffic lane at the toll point depends on the dynamic characteristics of the vehicles and, when the traffic flow is moving at a speed of 20 km/h, it is from 3.0 to 3.25 m for a light vehicle and from 3.5 to 4.5 m for a freight vehicle.

The efficiency of the functioning of toll points can be determined through the optimal number of toll points, considering the used toll collection system and the time spent by the driver to pass the toll point zones based on the queuing theory. At the same time, the maximum possible number of vehicles in the queue for a toll road and the waiting time for service should not exceed 0.135 Tₚ.
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