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REBUILDING TRACK LAYOUTS ON A SINGLE-TRACK RAILWAY LINE TO ACCOMMODATE INCREASED TRAFFIC VOLUME[1]

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This paper discusses the use of optimization methods in planning the location and layout of passing sidings on a single-track railway line to accommodate increased traffic load. A simple optimization model is presented and a means for taking into account the characteristics of the track layout within the constraints of the model are presented. Based on an analysis of the Poznań Wschód–Wągrowiec section of railway line no. 356, the practical applicability of this method for adapting infrastructure to traffic needs is demonstrated.

1. INTRODUCTION

One of the most important objectives in modernizing a railway network is a reduction in train travel time [15, 17]. On double-track lines, this objective is achieved primarily by increasing maximum running speed limits. On single-track lines, especially those with high traffic volume and high capacity utilization, stop times – which result from the need to stop to allow trains proceeding in the opposite direction to cross – have a significant impact on scheduled speed. Therefore, during the process of modernization, apart from increasing running speed limits, special attention should be paid to the number and location of passing sidings [12]. Methods used to design the locations of passing sidings on a single-track railway line can be divided into three groups [6, 14]: 1) methods based on the experience of the designer and analytical calculations, 2) simulation methods and 3) optimization methods. This article concerns only the third group.

This paper presents an optimization model for evaluating different options for rebuilding a single-track railway line in order to design the best possible track layout for the assumed objective function, which is the minimization of average scheduled travel time. In the next section, we provide a brief literature

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review, and then in section 3 we present a simple optimization model for a cyclical timetable on a single-track railway line. In section 4 we provide a model for taking into account the influence of building a new passing siding or short double-track section to allow two trains proceeding in opposite directions to cross simultaneous without stopping. Finally, in section 5 we demonstrate the practical applicability of this method using the example of the Poznań Wschód–Wągrowiec section of railway line no. 356.

2. LITERATURE REVIEW

One of the first models for optimizing a railway timetable on a single-track line was formulated in 1973 in [16]. Later studies developed models dealing with cyclic (e.g. [13]) and non-cyclic (e.g. [1]) variants of the problem. Much attention has been paid to the use of heuristics in finding an approximate solution when finding an exact, optimal solution is too complicated. Heuristics are often used in real-world applications of an optimization method – such as a complex railway network with high traffic volume [3, 4, 9]. Some studies have dealt with a robust version of the train timetable problem, in which the aim is to avoid delays. These models use stochastic programming techniques [5, 8]. The first model to allow direct optimization of siding locations was presented in [7]. Recent works (e.g. [14]) have dealt with a complex extension of this model, focusing on economic aspects of building new sidings, including zones with different construction costs.

In the literature, little attention has been devoted to detailed consideration of the characteristics of track layout in the optimization model, which is a crucial aspect to consider when using these methods during the process of modernizing railway infrastructure.

3. OPTIMIZATION MODEL

A railway network can be represented by a graph $G=(N,E)$, whose vertices (N) correspond to the traffic control posts and expedition posts, while its edges (E) correspond to the routes between these posts. A train timetable is defined by the times of arrival and departure from each post. Let N_t denote the set of successive vertices on the route of a train $t \in T$. The decision variables will then be the moments of arrival and departure of trains at particular posts:

$$\left(a_t^n, d_t^n\right), t \in T, n \in N^t \tag{3.1}$$

During the construction of a train timetable, a number of dependencies between a pair of selected events z_i and z_j should be taken into account (an event is understood as the arrival or departure of a train). These dependencies in general can be written as [2]:

$$l_{ij} \le z_j - z_i \le u_{ij} \tag{3.2}$$

$$l_i \le z_i \le u_i \tag{3.3}$$

In this way, acceptable dwell times, the journey times between two consecutive posts, and minimum headways are defined. For example, a constraint which imposes dwell time on train no. 1 at station A of not less than 1 minute and not more than 5 minutes has the form:

$$1 \le d_1^A - a_1^A \le 5 \tag{3.4}$$

In a cyclic train timetable, with cycle time *c*, all analyzed events belong to a set $\{0,1,\ldots,c-1\}$ and constraints concerning a pair of events can be formulated as:

