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Determination of capacity and comfort indicators of a passenger elevator

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Introduction. Elevators are mass weight-handling units used by millions of residents of multi-storey buildings. Safety of elevator units and comfort of their use are determined not only by the correct choice of their design and parameters, but first of all, by the organization of the maintenance system. Each elevator is an individual unit that serves a residential building with a specific number of passengers, number of floors and other features. However, regulatory documents recommend standard maintenance plans. There is the need to establish the relationship between the loading modes of the main components and the optimal scheme of technical and repair works. The present work is devoted to the solution of this problem, along with the study of transport comfort.
Problem Statement. The operation of the elevator in a residential building with a number of floors N occurs in separate cycles. Standing, lift call, and destination floors are random variables for which probabilistic characteristics must be reliably established. In general, the elevator operation mode includes three stages: calling to the passenger boarding level, moving with passengers to the destination level, and waiting for the next cycle. There are stops inside the movement stages.
The specific problem of mathematical description of the random process of implementing the operating characteristics of the main drive of the elevator is reduced to two directions: 1) the development of mathematical models for the formation of the main indicators of the main elevator drive load during the cycle (net machine time τ_{mi} and the number of switches n)$_i$; 2) the study of the relationship between passenger traffic, building residential density and cycle duration.
Theoretical Part. To meet these objectives the authors have performed the studies of the following main processes characterizing the functioning of the lift, the level of capacity of the transport drive and comfort: the development of mathematical models of formation of indicators of the elevator drive load; the establishment of the relationship of traffic flow, residential density and the duration of the cycle; development of methodology for calculation of the number of flights went by the elevator in different modes; development of methods of calculating the transport comfort indicator; justification of the structure of the algorithm for modeling the operating modes of the elevator.
Conclusion. The paper provides the results, which complement the theoretical provisions for determining the capacity and transport comfort of elevators.

Keywords: passenger elevator, load level, transport comfort, operating mode, machine time coefficient, specific number of switches, mathematical models of elevator operation, simulation algorithm**.**

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Introduction. According to the definition formulated in the regulatory standard, "an elevator is an intermittent action lifting machine designed for lifting and lowering people and (or) cargo in a cabin moving along rigid rectilinear guides, which have an angle of inclination to the vertical of no more than 15°" [1]. Most high-rise buildings around the world are equipped with these devices. To date, about 500 thousand elevator units are in operation in Russia. The scale of design, manufacture and application of elevators will increase due to the growth of multi-storey construction of residential and public buildings.

The requirements for elevator units are defined by the main document — the Technical Regulations of the Customs Union [2]. Among them, the most important requirements are the safety and comfort of passengers. Obviously, each of these requirements can be represented in the form of multi-factor dependencies that must be taken into account when designing, manufacturing and operating elevator units.

Safety in the operation of an elevator unit mainly depends on two groups of factors:

— the load level of the load-bearing elements and its compliance with the regulatory values;

— ensuring the necessary quality of maintenance.

It is obvious that the scope and content of maintenance procedures should be related to the actual loads acting on the power elements of the unit, primarily the main drive, including the rope-traction mechanism, the door drive, and a number of others.

The loads of the main drive subsystem — engine, transmission, rope-traction mechanism — are formed in accordance with the operating mode. For the cyclic mode of operation of an elevator unit, it is important to distinguish two main kinematic indicators: the relative operating time of the drive and the number of switches on (decelerations) per the unit of time. Each of these indicators indirectly characterizes the operating torques and forces in the critical nodes. The establishment of these indicators does not exclude the need to determine the actual loads. The work of Khazanovich G. S., Otrokov A. V., Aprishrin D. S. Computer Modeling of Dynamic Processes of Passenger Elevators at Casual External Influence is devoted to these issues [3]. At the same time, the information on the regime kinematic indicators will allow you to pre-evaluate the degree of power load of the elevator unit without complex calculations.

The indicator "transport comfort" is defined by GOST R 52941-2008 (ISO 4190-6: 1984). National Standard of the Russian Federation. Passenger elevators [1]. It represents the interval of movement of elevators, expressed as the period of time between two consecutive departures of elevator cabins in a given direction on the main landing floor. At the same time, the main landing floor is the floor where people entering the building have access to the elevators.

The authors emphasize that the indicator of transport comfort is a random variable — it is the time interval between two consecutive cycles when the elevator moves up from the first floor to the destination floor. The comfort indicator, of course, in real conditions varies from the minimum to the maximum value. The most representative value of the comfort indicator can be the average value in different periods of daily operation: morning, afternoon, evening and night.

The cycle consists of the following elements: calling, elevator moving from the waiting floor to the first floor, a random number of passengers landing on the first floor, moving up to the destination floor with random stops. To calculate the average load and transport comfort of the elevator, the following initial data are required:

— number of floors of the building — N;

— distance between floors — h, m;

— the average speed of the elevator car — v, m/s;

— elevator load capacity as the maximum number of passengers — R;

— statistical series of the distribution of the number of passengers — r entering the elevator for the next i-th flight;

— distribution series of the number of the elevator standing floor number — L when calling it from the first floor or intermediate floors;

— distribution series of the number of intermediate stops — $R_п$ when the elevator moves from the first floor to the final destination floor — S;

— distribution series of the number of elevator stops when moving up with passengers — n;

— distribution function of the cycle duration — τ or the waiting time for the next cycle — Δ.

The justification of the list of other source data is given in the process of presenting the material of the article.

It is obvious that the indicator of transport comfort, as well as the characteristics of the elevator load, can be obtained only on the basis of simulation of the operating mode of the unit as a random process. These tasks can and should be solved together based on the unified mathematical models for the formation of kinematic characteristics of an elevator unit.

