ASSIGNING STOPS FOR CONTAINER TRAINS TO PERFORM FREIGHT OPERATIONS ALONG THE ROUT

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For freight transportation services that involve the permanent formation of rolling stock and the ability to make stops at stations along the route for freight operations, it is necessary to create a methodology for determining the optimal plan of stops. The subject of the research is the organization of traffic management for container trains of permanent formation that stop at stations along the route to carry out freight operations. The authors conclude that the provisions for developing a freight train formation plan cannot be used to adapt it to the needs of container train of permanent formations making passing stops. But some approaches to developing a plan for long-distance passenger train formation can be taken as a basis. To develop the methodology, it is proposed to distribute the total volume of container traffic between trains on individual routes (including those where trains skip some stops) taking into account compliance with a list of restrictions. The value of operating costs is used as a criterion to evaluate the efficiency of the stops plan for the set of container trains of permanent formation at the railway district. For railway districts where more than 5 stations, determining a rational stop plan becomes a large-scale task. Authors propose using an algorithm that can be implemented in any programming language to facilitate the processing of source data and the creation of a mathematical representation of a linear programming problem. The results of the research include the method for assigning stops to container trains of permanent formation and an algorithm for automated task of research formation.

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Introduction

In order to establish a highly competitive service in the field of railway freight transportation, specialists from scientific and production teams have worked for several years to develop a product for organizing container trains with permanent formations. It is assumed that this new product will include planned stops along the route of the container train for freight operations. In 2020, "Cold Express" [1,2] technology was approved officially and work continued on developing services for goods that do not require special temperature maintenance during transport and storage.

Regardless of the individual characteristics of the services being developed, they are united by the possibility of passing stops for freight operations.

In accordance with the ideological features of the “Cold Express” service products and their analogues, there are four ways to organize train assignments in railway districts [3]:

1) transportation by through trains from the station of departure to the station of final arrival without carrying out associated freight operations, which corresponds to the current practice of organizing containerized through-trains;

2) transportation, with stops at each station along the route, similar to a passenger train traveling at normal speed and making stops, even if there are no passengers boarding or disembarking;

3) transportation with scheduled stops at certain stations along the route (similar to a fast passenger train that makes stops at stations with high passenger demand);

4) transportation on short routes without breaking up of a train and passing freight operations.

At the same time, methods 1 and 4 can be implemented using the current technology of working with through trains, in which it is necessary to accumulate a sufficient number of containers. However, methods 2 and 3 do not yet have functional prototypes for freight transportation on railways (with the exception of mail and baggage trains). At the same time, methods 2 and 3 have similarities with passenger transportation.

In the studies of scientists, examining the presence of stopovers along the route, conclusions are drawn regarding the need to strike a balance between the potential accessibility of transportation for the main target audience and the importance of route speed, which often determines the advantage of alternative modes of transportation [4-9]

However, economic feasibility should be considered as an additional parameter in freight transportation by rail. Also, in order to ensure rational use of railway district capacity [10,11] and high reliability of train schedule execution, it is necessary to reasonably assign stops for freight (container) trains with permanent formation.

In this paper, a methodology is proposed that allows the use of understandable tools to determine the rational purpose of stops on routes of container trains with a permanent formation in the railway district under consideration.

Materials and methods

Clearly, the current methodology for developing a plan for making-up of freight trains is not applicable to the resolution of this paper's issue. A unique aspect of container trains with a permanent formation is the alteration in the composition of the containers as they transit through stations for freight operations, and the uncertainty in determining whether a given train should be classified as a through train or a pick up goods train.

The rationale behind the development of a methodology for allocating passing stops to freight (container) trains of permanent formation [12] can be grounded in the principles that underpin the operation of long-haul passenger services [13-17].

Table 1 shows some parameters describing the distribution of the total volume of container traffic correspondence between trains in a railway district.