$$l_{ij} \le (z_j - z_i) mod(c) \le u_{ij} \tag{3.5}$$

Modulo operation (mod) can be replaced by the following, equivalent notation:

$$l_{ij} \le z_j - z_i + p_{ij} \cdot C \le u_{ij} \text{, where} \tag{3.6}$$

$$p_{ij} = \begin{cases} 0, gdy\ z_j \ge z_i \\ 1,\ gdy\ z_j < z_i \end{cases} \tag{3.7}$$

For example, a constraint arising from the locations of the posts on the line, which imposes a minimum headway between trains on the S1 and S2 lines on section AB, running on a cycle of 60 minutes, can be formulated as follows:

$$6 \le \left(a_{S1}^B - a_{S2}^B\right) mod(60) \le 50 \tag{3.8}$$

This constraint guarantees that a train on the S1 line does not arrive at station B earlier than 6 minutes after the arrival of a train on the S2 line. Furthermore, a train on the S2 line does not arrive at station B earlier than 10 minutes after the arrival of a train on the S1 line.

Moreover, for trains on the S1 and S2 lines operating on the same route AB, the following condition may be introduced:

$$\left(d_{S1}^A - d_{S2}^A\right) mod(30) = 0 \tag{3.9}$$

$$\left(a_{S1}^B - a_{S2}^B\right) mod(30) = 0 \tag{3.10}$$

The aims of optimization are usually minimization of journey time for a passenger or cargo from the start point to the destination, minimization of costs related to rolling stock utilization and the scheduling of work for train crews, and maximization of timetable reliability [10]. In our model, we used minimization of the sum of all trains' travel time from the starting point to the destination as an objective function. Since we assumed that journey time between two consecutive characteristic points is strictly determined, it is sufficient to minimize total dwell time, which on a single-track railway line is dependent on the location and track layout of traffic posts:

$$Min\left(\sum_{t\in T}\sum_{n\in N^t}\left(d_t^n - a_t^n\right)mod(c)\cdot w_t^n\right) \tag{3.11}$$

We took into account the possibility of a differentiation in time weights (w_t^n). These weights may be dependent on e.g. the number of passengers. Therefore, during the morning rush hour, it is reasonable to assign a higher weight to trains travelling in the direction of the center of an urban agglomeration, which are more crowded.

Such a formulation of the issue is a linear programming problem, and may be solved using commercial software, such as IBM ILOG CPLEX or Gurobi Optimization. After developing an optimization model, studies for a particular track layout are limited to the preparation of input data (driving times, minimum headways, and the location of posts at which overtaking and crossing of trains is possible), after which an optimal timetable for the assumed objective function is automatically generated.

4. MODEL'S UTILITY IN PLANNING THE REBUILDING OF SINGLE-TRACK RAILWAY LINE

A project for modernizing railway infrastructure usually involves several options. Using an optimization method makes it possible to assess which option will enable realization of the best possible timetable in terms of the assumed criterion (or set of criteria).

For example, on a single-track railway line one may consider different options for the location of stations and sidings. Figure 1 illustrates a train graph (time-space diagram) on a section limited by sidings A and C, with a train stop at point B. It was assumed that the timetable is cyclical and a cycle is denoted by *c*. The shaded area represents the time period in which it is possible to add a time-space path for train no. 2, if train no. 1 is already scheduled. We used the following notations:

- TT_i^{mn} – travel time of train *i* between points *m* and *n*,
- DT_i^m – dwell time of train *i* at point *m*,
- Tk^m – crossing time for two trains proceeding in opposite directions at point *m*,

– $hda_{ij}^{min,m}$ – minimum headway time between departure of train i from station m and arrival of train j at station m.

