The task of organizing suburban and urban traffic on sections with branches

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Abstract. The article deals with the problem of organizing train traffic on sections with branches, analyzes possible separate routes on the "trunk" and "branch" sections, as well as routes with "fork" traffic. The authors emphasize the need to comply with a number of conditions that take into account the interests of passengers and suburban companies for the organization of passenger traffic on railway transport. The goal function is set to minimize the difference between the mileage of empty seats (as a condition that reflects the interests of the suburban company) and the overpopulation of the train (as a criterion that ensures a comfortable ride for the passenger). To solve this problem, the authors suggest using a genetic algorithm as a tool that allows you to perform a directed search of competitive options. The article describes the method of applying the genetic algorithm, the formation of "parent" variants and "offspring" variants, compliance with a number of restrictions and ranking of "offspring" variants for the selection of the best "species".

1. Introduction

There is a lot of research in terms of finding optimal solutions for the organization of traffic on radial and diametric railway lines. However, the questions of traffic organization and determining the optimality of various criteria for lines with branches are not sufficiently consecrated in the research of Russian and foreign scientists.

The article considers a line with branches as a special case of a radial railway line.

In the most simplified form, a radial railway line can be represented as a segment (figure 1), where A and B are the end stations.

**Figure 1.** Simplified image of a radial railway line.

There may also be complicated radial lines with forks, where a, b, ..., n are the end points on the branches (figure 2).

**Figure 2.** Simplified image of a radial railway line with branches.
The number of branches branching off from the main "trunk" may be different, but the most common cases are with the number of branches equal to 2.

For the full functioning of the transport service, several conditions must be met. In a transport service, the values of some criteria have a direct impact on others.

![Figure 3. Influence of transport service parameters on each other.](image)

Figure 3. Influence of transport service parameters on each other.

The effect of stopping points disposition on the total travel time is more detailed discussed in the article [1].

This research will examine the dependencies that affect the number of threads in the train schedule, as well as the dependence of rolling stock occupancy on the amount of passenger traffic and determining the optimal number of train threads for one hour of the peak period on the line with branches.

To indicate such dependencies, the following parameters are considered: the capacity of the section, the applied means of interval control (SIR), the value of the passenger traffic, and the geometric parameters of the line.

2. Materials and Methods
For the case shown in figure 1, the capacity of the section can be expressed in trains (pairs of trains) per day, hour, etc.

For lines with intensive suburban-urban electric train traffic, the most important is the development of passenger traffic during "peak" periods. Therefore, further calculations will include the value of the hourly capacity of the line to assess the possibility of traffic during "peak hours". Equipment and organization of the line's operation technology that allows you to master transportation in "peak" periods "will be able to master" non-peak " periods.

On the AB line segment (see figure 1), the required number of trains per hour can be determined as follows [2], [3]:

\[
N = \max \left( \frac{P_p}{C_v} \cdot \frac{60}{I} \right)
\]  

(1)

Where:
N – number of trains per hour;
\(P_p\) - the maximum passenger traffic value for one peak period hour;
\(C_v\) – vehicle capacity;
I – the accepted value of the interval between trains;
The interval between trains (I) is set based on the SIRs used.

Passenger traffic value - forecast of demand for transportation by a specific type of transport;

\( C_v \) – the vehicle capacity, depending on the accepted rolling stock and the number of cars in it.

If \( \frac{60}{I} > \frac{p_v}{C_v} \), then N can actually be taken as \( \frac{60}{I} \) or be less, depending on the required development of passenger traffic.