Table 1

Variables and their designations

Variable	Defining of variables
Description of the railway district	
ST	The total number of stations on the railway district where freight trains of permanent formation are using
st	The station at the railway district
dep	The departure station for freight trains of permanent formation on the railway district
arr	The arrival station for freight trains of permanent formation on the railway district
$DepList$	A list of all departure stations in the railway district where freight trains with permanent formation are used
i	The position number of the departure station in the list $DepList$
$ArrList$	A list of all arriving stations on the railway district where freight trains with permanent formation are used
j	The position number of the arriving station in the list $ArrList$
Variables describing the volume of correspondence at the railway district and container trains of permanent formation	
$Corr\ (dep, a$	The volume of container traffic correspondence between the departure station dep and arriving station arr
$CorrList$	List of container traffic correspondences on the railway district
tr	Possible route of a container train of permanent formation on the railway district
n_{tr}	the number of freight trains on the route tr (takes a positive integer value) $n_{tr} > 0\ ,\quad n_{tr} \in \lvert\mathbb{Z}\rvert,\quad \forall\ tr \in RouteList$
Cap_{tr}	The capacity of trains on the route tr
$RouteList$	A list of all possible routes of container trains of permanent formation on the railway district
$p(corr, tr)$	The part of the volume of correspondence $Corr\ (dep, arr)$ which can be transported by the trains on the route tr $p(corr, tr) > 0\ ;\ \forall\ (c, r) \in K$
$PList$	List of variables $p(corr, tr)$
K	a set of pairs $(corr, tr)$, in which correspondence $(Corr)$ can be transported by the trains on the route tr without transshipment operations ($arr_{corr,tr} > 0$ и $dep_{corr,tr} > arr_{corr,tr}$)
$T_{tr,st}$	Total load of freight trains on the route (r) on the railway district, after passing the freight train station n
Variables describing economic parameters	
RC_{tr}	The amount of operating costs for the train route tr (route cost)
SC_{st}	The amount of operating costs per stop at the station st (station cost)
OC_{tr}	The total cost of the route tr

The key factor in determining the overall feasibility of a proposed train's stop plan is to minimize the cost [18] of implementing traffic management measures. It is essential to take into account the costs associated with the train route and each individual stop on that route (Eq.1).

$$OC_{tr} = RC_{tr} + \sum SC_{st} \,, \quad (1)$$

To put it another way, a comprehensive analysis of the economic viability of different scenarios for container train of permanent formation stops plan can be conducted through the process of comparing relevant parameters OC_{tr}.

As additional evaluation criteria, the density of the route network coverage, the coverage of the potential customer base, the indicator of competition with other freight services, and others can be used. However, this study is only focused on economic assessment.

As assumptions in the further methodology, the following is accepted:

– stations which can be used for freight operations with container trains of permanent formation are known in advance;

– ontainer traffic correspondence has a one-way direction;

– information about the capacity of freight trains is known in advance;

– capacity parameters are unified for all container trains and are presented in the TEU;

– the correspondence values are also pre-converted and presented in the TEU;

–there is no provision for the transfer of containers between trains during transportation.

– the capacity of stations is not restricted in terms of the number of trains they are able to accommodate and operate.

In order to work with variables correctly, it is necessary to establish some restrictions that will approximate the conditions to the real-world ones.

Firstly, all correspondence must be transported. The total number of correspondence parts, $p(corr, tr)$, is divided among trains operating on tr routes. Division of correspondence should comply with the condition that the total load of each freight train after freight operations at station st is less than or equal to the specified load capacity.

$$T_{tr,st} = \sum_{corr:\ 0 < dep_{corr,tr} \le st,\ \ arr_{corr,tr} > st} p(corr, tr) \,, \quad (2)$$

Checking the correctness of the distribution of the total volume of correspondence into parts $p(corr, tr)$ is determined by reverse addition. Therefore, if both sides of equation (3) are equal, then the statement about ensuring transportation of all containers from departure stations to arrival stations can be considered reliable.

$$\sum_{tr} p(corr, tr) = Corr(dep, arr), \qquad Corr \in CorrList, \quad (3)$$

Since the concept of container trains of permanent formation allows for stopping at passing stations along the train's route, where containers can be unloaded and loaded, it is necessary to check the condition of the maximum loading of the train.

The number of containers scheduled for transportation on the container train of permanent formation must be less than or equal to such trains capacity (in TEUs) on each element of the railway district.

$$T_{tr,st} \le Cap_{tr} * n_{tr}, \qquad tr \in RouteList, \qquad (dep \to arr) \in tr \quad (4)$$

In order to minimize costs for all train routes used to transport containers in accordance with the specified requirements, formula (5) can be considered as the objective function.

$$F = \sum_{tr \in RouteList} OC_{tr} * n_{tr} \to min \quad (5)$$

The presented mathematical formulation of the problem leads to the subsequent optimization of solutions using integer linear programming techniques.