Research Rationale. The relevance of this study arises from the need to assess the level of load of the main power units of the elevator unit and transport comfort in advance, at the stage of designing the elevator or choosing a standard size from among the proposed options. This will allow you to determine in advance the type and characteristics of the engine, the speed of the cabin and other indicators.

The aim of the work is to develop a mathematical apparatus for providing the process of simulation of kinematic modes of operation of passenger elevators, which allows you to set the indicators of congestion and transport comfort of passenger elevator units.

Problem Statement. The elevator operates in a residential building with a number of floors N in separate cycles. The number of an arbitrary cycle is denoted by i, $1 \le i \le I$, where I is the total number of cycles for a certain observation period. Each cycle consists of three periods:

1) a call in which the elevator moves without passengers from the standing level after the previous cycle on the floor L to the passengers waiting level on the floor M;

2) movement of the elevator with passengers from the floor M to the destination floor S;

3) a pause of Δ duration, s (Fig. 1).

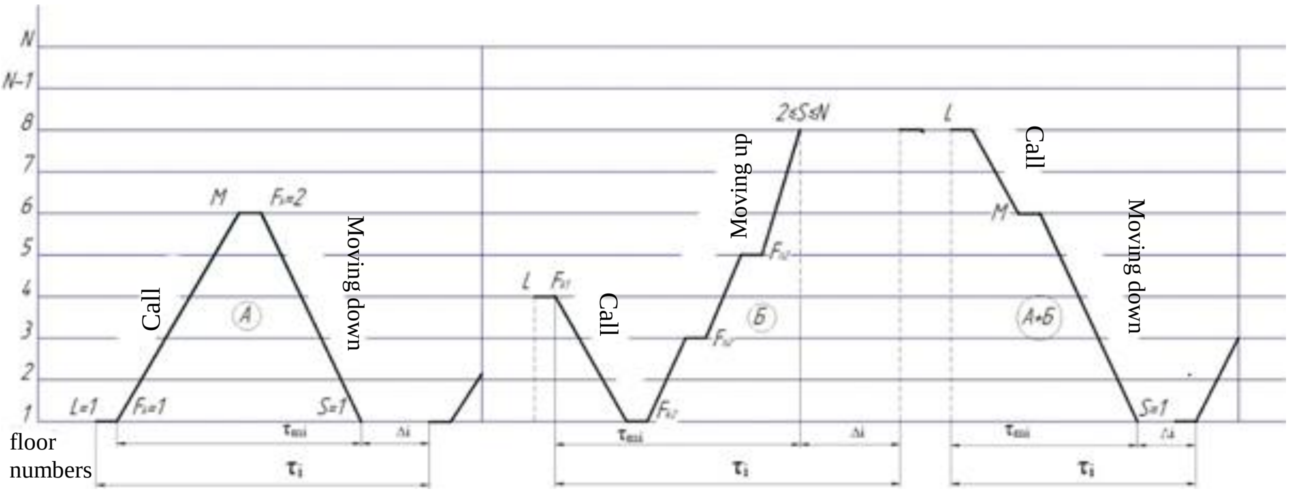


Fig. 1. Kinematic structure of the cycles: A — call and movement to the first floor without intermediate stops; B — call and movement from the first floor to an arbitrary floor S with intermediate stops; A+B — call from an arbitrary floor L to an arbitrary floor M and movement to the first floor without intermediate stops (vertical — floor numbers, horizontal — conditional time in minutes)

The values L, M, and S are random integer variables that take values in the ranges:

— when the elevator is supposed to move down to the first floor (cycle A) — $1 \le L \le N$; $2 \le M \le N$; S=1;

— when the elevator is supposed to move up from the first floor (cycle B) M=1 to the destination floor S, $2 \le L \le N$; $2 \le S \le N$.

Within each of the 1 and 2 periods, there are intermediate R_{ni} and final R_{ki} stops, at each of which the main drive is activated (decelerated), the number of which in each cycle is equal to n_i, as well as doors open and close with passenger entry and exit.

After the end of the 1 and 2 periods, there is a random pause time Δ_i before the start of the next cycle. The value of Δ_i is a continuous random variable that depends primarily on the actual passenger traffic. The total duration of an arbitrary cycle is indicated by τ_i, and the duration of the drive operation, measured in net machine time in minutes (NMT), is indicated by τ_{mi}.

Thus, the specific task of the mathematical description of the random process of implementing the operating characteristics of the main drive of the elevator is reduced to two directions:

1) development of mathematical models for the formation during the cycle of the main indicators of the load of the main elevator drive: net machine time τ_{mi} and the number of switches n_i, including:

— when the elevator moves down (cycle type A);

— when the elevator moves up (cycle type B);

— with stochastic alternation of directions of movement (cycle type A+B);

2) study of the relationship between the passenger traffic, residential building density and cycle duration.

Theoretical Part. Mathematical models of the formation of elevator drive capacity indicators. Let us denote the random distance went by the elevator cab in the i-th cycle, $K_{\text{прi}}$. If the interstorey distance (in meters) is h=const, and the average speed, taking into account acceleration and deceleration — is v m/s, then the average net machine time (NMT) per cycle in the interval 1≤i≤I will be:

$$\tau_{m\text{ср}} = \frac{h}{60v} \cdot \frac{\sum_{i=1}^{I} \text{К}_{\text{пр}i}}{I}, \tag{1}$$

and the average number of switches on of the main drive per NMT minute:

$$n_{\text{ср}} = \frac{\sum_{i=1}^{I} n_i}{I} \cdot \frac{1}{\tau_{m\text{ср}}} = \frac{\sum_{i=1}^{I} n_i}{\sum_{i=1}^{I} \text{К}_{\text{пр}i}} \cdot \frac{60v}{h} \tag{2}$$

The above relations allow us to draw preliminary conclusions:

— the average value of the net machine time of the cycle $\tau_{m\text{ср}}$ depends proportionally on the accumulated number of spans passed by the cabin $\sum_{i=1}^{I} \text{К}_{\text{пр}i}$ and inversely proportional to the average speed of the cab;

— the average specific number of $n_{\text{ср}}$ switches on is proportional to the average speed of the elevator v per cycle, with an increase in speed v , the average number of switches on per minute of the NMT increases proportionally.

