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Rapid planning of mixed-structure train organization in the context of non-proportional wagon-flows

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Abstract:

It is important to deliver cargo wagons to intermediate stations in the shortest possible time, then quickly remove them when empty. If wagon-flows are non-proportional, organization of district, pickup freight, and mixed-structure trains over a 1-year period is usually ineffective. Here, we develop a method ensuring rapid movement of all three train types. We organize local wagon-flows by considering work volumes. We perform calculations at selected train addresses (example: station "Ch") when organizing the three types of trains.

Key words: the plan of freight train formation, railway system, wagon-flows, mixed-structure trains, the method of the rapid planning

Introduction

Wagon movements at stations and timely goods delivery are important. Planning of freight trains (PFT) at technical stations must be enhanced, processing times reduced, and train movements optimized. The PFT of JSC "Uzbekistan railways" is shown in Figure 1.

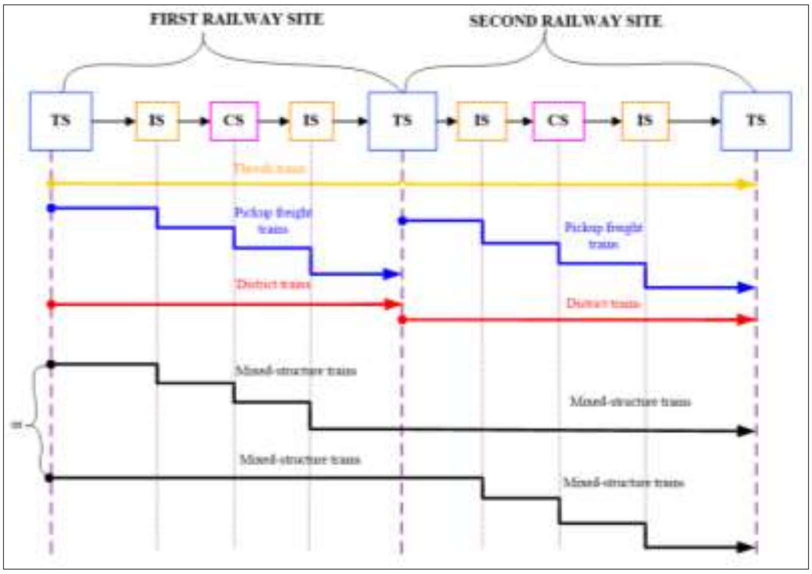

Fig.1. Description type of the trains in JSC "Uzbekistan Railways"

TS- Technical station (Marshalling station or Section station); IS- intermediate station; CS- Cargo station.

Freight trains formed at technical stations are divided into through trains that run without processing through one or more marshalling or section stations (yellow in Fig. 1); district trains that are not re-formed at other stations (red in Fig. 1); and pickup freight trains that deliver wagons to and collect other wagons from intermediate stations (blue in Fig. 1). and pickup freight trains that deliver wagons to and collect other wagons from intermediate stations (blue in Fig. 1). The pickup freight trains depart from designated stations at fixed times, regardless of their number of wagons. Pickup freight

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trains include mixed-structure trains servicing several stations, which are changed at some stations but not others (black in Fig. 1); clean-up trains, which are sent from marshalling or section stations to intermediate (or cargo) stations or back from such stations to the marshalling or section stations for cleaning and later delivery of wagons to individual stations; and transfer trains, which move wagons between stations. The PFT specifies the types of trains to be sent to each station, the destinations of all wagons, and the trains to be used to move empty wagons. During PFT, stations are weighted [1] using differential norms (planned formation of pickup freight, transfer, clean-up, and mixed-structure trains); section norms (planned district train formation); generalized norms (planned formation of through trains); and parallel norms (trains transporting perishable goods [these are rigorously scheduled] and long-distance trains). Because all trains (pickup freight, transfer, clean-up, and mixed-structure) are planned using different norms, it is difficult to optimally weight the trains and the numbers of wagons.