The amount of data that needs to be processed to solve the problem of selective stop assignment generates a high-dimensional problem.

This is clearly demonstrated in Figure 1 (left side). For example, we propose to compare identical circulation railway districts where located five stations. At three stations of the railway districts, container trains of permanent formation can stop for freight operations (unloading or loading containers).

The assignment of stops for all container trains in a permanent formation at all stations along the route will allow the operation of 10 different train routes within the railway district (and the choice of the optimal combination thereof). But if the stops are not at all stations, the optimal combination would be chosen from 26 possible routes.

The determination of the number of routes from which an optimal combination should be formed can be calculated using Equation (6), if trains will stop at every station along the route. Or, if trains do not stop at some stations, then Equation (7) can be used.

$$R^{sum}_{every} = \frac{ST * (ST - 1)}{2}, \quad (6)$$

$$R^{sum}_{part} = 2^{ST} - ST - 1 \quad (7)$$

The change in the number of possible routes, depending on the size of the railway district, is shown in Figure 1 (right side).

Therefore, in order to work with large railway districts, it is necessary to take into account the possibility of speeding up the processing of initial data and forming a system of equations.

Development of algorithm

Before starting the algorithm, it is necessary to prepare source data for conversion to a format suitable for processing [19].

In this paper, we propose to set the initial data about the correspondence of container flows [20] and the initial data for operating costs for train routes in a matrix format. At the same time, we suggest placing departure stations vertically in matrix tables, and arrival stations horizontally.

Since the assumptions to the methodology indicate a single direction of container flow, the data below the diagonal of the matrix and the diagonal itself are filled with values "0".

The costs of train stops can be presented in a matrix or list format, depending on the researcher's preferences. At the same time, values of stop costs should be sorted depending on the serial number of stations in the railway district where freight trains of permanent formation are used.

