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Methodology for Designing Road Vehicle Service Facilities

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ABSTRACT

In modern methods of technological design, the capacity of service facilities depends on the number of cars entering them per unit of time. At the same time, regardless of the type of service object, the number of visits is somehow associated with intensity of the vehicle traffic on a given road, as well as with one of the characteristics that determine speed of this event. Such a characteristic, for example, for service or maintenance stations is intensity of vehicle failures, for fuelling stations – intensity of fuel consumption, for hotels and parking lots – intensity of the onset of fatigue for drivers and passengers. This gives ground for conclusion that there is a significant similarity between the processes that result in an event that can be called a visit to a service facility. Thus, the purpose of this theoretical study was to develop a common approach applicable to all road service facilities to determine the number of such events, as well as to develop a common methodology for their design.

A characteristic feature of operation of service objects is a time-varying flow of demand for the operation of service facilities, as well as variable labour intensity and duration of troubleshooting or the provision of other service services. Systems in which the moments of receipt of requests for service and the duration of the services themselves are variable and random are called a queuing system. Therefore, to justify the number of car arrivals at road service facilities, the authors proposed a probabilistic method, the main tools of which are provisions and mathematical apparatus of the queuing theory.

The main condition for functioning of the queuing system is the ratio between the incoming flow of requirements and the absolute throughput of the system. Thus, the mathematical model proposed by the authors considers the performance indicators of service facilities, depending on the size of the incoming flow of requirements and its variation, on the one hand, and on the throughput and performance of service facilities, on the other hand.

Keywords: *road transport, road service facilities, technological design methodology, queuing theory.*

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INTRODUCTION

It is known that the capacities of such road service facilities (RSF) for vehicles located in the European part of the Russian Federation as motorway service stations (MSS), fuelling stations (FS), transit hotel establishments (THE), which include motels, campsites, rest areas (RA) and parking lots (PL) have an average annual occupancy rate of no more than 30–40 % [1–3]. This suggests that the design capacity of these facilities does not meet the required one, i. e., there are obvious shortcomings in the methodology of their design [4–7].

At the same time, the intensity of emergence of conditions making care visit RSF are stochastic in nature, therefore, quantitative assessment of such an event can only be judged with a certain probability.

Thus, improving the methodology for designing road service facilities for cars is an important and relevant task.

The *objective* of this study is to develop conceptual provisions of the general methodology for technological design of road service facilities for vehicles.

To achieve this objective, it is necessary to solve the following tasks:

• To develop a universal mathematical model for determining the number of car arrivals at a road service facility.

• To develop an economic and mathematical model for optimising main parameters of road service facilities.

• To develop a scheme-algorithm for implementation of a common methodology for technical calculation and design of road service facilities.

RESEARCH METHODOLOGY

The processes of operation of such complex systems as RSF are best described using a probabilistic method, among the main tools of which are the provisions and mathematical apparatus of the queuing theory (QT) that are suggested to be applied [2; 8].

QT considers queuing systems (QS) with waiting and denials in servicing [9]. Logical analysis shows that to describe the functioning of road service stations and fuelling stations, it is advisable to use the analytical apparatus of the QS with waiting, and for objects such as THE, RA and PL – with refusals to service applications [10–14]. The main elements of a QS with failures are incoming and outgoing flows of applications, and for a QS with waiting, the queue of applications [10–14].

Studies show that the process of arrival of applications to various QS differ from the simplest Poisson flow [12; 13]. However, when replacing the characteristics of flows that are not related to the simplest ones with the corresponding characteristics of a stationary Poisson flow of events, it is possible to obtain results that are satisfactory in terms of accuracy with a significant simplification of the analytical apparatus. In addition, it is possible to obtain a technological effect, which consists in the fact that QS, designed for the simplest flows, which are the most intense, when less intense flows of other structures appear, work more stably [12; 14].

RESEARCH RESULTS

A Universal Mathematical Model for Substantiating the Number of Car Arrivals at RSF

In case of the simplest flow, the probability of the appearance in time t of exactly K arrivals of cars on RSF is determined by the Poisson law [9]:

$$P_k(t) = \sum_{k=0}^{k} \frac{a^k}{K!} \cdot e^{-a} \geq [P_R], \quad (1)$$

where a – the Poisson parameter, which determines the average value of the number of car arrivals at RSF during the time t, units;

$[P_R]$ – given probability with which the value of K is determined.