If \( \frac{p_v}{C_v} > \frac{60}{I} \), then it is necessary to understand that the line is not able to pass the number of trains equal to the \( \frac{n_b}{b_v} \) ratio. In this case, it is necessary to look for solutions to increase the capacity or transportation capacity of the line. The passenger flow value \( (P_p) \), as well as the parameter 60, is a constant. The variables I and \( B_v \) remain. It is necessary to understand that reducing the parameter I will require upgrading the SIR, which is very expensive. The \( B_v \) parameter remains. Initially, you can increase the number of cars until the inequality takes the following form: \( \frac{60}{I} \geq \frac{p_v}{C_v} \). However, there is a restriction related to the length of passenger platforms on the section. If the maximum increase in the number of cars in the composition fails to meet the inequality \( \frac{60}{I} \geq \frac{p_v}{C_v} \), it is necessary to replace the used rolling stock.

If we consider the capacity of a line with "fork" traffic, we must understand that the number of trains sent to branches depends on the number of trains on the main section.

There are private scientist opinions and real cases of forced transfer at the docking station (station B, figure 2). A similar experience is being implemented in the Izmir railway hub (Turkey). Forced transfer is accompanied by a turnover of trains on each of the branches and the main trunk (figure 4).

\[ \text{Figure 4. Simplified representation of train turnover patterns on a line with branches during "forced transfer at a zone station «B».} \]

Of course, this solution will allow you to organize a comfortable interval for individual sections. However, if there is a possible failure in traffic, it may disrupt the passenger delivery to remote areas. Also, in this case, the capacity utilization of the zone station B increases (figure 2), capital and operating costs for its maintenance increase. In addition, each branch will have to operate only the rolling stock that is used on this line, without including these trains in the overall turnover schedule. It is also worth understanding that there is a high probability of reducing the amount of passenger traffic if you need to make a forced transfer.

In order to evaluate various options for organizing traffic on a branched section, separate routes on the "trunk" and "branch" sections, as well as routes with fork traffic, will be analyzed.

On a line with "fork" traffic, the capacity of each branch should also ensure the development of passenger traffic. The total number of trains running on routes Aa, Ab, A..., An must not exceed the capacity of the "trunk" section AB. It is also logical to assume that the value of passenger traffic on the branches is less than on the AB section. Therefore, it is necessary to provide the turnover of trains at station B.
In order to determine the number of trains that turn around at station b, a, b,..., n, it is necessary to
determine the capacity of the AB section. At the same time, the $P_p$ value must be represented as the
passenger traffic density.

The number of train threads on branches with equal values of passenger traffic on each branch in
the most primitive case, if there is no turnover at zone station B, can be found as $N/j$, where j is the
number of branches from the main trunk. But in practice, the value of passenger traffic on each of the
branches may be different from each other. Therefore, the $N/j$ ratio must be adjusted, depending on the
values of the passenger traffic on each of the branches.

The number of train threads laid on branches must relate to each other in the same way as the
values of the corresponding passenger flows relate to each other.

$$\frac{N_{Ba}}{N_{bb}} = \frac{P_{Pa}}{P_{Pbb}}; \quad \frac{N_{Ba}}{N_{Bb}} = \frac{P_{Pa}}{P_{Pbb}}; \quad \text{etc.}$$

If one of the branches has a significantly higher passenger traffic value than the other branches, the
required number of threads will be higher than the other branches with the same ratio. In this case, it is
necessary to determine the optimal set of "schemes" and the order of alternating assignments in them.
As a "schema" refers to the set of destination stations for the train routes.

If the number of required trains per hour is >1, then it is necessary to maintain a certain interval
between such trains on the branches. So, if in a particular case, the number of threads required is 2,
then the optimal interval between them will be 30 minutes, for three threads-20 minutes, and so on.

When servicing sections with branches, you should pay attention to the operation of junction
stations. A junction station within the framework of suburban-urban passenger service must operate
under conditions of processing all categories of trains and corresponding passenger flows.

It is necessary to develop a methodology that defines a strict sequence of trains arrival order from
branches and departure of those trains for which the zone junction station is the final one on the route.

Departure of trains of all routes from the zone junction station must ensure the complete passengers
delivery.