After analyzing the formulas, we came to the conclusion that in order to develop adequate statistical models of the kinematic characteristics of the operating modes of the elevator drive, it is necessary to specify the order of the elevator movements in different directions and to determine statistical approaches to calculating the total or average values of the number of switches on and the number of spans went by the cabin. For this purpose, as shown earlier, three cases are distinguished: the movement of the elevator down from an arbitrary floor to the first floor without intermediate stops (cycle A), the movement of the elevator up with a random number of intermediate stops (cycle B), and the combined version with a different combination of cycles A and B.

Let us consider cycle A as the initial one, which is typical for the morning time: the movement of passengers is from an arbitrary floor M down to the first floor S=1 without intermediate stops.

Each cycle starts with the elevator standing on the first floor, L=1. The floor of the call is arbitrary in the range from M=2 to M=N. In this case, the elevator operation cycle has two stages:

1) the movement of the elevator on call from floor L=1 to an arbitrary floor 2≤M≤N. Since the random variable M is distributed a priori according to the law of uniform density, the average number of spans that the elevator passes in the first stage is equal to $\text{К}_{\text{пр}1}$=1/2·(N+2);

2) the movement of the elevator from floor M to the first floor; it is obvious that, by analogy with stage 1, the average number of spans passed by the elevator during the down trip is determined by the same expression- $\text{К}_{\text{пр}2}$=1/2·(N+2).

Then the total average number of spans per cycle is

$$\text{К}_{\text{пр}} = \text{К}_{\text{пр}1} + \text{К}_{\text{пр}2} = N+2. \tag{3}$$

Using the formula (2) to calculate the $n_{\text{ср}}$, we get the total number of switches on for I cycles. It is obvious that each considered cycle has exactly two switches on: the first — at the beginning of the movement of the elevator from standing floor L=1 to call floor M, the second — at the beginning of the movement from call floor M to the first floor. Then the total number of switches on for I cycles will be

$$\sum_{i=1}^{I} n_i = 2 \cdot I.$$

The total number of spans passed by the elevator in I cycles is equal to the sum of random values from $K_{\text{пр}.i} = 1$ to $K_{\text{пр}.i}$=N-1, and the probabilities of these values are the same and equal to P_i=1/I. The average value of the number of spans passed by the elevator, as shown above, is equal to $\text{К}_{\text{пр}}$=N+2, and the total number of spans is $\sum_{i=1}^{I} K_{\text{пр}.i}$=I(N+2). Then

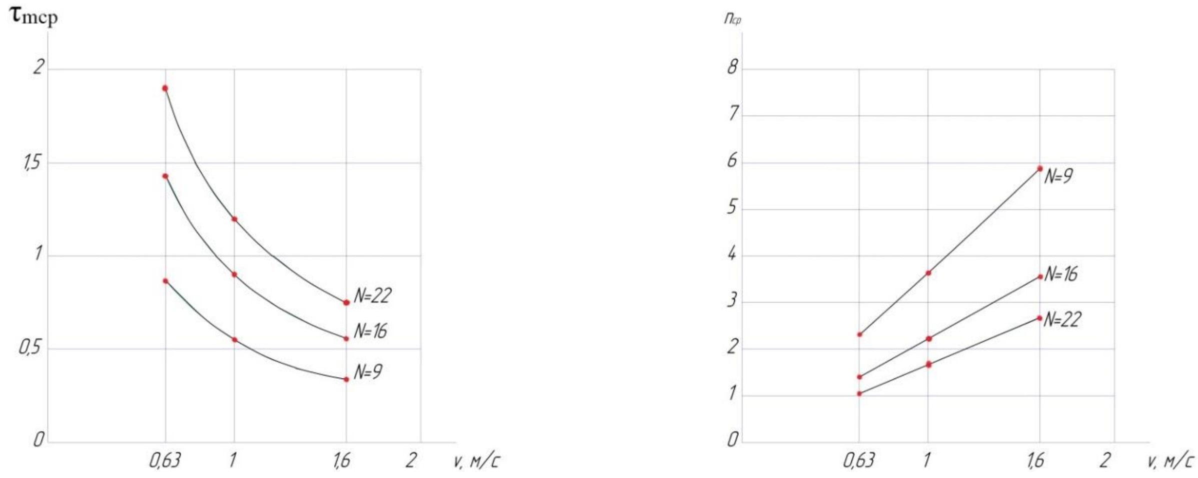
$$n_{\text{ср}} = \frac{2I}{I(N+2)} \cdot \frac{60v}{h} = \frac{120v}{(N+2) \cdot h}. \tag{4}$$

As it can be seen in the formula (4), the average number of the main drive switches on per minute of its net operating time in the morning mode is proportional to the speed of the cab and inversely proportional to the number of floors of the building.

The average NMT for the period of one random cycle will be

$$\tau_{mcp} = \frac{h(N+2)}{60v}. \quad (5)$$

Figure 2 shows graphs of τ_{mcp} (min. NMT) and n_{cp} (1/ min. NMT) as a function of speed v and the number of floors of building N.



a) b)

Fig. 2. Dependences for cycles of type A — τ_{mcp} (min. NMT) (a) and the specific number of switches on n_{cp} (1/min. NMT) (b) on the speed of the cab v and the number of floors of building N

Let us consider the features of mathematical models for cycle B (Fig. 1). The cycle consists of the operation of calling the elevator to an arbitrary floor M from the first floor and moving with passengers on the segment M, S=1. It is obvious that the average number of spans is determined similarly to the cycle (A), formulas (4) and (5) are valid.

