Development of enhanced method for planning train locomotives ready to operate the next day

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Abstract. A series of methods for planning the use of train locomotives has been developed. However, existing scientific research does not clearly specify how the arrival and departure times of freight trains are determined in train schedules, and locomotives are assigned to trains based on the condition of "Locomotive waits for train". This article proposes a methodology for determining the average time of stay for train locomotives and trains at the boundaries of train sidings for all scenarios ranging from the condition of "Train waits for locomotive" to "Locomotive waits for train". The EGM program has been developed and created for calculating the fleet of freight locomotives based on the graphical movement time of trains, and an enhanced method for planning the effective use of train locomotives has been developed based on minimizing the downtime of rolling stock within the boundaries of towing sidings.

1 Introduction

The operation of train locomotives is a complex multi-level scientific and technical problem. Therefore, there are several scientific works aimed at solving this problem [1-22]. In all existing scientific works, the operational fleet of train locomotives is determined based on analytical and graph-analytical methods, with the latter being the most accurate [23]. The calculation of the locomotive fleet utilization requirement is based on the graph-analytical method using train movement schedule data. However, existing scientific works do not explain how the arrival and departure times of freight trains are determined in the train schedule, which is based on the condition of attaching locomotives to trains of "Locomotive waits for train". If we look at the current cost standard, one locomotive-hour (including its crews) costs 271,855 sum, and one wagon-hour costs 973 sum. Considering that a train consists of a maximum of 57 wagons (in most cases), the waiting time for a locomotive is 55,461 sums. Therefore, one hour of waiting for one locomotive is equivalent to waiting for 5 trains. This highlights the need for developing an effective proactive plan for using train locomotives in a market economy.

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2 Materials and methods

It is known that to minimize the waiting time of train locomotives at turning points on railway sections, station arrival and departure times must be taken into account in the schedule. In general, the maximum and minimum number of stops for locomotives and train components at turning points (respectively, $t_{max(lok)}$, $t_{max(tar)}$, $t_{min(lok)}$, $t_{min(tar)}$) are determined as shown in *Fig. 1*. Due to the variable schedule, any train ready for departure will have to wait (t_k) for the section to become available. The value of t_k is determined based on the technical equipment of the railway section and train flow parameters.

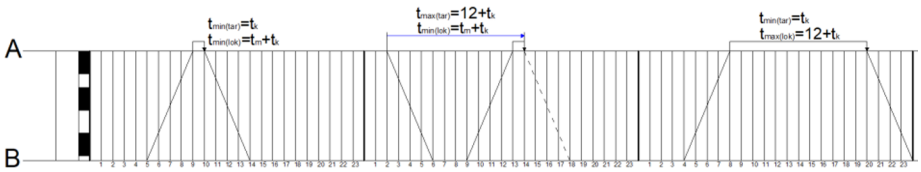

Fig. 1. Schematic representation of the maximum and minimum number of locomotive and train stops at turning points.

As seen in *Fig. 1*, the minimum number of train locomotives standing at turning points corresponds to the condition of attaching locomotives to trains of "Train waits for locomotive", while the minimum number of trains stops corresponds to the condition of "Locomotive waits for train". In the train movement schedule, the arrival and departure times of freight trains at stations are interrelated, and the maximum locomotive dwell times on train movement sections N_l can be determined as follows:

$$t_{\text{Max}(lok)} = \frac{12}{\sum N_l} + t_k, \text{ hour.} \quad (1)$$

It is known that in conditions equipped with modern information and management systems, it is possible to plan train movements for the next day. As a result, we can determine the departure time of freight trains from stations at each turning and transfer point for the day when train movements are planned. Table 1 shows the results of determining the departure-arrival time at the turning point for a flow of 18 freight trains.