The definition of the average number of car arrivals at a road service station is based on the concept of failure [12]. In the theory of reliability, a failure is understood as a random event, which consists in the loss of a working state by a car [15]. This concept refers to the car design, but it can also occur for other reasons, for example, due to lack of fuel in the tank, driver fatigue, etc. Therefore, to determine the average number of visits to any RSF, it is possible to use the mathematical apparatus developed to assess the probability of failures due to technical reasons. In this case, the quantitative value of a can be determined by the formulas [9; 12; 13; 16]:

$$a = p \cdot N = \frac{(1 - e^{-\omega \cdot R}) \cdot U_d \cdot \varphi \cdot \beta \cdot T}{T_d}, \quad (2)$$

where p – failure probability of one car;

N – the number of cars passing during the time t through the service area of RSF, units;

ω – failure intensity, km^{-1};

R – service area width, m;

U_d – average annual daily intensity of traffic on the road in the service area of RSF, car/day;

φ – correction factor depending on the type of RSF;

β – coefficient defined as the ratio of the average hourly traffic intensity during the hours of operation of RSF to the average hourly daily traffic intensity;

T – operating time of RSF per day, h;

T_d – duration of the day, h.

Expression (2) establishes the dependence of the average number of cars visiting a RSF on intensity of occurrence of events ω, the consequence of which this arrival is, the length of the road segment R serviced by this object, and, at the same time, determining the share of the total number of cars that can use its services under a given traffic intensity, as well as on the time of operation of the facility during the day. Moreover, the value of the ratio T/T_d determines the share of the daily traffic intensity of vehicles attributable to the operating time of RSF. Characteristics R, U_d, T and T_d are common for all types of RSF, and the values ω, φ and β establish the features of operation of various service objects from the point of view of the need for cars to enter them.

To determine the number of arrivals at a road service station, the Russian construction standards[1] stipulate the dependence of the number of cars that are forced to interrupt their travel on the distance travelled. On its basis, we in [17] obtained a functional dependence of the rate of vehicle failures on the width of the service area of a given object, which has the form:

$$\omega = c + \frac{b}{R}, \tag{3}$$

where c and b – approximation coefficients:

$c = 1{,}02305 \cdot 10^{-4}$ km^{-1};

$b = 4{,}92184 \cdot 10^{-4}$.

For road fuelling stations, the intensity of car arrivals is determined by the rate of emptying of fuel tanks, depending on their capacity and fuel consumption[1]:

$$\omega = \sum_{i=1}^{n} \frac{\psi_i \cdot q_i}{\varepsilon \cdot V_i}, \tag{4}$$

where n – number of types of vehicles included in the calculation;

ψ_i – the share of cars of the i-th type in the traffic flow: private cars $\psi_1 = 0{,}7$; trucks $\psi_2 = 0{,}25$; buses $\psi_3 = 0{,}05$[1];

q_i – average fuel consumption by cars of the i-th type: private cars $q_1 = 0{,}1$ l/km; trucks $q_2 = 0{,}305$; buses $q_3 = 0{,}41$[1];

ε – average coefficient of utilisation of the nominal capacity of fuel tanks of vehicles $\varepsilon = 0{,}55$[1];

V_i – average nominal capacity of fuel tanks of vehicles of the i-th type: private cars $V_1 = 51$ l; trucks $V_2 = 140$ l; buses $V_3 = 146$ l[1].

For hotels, motels, campsites and parking and rest areas, the intensity of car arrivals is determined depending on the daily mileage of cars using their services[1]:

$$\omega = \frac{1}{l_{\text{T}}}, \tag{5}$$

where l_{T} – daily mileage of transit cars, $l_{\text{T}} = 400–600$ km[1].

The method for determining the width of the service area R of various RSF in formula (2) is described in detail in the document[1].

For road service stations, the coefficient φ in formula (2) determines the share of the total number of vehicles that have encountered failures, which require a mandatory arrival at this facility. According to MADI [Moscow Automobile and Road Construction University] and RSN62–86 data, its value is φ = 0,35–0,45 [11].

For road fuelling stations, the value of the coefficient φ = 1,0, since all cars that have exhausted their fuel supply require refuelling [11].