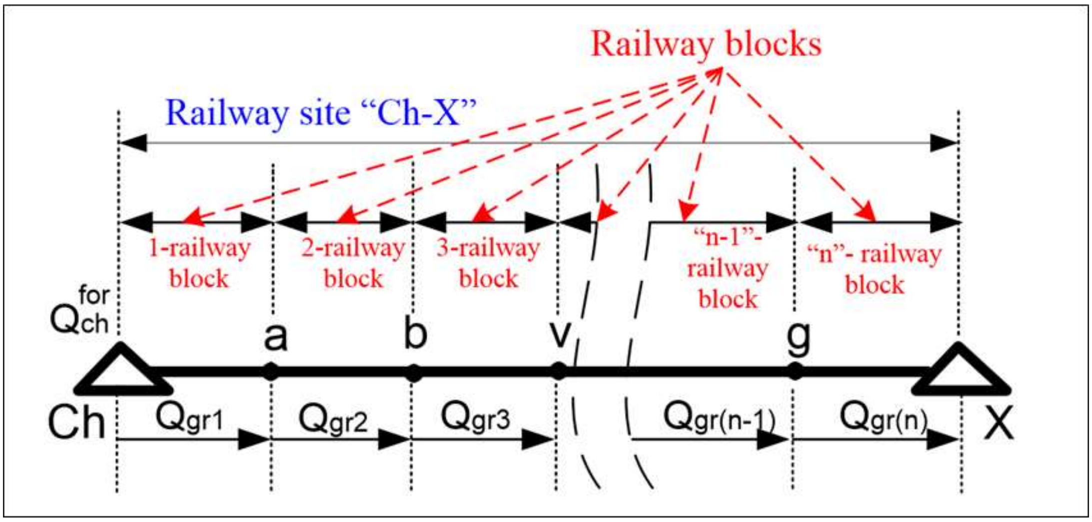

Fig. 2. Application of the differential norm in the formation of pickup freight trains

"Ch" and "X"– name of technical stations (shown a triangular shape); a, b, v,...,g – name of intermediate stations situated in "Ch-X" railway site (shown a round shape); Q_{Ch}^{for} *− gross weight of railway sites for the formation of trains at the technical station "Ch";* $Q_{gr(n)}$ *− the gross weight set on n- railway block.*

Figure 2 shows that if the gross weighting of pickup freight train formation at technical station "Ch" is $Q_{Ch}^{for} \leq Q_{gr1}$ and if $Q_{gr1} \geq Q_{gr2}$, $Q_{gr1} \geq Q_{gr3}$,...,$Q_{gr1} \geq Q_{gr(n)}$, pickup freight trains are formatted by reference to the Q_{gr1} norm because Q_{gr1} is greater than the norm set for all railway blocks. Furthermore, Q_{gr1} changes when moving to the second, third, and subsequent blocks. Depending on the number of intermediate stations and the numbers of wagons added at these stations, it can be difficult to determine the normative values of mixed-structure trains formatted at station "Ch." An appropriate choice of this value when forming mixed-structure trains departing to various railway blocks is essential. Individuals responsible for organizing train movements require assistance. Rapid wagon-flow planning methods are needed to meet the PFT requirements.

2. Planning of freight train movements

2.1. Planning for the railway network of JSC "Uzbekistan railways"

Paragraph 209 of the "The Rules of Technical Operation of Railways of The Republic of Uzbekistan" states that trains must be formatted in full compliance with the schedule and the PFT [2]. The train addresses and numbers (types) of the PFTs [3-6] developed by JSC "Uzbekistan Railways" for 2016/2017, 2017/2018, 2018/2019, and 2019/2020 are shown in Figure 3.

Figure 3 shows that the train formation plan for 2019/2020 differed from the train formation plans of the past 5 years. In particular, the number of through trains increased by 17%; the number of pickup trains decreased by 16%; the number of clean-up trains decreased by 27%; the number of transfer trains increased by 12%; the number of forwarder routes decreased by 80%; the number of district

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trains decreased by 13%; the number of mixed-structure trains increased by 20%; the PFTs for 2016/2017, 2017/2018, and 2019/2020 did not include multi-group clean-up trains, which were replaced by container trains in 2018/2019; and the number of shuttle trains remained unchanged compared with the numbers of shuttle trains in 2016/2017, but increased by 334% compared with the number of shuttle trains in 2017/2018.

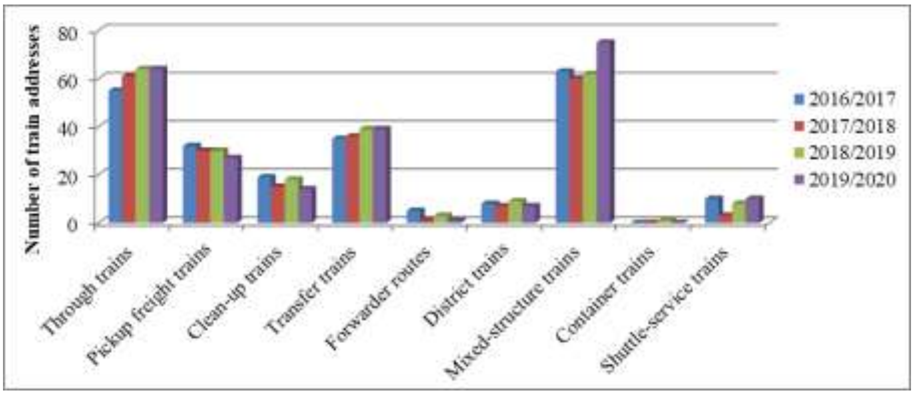

Fig. 3. Analysis the train addresses and numbers (types) in the PFT for 2016-2020 years