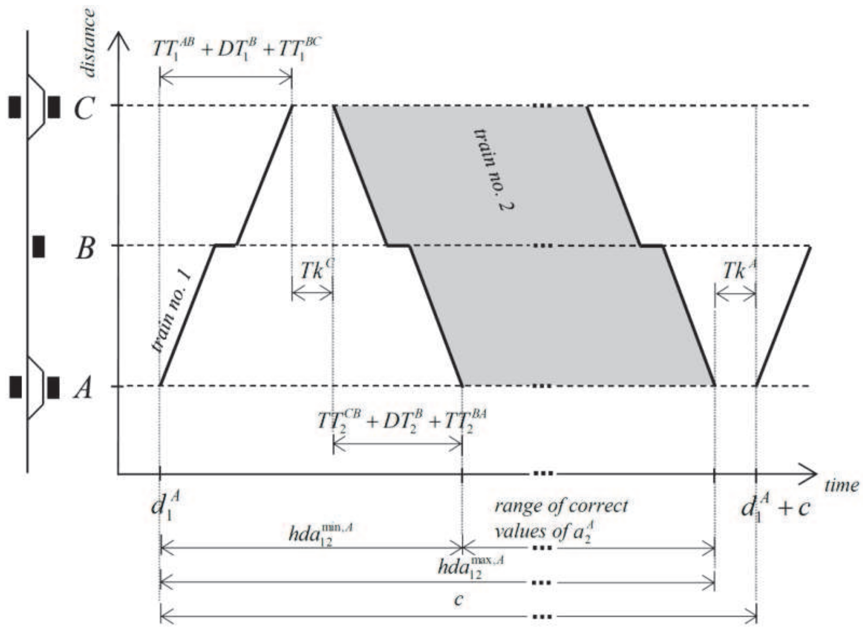

Fig.1 .Train graph (time-space diagram) on section AC – option with train stop at point B

In the discussed option, the timetable must include the following relationships between the departure of train no. 1 from siding A and the arrival of train no. 2 at this siding:

$$hda_{12}^{min,A} \le \left(a_2^A - d_1^A\right) mod(c) \le hda_{12}^{max,A}\text{, where:} \tag{4.1}$$

$$hda_{12}^{min,A} = \left(TT_1^{AB} + DT_1^B + TT_1^{BC}\right) + Tk^C + \left(TT_2^{CB} + DT_2^B + TT_2^{BA}\right) \tag{4.2}$$

$$hda_{12}^{max,A} = Tk^A \tag{4.3}$$

In the second option, we analyzed the location of the siding at point B. In figure 2, the darker shaded area represents the additional time period during which it is possible to add a time-space path for train no. 2 by building a siding at point B (two trains crossing at point B).

The increased range for the allowable moment of arrival of train no. 2 at siding A is reflected in the constraints of the model by the modification of $hda_{12}^{min,A}$:

$$hda_{12}^{min,A} = TT_1^{AB} + Tk^B + TT_1^{BA} \tag{4.4}$$

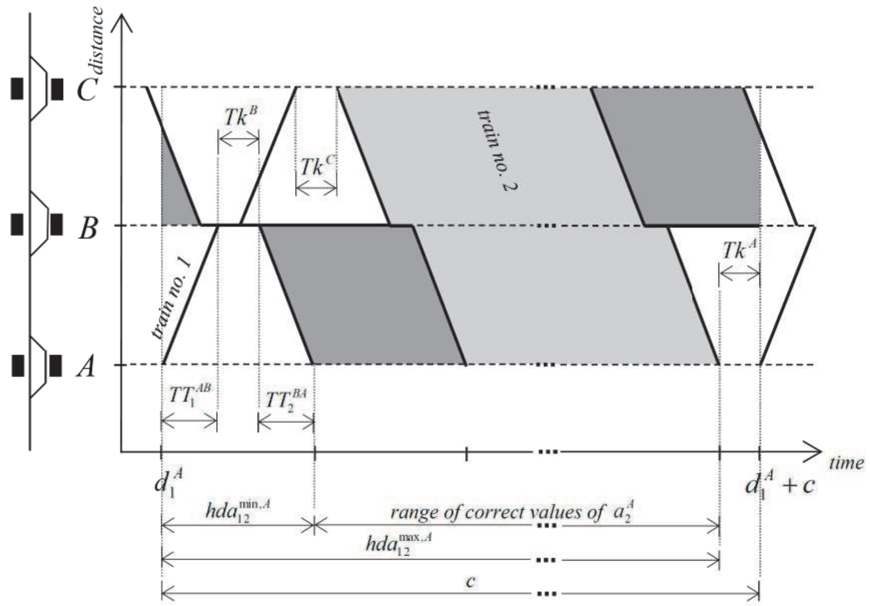

Fig. 2. Train graph (time-space diagram) on section AC – option with siding at point B