When calculating THE, it should be considered that road hotels are intended for car tourists and truck drivers performing long-distance journeys. Moreover, the capacity of THE facilities is determined based on the total winter flow of transit transport, and for campsites, the difference between the summer «peak» and the winter transport flow is taken[1]. At the same time, the indicator that determines the capacity of THE is not the number of arrivals, but the number of arriving customers. For these reasons, the value of the coefficient φ in formula (2) is determined by the expressions:

a) for hotels and motels:

$$\varphi = \delta_{\text{WP}} \cdot \alpha \cdot \beta_{\text{WP}} \cdot (\psi_{\text{P}} \cdot \gamma_{\text{P}} \cdot m_{\text{P}} + \psi_{\text{T}} \cdot \gamma_{\text{T}} \cdot m_{\text{T}}), \tag{6}$$

where δ_{WP} – coefficient taking into account the unevenness of the traffic intensity during the year, for the winter period: $\delta_{\text{WP}} = 0{,}5$[1];

[1] RSN 62-86. Guidelines for determining the composition of car service facilities and their placement on highways of national and republican significance in the RSFSR. Moscow, GiprodorNII publ., 1987, 68 p. [Electronic resource]: https://files.stroyinf.ru/Data2/1/4294854/4294854732.pdf?ysclid=lnd0um811v804686776. Last accessed 26.02.2023.

α – coefficient taking into account the average annual share of transit transport in the total flow of cars;

β_{WP} – coefficient taking into account the decrease in transit in winter period in relation to its average annual daily value, β_{WP} = 0,5[1];

ψ_P, ψ_T – coefficients taking into account, respectively, the share of transit cars and trucks of intercity traffic in the traffic flow;

γ_P, γ_T – coefficients taking into account, respectively, the share of passengers in transit private cars and drivers of trucks using the services of hotels and motels, γ_P = 0,5, γ_T = 0,8[1];

m_P, m_T – the average occupancy factor of transit private cars and the number of drivers of long-distance cargo traffic per car, respectively: m_P = 2,6, m_T = 1,5[1];

b) for campsites:

$$\varphi = (\delta_{SP} \cdot \beta_{SP} - \delta_{WP} \cdot \beta_{WP}) \cdot \alpha \cdot \cdot(\psi_P \cdot \gamma_P \cdot m_P + \psi_T \cdot \gamma_T \cdot m_T), \quad (7)$$

where δ_{SP} – coefficient taking into account the unevenness of the traffic intensity during the year, for the summer period δ_{SP} = 1,6[1];

β_{SP} – coefficient taking into account the increase in transit in the summer period in relation to its average annual daily value β_{SP} = 1,6[1];

c) calculation of rest areas as independent objects is carried out on the basis of the average daily traffic intensity of only trucks and private cars according to the formula:

$$\varphi = \alpha_P \cdot \psi_P \cdot \gamma_P + \alpha_T \cdot \psi_T \cdot \gamma_T, \quad (8)$$

where α_P, α_T – coefficient taking into account the average annual share of transit transport in the flow of private cars and trucks, respectively.

The operating time of RSF during the day is determined by the purpose of the object and the features of its functioning. The requirements for the mode of operation in the current regulations are contradictory.

Thus, the norms of technological design of road transport enterprises for road service stations recommend year-round work (365 days), in two shifts, with a shift duration of 8,2 hours.[2] In Russian construction standards[1], these facilities are calculated as for single-shift operation, 357 days a year, with a shift duration of 10,5 hours.

For fuelling stations and other RSF, a year-round, round-the-clock operation is recommended[1].

[2] ONTP-01-91/ROSAVTOTRANS (RD 3107938-0176-91). All-Union norms for technological design of road transport enterprises. Moscow, Giproavtotrans publ., 1991, 76 p. [Electronic resource]: https://ohranatruda.ru/upload/iblock/b00/4294848591.pdf. Last accessed 26.11.2022.

Given the value of the confidence probability (reliability) [P_R] of the result of calculating $P_k(t)$ in formula (1), we obtain for service stations, fuelling stations and rest areas (parking lots) the values of the daily number of car arrivals at these facilities, and for THE – the daily number of customer arrivals. Since the value of K calculated by formula (1) is related to a certain time, it is also the intensity of arrivals of cars or clients at a given object during the operation of RSF. In this case, the hourly intensity of visits λ (units/h) is determined by the expression:

$$\lambda = \frac{K}{T}. \quad (9)$$

For RSF operating around the clock (FS, THE, RA, PL):

$$T = T_d, \quad (10)$$

and for other facilities (service stations):

$$T = n_{SH} \cdot T_{SH}, , \quad (11)$$

where n_{SH} – number of shifts of the facility per day;

T_{SH} – duration of the shift, h.