Figure 3 shows that, in recent years, the demand for mixed-structure trains has increased. Each PFT covers 1 year. The PFT states that trains are to be formatted at full weight or full length. In exceptional situations, one wagon can be removed from the standard number or 90 tonnes can be removed from the standard weight [3-6]. On specific days of the year, considering non-proportional wagon-flows, the train dispatcher can allow the departure of incomplete mixed-structure trains. Therefore, to improve train formation, a regulatory framework is needed for modification (a decrease or increase) in the number of wagons; this should be included in the PFT. Many efforts have been made to improve train formation [7-9] by allowing wagon numbers to increase to some extent. However, this may restrict locomotive traction and overwhelm station capacity, limiting changes to the normative wagon counts. Some authors [10-13] have sought to reduce train costs by lowering wagon numbers; this can be very effective if small numbers of trains form at technical stations. Freight train wagon numbers can presumably be reduced by up to 17% when the freight distance is short and the daily wagon-flows are small [14]. However, short-haul freight trains increase the overall train number, imposing pressure on railway sites.

As the above discussion shows, information technology should be used to derive a method permitting rapid planning of district, pickup freight, and mixed-structure train movements. This would facilitate rational organization of local wagon-flows among railway sites on the basis of work volume.

2.2. Wagon variations of mixed-structure trains

Mixed-structure trains are formed from wagons that will form pickup and district trains. However, the numbers and types of wagons and the train weights must not exceed site norms [15]. Figure 4 shows the graph used to determine the maximum quantity of wagons that can be included in mixed-structure trains by reference to wagon flow to pickup and district trains..

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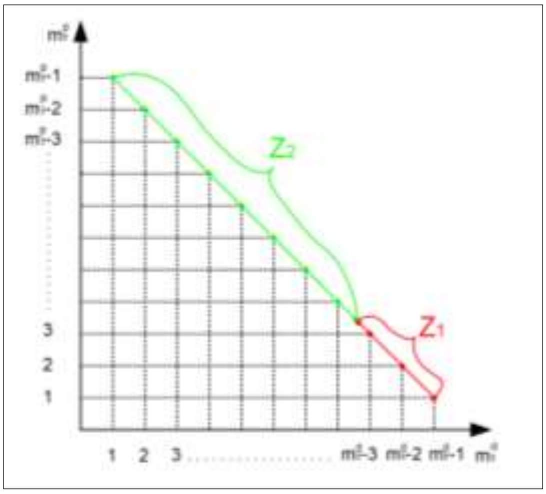

Fig. 4. The graph used to determine the maximum quantity of wagons that can be included in mixed-structure trains

The X-axis of Figure 4 shows the numbers of wagons for district trains (from "1" to the normal quantity) and the Y-axis shows the numbers of wagons for pickup trains (again, from "1" to the normal quantity). m_{T}^{d} and m_{T}^{p} are the standard numbers of wagons in district and pickup trains, respectively, at a particular technical station. m_{T}^{d}-1, m_{T}^{d}-2, and m_{T}^{d}-3; and m_{T}^{p}-1, m_{T}^{p}-2, and m_{T}^{p}-3 respectively, indicate that wagons 1, 2, and 3 are missing from district and pickup trains. The technical and economic justification limits when adding wagons collected for a pickup (or district) train to the wagons already collected are denoted by Z_1; the justification limit for creation of a mixed-structure train is Z_2.

When forming a mixed-structure train, there is a need to determine how many wagons will go to district and pickup trains. The following expression lists the possible options:

$$m_{\text{T}}^{d}(or\ m_{\text{T}}^{p}) \le \left\{\begin{matrix} 1+(m_{\text{T}}^{d}-1) \\ 2+(m_{\text{T}}^{d}-2) \\ 3+(m_{\text{T}}^{d}-3) \\ \dots\dots.\dots\dots\dots \\ \dots\dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots\dots \\ (m_{\text{T}}^{p}-3)+3 \\ (m_{\text{T}}^{p}-2)+2 \\ (m_{\text{T}}^{p}-1)+1 \end{matrix}\right\} \le m_{\text{T}}^{p}(or\ m_{\text{T}}^{d}) \qquad (1)$$

However, the standard number of wagons is not always considered, although train weight must be considered.