Criteria for determining the order of train handling at a zone junction station:

- the sequence of arrival at the junction station of trains from branches and their subsequent
departure along the main trunk should be excluded or minimized;
- a certain clock rates must be observed between trains (for example, arrival from branches –
every 30 minutes, departure from the zone station-every 10 minutes, etc.);
- the arrival and departure order of trains from the junction station must be made in a certain
sequence, excluding possible inconveniences of transfers.

We need a tool that allows us to make a reasonable sequence of arrival and departure of trains to
the junction station from different directions, taking into account the comfortable transfers. To do this,
we must also take into account the possible ways to make a transfer (overcoming staircases to go from
one platform to another, etc.), the arrival and departure time of trains in opposite directions in order to
understand whether there will be enough time for the passenger to navigate in space and make a
transfer.

A cross-platform transfer may be the most attractive option if the schedule is consistent. However,
not every track development and infrastructure of stations can provide this type of transfer.

When "linking" the arrival and departure of trains to ensure consistency of schedules, priority
should be given to the junction station closest to the metropolis. Since it is at such stations that the
maximum values of changes in the density of passenger traffic are observed.

The combination selections of trains arrival and departure should be made taking into account
combinatorial analysis.
3. Determining the number of trains of various purposes on sections with branches

Passenger transport plays a social role in any agglomeration. However, an infinite number of assigned trains can negatively affect the financial performance of the rolling stock operator. Therefore, it is necessary to take into account the interests of all parties when determining the number of trains assigned to each of the directions [4]. The authors’ works are devoted to the problems of organizing railway transport [7,8,9,10,11].

Passengers must be provided with seats in the passenger compartment of the rolling stock. It is not profitable for a suburban company (a rolling stock operator) to run trains whose occupancy is low. Therefore, the goal function can be set to minimize the mileage of empty seats and overpopulation of the train.

\[ F = \sum_i \left[ \sum_j \delta_{ij} l_i M_j - l_i D_i \right] \min, \]

where
- \( j \) - train destination,
- \( i \) - section number;
- \( M_j \) - the number of seats provided to passengers on the destination train \( j \);
- \( l_i \) - length of the \( i \)-th section;
- \( D_i \) - density of passenger traffic on the \( i \)-th section;

\[ \delta_{ij} = \begin{cases} 1, & \text{if the train of the } j \text{-th destination follows the } I \text{-th section}, \\ 0, & \text{otherwise} \end{cases} \]

The number of seats available to passengers on the destination \( i \) train is determined as follows:

\[ M_j = \sum_k x_j m_{jk} \]

where:
- \( k \) - configuration of the passenger car;
- \( x_j \) - number of trains with the \( j \)-th destination;
- \( m_{jk} \) - the number of seats provided in all cars of the \( j \)-direction train.

Thus, the goal function (2) takes the following form:

\[ F = \sum_i \left[ \sum_j \left( \delta_{ij} l_i \sum_k x_j m_{jk} \right) - l_i D_i \right] \min, \]

A number of restrictions must be taken into account for the goal function:

- limit related to line capacity:
\[ \sum_j \delta_{ij} x_j \leq \frac{60}{l_i}, \]  

- limit related to the line’s transportation capacity:
\[ x_j \geq 0; \quad x_j \leq \frac{\max \left( \delta_{ij} D_i \right)}{\sum m_{jk}}, \]

- limit related to the possibility of rolling stock turnover at the zone station:
\[ \sum_j x_{jr} \leq \frac{N_{\text{rail trucks}} \times 60}{t_{\text{reception}} + t_{\text{turnover}} + t_{\text{departure}}}, \]

where:
- \( r \)-turnover station;
- \( x_{jr} \) - the number of \( j \)-destination trains that are turned over at the \( r \) station;
- \( N_{\text{rail trucks}} \) - the number of turnover paths at the turnover station \( r \);
- 60 - number of minutes per hour;
- \( t_{\text{reception}} \) - the time required to receive the train;
$t_{\text{turnover}}$ - the time required to complete the turnover of rolling stock;
$t_{\text{departure}}$ – the time required for the train to leave the station.