The most important characteristic of any QS is their load factor or, in other words, the reduced flow density of applications (visits) ρ, which is determined from the relation [9; 10]:

$$\rho = \frac{\lambda}{\mu}, \quad (12)$$

where μ – intensity of servicing applications, units/h.

The value of μ is defined as the reciprocal of the average service time regarding one application $t_0(r)$ [9; 10], i. e.:

$$\mu = \frac{1}{t_0}. \quad (13)$$

According to formula (12), it is possible to calculate simultaneously the main characteristic of any RSF, which determines its size or capacity:

$$n_M = \frac{\lambda}{\mu}, \quad (14)$$

where n_M – a main parameter of RSF: for service stations – the number of working posts; for fuelling stations – the need for fuel dispensers; for THE – the need for places to accommodate guests; for RA (PL) – the number of parking spaces.

At the same time, for QS with waiting (MSS, FS), the value of n_M obtained by calculation by formula (14) is rounded down to the nearest integer, and in systems with failures (THE, RA, PL) – upwards.

Economic and Mathematical Model for Optimising the Main Parameters of RSF

The next stage in development of a general methodology for the technological design of road service facilities is optimisation of control parameters, variables that determine the direction and speed of change or effective functioning of such systems.

The control parameters λ, μ, ρ, n_M make it possible to determine all the characteristics of the efficiency of functioning of systems that are identified as QS with denials to servicing requests (THE, RA, PL). As such characteristics for the specified RSF are used:

P_0 – the probability that all service channels (bed, car parking space) are free;

P_{REF} – the probability of refusal to service the application;

Q and A – relative and absolute capacity (throughput) of RSF;

n_{BC}, n_{IC} – the average number of busy and idle service channels;

t_{QS} – average residence time of an application in RSF system [10].

For QS with a limited queue length (MSS, FS), it is necessary to pre-calculate one more parameter of the system – the number of places in the queue. The method of its determination is described by us in [17]. In addition, it is necessary to calculate the average length of the queue of applications r_Q, as well as the average time spent by an application in the queue t_Q [9; 10; 17]. In this case, it becomes possible to calculate all the characteristics of the efficiency of functioning of FS and SS.

In connection with the foregoing, it is proposed to use an economic-mathematical model as a simplified representation of the process under study, with the help of which it is possible to evaluate the change in its efficiency with possible changes in its input parameters and having the following structure:

$$u_0 = S_{LI} \cdot \lambda \cdot P_{REF} + S_{OP} \cdot n_{BC} + \\ + S_{DC} n_{IC} + S_{LS}(r_Q + r_{SER}) \rightarrow \min, \qquad (15)$$

where u_0 – total costs from functioning of the system as part of RSF-cars, rub./h;

S_{LI} – lost income of RSF due to refusal to service the application (car or clientele), rub./unit, rub./person;

S_{OP} – the cost of operating one service channel: for MSS – one working post; for FS – one fuel dispenser; for THE – one bed; for RA and PL – one parking space, rub./unit. h;

S_{DC} – costs from downtime of one service channel, rub./unit. h;

S_{LS} – losses due to vehicle downtime, rub./car h;

r_{SER} –average number of applications in service.

The practical significance of the proposed economic and mathematical model mainly lies in predicting the behaviour of endogenous variables under certain assumptions regarding the behaviour of exogenous variables and the ability to significantly reduce the complexity of calculations. The criterion for optimising the controlled parameters is the minimum of total costs of the system, which increases the economic stability of functioning of RSF [18; 19].

Methodology for Substantiating RSF Parameters

The use of the proposed general methodology for technical calculation and design of road service facilities involves implementation of several stages (Pic. 1).