2.3. Exploitation costs of pickup freight, district, and mixed-structure trains imposed by formation and movement

Many scientists have sought to reduce transport operating costs and delivery times [16]. The double-stack train system reduces train numbers, increases container loads, shortens wait times at terminals and harbors, and reduces unit costs and delivery times. Double-stack trains currently run in the U.S.A., Canada, and other countries. Reference [17] describes management methods that increase the efficiencies of passenger and freight railway transport. Exploitation costs are the costs incurred from the time of wagon assembly to the next train station. The calculations are sequentially performed. The exploitation costs associated with the formation of pickup freight train formation and movement are:

- Exploitation costs at the station (assuming that the train is formatted at station "Ch") where the pickup freight train format is (E_{Ch}^{pic}), UZS;
- General exploitation costs at intermediate stations where freight is collected ($E_{int.st}^{pic}$), UZS;
- General exploitation costs of railway blocks in the region (E_{rblock}^{pic}), UZS;
- Exploitation costs associated with pickup freight train arrival at the last (distributed) station (i.e., station "X") ($E_{arr(X)}^{pic}$), UZS;
- Exploitation costs associated with pickup freight train sorting at the last station ($E_{sort(X)}^{pic}$), UZS.

The total exploitation costs associated with pickup freight train formation are calculated as the sum of the above:

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$$\sum E_{pic} = E_{Ch}^{pic} + E_{int.st}^{pic} + E_{rblock}^{pic} + E_{arr(X)}^{pic} + E_{sort(X)}^{pic}, \text{ UZS} \quad (2)$$

Each element of (2) can be calculated based on published formulae [18].

The exploitation costs associated with the formation of district trains and organization of their movement include:

- Exploitation costs at the station where the district train is formed (E_{Ch}^{dis}), UZS;
- General exploitation costs of railway blocks in the region (E_{rblock}^{dis}), UZS;
- Exploitation costs associated with arrival of the district train at the last station ($E_{arr(X)}^{dis}$), UZS;
- Exploitation costs associated with distribution of the district train at the last station ($E_{sort(X)}^{dis}$), UZS.

The total exploitation costs are calculated as the sum of the above:

$$\sum E_{dis} = E_{Ch}^{dis} + E_{rblock}^{dis} + E_{arr(X)}^{dis} + E_{sort(X)}^{dis}, \text{ UZS} \quad (3)$$

Each element of (3) can be calculated using published formulae [18, 19].

The general exploitation costs for mixed-structure train formation and delivery of wagons to their destinations include:

- Exploitation costs at the station where the mixed-structure train is formatted ($E_{Ch}^{mix-str}$), UZS;
- General exploitation costs at intermediate stations where mixed-structure train movement is organized ($E_{int.st}^{mix-str}$), UZS;
- General exploitation costs of railway blocks in the region ($E_{rblock}^{mix-str}$), UZS;
- Exploitation costs associated with arrival of the mixed-structure train at the last (distributed) station ($E_{arr(X)}^{mix-str}$), UZS;
- Exploitation costs associated with sorting of the mixed-structure train at the last station ($E_{sort(X)}^{mix-str}$), UZS.

The total exploitation costs are calculated as the sum of the above:

$$\sum E_{mix-str} = E_{Ch}^{mix-str} + E_{int.st}^{mix-str} + E_{rblock}^{mix-str} + E_{arr(X)}^{mix-str} + E_{sort(X)}^{mix-str}, \text{ UZS} \quad (4)$$

Each element of (4) can be calculated based on published formulae [18, 20].

2.4. Dependence of exploitation costs on locomotive[1)] performance, train organization, and movement organization

When formatting any train, the weight and length norms are important. If a norm is not met, locomotive performance deteriorates. Locomotive performance reflects the mean daily mileage and mean train weight, thus [21]:

$$W_{lok} = \frac{Q_{gr} \cdot S_{lok}}{(1+\beta_{aux})}, \text{ tonne-km-gross} \quad (5)$$

where W_{lok} is the locomotive performance (tonne-km-gross),
Q_{gr} is the gross weight of the freight train (tonnes),
S_{lok} is the mean daily distance travelled (km), and
β_{aux} is an auxiliary travel distance coefficient.

The gross weight of a freight train is the number of wagons by the wagon weight:

$$Q_{gr} = m_n \cdot q_{gr}, \text{ tonnes} \quad (6)$$

where m_n is the number of wagons in the train, and
q_{gr} is the weight of each wagon (tonnes).

The mean daily travel distance of a locomotive increases with its working hours. The mean daily distance is determined by dividing the linear distance[2)] ($\sum m_{line}\, s$) by the distance travelled by the fleet ($\sum mt_{fl}$):

$$S_{lok} = \frac{\sum m_{line} s}{\sum mt_{fl}}, \text{ locomotive - km} \quad (7)$$

[1)] There are two types of locomotives on the JSC “Uzbekistan railways”.
- train locomotive is a type of locomotive that specializes in the carriage of goods and passengers at wagons.
- shunting locomotive is a type of locomotive that specializes in performing shunting operations within a station.