Table 1. The departure time of freight trains at the turning point

o/n	Paired train number	Arrival date of paired trains	Arrival time of paired trains	Unpaired train number	Departure date of unpaired trains	Departure time of unpaired trains
1	2034	18.07.2022	20:24:00	2033	18.07.2022	20:18:00
2	2036	18.07.2022	22:22:00	2035	18.07.2022	23:04:00
3	2002	18.07.2022	00:12:00	2001	18.07.2022	0:48:00
4	2004	18.07.2022	00:48:00	2003	18.07.2022	1:27:00
5	2006	18.07.2022	01:19:00	2005	18.07.2022	2:39:00
6	2008	18.07.2022	03:38:00	2007	18.07.2022	3:07:00
7	2010	18.07.2022	04:39:00	2009	18.07.2022	3:41:00
8	2012	18.07.2022	06:15:00	2011	18.07.2022	4:09:00
9	2014	18.07.2022	06:28:00	2013	18.07.2022	6:25:00
10	2016	18.07.2022	07:47:00	2015	18.07.2022	6:43:00
11	2018	18.07.2022	08:57:00	2017	18.07.2022	7:11:00

12	2020	18.07.2022	10:07:00	2019	18.07.2022	8:06:00
13	2022	18.07.2022	13:11:00	2021	18.07.2022	9:46:00
14	2024	18.07.2022	15:42:00	2023	18.07.2022	11:14:00
15	2026	18.07.2022	16:31:00	2025	18.07.2022	14:14:00
16	2028	18.07.2022	18:10:00	2027	18.07.2022	14:48:00
17	2030	18.07.2022	18:31:00	2029	18.07.2022	17:34:00
18	2032	18.07.2022	18:53:00	2031	18.07.2022	18:35:00

Based on the data presented in Table 1, potential connections of train locomotives at the turn station have been established. We will develop an enhanced method for planning the efficient utilization of train locomotives based on the number of operational train units available. This method will determine the idle time of train locomotives and trains at the turning points. In this case, we define the arrival time of trains at Station 1 as t_i^l and the departure time from Station 1 as T_j^l, where $i=\overline{1,N_l}$; $j=\overline{1,N_l}$. The departure and arrival graphs of freight trains from the station (Tables 1-2) divide the time axis of the shift station into *k* segments. In this scenario, the number of components increases after the arrival of each train at the station and decreases from $\min k_v = 0$ to $1 \le v \le 2N_l + 1$ units after the departure of each train. Otherwise, at least one component will remain at the turn station for a day, allowing the determination of all κ_V.

In the case where the number of components equals the number of components, we allocate portions of κ_V to the components present at the turn station during the time interval. In this scenario, the receiving schedule t_i^l can be linked to the dispatch schedule without increasing the number of locomotives when the indices of all segments belonging to $[t_i^l; T_j^l]$ are $k_v > 0$. Otherwise, connecting these schedules would result in an increase in the total number of locomotives. For example, the t_{1i} schedule can be linked to T_1^l or T_2^l, but the t_1^l schedule cannot be linked to T_3^l because such a connection would increase the demand for locomotives.

Table 2 provides an example of a matrix depicting potential connections of locomotives.

Table 2. Example of a matrix depicting potential connections of locomotives.

t_i^l \ T_j^l	T_1^l	T_2^l	T_3^l	T_4^l	T_5^l	T_6^l
t_1^l	0	0	1	1	1	1
t_2^l	1	1	0	0	1	1
t_3^l	1	1	0	0	1	1
t_4^l	1	1	1	1	0	0
t_5^l	1	1	1	1	0	0
t_6^l	1	1	1	1	1	1

$\{x_{ij}^{i}\}$ We input the connectivity matrix:

$$\left\{x_{ij}^{l}\right\} = \left\{\begin{matrix} 1, \text{ If the arrival schedule } t_i^l \text{ is linked} \\ \text{to the departure schedule } \left[T_j^1\right]; \\ 0 - \text{otherwise} \end{matrix}\right\} \tag{2}$$

If each arrival schedule t_i^l can be linked to at most one departure schedule T_j^i, and conversely, each schedule T_j^i can be linked to at most one schedule t_i^l, the following inequality holds:

$$\sum_i x_{ij}^l \le 1, \forall_j; \sum_j x_{ij} \le 1, \forall_i . \tag{3}$$

In other words, each row of the connectivity matrix contains at most one unit (*Fig.2*).

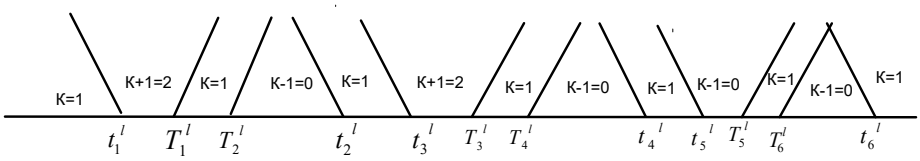

Fig. 2. Illustration of potential connections of train locomotives at the turn station.