On lines with particularly high traffic intensity, we may consider building a short double-track section to enable dynamic crossing and the possibility of overtaking trains. Such a variant is shown in figure 3.

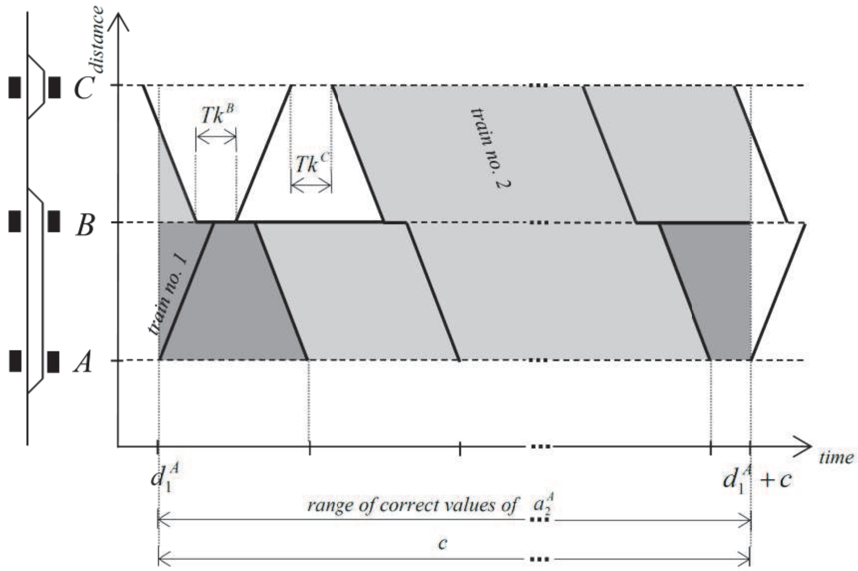

Fig. 3. Train graph (time-space diagram) on section AC – option with short double-track section between points A and B

In figure 3, the darker shaded area represents the additional time period during which it is possible to add a time-space path for train no. 2 due to the building of the short double-track section AB. Thus, the departure of train no. 1 from siding A and the arrival of train no. 2 are collision-free, and therefore:

$$0 \le \left(a_2^A - d_1^A\right) mod\left(c\right) \le c \tag{4.5}$$

5. CASE STUDY

The utility of the method presented above for solving real-world problems was verified using as an example an analysis of the Poznań Wschód–Wągrowiec section of railway line no. 356. An analysis conducted previously in connection with the Poznań Metropolitan Railway project [11] proved that increasing the frequency of trains within the agglomeration to 30 minutes on the Poznań Wschód–Murowana Goślina section and to 60 minutes on the Murowana Goślina–Wągrowiec section in both directions would lead to a significant reduction in the average journey speed. This effect is caused by the increased stop times at sidings, necessary to allow trains proceedings in opposite directions to cross.

Using the optimization method on the train timetable, we analyzed different options for adapting the railway infrastructure on line no. 356 to this increased traffic intensity. We formulated the optimization model in Open Programming Language (OPL) and used IBM ILOG CPLEX software to solve the problem. The time required to find an exact solution for the analyzed layout, using the program's default settings, was less than 2 minutes; therefore, we did not focus on searching for the most effective (shortest) method of solving the optimization problem.