[2)] Including locomotive running mileage with loaded and empty train and locomotive only single journey. In mountainous areas, a locomotive may be added at the end of the train for push-pull operation.

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The mean daily travel distance varies according to the type of traffic (freight, passenger) and type of traction (electric, diesel) for all locomotives. The auxiliary travel distance is the locomotive share of the total auxiliary distance and is:

- for a linear run:

$$\beta_{aux} = (\sum m_{line} s - \sum ms)/\sum m_{line} s \quad (8)$$

- for all runs:

$$\beta_{aux} = (\sum m_{line} s - \sum ms)/\sum MS \quad (9)$$

where $\sum ms$ – the locomotive is at the head of the train (locomotive-km),
$\sum MS$ – total travel distance (locomotive-km).

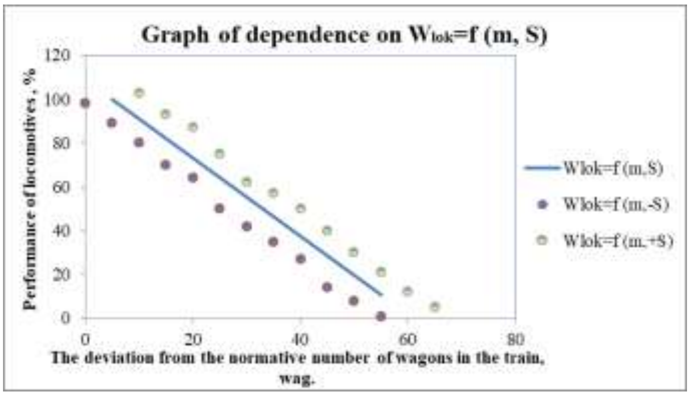

Fig. 5. Graph of the dependence of locomotive performance on the deviation from the normative quantity of wagons
m *– the normative number of wagons in the train;* ***S*** *– walking distance of a locomotive on the installed norm;* ***+S*** *– the excess walking distance of a locomotive from the installed walking norm;* ***-S*** *– the less walking distance of a locomotive from the installed walking norm.*

Hence, weight and length standards directly affect locomotive performance. If trains are not appropriately formatted, locomotive performance decreases. Any deviation from the normative quantity of wagons is inversely proportional to locomotive performance [22] (Fig. 5), imposing additional technical and economic costs.

3. Rapid planning of train formation

3.1. Rapid planning of district, pickup freight, and mixed-structure trains depending on work volume

Wagon collection plays an important role when organizing the movements of district, pickup freight, and mixed-structure trains on the specialized sorting tracks of technical stations. The assistant stationmaster, station dispatcher, and duty officer must make clear and quick decisions; all should always be aware of current wagon status. If the wagon-flows to the tracks that manage district and pickup trains satisfy the established norms, it is possible to regulate the movements of mixed-structure trains. Figure 6 shows the essence of our method. Formation of all three train types is pre-set by calculating the exploitation costs of wagon-flows. Figure 6 shows that if wagons that are to go in the same direction attain particular levels on the specialized tracks, the person in charge (when authorized by a supervisor) can change the train type and order its departure. This reduces the wagon wait time below the norms. However, such rapid planning is appropriate only if the exploitation costs for movement of mixed-structure trains are less than the exploitation costs for movement of district and pickup freight trains. Otherwise, it is preferable to wait until all wagons that fit the norms of district or pickup freight trains are assembled, then send them off.

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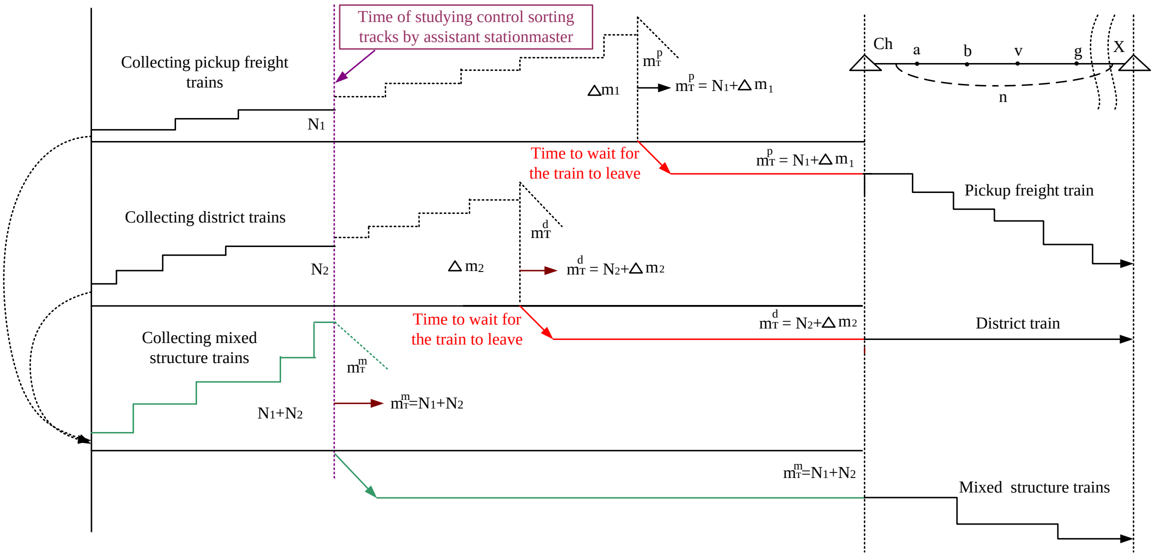