Calculation of the number of spans passed by the elevator in the so-called mixed mode A+B. Mixed mode in a residential building with a number of floors N is the case, in which the elevator is moving down to the first floor (S=1) from the call floor M, provided that before the call the elevator was on the standing (waiting) floor L (Fig. 1). In this case, the cases L>M and L<M are possible. It is necessary to find a mathematical expression for calculating the average number of spans passed by the elevator when moving from floor L to floor M. Let us denote this value $K_{пр.A+B.}$. Obviously, the number of spans in the i-th cycle is equal to $K_{пр.(A+B)i}=|M_i–L_i|$. It should be noted that to calculate the average value of a random variable $K_{пр.(A+B\ )}$, it is necessary to consider the numbers M and L as a system of random variables. Each value M, which can take integer values 2≤M≤N, corresponds to a series of values of the value L from the range 1≤L≤N. Since a random variable M can take the number of values N–1, and L — the number of values N, the total number of combinations (M, L) will be $W_N=N(N–1)$. For example, for buildings with the number of floors N=9 — $W_N=72$, for N=16 — $W_N=240$, for N=22 — $W_N=462$.

Let us note that for a fixed value M_i, the chain $|M_i–L_i|$ consists of two sections. The first section is a decreasing series of natural numbers: M-1; M-2;...; M=L. The second section is an increasing series of natural numbers: M–(L+1); M-(L+2);...; M-N. For example, for N=7 and M=3, the results correspond to the data shown in Table 1.

Table 1

Change in the number of spans |M–L| from the standing level L for M=3 (example)

M	3	3	3	3	3	3	3
L	1	2	3	4	5	6	7
$\lvert M_i–L_i \rvert$	2	1	0	1	2	3	4
Series	Decreasing			Increasing			

As you can see, both series are arithmetic progressions with the same denominator equal to one. The sum of the terms of an arithmetic progression is determined by the formula $S_n=n(a_1+a_n)/2$, where n is the number of terms, a_1,a_n

are the values of the first and last terms of the progression [4]. Then the sums of the terms for the decreasing series Σ_I=M(M-1)/2, for the increasing series Σ_{II}=(N-M)

$$[1+(N-M)]/2=[(N-M)+(N-M)^2]/2.$$

For example, for N=7 and M=3: Σ_I=M·(M-1)/2=3·2/2=3; Σ_{II}= [(N-M)+(N-M)^2]/2 = [(7-3)+(7-3)^2]/2=10, which corresponds to the data in the table.

Thus, the sum of the terms of the two sections for a specific fixed value of M is determined by the formula:

$$К_{пр1ц} = \Sigma_I + \Sigma_{II} = \frac{1}{2}[M(M-1) + (N-M) + (N-M)^2]$$

After simple transformations, we get:

$$К_{пр1ц} = M^2 + \frac{N(N+1)}{2} - (N+1)\cdot M. \quad (6)$$

In total, the number of such chains when M changes from 2 to N will be N-1 pieces. Then the total number of spans that can be implemented in each particular cycle is determined by summing when M changes from 2 to N:

$$К_{пр\Sigma} = \sum_{M=2}^{N} M^2 - \sum_{M=2}^{N} M - \sum_{M=2}^{N} M\cdot N + \sum_{M=2}^{N} \frac{1}{2}(N^2+N).$$

When calculating partial sums, we use Fermat's formula for the first term [4]:

$$\sum_{M=2}^{N} M^2 = \frac{N(N+1)(2N+1)}{6} - 1. \quad (7)$$

Formula (7) is presented for the case when the sum of squares starts from M=2.

The sums in which M is included in the first degree are arithmetic progressions, the method of calculating of which is shown above.

The last term is calculated by the formula:

$$\sum_{M=2}^{N} \frac{1}{2}(N^2+N) = \frac{N(N+1)}{2}\cdot(N-1),$$

where the factor (N-1) indicates the number of addition operations when M changes from 2 to N. As a result, the sum takes the form:

$$К_{пр\Sigma} = \frac{N}{2}(N^2-1) + \frac{N(N+1)(2N+1)}{6} - 1 + (N^2-1)\frac{2+N}{2}.$$

Giving such terms, we get a formula for calculating the possible total number of options for spans passed by the elevator in the cycle (A+B):

$$К_{пр\Sigma} = \frac{1}{6}N(N+1)(2N+1) - N^2. \quad (8)$$

Expression (8) is a variation of Fermat's formula for the considered case of summing the number of spans [5]. To perform calculations, expression (8) can also be written as:

$$К_{пр\Sigma} = \sum_{M=1}^{N-1} M^2. \quad (9)$$

The average number of spans passed by the elevator cab in one cycle during the period of movement from standing floor L to call floor M:

$$К_{пр(L-M)} = \frac{К_{пр\Sigma}}{W_N} = \frac{N(N+1)(2N+1)}{6N(N-1)} - \frac{N^2}{N(N-1)} = \frac{(N+1)(2N+1)-6N}{6(N-1)} \quad (10)$$