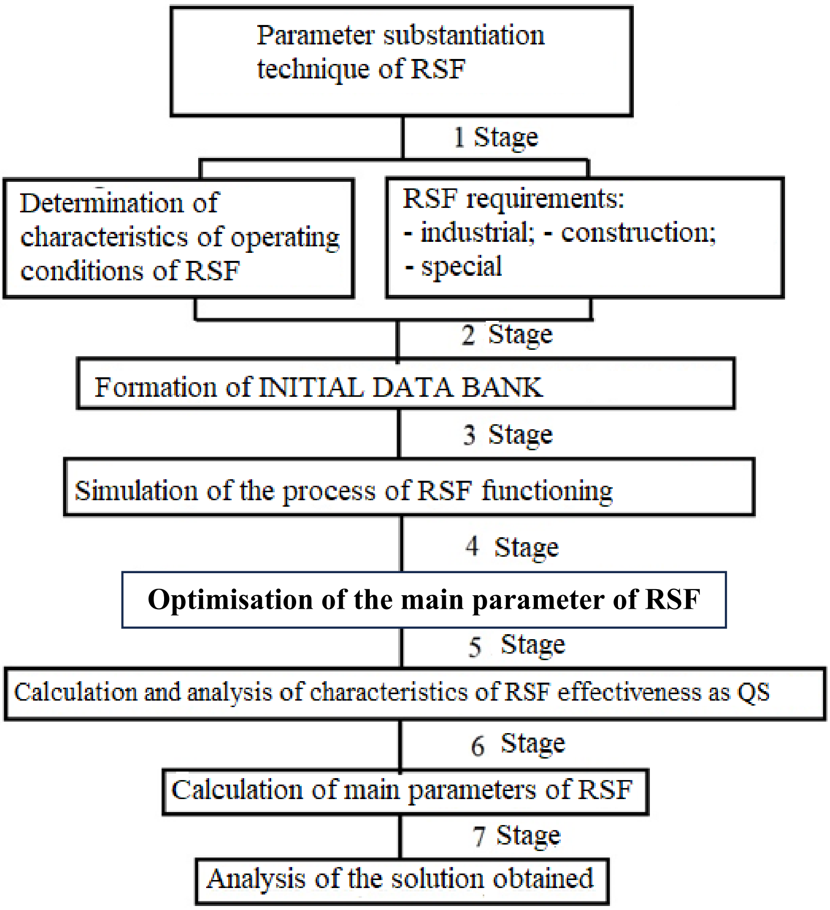
At the first stage, it is supposed to determine the values of the characteristics of external and internal factors that determine the conditions for functioning of RSF. External factors include the average daily traffic intensity on the road at the location of the facility, the structure of the traffic flow and the rate of cars' failures, the size of the service area. Internal factors include the number of days of work per year, the number of shifts, the duration of the shift, the average time to service the application. In addition, at the first stage, based on the study of existing standards, the requirements for the location, size, structure, and safety of RSF are determined.

The second stage is aimed at development of a data bank on RSF necessary to ensure its technical calculation and design.

The third stage involves development of an economic and mathematical model for operation of RSF with determination of the quantitative values of the indicators included in expressions (2) and (15).

The fourth stage is implemented based on mathematical models (1), (2), (15) and involves the search for the probability value $P_к(t)$, which corresponds to the minimum value of the efficiency criterion u_0, as well as the corresponding value of the main parameter of RSF.

At the fifth stage, the quantitative values of the characteristics of the efficiency of RSF, as of



Pic. 1. Methodology for substantiating RSF parameters [performed by the authors].

a QS, are calculated, corresponding to the optimal value of its main parameter.

The sixth stage involves calculation of main parameters of RSF: for MSS – geometric dimensions that determine the area and building volume; for FS – the size and area of the fuelling site, storage of petroleum products and the operator's building; for THE – the area and construction volume of the building, the size of the parking of customers' cars; for RA and PL – geometric dimensions and areas.

The seventh stage is implemented by comparing the results of the decisions obtained with the current standards, requirements, and standard designs.

CONCLUSIONS

As a result of the study, the following conclusions can be drawn:

1. The currently used methods for designing road service facilities are not efficient enough and require improvement.

2. The factors that determine the conditions for RSF operation, in the probabilistic-statistical sense, are random, therefore, for their technological design, it is advisable to use the methods of probability theory.

3. The processes that result in car arrivals at RSF are similar, which makes it possible to use a single calculation methodology for all facilities.

4. Mathematical models have got their development to substantiate the average number of car arrivals at service facilities and optimise their main parameters.

5. A methodology for substantiating RSF parameters has been developed that determines the general sequence of the process for implementing the methodology for calculating any road service facilities.

Of course, soon, work will be carried out to verify the adequacy of the obtained mathematical model, if necessary, to refine it and create a computation program.

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