Fig. 6. Rapid planning of district, pickup freight, and mixed-structure trains depending on work volume:
N_1 – number of collected wagons for pickup freight train to time of studying control sorting tracks by assistant station; N_2 – number of collected wagons for district train to time of studying control sorting tracks by assistant station; Δm_1 – number of collected wagons for pickup freight train after time of studying control sorting tracks by assistant station; Δm_2 – number of collected wagons for district train after time of studying control sorting tracks by assistant station; m_T^p – norm number of wagons for pickup freight train; m_T^d – norm number of wagons for district freight train; m_T^m – norm number of wagons for mixed-structure freight train; n – the number of intermediate stations in the railway site;

Furthermore, this method works in practice only if chronometric wagon-flows in specified directions over time are mathematically calculated. This was done at sorting station "Ch" of JSC "Uzbekistan Railways." At "Ch," pickup freight trains arrive from five directions and pickup trains depart in these directions [23]. The parameters used to calculate the technical and economic exploitation costs of all train types from the time of formation to arrival at the next station are shown in Table 1.

Table 1. Parameters used for organization of all train types.

№	Parameter	Symbol	Value
1	Cost of one wagon-hour, UZS	e_{w-h}	973
2	Cost of one brigade locomotive-hour, UZS	e_{l-h}	157 585
3	Cost of one brigade shunting locomotive-hour, UZS	e_{l-h}^{shunt}	218 913
4	Electricity cost per kilowatt-hour, UZS	e_{el}	450
5	On tonne-km-gross cost, UZS	e_{tkgr}	10
6	Factor used to convert locomotive-hour costs to wagon-hour costs	Э	224,9
7	Loading for shunting locomotive	Ψ_{lok}^{shunt}	0,15
8	Proportion of trains departing directly from the sorting park, %	ς_{df}	0
9	Number of shunting locomotives engaged in formatting trains and placing them in the departure park, lok.	M_{lok}	1

Table 2 provides the basic information required when calculating the exploitation costs for organization of all train types when the norm wagon number is m_T^m*=50* at the railway site under study.

Table 2. Basic information required for calculation of exploitation costs (norm wagon number m_T^m=50).

№	Number and type of the train	Time when first group of collected wagons arrives at the sorting track	Time required by assistant stationmaster to control sorting	Number of wagons collected when planning conducted	Collection completion time and planned departure time	Number of wagons in the train	Intermediate stations	Shunting works with wagons at intermediate stations (+)	(-)
1		03:01:00	09:00:00	15	16:00:00	45	a*	11	2/8

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	3401 (pickup freight train)						b	9	1/5
							v	12	2/4
							g	14	2/8
							…	…	…
							X	0	6/25
2	3001 (district train)	03:01:00	09:00:00	35	14:55:00	50			
3	3449 (mixed-structure train)	03:01:00	09:00:00	50	09:00:00	50	a	11	1/4
							b	0	0
							v	0	0
							g	6	1/4
							…	…	…
							X	35	

(+) – number of wagons added to pickup freight or mixed structure trains at intermediate stations;
(-) – number of wagons separated from pickup freight or mixed structure trains at intermediate stations;
… –other intermediate stations;
[note] *: ***'11'*** loaded wagons must be added to *3401-pickup freight train* at *a*-intermediate station; ***'2'*** loaded wagons and ***'8'*** empty wagons must be separated from *3401 pickup freight train* at *a*-intermediate station.