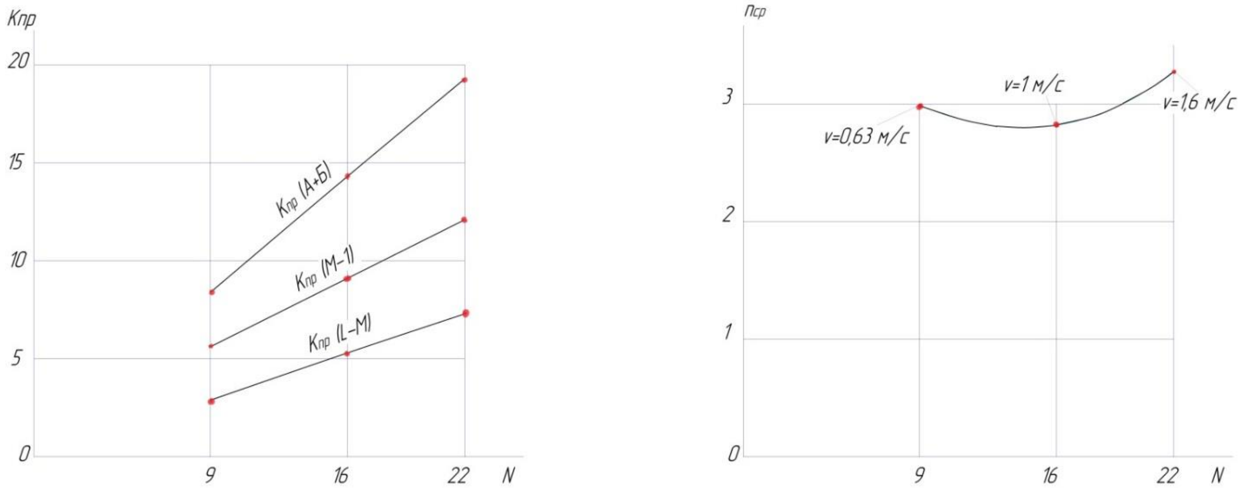
When the elevator moves from call floor M to the first floor, the average number of spans, as shown earlier, will be $К_{пр(M-1)}$=1/2·(N+2). Then the general expression for calculating the average number of spans passed by the elevator in (A+B) cycle will take the form:

$$К_{пр(А+Б)ср} = \frac{(N+1)(2N+1)-6N}{6(N-1)} + \frac{N+2}{2}. \quad (11)$$

Formulas (3), (10) and (11) are universal relations for calculating the average number of spans passed by the elevator in cycles of various types. The constructed graphs give an idea of the dependencies of the components of $К_{пр}$ in the function of the number of floors N (Fig. 3).

According to the known value $К_{пр(А+B)ср}$, it is possible to determine the net machine cycle time $\tau_{мср}$ and the specific number of switches on $n_{ср}$ using formulas (1), (5). This requires individual indicators of the elevator and the residential building — the average speed of movement v and the interstorey height h.

Mathematical relations (3), (4) and (11) allow us to obtain the component of the average cycle duration in individual periods of elevator operation, which is necessary for simulation modeling



a) *b)*

Fig. 3. The dependencies of the average number of spans passed by the elevator, and the specific number of switches on in the cycles of the A+B type on the number of floors of the building and the speed of the cab: a — the number of spans by components when calling (L–M), movement (M-1), and the total; b — the number of switches on per minute in the NMT at cab speeds corresponding to the number of floors of the building

Relationship between passenger traffic, residential building density, and cycle duration. The duration of the elevator cycle τ_i is one of the most important indicators that determine the workload and transport comfort of the unit.

The components of the value τ_i are given above. It is obvious that the main factor determining the average duration of the $\tau_{ср}$ cycle is the passenger traffic (PT) $A_л$. This indicator is one of the specified values set by the corresponding standard [1]. The initial average passenger traffic according to [1] is determined by the formula:

$$A_{1p} = 12 \cdot A_{п.л} \cdot \frac{(N-N_н)\cdot Y}{100N}, \qquad (12)$$

where $A_{п.л}$ — the number of passengers in the building or blocks of flats using the elevator,

$$A_{п.л} = (N - N_н) \cdot C_{кв} \cdot d_{кв}, \qquad (13)$$

N — the number of occupied floors; $N_н$— the number of floors, tenants of which do not use the elevator (usually $N_н$=1); Y — the indicator of PT intensity, characterizing the number of people to be transported within a five-minute interval, in percentage terms of the number of people using the elevator (i=4–8%); $C_{кв}$ — the average number of apartments on one floor; $d_{кв}$ — the number of people per apartment, using the elevator; according to [1] this figure is recommended in the range of 1, 2-3.

The analysis shows that the application of the indicator $d_{кв}$ to all elevators leads to incorrect results: the average number of residents in a single apartment $d \leq d_{кв}$.

It is logical to assume that the number of residents using the elevator is proportional to the total number of residents of the riser blocks of flats or building. In this case, the calculation will not be related to the value $d_{кв}$ — the average number of residents of a separate apartment who use the elevator. It is more reasonable to enter a single conditional indicator in expression (13), which depends only on the number of residents of a given building or riser blocks of flats. Each building or riser blocks of flats must be characterized by individual indicators: the number of building floors N, the total (list) number of residents Z and a single indicator — the share of the number of residents using the elevator $d_{жо}$. Then the number of passengers of building or riser blocks of flats using the elevator $A_{п.л}$, can be determined by the formula:

$$A_{п.л} = Z \cdot \frac{M_k - M_{1k}}{M_k} \cdot d_{жд}, \qquad (14)$$

where M_k — the total number of apartments in the building (blocks of flats); M_{1k} — the number of apartments in the building (blocks of flats), tenants of which do not use the elevator.

Then, taking into account recommendations [1] and the proposed changes, the estimated hourly passenger traffic can be determined by the formula:

$$A_{1p} = 0{,}12 \cdot Z \cdot \frac{M_k - M_{1k}}{M_k} \cdot d_{жд} \cdot \frac{(N - N_{н}) \cdot Y}{N}. \qquad (15)$$

The calculated average minute PT will be:

$$A_{1p} = 0{,}002 \cdot Z \cdot \frac{M_k - M_{1k}}{M_k} \cdot d_{жд} \cdot \frac{(N - N_{н}) \cdot Y}{N}. \qquad (16)$$

Expression (16) provides a formula for calculating the average cycle duration. To do this, we will enter the average cabin capacity rate in the r_{cp} cycle. The value r is random, the distribution series of which is established experimentally. The data on the distribution series are given in [5], for most cases at R=5 people r_{cp}=2.25, R=8 r_{cp}=2.85.