For a railway section with a certain number of stations, a locomotive train movement schedule can be constructed based on the specified timetable. We assume $l = 1, 2$. The indices k_v are determined with respect to the segments of the time axis (*Fig. 3*).

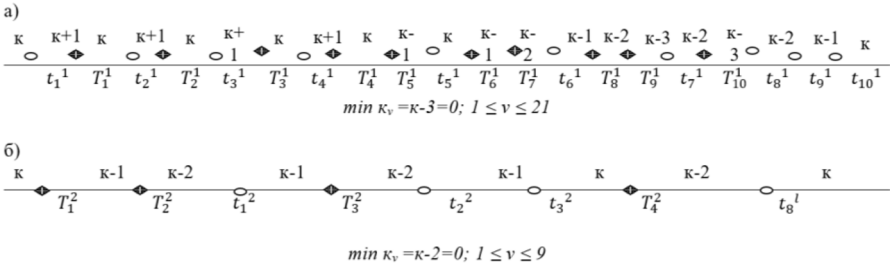

Fig. 3. Order of determining the relationship between indices and sections of the time axis.

3 Results and discussion

Let's construct the matrices of potential connections for the first (Table 3) and second (Table 4) turn stations.

Table 3. Connectivity matrix for the first turn station.

	t_i^1 \ T_j^1	T_1^1	T_2^1	T_3^1	T_4^1	T_5^1	T_6^1	T_7^1	T_8^1	T_9^1	T_{10}^1
$\{x_{ij}^1\}=$	t_1^1	1	1	0	1	1	1	1	1	1	1
	t_2^1	1	1	1	0	1	1	1	1	1	1
	t_3^1	1	1	1	1	1	0	1	1	1	1
	t_4^1	1	1	1	1	0	1	1	1	1	1
	t_5^1	1	1	1	1	1	1	1	0	1	1
	t_6^1	1	1	1	1	1	1	1	1	0	1
	t_7^1	1	1	1	1	1	1	1	1	1	0
	t_8^1	1	1	1	1	1	1	1	1	1	1
	t_9^1	1	1	1	1	1	1	1	1	1	1
	t_{10}^1	1	1	1	1	1	1	1	1	1	1

Table 4. Connectivity matrix for the first turn station.

	t_i^2 \ T_j^2	T_1^2	T_2^2	T_3^2	T_4^2
$\{x_{ij}^2\}=$	t_1^2	1	1	0	1
	t_2^2	1	1	1	0
	t_3^2	1	1	1	1
	t_4^2	1	1	1	1

For each of the matrices in Tables 3 and 4, locomotives are associated with trains starting from the condition “Container awaits locomotive”, which corresponds to Table 1. This association continues until the condition “Locomotive awaits content” is met (Table 5).

Table 5. The results of attaching locomotives to trains based on the condition "Locomotive awaits train" at the turn station.

O/n	Paired train number	Departure date of paired trains	Departure time of paired trains	Unpaired train number	Departure date of unpaired trains	Departure time of unpaired trains
1	2034	18.07.2022	20:24:00	2003	19.07.2022	1:27:00
2	2036	18.07.2022	22:22:00	2005	19.07.2022	2:39:00
3	2002	18.07.2022	00:12:00	2007	18.07.2022	3:07:00

4	2004	18.07.2022	00:48:00	2009	18.07.2022	3:41:00
5	2006	18.07.2022	01:19:00	2011	18.07.2022	4:09:00
6	2008	18.07.2022	03:38:00	2013	18.07.2022	6:25:00
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8	2012	18.07.2022	06:15:00	2017	18.07.2022	7:11:00
9	2014	18.07.2022	06:28:00	2019	18.07.2022	8:06:00
10	2016	18.07.2022	07:47:00	2021	18.07.2022	9:46:00
11	2018	18.07.2022	08:57:00	2023	18.07.2022	11:14:00
12	2020	18.07.2022	10:07:00	2025	18.07.2022	14:14:00
13	2022	18.07.2022	13:11:00	2027	18.07.2022	14:48:00
14	2024	18.07.2022	15:42:00	2029	18.07.2022	17:34:00
15	2026	18.07.2022	16:31:00	2031	18.07.2022	18:35:00
16	2028	18.07.2022	18:10:00	2033	18.07.2022	20:18:00
17	2030	18.07.2022	18:31:00	2035	18.07.2022	23:04:00
18	2032	18.07.2022	18:53:00	2001	18.07.2022	0:48:00

In the case of an odd train schedule, information about train locomotives that are candidates for backup dispatch can be obtained using programs developed within the scope of the research [1].