Thus, for the organization of passenger traffic on railway transport, a number of conditions must be met that take into account the interests of passengers and suburban companies.

Due to the large dimension of the problem, finding the optimal solution by iterating through all possible options is difficult.

4. Results

To solve this problem, the authors of this study suggest using a genetic algorithm as a tool that allows for a directed search of competitive options [5], [6].

The possibility of using a genetic algorithm to find the optimal (or close to optimal) option for organizing traffic on a line with branches is considered on an arbitrary example (figure 5).

For a line with two branches, the following custom input data is set:
- The length of the section "AB" is 30 km, "Bc" – 12 km, "Bd" - 10 km.
- The maximum density of passenger traffic on the section "AB" is 5000 passengers/hour, "Bc" – 1500 passengers/hour, "Bd" – 1200 passengers/hour.
- The minimum interval between trains on any section is 10 minutes.
- The rolling stock turnover time at the zone station is 15 minutes.
- The number of working tracks at the station "B" – 2, "c" – 1, "d" - 1.
- The line is used for rolling stock of uniform length, including 2 head cars with a capacity of 100 passengers and 5 trailer cars with a capacity of 130 passengers each. Thus, the total capacity of the train in the example is 850 passengers.

"X1" – "X5" reflect the possible number of trains per hour on a particular route.
At the beginning of the solution, a set of ten possible solutions is formed. Each solution is a chromosome from a sequence of genes (the number of trains on each of the routes).

Thus, the initial "population" consisting of 10 variants may consist of the sets shown in table 1.
Table 1. Set of "parent" options for running the genetic algorithm.

| № п/п | X1 | X2 | X3 | X4 | X5 |
|-------|----|----|----|----|----|
| 1     | 2  | 2  | 1  | 2  | 2  |
| 2     | 3  | 0  | 1  | 2  | 2  |
| 3     | 4  | 0  | 2  | 0  | 0  |
| 4     | 0  | 2  | 1  | 0  | 5  |
| 5     | 0  | 1  | 1  | 0  | 6  |
| 6     | 1  | 1  | 1  | 1  | 4  |
| 7     | 0  | 2  | 1  | 0  | 4  |
| 8     | 0  | 2  | 1  | 1  | 4  |
| 9     | 0  | 0  | 0  | 0  | 6  |
| 10    | 0  | 0  | 0  | 0  | 0  |

Then each option is checked for compliance with the specified restrictions.
In addition to the fact that the number of trains per hour cannot be more than 6, it is necessary to check the possibility of turnover of trains at the zone station "B" or the end stations of branches.
The restriction is checked using the formula (7) and taking into account the source data on the number of paths for a turn and the turn time indicated in the source data of the example. Thus, we have the following restriction on the maximum speed of trains at stations:

B – 8 trains per hour; c and d - 4 trains per hour.

Restrictions on the line's carrying capacity for routes that depend on the capacity of rolling stock and the maximum passenger density are shown in table 2.

Table 2. Restrictions on the number of trains per hour on each of the routes considered, depending on the carrying capacity of the sections.

| X1 | X2 | X3 | X4 | X5 |
|----|----|----|----|----|
| 6  | 2  | 2  | 6  | 6  |

The calculation can be performed in any analytical software package. As part of the research, the search for the optimal way to organize traffic on a line with branches was performed in the MS Excel product.

After forming ten "parent" options, each was checked for compliance with the restrictions. The compliance of a particular value "X" option, the number of trains on a certain route is marked with the number "0", the compliance to the restriction number "1". After checking each route separately, the option was checked for overall compliance with the restrictions. To do this, all the check values were added together. If the total value was "0" - the option for the number of trains on the routes passed the restrictions, if the corresponding cell was assigned a value other than "0", the option was recognized as not having passed the check for compliance with the restrictions. Also, for each option, the value of the goal function was calculated in order to then get the sum of the top ten options and compare the value with the next or previous generation. A visualization of how restrictions are met by each option is shown in figure 6.
Figure 6. Generating and displaying data on compliance with restrictions for each option in MS Excel.