We first defined the *Wmin* variant, which represents minimum journey time, without taking into consideration longer dwell times for the crossing of two trains. Next, in the *W0* variant we analyzed the introduction of cyclic traffic with increased frequencies on existing track layouts. These assumptions required increasing dwell times. Using the optimization model, we generated a train timetable characterized by the lowest possible value for the objective function, which was the weighted sum of journey times. We considered the morning rush hour, so trains travelling in the direction of Poznań were given 4 times greater weight than trains travelling in the opposite direction. During the afternoon rush hour, we reversed these priorities.

We then examined whether building an additional siding at different locations would enable a reduction in the weighted sum of journey times (increasing the average journey speed). We analyzed the locations of all existing train stops. We obtained the smallest value for the objective function for the timetable, taking into account the siding in Owińska – this variant was denoted W1.

The next step was to consider the building of a short double-track section between two posts, enabling the dynamic crossing of two trains. The most advantageous location was the Owińska–Bolechowo section – this variant was denoted W2.

The results of this analysis were illustrated as timetables in the form of train graphs, generated in the process of optimization for the morning rush hour for variants W0, W1 and W2 (figure 4). In addition, figure 5 shows the corresponding average journey times in different variants.

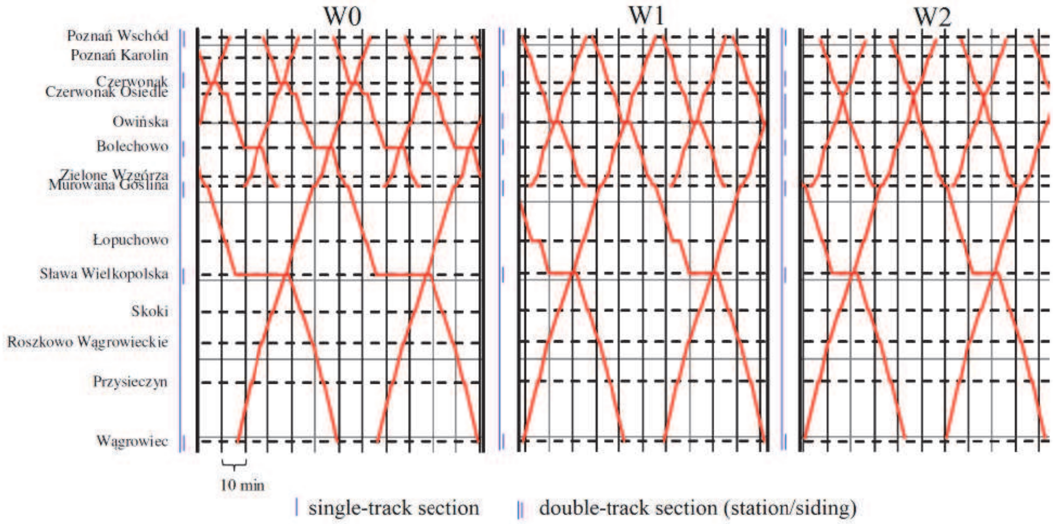

Fig. 4. Train graph on the Poznań Wschód–Wągrowiec section in variants W0, W1 and W2, generated in the optimization process