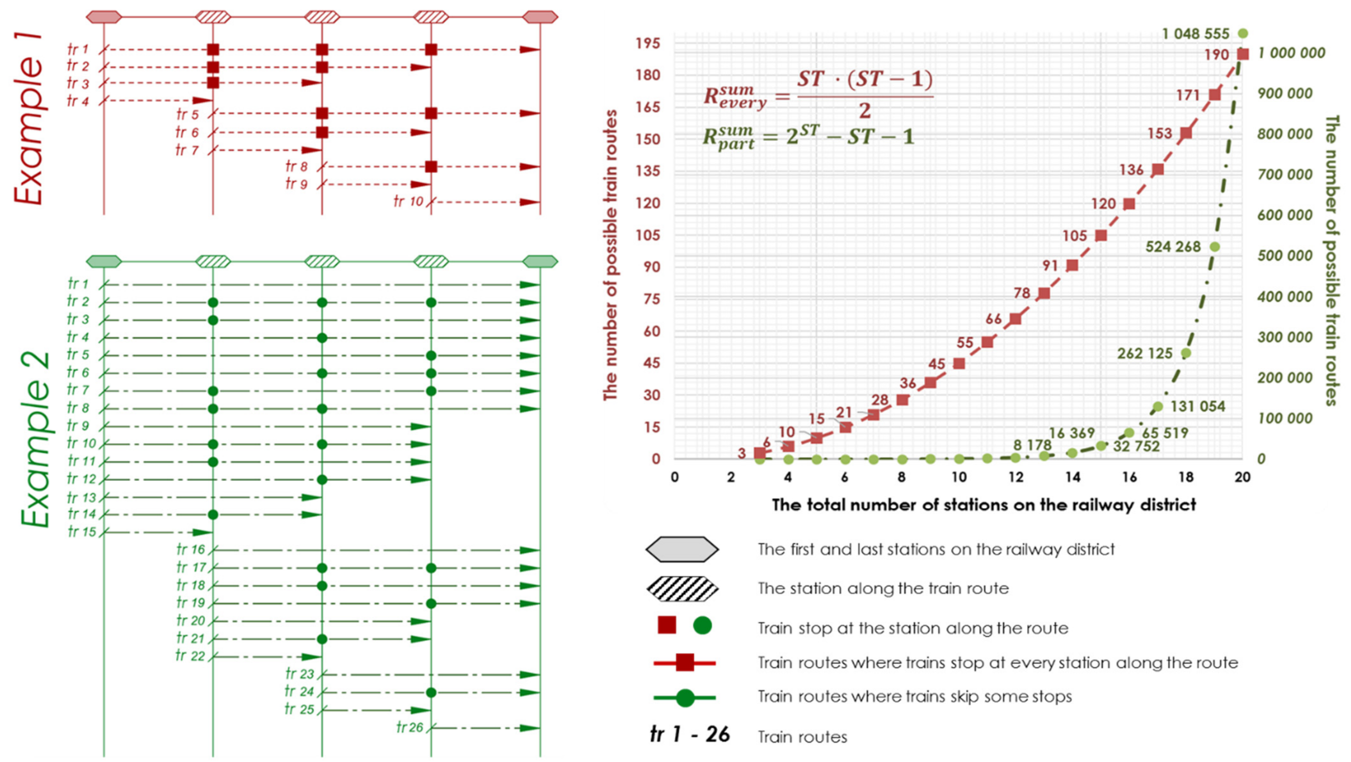

Fig. 1. A railway district with a set of stops along the route of container trains of permanent formation (Example 1 – trains stop at every station along the route; Example 2 – trains skip some stops)

Step 1. When sequentially sorting through the cells of the correspondence matrix, the occupancy of rows and columns is analyzed. If the cell value in a given row is not equal to "0", the sequence number corresponding to that row is added to the list of departure stations (***DepList***), and the corresponding sequence number for the given column is added to the list of arrival stations (***ArrList***). The iteration cycle should be set up so that duplicate values are excluded from the lists. In particular, there should not be two or more identical starting points in the list of departure stations.

Step 2. On the next step, the algorithm must analyze the correspondence matrix again. The outcome of this analysis should be the creation of a list of container traffic correspondences in the railway district (***CorrList***).

The analysis is performed sequentially, starting from the top-left cell of the first row in the input data. Then, with a column step of +1, the transition is made to the next cell on the same row, until the final cell in that row has been reached. After this, a transition to the first cell in the next row occurs, and the analysis continues according to the same principle. It is important to note that the ordinal position of the column that was analyzed at the start of each row must be equal to the ordinal value of "number of rows + 1" in order for the analysis to proceed correctly.

If the cell value does not equal "0", a new element $Corr\ (dep, arr)$ is added to the ***CorrList***, where the value of "$Corr$" corresponds to the value in the cell, "dep" represents the sequence number of the departure station, and "arr" indicates the destination station.

Step 3. At this step, it is necessary to make a list of possible routes for two variations:

– xample 1: Trains stop at every station along the route;
– xample 2: Trains skip some stations.

The creation of a list of train routes (let's call it $RouteList$) will be based on the lists of $DepList$ and $ArrList$.

Creating a list of routes for example 1

In the $DepList$ and $ArrList$, elements are consistently compared to each other, considering the constraint that the value of an element in $ArrList$ must be strictly greater than the corresponding value in $DepList$. If such a pair of elements is found, it is added to the $RouteList$ as a string. In this case, the first element of the string in the $RouteList$ will correspond to the value of the analyzed element from the $DepList$, and the last element of the string will correspond to the analyzed element from the $ArrList$. The intermediate elements of the line must fit in step 1.

Creating a list of routes for example 2

For example 2, the elements of the $DepList$ and $ArrList$ are consistently compared in the same way as in example 1 above. The step between the elements in the string entered into the $RouteList$ is generated based on the logic of representing numbers in the binary system (Gray codes). An example of a string representation of the range between $i \in DepList$ and $j \in ArrList$ in a railway district with four stations is shown in Table 2.

Step 4. At the fourth step, the elements of a pair of lists are compared (pair $CorrList$ and $RouteList1$ or pair $CorrList$ and $RouteList2$). If $dep, arr \in tr$, then $p(corr, tr)$ should be added to the list of variables $PList$ (the designation is provided in Table 1). Additionally, for each potential route of a container train with a fixed formation tr, a further variable $n(tr)$ is introduced.

Step 5. The generated lists of task variables make it possible to proceed to writing the objective function (equation 5). Each train is assigned a value, which represents the operating cost (RC_{tr}) as well as the cost associated with each stop (SC_{st}) on its route.