Check for compliance limit the number of trains per hour on each of the proposed routes, depending on the transportation capacity of the section as follows: if the value of the test cells is less than or equal to the appropriate limit from table 2, the bottom cell is assigned the value "0", otherwise "1". Thus, under each cell containing information about the number of trains per hour on the route, a cell containing information about compliance with this restriction is filled in.

After checking each value of the number of trains on the route for compliance with restrictions, a total check of the option for compliance with restrictions is performed (figure 6). The total check is a comparison of the sum of the values of green and yellow cells with the value "0" or "1". If the sum of all values of green and yellow cells is equal to "0", this option is competitive, but if it is equal to" 1", it is not competitive due to non-compliance with restrictions.

For further analysis, the value of the target function (4) is also calculated. The value is assigned to the cell opposite the sequential number of the variant (figure 6).

After the evaluation of compliance with the restrictions of the "parent" variants, the variants are crossed with each other to form a new "offspring" by partially combining the "genes" from the two "parent chromosomes". In a specific example, a new "offspring" is obtained by combining the first two" genes "in a set from one" parent chromosome "and the next three from the second" parent chromosome " (figure 7).

Figure 7. Schematic image of the formation of the «offspring» species.
"The offspring chromosomes" are checked for compliance with the restrictions. For the formation of the next generation, both offspring and parents are taken into account. Using function (4), each decision (species) is evaluated. Those solutions that do not pass the restriction are not included in the generation of offspring. Then 10 solutions with the minimum value of the goal function are selected from all solutions and the total score \( Q \) of these species is calculated. Then the next iteration of the algorithm is performed. Iterations are made until the total score of the top 10 species is equal to the total score of the previous generation.

\[
Q_q = Q_{q-1}
\]

(8)

where:

\( q \) - sequential number of the generation

In this example, the top 10 of the first generation includes the sets shown in table 3.

| New numbers assignment | n / a parent species number from table 1 | X1 | X2 | X3 | X4 | X5 | Value of the goal function |
|------------------------|----------------------------------------|----|----|----|----|----|-----------------------------|
| *1                     | 6-4                                    | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *2                     | 6                                      | 1  | 1  | 1  | 1  | 4  | 10400                       |
| *3                     | 6-8                                    | 1  | 1  | 1  | 1  | 4  | 10400                       |
| *4                     | 5                                      | 0  | 1  | 1  | 0  | 6  | 14300                       |
| *5                     | 4-9                                    | 0  | 2  | 0  | 0  | 6  | 17400                       |
| *6                     | 7-9                                    | 0  | 2  | 0  | 0  | 6  | 17400                       |
| *7                     | 8-9                                    | 0  | 2  | 0  | 0  | 6  | 17400                       |
| *8                     | 5-9                                    | 0  | 1  | 0  | 0  | 6  | 22800                       |
| *9                     | 9-5                                    | 0  | 0  | 1  | 0  | 6  | 24500                       |
| *10                    | 10-5                                   | 0  | 0  | 1  | 0  | 6  | 24500                       |
| Total                  |                                        |    |    |    |    |    | 168000                      |

The top 10 of the second generation includes the variants shown in table 4.