Table 2 shows that the formatting of trains 3401, 3001, and 3449 began when the first groups of wagons arrived on the sorting tracks at 03:01:00 *(Column 3)*. The assistant stationmaster made decisions at 09:00:00 *(Column 4)*, at which time 15 wagons were on the pickup train sorting track and 35 wagons were on the district train track *(Column 5*). Thus, the number of wagons departing in the same direction was equal to the norm quantity of the railway site. The assistant stationmaster clearly and quickly ordered departure of a mixed-structure train at 09:00:00, without waiting for further wagon collection. The departure times were 16:00:00 for train 3401 and 14:55:00 for train 3001. In this manner, it is possible to rapidly plan the movements of all trains by reference to the wagons that will be collected by pickup freight and district trains at the time of departure of any mixed-structure train.

3.2 Practical application of the proposed method

Depending on work volume, our rapid planning method is effective, as revealed by PTC Mathcad simulations. We explored several options for optimal formatting and departure of pickup freight and district trains. Because wagon flows are non-proportional, the wagon numbers collected for pickup freight and district trains vary. The departure times of mixed-structure trains are those at which the wagon numbers attain site norms. Figure 7 illustrates this approach.

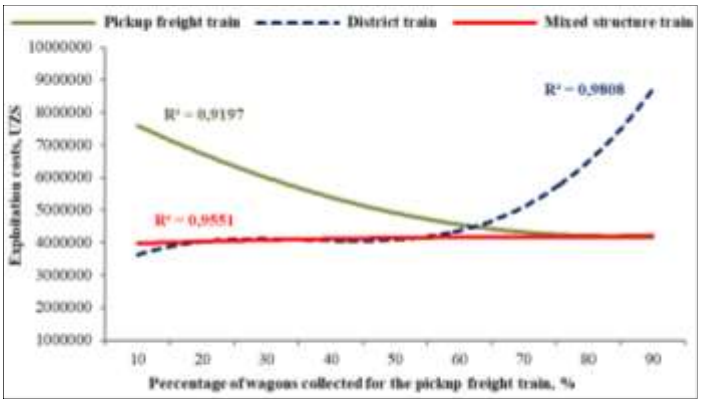

Fig. 7. Changes in exploitation costs at movement of trains under the conditions of the constant norm of the mixed-structure trains set on railway sites

All exploitation costs were determined when moving all train types from one technical station to another. Of the various options, the options shown in Figures 7 and 8 were optimal. As shown in Figure 8, the collecting wagon-flow for pickup freight trains was constant, while the collecting wagon-flow for the district trains was variable. The normative number of wagons in mixed-structure trains (based on wagon-flow) was also variable.

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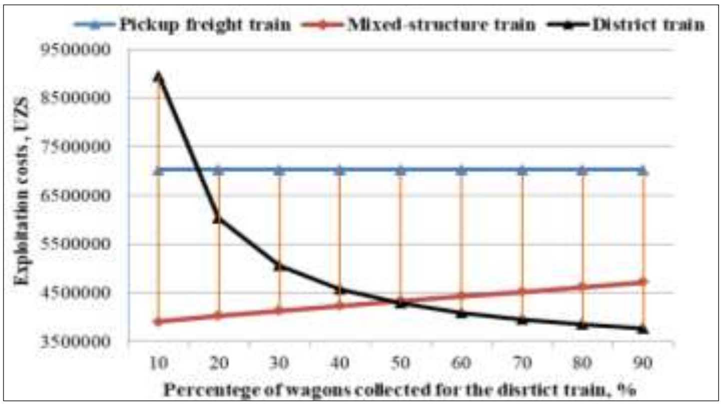

Fig. 8. Changes in the exploitation costs at movement of trains under the conditions of the variable norm of the mixed-structure trains set on the railway sites

The exploitation costs of all trains under formation were calculated (Fig. 8). The "best option" for all trains was selected from Figures 7 and 8 (Table 3).

Table 3. Rapid planning of train movement.

№	Type of option	Type of collecting train	Proportion of wagons collected to the decision time, %	Possible time frame for departure of priority trains	Priority train type	Suggestion and conclusion
1	By reference to constant site norms for mixed-structure trains	Pickup freight train	20	N_1<20	District train	Waiting for collection of all wagons and then dispatching a district train is better than ordering the departure of a pickup freight train and a mixed-structure train
		District train	80			
		Mixed-structure train	100			
2	By reference to constant site norms for mixed-structure trains	Pickup freight train	60	20<N_1<60	District train or Mixed-structure train	For a pickup freight train, it is acceptable to add collected wagons to the district train and send it off as a mixed-structure train. It is also acceptable to send off the district train while waiting for wagon collection
		District train	40			
		Mixed-structure train	100			
3	By reference to constant site norms for mixed-structure trains	Pickup freight train	80	60<N_1<80	Mixed-structure train	To create a "district train," it is optimal to add collected wagons to a pickup freight train and send it off as a mixed-structure train
		District train	20			
		Mixed-structure train	100			
4	By reference to constant site norms for mixed-structure trains	Pickup freight train	80	N_1>80	Pickup freight train or Mixed-structure train	Here, early departure of a mixed-structure or freight train is most appropriate; a district train follows later
		District train	20			
		Mixed-structure train	100			
5	By reference to constant site norms for mixed-structure trains	Pickup freight train	100	N_2<50	Mixed-structure train	Here, early departure of a mixed-structure train is most appropriate; pickup freight and district trains follow later
		District train	50			
		Mixed-structure train	50			
6	By reference to constant site norms	Pickup freight train	100	N_2>50	District train	Here, early departure of a district train is most appropriate; pickup
		District train	50			