Table 2

An example of representing a string, which is equivalent to a set of stops on each container train route within a 4-station handling range

Variations of routes on the railway district $2^{ST} - ST - 1$	Serial number of the train route	The terminus stations of the route in the format $i - j$	The number of possible routes between stations i и j	A sequence of integers in the decimal system from 0 to $2^{j-i-1} - 1$	Writing a number in binary number system format	Combinations of stops in a given route range
11	1	1– 2	1	0	0	1-2
	2	1–3	2	0	0	1-3
	3			1	1	1-2-3
	4	1–4	4	0	00	1-4
	5			1	01	1-*-3-4
	6			2	10	1-2-*-4
	7			3	11	1-2-3-4
	8	2-3	1	0	0	2-3
	9	2-4	2	0	0	2-*-4
	10			1	1	2-3-4
	11	3-4	1	0	0	3-4
The "*" sign indicates the skipping of a potential stop at the station						

Step 6. At this step, all routes are checked for compliance with the restrictions (Equation 4).

Step 7. At this step, the distribution of the total volume of correspondence into parts on every route are checked by Equation 3.

Step 8. Print systems of equations for both examples (Example 1: trains stop at every station along the route; Example 2: trains skip some stops).

Results and discussion

The algorithm described in this paper has the potential to facilitate the process of developing a system of equations to solve the problem of determining the rational purpose of stops along the routes of container trains with permanent formations.

When solving such problems, initial data can be entered into a table (matrix) using Microsoft Excel. To process the data and run an algorithm, as well as to solve a system of equations, it is advisable to use a programming language such as Python, which is accessible. The general-purpose Python programming language and PyCharm software were used in this study.

Example	№1	№2
The number of possible routes	15	19
The number of freight trains	129	113
Total number of stops	765	50
The volume of correspondence processed, TEUs	18 381	18 381
The total cost of the routes, thousand rubles/month	227 729	213 615