| Variant number | X1 | X2 | X3 | X4 | X5 | Value of the goal function |
|----------------|----|----|----|----|----|-----------------------------|
| *21            | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *31            | 1  | 1  | 1  | 0  | 5  | 8900                        |
| 64             | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *12            | 1  | 1  | 1  | 1  | 4  | 10400                       |
| *13            | 1  | 1  | 1  | 1  | 4  | 10400                       |
| *23            | 1  | 1  | 1  | 1  | 4  | 10400                       |
| *32            | 1  | 1  | 1  | 1  | 4  | 10400                       |
| 6              | 1  | 1  | 1  | 1  | 4  | 10400                       |
| 68             | 1  | 1  | 1  | 1  | 4  | 10400                       |
| *49            | 0  | 1  | 1  | 0  | 6  | 14300                       |
| Total          |    |    |    |    |    | 103400                      |
In the third generation, the best variants were "species with the same sets of chromosomes" obtained by "crossing" different "parent species" (table 5).

Table 5. Set of the best individuals from the third generation.

| Variant number | X1 | X2 | X3 | X4 | X5 | Value of the goal function |
|----------------|----|----|----|----|----|-----------------------------|
| *21_*31        | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *21_64         | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *31_*21        | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *31_*64        | 1  | 1  | 1  | 0  | 5  | 8900                        |
| 64_*21         | 1  | 1  | 1  | 0  | 5  | 8900                        |
| 64_*31         | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *12_*21        | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *12_*31        | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *12_64         | 1  | 1  | 1  | 0  | 5  | 8900                        |
| *13_*21        | 1  | 1  | 1  | 0  | 5  | 8900                        |
| Total          |    |    |    |    |    | 89000                       |

In the fourth generation, the best variants were "species with the same sets of chromosomes", obtained by "crossing" different "parent species". The total value of the goal function for the top 10 individuals of the fourth generation coincides with the values of the sum in the third generation and is 89000, therefore, the crossing process has come to an end and the optimal set of trains in each of the directions has been found.

Next, you need to arrange the trains at station B (node station of any example) on arrival and departure.

Figure 8 shows a sketch train schedule for the branched section (figure 5). The sketch train schedule is made without taking into account the "linking" of trains in turnover. A sketch train schedule constructed for an arbitrary example can also not reliably reflect the time of the train on the stage, since this indicator depends on the characteristics of the rolling stock and the profile of the track.
Figure 8. A fragment of the sketch train schedule during the "peak" period for the section under consideration with branches.

It is obvious that at the station "B" it is necessary to provide a comfortable transfer for trains from the directions "AB" to the trains of the directions "Bc" and "Bd". For this purpose, a minimum interval of 5 minutes is provided between trains of the above directions. This value is taken as an example. However, the comfortable duration of the minimum interval between trains that a passenger can potentially transfer to should take into account the specifics of the railway infrastructure object and the specifics of the path for making such a transfer (overcoming staircases, switching to another platform, etc.).

In this example, the probability of possible transfer of passengers from trains of the "dB" direction to trains of the "Bc" direction is also taken into account. The convenience of a return transfer (i.e. from the direction "cB" to "Bd") is difficult to call "comfortable "due to the rare running of trains on the direction "Bd".

When drawing up train schedules for real sections, it is necessary to analyze the demand for passenger traffic in opposite directions (in this example, the sections "cB – Bd" and "dB – Bc"), which allows you to determine the need to link the arrival of trains in opposite directions.

5. Discussion
The proposed mathematical model with the use of genetic algorithms as a result of calculations allows you to get a reliable result and can be tested on a real object.

The using of genetic algorithms allows to reduce the time, spending for searching of competitive variants and selecting optimal variants for solving the described problem.

In further research, it is planned to improve the genetic algorithm by using combinatorial analysis in order to automatically select combinations of arrival and departure of trains at the junction station, taking into account various factors.

6. Conclusion
The method of determining the optimal solution for assigning suburban-urban trains on branched sections for each of the possible routes uses the values of passenger traffic density, rolling stock characteristics, and infrastructure limitations of the line as input data. If it is necessary to perform calculations for promising areas, you should use forecast values.

Calculations can be performed in any analytical software package, but writing a simple program for calculations will significantly reduce the time needed to form new generations and select the best options.

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