Thus, for r possible connections of locomotives to trains from the state of “Train awaits locomotive” to the condition of “Locomotive awaits train”, the average idle times of train locomotives and trains at the boundaries of train tracks (*l; l+1*) can be determined as follows:

$$\bar{t}_{lok}^{l;l+1(r)} = \frac{\sum_{i=1}^{N_{l;l+1}} t_{lok}}{N_{l;l+1}}, \text{ hour;} \tag{4}$$

$$\bar{t}_{tar}^{l;l+1(r)} = \frac{\sum_{j=1}^{N_{l;l+1}} t_{tar}}{N_{l;l+1}}, \text{ hour.} \tag{5}$$

In turn, for r variants, the fleet of train locomotives in operation on the *e*-th terminal track (excluding TO-2) is determined as follows:

$$M_{fp(e)}^{r} = \frac{N_l}{24}\left(\frac{2 \cdot L_{uch}}{V_{uch}} + \bar{t}_{lok}^{l(r)} + \bar{t}_{lok}^{l+1(r)}\right), \text{ loc.} \tag{6}$$

Within the scope of the research, a software program for the Railway Traffic Control System (RTCS) was developed to calculate the fleet of freight locomotives based on the graphical train movement time. This program automatically calculates the fleet of freight locomotives based on r parameters, considering the number of freight trains, their arrival and departure times at the station, speed of movement on the sections, and the distance of transportation. The results obtained from the program are.

The results of determining the operational fleet of train locomotives for r variants of locomotive and train compositions present at the turn station (In case there are $V_{yч}=30$ km/h; $L_{yч}$=300 rm, N_l=18 train) (Table 6).

The results of determining the operational fleet of train locomotives for r variants of locomotive and train

Table 6. The results of determining the operational fleet of train locomotives for r variants of locomotive and train.

r	$\bar{t}^{l(r)}_{lok}$	$\bar{t}^{l(r)}_{tar}$	$\bar{t}^{l+1(r)}_{lok}$	$\bar{t}^{l+1(r)}_{tar}$	$M^{r}_{fp(e)}$
1*	0,57	1,68	0,92	1,62	17,48
2	0,97	0,75	1,15	0,92	16,25
3	1,63	0,08	2,02	0,22	15,23
4**	2,88	0	2,73	0	15,00

* “train waits for locomotive” (On condition of);

** “locomotive waits for train” (On condition of).

As depicted in Table 6, the operational fleet of locomotives exhibits a variation of up to 16% when considering different options for attaching train locomotives to formations, transitioning from condition 1 to condition 2. Consequently, the implementation of conditions for connecting train locomotives to trains, taking into account the number of locomotives prepared for tomorrow's operations, establishes a foundation for the efficient utilization of rolling stock in situations where there is a shortage of train units.

Therefore, it became feasible to determine the average dwell times of train locomotives and trains at the boundaries of train shoulders for r options, ranging from the "Train awaits locomotive" condition to the "Train awaits train" condition. This determination was based on the number of train units ready for the following day's operations and the train work plan. Thus, an advanced method was developed for the effective planning of train locomotive utilization.

4 Conclusion

1. It has been established that the accumulation processes of freight train components follow the Erlang distribution law with different distribution parameters. As a result, based on these times, it was possible to determine the departure time of freight trains from assembling stations and the arrival time of each freight train at the next technical station.

2. A methodology has been developed to determine the average dwell time of train locomotives and trains within terminal tracks for r variants from the "Train awaits locomotive" condition to the "Locomotive awaits train" condition. It has been demonstrated that the operational fleet of locomotives (in the investigated case) differs by up to 16% depending on the options for attaching train locomotives to formations from condition 1 to condition 2. Therefore, the application of conditions for attaching train locomotives to trains based on the number of train locomotives ready for work tomorrow creates a basis for the efficient operation of rolling stock.

3. A software program for the Railway Traffic Control System (RTCS) has been developed to calculate the fleet of freight locomotives based on the train schedule. As a result, an advanced method for effectively planning the utilization of train locomotives has been developed, based on minimizing the idle time of rolling stock within terminal tracks.

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