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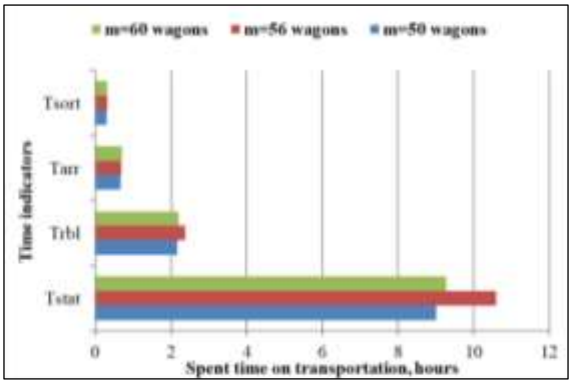
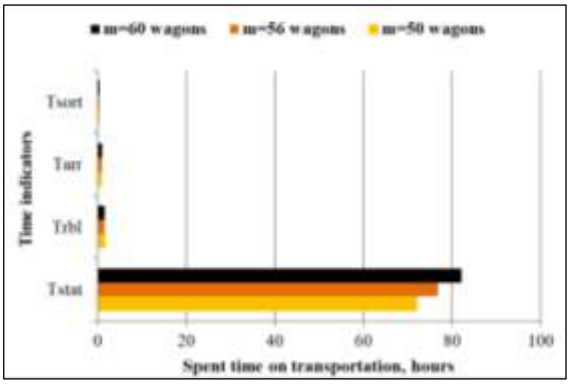
	for mixed-structure trains	Mixed-structure train	50			freight and mixed-structure trains follow later

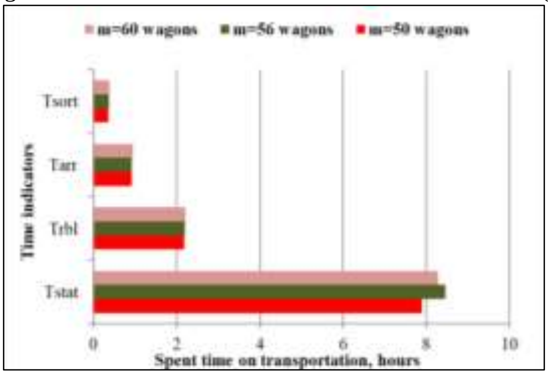
Rapid technical and economic calculations determine when mixed-structure trains are formatted. In railway systems, time is very important. Depending on train type, the times relevant to district, pickup freight, and mixed-structure trains are time spent at technical stations (T_{stat}); movement time (including time spent at intermediate stations for pickup freight and mixed-structure trains) (T_{rbl}); time required on arrival at a technical station (T_{arr}); and time required for sorting at a technical station (T_{sort}). These times are shown in Figure 9 for the three types of trains.



(a) pickup freight train



(b) district train



(c) mixed-structure train

Fig. 9. Changes spent time in the process of arriving trains (a, b, c) to their destination

As shown in Figure 9, the times spent on railway blocks (15–20% for pickup freight and mixed-structure trains, 1–5% for district trains) were longer than were the times required for station processing and sorting because of the many intermediate stations (often irrationally located) and inefficiencies in adding and separating wagons at these stations. Of all exploitation costs, 80% of the exploitation costs for pickup freight and mixed-structure trains were incurred when stopped at intermediate stations, when adding and separating wagons, and when moving. Greater numbers of pickup freight and mixed-structure wagons for intermediate stations were associated with greater exploitation costs. District trains spent 80–90% of time at stations; the figures for pickup freight and mixed-structure trains were 70–75% and 65–70%, respectively. Train formatting at technical stations is very slow, shunting locomotives are few in number, and railway blocks are often occupied by other trains.

4. Conclusion

We present a rapid planning method for organization of mixed-structure trains to enhance transport operations; we reduce the exploitation costs under non-proportional wagon-flow conditions. The method has been included in the PFT of JSC "Uzbekistan Railways" 2020/2021 for 25 sites handling all three train types. The method reduces loading of station, enhances wagon-flow, increases locomotive performance, and reduces cargo delivery time.

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