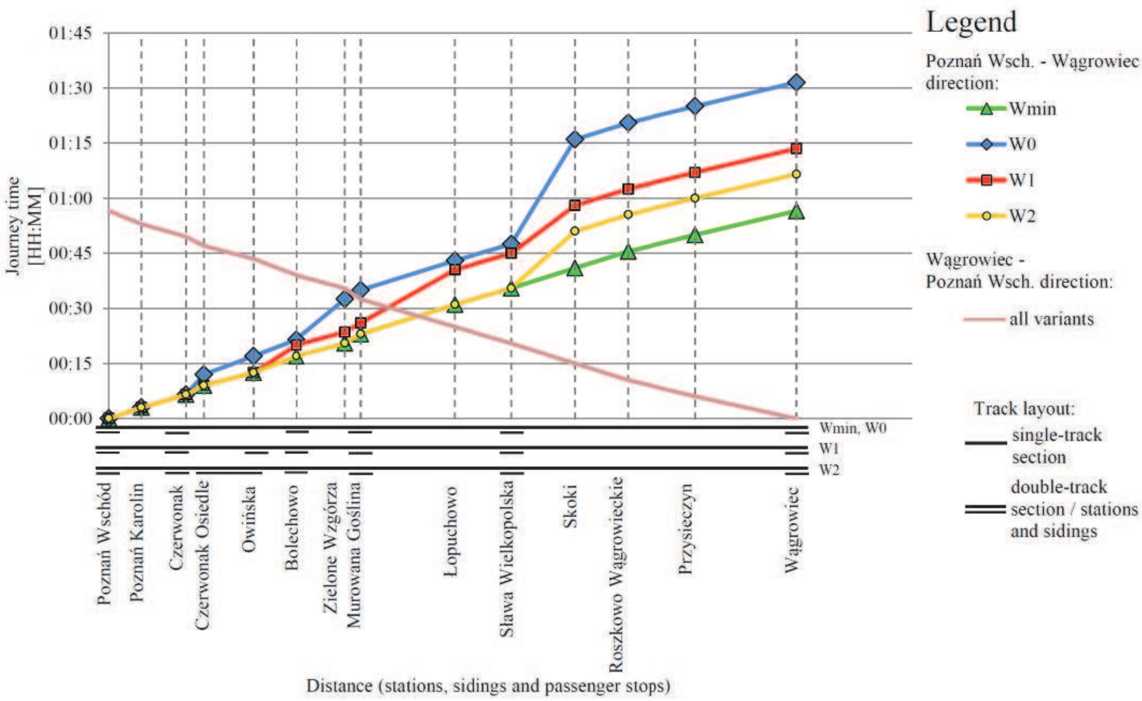

Fig. 5. Journey time, including dwell times, on the Poznań Wschód–Wągrowiec section in different variants for the rebuilding of track layouts

In the direction of Poznań, journey time in all variants is equal to the minimum, which is a consequence of higher weights being assigned to trains travelling in this direction during the morning rush hour. In the opposite direction, the necessity of trains crossing results in a longer journey time. In variant W0, the location of existing posts requires three crossings of trains (withone stop time of more than 20 minutes), which results in a longer journey time from Poznań Wschód to Wagrowiec of up to 35 minutes. Due to the building of an additional siding in Owińska (variant W1), the number of train crossings is reduced to two and the journey time is only extended by just 17 minutes. It is noteworthy that according to the timetable developed in this variant, the sidings in Czerwonak and Bolechowo will be used only in the event of delays. Assuming a second track on the Owińska–Czerwonak Osiedle section (variant W2), train crossings also take place twice, but one of them is done dynamically – as a result, the extension of the journey time to Wagrowiec is reduced to just 10 minutes. In practice, the timetable in the area of a dynamic siding is constructed in such a way that the crossing of trains takes place in the middle of a double-track section, so the timetable shown in figure 4 requires a few minutes' correction.

It should be emphasized that the example presented above illustrates only the possibility for using the optimization method to create a train timetable during the process of modernizing railway infrastructure. This example does not exhaust the complexity of the problem of adapting railway line no. 356 to the Poznań Metropolitan Railway project. For example, we did not consider the Poznań Wschód–Poznań Główny section, nor the Poznań Główny station, which may be crucial to the project. In addition, elimination of some of the speed restrictions on railway line no. 356 may lead to different conclusions in terms of the optimal location of sidings. Our analysis also did not consider the economic aspects of this infrastructure expansion nor the aspect of timetable reliability. We are going to devote future research to the extension of our model to deal with these issues.

6. CONCLUSIONS

The number and location of sidings on a single-track railway line with high traffic volume have a crucial meaning for trains' journey time and for the efficiency of railway infrastructure modernization, especially for the efficiency of increasing speed limits. In the process of planning the modernization of railway infrastructure, an optimization method for creating a train timetable may be used as a tool for supporting decisions. By using an optimization method and commercial software it is possible to create automatically a timetable which is characterized by the lowest or highest value of the objective function for different assumed variants of track layout. The characteristics of track layout are reflected in the constraints of the model. In this way, the designer may assess the impact of various project features on the future railway timetable and, as a consequence, develop track layouts better adapted to traffic needs. Note, however, that the presented method does not take into consideration train delays, and therefore the model should be extended or simulation methods should be used as a complement to the analysis.