The estimated average duration of the cycle τ_{cp} (min/cycle) is defined as the quotient of the average cabin capacity in the r_{cp} cycle divided by the average minute cargo flow A_{1p},, i.e.

$$\tau_{cp} = r_{cp}/A_{1p}. \qquad (17)$$

After simple transformations, we get:

$$\tau_{cp} = \frac{500 \cdot M_k \cdot N \cdot r_{cp}}{Z \cdot (M_k - M_{1k}) \cdot d_{жд}(N - N_{н}) \cdot Y}. \qquad (18)$$

Expression (18) allows us to make a qualitative assessment of the influence of the main factors on the cycle duration that provides a given passenger flow. If we assume that the ratios N/(N–$N_{н}$) and M_k /(M_k–M_{1k}) are close to one, then the main influencing factors are the capacity level of the cabin with passengers r_{cp} (proportional dependence) and the conditional design number of passengers using the elevator, $Z \cdot d_{жд} \cdot Y$ (inversely proportional dependence).

A set of mathematical models (4), (5), (11) and (18) allows us to calculate the average values of the main kinematic characteristics of the elevator operating mode, as well as to obtain all the necessary initial data to start the simulation process. Let us consider the procedure for calculating the average values of the machine time coefficient K_{mcp}, the specific number of swithes on of the main drive per NMT minute n_{cp} and the duration of the pause before the next cycle Δ_{cp}.

It is well known, that K_{mcp} is the ratio of the elevator's NMT per cycle τ_{mcp} to the total average value of the duration of the cycle τ_{cp} — formula (18). The calculation of τ_{mcp} is a separate task for analyzing the general operating mode of the elevator over a long period of time. As shown above, there are three main cycles — A, B and A+B, in each of which the average value of the NMT is determined by individual ratios: for cycles A and B — this is formula (5), for cycle A+B — formulas (1) and (11). To calculate the average value τ_{mcp}, it is necessary to additionally set the ratio of the share of each of the cycles in the overall structure of the mode. The parts of cycles of different types we denote γ_A, γ_B and $\gamma_{(A+B)}$, respectively, with $\gamma_A+\gamma_B+\gamma_{(A+B)}=1$. Cycles of type A —the elevator moves mainly to the first floor, morning mode, type B — evening mode, type A+B — day and night modes. The average duration of the NMT at different speeds for all elevators (regardless of the number of floors of the building) can be determined by the formula:

$$\tau_{mcp} = \frac{h}{60 v(N)} \left[(\gamma_A + \gamma_Б) \cdot (N + 2) + \gamma_{(A+Б)} \cdot К_{пр(A+Б)cp} \right], \qquad (19)$$

where $К_{пр(A+B)cp}$ — is calculated by the formula (11); $v(N)$ is the dependence of the accepted elevator speed on the number of floors of the building.

Expression (19) indicates that under the known cycle alternation mode, the value of the average NMT depends primarily on the number of floors of the building and the speed of movement of the elevator cab. For example, in Fig. 4, (Graph a), the dependence τ_{mcp}=f(N) is given at $(\gamma_A + \gamma_B) = 0.8$, v=1 m/s; in Graph b, the change in NMT at the cab speeds corresponding to the number of floors of the bilding is shown in Fig. 3b.

Mathematical model of a random variable — the duration of waiting for the next cycle. These data can be used to justify the initial parameters for the simulation process. For a full-scale implementation of the cycle-by-cycle simulation process, knowledge of the functions or distribution density of random variables is required, a list of which is presented in the introductory part of the article. The distribution series of discrete quantities M, L, S and the absolute value of the difference |M-L| are considered above. The method for calculating and modeling the random number of elevator stops when moving with passengers up from the first floor is given in the work of D.S. Apryshkin and G.Sh. Khazanovich "Methodology and algorithm for simulating the operating modes of a passenger elevator" [5]. Let us consider the determination of a random waiting time for the next cycle Δ.

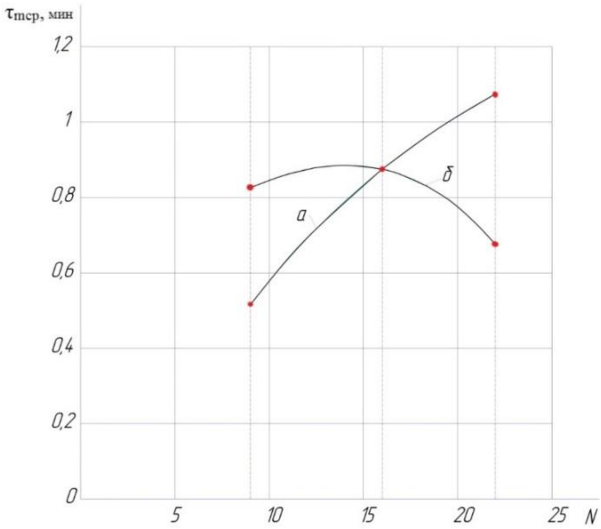


Fig. 4 Influence of the number of floors of a residential building (N) on the average values of the NMT cycle

The ratio between the time elements of the cycle gives the ratio

$$\tau=(\Delta+\tau_{m}+\tau_{пз}), \quad (20)$$

where $\tau_{пз}$ — the total time spent on passengers loading and unloading.