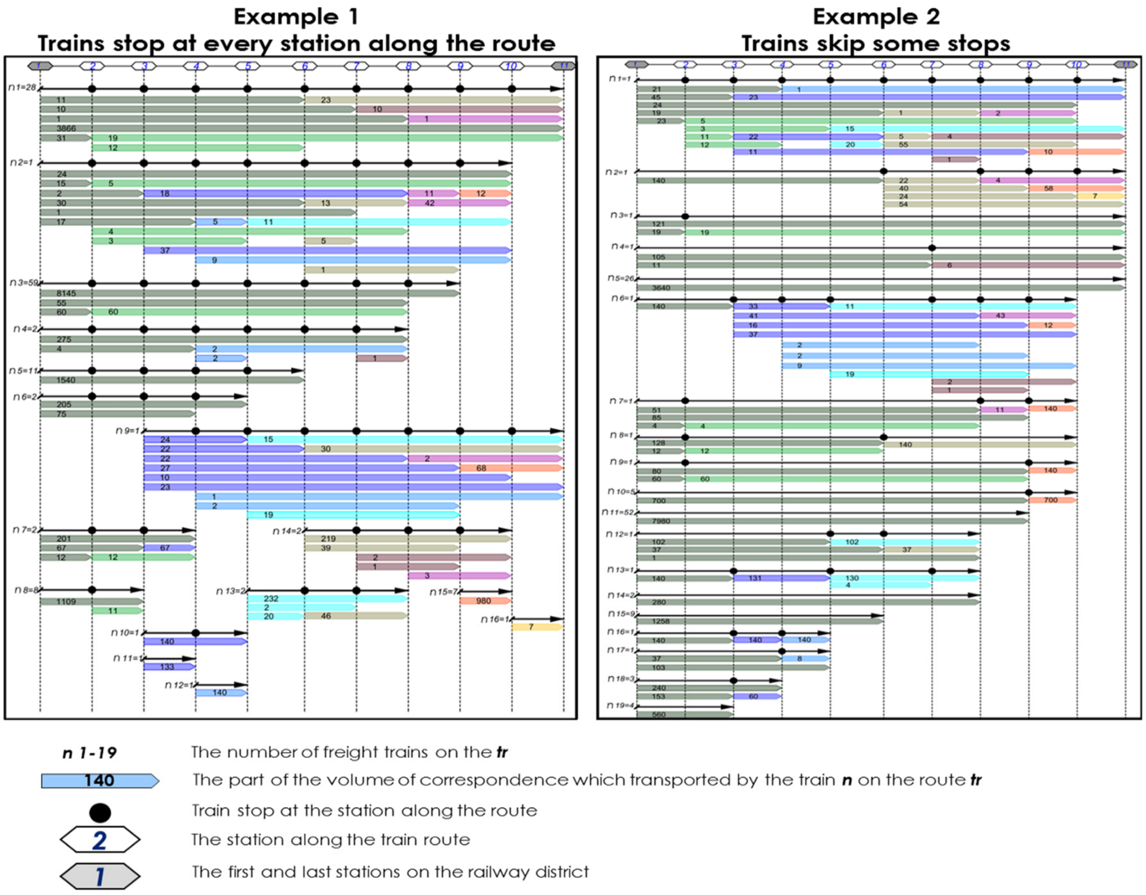

Fig. 2. Visualization of the optimal solution to the problem of scheduling container train stops, considering all relevant constraints

In this research, a railway district with 11 stations was analyzed to determine the rational purpose of stops along routes of container train services with permanent formations. This railway district is a model for the Moscow – Krasnoyarsk railway route, which is the pilot route of "Cold Express" service. Calculations were performed on a personal computer at home with no restrictions on working time. To solve the system of equations, calculations were performed using the algorithm in PyCharm within 21 hours.

Any programming language and integrated development environment available can be employed to generate code that reflects access to source data, its processing within the confines of an algorithm, and the formation of a system of equations, as well as the search for the optimal combination of train routes.

The results of the calculation for the railway district with 11 stations are shown in Figure 2.

As can be seen from Figure 2, when optimizing the train schedule for a particular railway section, the total cost of operation varies by 6% depending on the set of trains routes chosen and whether or not certain stops are included.

Conclusion

For container trains of a permanent formation, which make scheduled stops at intermediate stations along the route for the unloading or loading of containers, there is no established procedure for assessing the appropriateness of scheduling these stops. The criteria for optimality proposed in this paper – minimization of operational expenses – may not be the only factor in arriving at a final solution. However, it can serve as a basis for comparing alternative solutions until a more advanced methodology is developed.

The result of solving this paper's problem is a certain combination of the number of trains on each possible route, taking into account the minimum operating costs compared to alternative combinations.

In addition to the above-mentioned improvements, it is possible to introduce variables that reflect the need for a technical stop in order to change the train locomotive or the locomotive crew. Additionally, indicators can be introduced that reflect the possibility of combined technical and freight operations.

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НАЗНАЧЕНИЕ ПОПУТНЫХ ОСТАНОВОК КОНТЕЙНЕРНЫМ ПОЕЗДАМ ДЛЯ ВЫПОЛНЕНИЯ ГРУЗОВЫХ ОПЕРАЦИЙ В ПУТИ СЛЕДОВАНИЯ

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Аннотация

Для сервисов грузовых перевозок, предусматривающих постоянную композицию подвижного состава на всем маршруте следования и возможность совершения остановок на станциях маршрута для попутных грузовых операций необходима разработка методики, определяющей рациональность предлагаемого плана остановок. Предметом исследования является организация движения контейнерных поездов постоянного формирования, осуществляющих попутные грузовые операции. Авторы приходят к выводу, что положения разработки плана формирования для грузовых поездов не могут использоваться для адаптации под нужны контейнерных поездов постоянного формирования, совершающих попутные остановки. Но некоторые подходы к разработке плана формирования пассажирских поездов дальнего следования могут быть приняты в качестве основы. Для разработки методики предлагается суммарный объем корреспонденции контейнеропотоков распределять между поездами отдельных маршрутов (в том числе маршрутов с частично отмененными остановками) с учетом соблюдения перечня ограничений. В качестве критерия эффективности, оценивающего рациональность плана остановок для всего набора контейнерных поездов постоянного формирования на полигоне, рассматривается величина эксплуатационных затрат. Для участков обращения, состоящих более чем из пяти станций, задача определения рационального плана остановок принимает большую размерность. Для упрощения работы с исходными данными и формирования математической записи задачи линейного программирования предлагается использование алгоритма, который так же может быть записан на любом языке программирования. К результатам исследования относится методика назначения остановок, а также алгоритм автоматизированного формирования задачи.

Ключевые слова: *контейнерный поезд постоянного формирования, корреспонденции контейнеропотока, грузовые операции, планирование остановок, экономическая эффективность.*

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