LITERATURE

[1] Brännlund U., Lindberg, P. O., Nõu A., Nilsson J.-E.: *Railway Timetabling using Lagrangian Relaxation*. Transportation Science 32/1998, 358-369.

[2] Cacchiani V., Toth P.: *Nominal and robust train timetabling problems*. European Journal of Operational Research 219/2012, 727-737.

[3] Caprara A., Fischetti M., Toth P.: *Modeling and solving the train timetabling problem*. Operations Research 50/2002, 851-861.

[4] Caprara A., Monaci M., Toth P., Guida P.L.: *A Lagrangian heuristic algorith for a real-world train timetabling problem*. Discrete Applied Mathematics 154/2006, 738-753.

[5] Fischetti M., Salvagnin D., Zanette A.: *Fast approaches to improve the robustness of a railway timetable*. Transportation Science 43/2009, 321–335.

[6] Garcia A., Garcia I.: *A simulation-based flexible platform for the design and evaluation of rail service infrastructures*. Simulation Modelling Practice and Theory 27/2012, 31-46.

[7] Higgins A., Kozan E., Ferreira L.: *Modeling the number and location of sidings on a single line railway*. Computers & Operations Research 24(3)/1997, 209-220.

[8] Kroon L.G., Dekker R., Maróti G., Retel Helmrich M.R., Vromans M.J.C.M.: *Stochastic improvement of cyclic railway timetables*. Transportation Research Part B 42(6)/2008, 553–570.

[9] Lee Y., Chen CY.: *A heuristic for the train pathing and timetabling problem*. Transportation Research Part B, 43/2009, 837-581.

[10] Peeters L.: *Cyclic Railway Timetable Optimization.* PhD thesis, Erasmus University of Rotterdam, 2003.

[11] Rychlewski J., Plucińska E.: *Analysis of the technical infrastructure and railway traffic for the initial phase of the Poznań Metropolitan Railway project*. Poznań Metropolis Association, 2015 (in Polish).

[12] Rychlewski J.: *Adjusting the passenger rail traffic on the lines connecting Poznań with Wągrowiec. Materials of the 5th Conference of Science & Technology "Transport and sustainable development"*, Poznań 17-19 may 2005, 177-190 (in Polish).

[13] Serafini P., Ukovich W.: *A mathematical model for periodic event scheduling problems*. SIAM Journal on Discrete Mathematics 2/1989, 550-581.

[14] Shih M.Ch., Lai Y.Ch., Dick T., Wu M.H.: *Optimization of siding location for single-track lines*. Transportation Research Record: Journal of the Transportation Research Board 2448/2014, 71-79.

[15] *Transport Development Strategy until 2020 (with outlook to 2023)*. Ministry of Transport, Construction and Maritime Economy, Warsaw 2013 (in Polish).

[16] Szpigel B.: *Optimal train scheduling on a single line railway*. Operations Research 72/1973, 344-351.

[17] *Transport white paper – roadmap to a single European transport area – towards a competitive and resource efficient transport system*. European Commision, COM(2011) 144 final, Brussels, March 28.

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PRZEBUDOWA UKŁADÓW TOROWYCH W CELU DOSTOSOWANIA JEDNOTOROWEJ LINII KOLEJOWEJ DO ZWIĘKSZONEGO OBCIĄŻENIA RUCHEM

Streszczenie

Artykuł prezentuje wykorzystanie metody optymalizacyjnej do projektowania lokalizacji i układu mijanek na linii jednotorowej w celu jej dostosowania do obciążenia ruchem pociągów. Zaprezentowano model optymalizacyjny i pokazano sposób uwzględnienia w ograniczeniach modelu charakterystyk układu torowego. Na przykładzie prostych analiz linii kolejowej nr 356 na odcinku Poznań Wschód –Wągrowiec wykazano możliwość praktycznego wykorzystania metody do przystosowania infrastruktury do potrzeb ruchowych.

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