Moving on to the average values, we get

$$\Delta_{ср}=\tau_{ср}-\tau_{mср}-\tau_{пзср}. \quad (21)$$

The average values of the components $\tau_{ср}$ and $\tau_{mср}$ are calculated using formulas (18) and (19), respectively. The total time $\tau_{пзср}$ depends on the number of stops $F_{пв}$ and the average duration of one stop $t_{1.пв}$

$$\tau_{пз}=F_{пв}\cdot t_{1.пв}. \quad (22)$$

The number of stops in the cycle consists of the final stops $F_{пвк}$ and intermediate stops $F_{пвп}$ and depends on the type of movement — A, B or A+B. When the elevator is moving down, there are no intermediate stops, the number of final stops for cycles of any kind is equal to two, i.e. $F_{пвк}=2$. The number of intermediate stops during the upward movement of the elevator is determined by the method described in [5].

The random variable Δ, as an element of the queuing system, is modeled according to the exponential law with the parameter $\Delta_{ср}$ [6–7]. The probability density has the form:

$$f(\Delta)=\frac{1}{\Delta_{ср}}e^{-\frac{\Delta}{\Delta_{ср}}}. \quad (23)$$

Capacity of the elevator unit. The mathematical models of the elevator functioning processes justified above allow us to solve the problem of determining the maximum capacity of the unit, $Q_{пр}$, people/hour. The basis is the duration of the combined cycle NMT (A, B, A+B) in total with the duration of stops for passengers loading and unloading, as well as the average number of passengers transported per cycle, i.e.

$$Q_{пр}=\frac{60\cdot d_{ср}}{\tau_{mср}+\tau_{пзср}+\delta}, \quad (24)$$

where δ — admissible waiting time for the next cycle, not more than one minute; $\tau_{mср}$ is calculated by \ formula (19); $\tau_{пзср}$ — is calculated by formula (22).

Expression (24) allows us at the design and selection of an elevator unit stage to analyze the impact of critical factors on its average capacity — the number of floors, speed and capacity of the cabin. The obtained values $Q_{пр}$ should be compared with the estimated hourly passenger flow $A_{1р}$(16) and we should determine the safety margin of the ППП.

Calculation of the indicator of transport comfort of the elevator unit. First of all, it is necessary to establish the average possible interval of movement of the cab from the first floor of the building [1]. In accordance with the notation, it is necessary to calculate the average interval of B cycle at a known frequency of these cycles γ_B. If we determine the average NMT of B cycle, in accordance with (5) and take into account the loss of time for doors opening and closing according to (22), the average time after which the lift will be in position before lifting from the ground floor, will be:

$$\tau_{ТК} = \frac{1}{\gamma_Б}\left[\frac{h(N+2)}{60v(N)} + F_{ПВ.Б}\cdot t_{1.ПВ}\right] + \delta_1, \quad (25)$$

where $\tau_{ТК}$ — the average indicator of transport comfort of the elevator, min.; $F_{ПВ.Б}$ — the average number of stops at lift motion in a B cycle from the first floor; δ_1 — the conditional waiting time for the next cycle (10 sec.).

To assess the current level of transport comfort in the modeling process, in the numerator of formula (25) instead of (N+2), the actual number of stairs is inserted, passed by the elevator in B cycles from the first floor, Δ_B:

$$\tau_{ТКБ} = \frac{1}{\gamma_Б}\left[\frac{h\cdot\Delta_Б}{60v(N)} + F_{ПВ.Б}\cdot t_{1.ПВ}\right] + \delta_1. \quad (26)$$

As it can be seen from expression (25), the calculated average index $\tau_{ТК}$ depends on the number of floors of the building, the average speed of the cabin, the number of stops with passengers loading and unloading, and the specific number of B cycles in the total number of cycles. The result of the calculation according to formula (25) characterizes the transport comfort of the elevator unit for the entire daily period of its operation. To assess the transport comfort during the hours of the highest load of the elevator with B cycles (the so-called evening mode), the share of this mode is significantly increases (Table 2).

To assess the level of transport comfort, boundary values are introduced: up to 60 s. — excellent, 60-80 s. — good, 80-100 s. — satisfactory. As it can be seen in the table, it is impractical to evaluate the average values of the level of transport comfort, since the calculated indicators are significantly lower than those established by the standard. For the evening mode, the values of $\tau_{ТК.веч.}$ are close to good or satisfactory values. The main means of increasing the level of transport comfort of the elevator is to increase the average speed.

Table 2

Calculation of the values of the transport comfort indicator of standard elevators

N	v,m/s	$F_{ПВ.Б}$	$t_{1.ПВ}$,c	$\gamma_{Б.ср}$ / $\gamma_{Б.веч}$	δ_1, c	$\tau_{ТК.ср}$,c	$\tau_{ТК.веч.}$, c
9	0.63	2	8	0.4 / 0.9	10	180.5	80.2
16	1.0	2	8	0.4 / 0.9	10	185.5	82.4
22	1.6	2	8	0.4 / 0,9	10	163.4	72.6

When calculating and analyzing the main indicators of elevator units, the requirements of regulatory documents were taken into account [1–2, 8–10].

The structure of the algorithm for modeling the operating modes of the elevator in order to assess the capacity and transport comfort. The description of a complete algorithm for simulating elevator operating modes is a complicated task. In this regard, the structure of the algorithm and brief explanations to it are given below (Fig. 5).

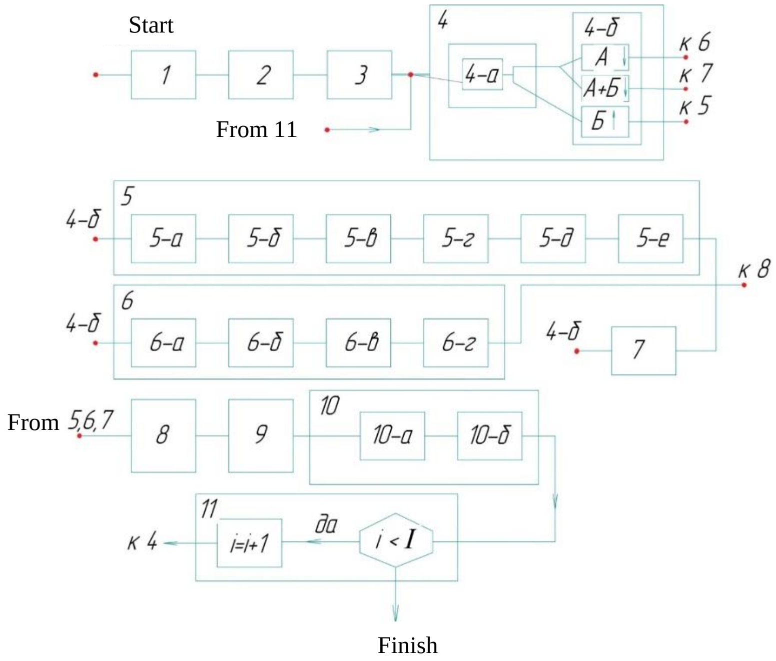


Fig. 5. The structure of the algorithm for simulating the operating modes
and the indicator of transport comfort of the elevator unit

The simulation procedure consists of the following main blocks:

1 — input of the initial data, which are divided into groups: characteristics of a residential building, elevator unit and general characteristics of the mode — N, $N_н$, h, Z, $d_{жд}$, M_k, M_{k1}; v, R; Y, $ɣ_A$, $ɣ_B$, $ɣ_{A+B}$, d_{cp}, $F_{ПВ}$, $t_{1ПВ}$, δ, I;

2 — calculation of the average initial indicators necessary for modeling the duration of the pause between the cycles of the Δ_{cp} (21), the transport comfort indicator τ_{TK} (25) and the capacity of the elevator unit $Q_{пр}$ (24): $K_{пр(A+B)cp}$ (11), τ_{cp} (18), τ_{mcp} (19), $\tau_{пзср}$ (22), n_{cp} (2), A_{1p} (15);

3 — input of the initial conditions: cycle number i, elevator standing floor L_i;

4 — determination of a random cycle in accordance with the direction of motion (4-a), distribution $ɣ_A$, $ɣ_B$, $ɣ_{A+B}$: A, B or A+B (step 4-b);

5 — when moving up from the first floor (cycle B) — simulation of the destination floor number S_i (5-a), calculation of the number of spans $K_{прi}$=(L–1)+(S–1) — (5-b), the number of final stops F_{ki} (5) and simulation of the number of intermediate $F_{п1}$ stops (5-d), calculation of the cycle NMT τ_{mi} by formula (1) and the specific number of switches on n_i according to formula (2) — (step 5-e), calculation of the current transport comfort by formula (26) — (step 5-f) [5];

6 — when moving down to the first floor from any floor M (series A): simulation of the random number of floor call M_i (6-a), calculation of the number of spans $K_{прi}=(|L_i–M_i|)+(M_i–1)$ — (6-b), the number of final stops F_{ki} — (6-c) and calculation of the cycle NMT τ_{mi} by formula (1) and the specific number of switches on n_i according to formula (2) — (6-d);

7 — when moving down to the first floor from any floor M when the elevator is standing on any floor L (cycle A+B) simulation is performed in the hotel subroutine;

8 — at the end of the i-th cycle, the main kinematic indicators τ_{mi}, n_i and the final floor of the elevator L_{i+1}1 are fixed;

9 — a random value of the pause between cycles Δ_i is modeled according to formula (23);

10 — summers of kinematic indicators τ, τ_m, n, $\tau_{ТКБ}$ and transport comfort indicator $\tau_{ТКБ}$ are formed (step 10-a), and the average values for i cycles are calculated (10-b);

11 — the condition i<I is checked; when it is executed, the number of the next cycle i+1 is entered, and the simulation continues from step 4.

The results of the simulation will be presented in the next issues of the journal.

Conclusion. The current issues of establishing the main indicators of capacity and transport comfort of elevators of residential buildings are considered. These indicators determine the safety and usability of elevator units. Despite the existence of a number of state standards regulating the main parameters of passenger elevators, these documents do not reflect the issues of the formation of kinematic indicators and transport comfort of elevator units as a random process. In the course of the study, the following results have been obtained, the conclusions have been made:

The general problem of the elevator cycle-by-cycle operation is formulated with the identification of the influencing factors as random variables.

Adequate mathematical models for the formation of elevator drive load indicators have been developed, which allow determining the current and average values of the machine time coefficient and the specific number of switches on.

For the first time, the formulas for calculating the number of spans passed by the elevator in mixed modes are justified. Universal dependencies of the distance passed on the number of storeys of the building are established.

The relationship between passenger traffic, residential building density, and cycle duration is studied, and the ratio is obtained for the average cycle duration that provides a given elevator capacity.

The mathematical model of the waiting time for the next cycle is justified, which makes it possible to conduct a cycle-by-cycle simulation of the process.

The formula is obtained for calculating the maximum capacity of the elevator, which takes into account the duration of operation in net machine time and the average degree of the elevator cab capacity.

A mathematical model has been developed for calculating the main indicator — the transport comfort of the elevator unit. The most important influencing factors are identified.

The structure of the algorithm for simulating the operating modes of elevators has been developed in order to establish the capacity and transport comfort.

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Contribution of the authors:

D. S. Apryshkin — formulation of the purpose and program of the research, derivation of mathematical models, development of simulation algorithm; G. S. Khazanovich — study of the basic modes of operation of elevator units, the influencing factors rationale, consultation in the derivation of mathematical models, algorithm development.