ARCHIVES OF TRANSPORT *ISSN (print):* *0866-9546*
Volume 76, Issue 4, 2025 ***e-ISSN (online):*** *2300-8830*
DOI: *10.61089/aot2025.xvewz014*

APPLICATION OF RAILWAY MICROSIMULATION MODELS TO EVALUATE INVESTMENT STRATEGIES FOR SINGLE-TRACK RAILWAY LINES

Piotr FRANKE-WĄSOWSKI[1], Bálint CSONKA[2], Kacper Krzysztof KLITOŃCZYK[3], Jolanta ŻAK[4]

[1, 3, 4] Faculty of Transport, Warsaw University of Technology, Warsaw, Poland

[2] Budapest University of Technology and Economics, Budapest, Hungary

Abstract:

Railway transport in Europe is currently experiencing a surge, driven by sustainable development strategies. However, rising demand poses significant challenges for infrastructure managers, particularly regarding single-track regional lines, which often constitute system bottlenecks. This article presents a methodology for evaluating and selecting optimal infrastructure investment variants using dynamic microsimulation, addressing the problem of limited capacity and traffic instability on single-track sections. The study utilises OpenTrack software to conduct stochastic microsimulations of railway traffic. The research focuses on a case study of the Poznań – Piła railway line (No. 354) in Poland. Six infrastructure variants were defined and analysed, ranging from the "do-nothing" base scenario, through the construction of passing loops and partial double-tracking, to full double-tracking. These variants were tested under two operational scenarios: a standard periodic timetable and an intensified high-frequency timetable (with a 30-minute interval), applying random primary delays to assess system resilience. Key performance indicators included secondary delays, infrastructure occupation, and delay dispersion. The simulation results demonstrate that the base variant is highly unstable and prone to delay propagation. The study revealed that targeted point investments, such as a strategically located passing loop, can effectively reduce secondary delays by approximately 50% under moderate traffic conditions, offering a high cost-benefit ratio. However, for high-frequency services, partial double-tracking proved insufficient, as it merely shifted bottlenecks to the remaining single-track sections rather than eliminating them. Only the full double-tracking variant guaranteed system stability and reliability under heavy traffic load. The research confirms that microsimulation is an indispensable tool in the investment decision-making process, enabling the identification of potential bottlenecks that static methods often fail to capture. The findings suggest that while partial modernisation is effective for immediate relief, long-term strategies for high-frequency regional connections require comprehensive infrastructure expansion. The study provides practical recommendations for planning the development of regional railway networks to ensure operational reliability.

Keywords: *railway microsimulation models, railway infrastructure, single-track line, traffic reliability*

To cite this article:

Franke-Wąsowski, P., Csonka, B., Klitończyk, K. K., Żak, J. (2025). Application of railway microsimulation models to evaluate investment strategies for single-track railway lines. Archives of Transport, 76(4), 115-136. https://doi.org/10.61089/aot2025.xvewz014

Contact:

1) piotr.franke@pw.edu.pl [https://orcid.org/0009-0004-5997-3103] – corresponding author; 2) csonka.balint@kjk.bme.hu [https://orcid.org/0000-0002-4976-8294]; 3) kacper.klitonczyk.stud@pw.edu.pl [https://orcid.org/0009-0002-2161-0724]; jolanta.zak@pw.edu.pl [https://orcid.org/0000-0002-2352-7978]

1. Introduction

Railway transport in Europe is becoming a vital element of sustainable development strategies. Rising ecological awareness, increasing urbanisation, and the strategic goals of the European Union, such as those contained in the "European Green Deal" and the "Sustainable and Smart Mobility Strategy", unequivocally indicate the necessity of increasing the share of rail in both passenger and freight markets. The growth in demand for railway services observed in recent years poses a fundamental challenge for infrastructure managers and policymakers: how to meet growing transport needs effectively, economically, and reliably. The answer to this challenge must be the thoughtful and strategic development of the railway network's capacity, which constitutes the backbone of the entire system.
This problem is particularly acute in the case of regional lines, many of which, including those in Poland, remain single-track. These often constitute bottlenecks in the transport system, limiting not only the number of trains that can be run but also negatively affecting punctuality and the network's resilience to disruptions. Increasing the frequency of trains on such lines leads to the rapid exhaustion of capacity reserves, meaning that even a minor delay of a single train can have a cascading effect on the movement of others. In this situation, infrastructural investments become necessary, ranging from the construction of additional passing loops and station modernisation to the addition of a second track on the most heavily burdened sections. However, each of these actions involves a different scope, cost, and potential effect.
Simultaneously, budget constraints force the rationalisation of the decision-making process. Concern for the efficiency of public spending means that merely identifying an investment need is no longer sufficient; a thorough analysis and comparison of various implementation scenarios is essential. The selection of the optimal investment variant must be based on objective, measurable criteria that consider both the improvement of traffic parameters and the life cycle costs (LCC) of the investment, as well as the benefits for passengers and operators. Traditional analytical methods, often based on static calculations, may prove insufficient to capture the complex and dynamic nature of railway traffic, especially under conditions of network saturation.
For this reason, microsimulation models are a crucial tool. They enable the creation of a dynamic, digital representation of the railway network, including its infrastructure, control systems, and planned timetable. By simulating the movement of each train individually, considering its traction characteristics and mutual interactions, it is possible to precisely examine the functioning of the line under various expansion, reconstruction, and modernisation variants. Microsimulation analysis enables not only the assessment of capacity but also the testing of the system's resilience to delays, identifying potential traffic conflicts, and quantifying the impact of planned infrastructural changes on travel time, punctuality, and traffic flow. It thus becomes invaluable support in the process of making strategic investment decisions.
This article presents the practical application of microsimulation techniques for evaluating and selecting investment variants, using the example of a regional single-track railway line. The paper presents a research methodology based on the use of specialised software for railway traffic modelling. Based on a case study of the Poznań – Piła line in Poland, a comparative analysis of several modernisation scenarios was performed, ranging from the "do-nothing" variant to the expansion of point and linear infrastructure.
The article's structure includes a literature review, a description of the methodology and research tools, a characterisation of the case study, and a presentation of simulation results along with their interpretation. The study closes with conclusions and recommendations regarding railway infrastructure development planning.

2. Literature review

2.1. Challenges associated with infrastructure investments on single-track lines

The analysis and evaluation of investment variants in railway infrastructure is a complex process requiring the application of advanced analytical, optimisation, and simulation methods (Wojnar et al., 2022; Nikolayzik et al., 2024). It gains particular importance in the context of single-track lines, which, due to their operational specificity, constitute one of the most significant challenges for modern railway systems. Their fundamental limitation stems from the necessity of crossing and overtaking trains at strictly defined operational points, such as stations or passing loops. This fundamental constraint makes these lines particularly susceptible to the formation of bottlenecks, the identification of which is essential for capacity improvement (Hong, 2023). They are also characterised by lower resilience to disruptions compared to double-track lines (Sogin et al., 2013).

A significant bottleneck, identified in numerous studies, is the point infrastructure itself used for train handling. An insufficient number of passing loops or their non-optimal spacing along the route significantly limits flexibility and the maximum number of trains that can service the line (Shih et al., 2014). An equally important problem, especially in the context of freight transport development, is the insufficient length of additional tracks (sidings) at stations and passing loops. As indicated by authors (Dick et al.,2019; Gołębiowski, 2019), operating trains that exceed available station track lengths or platform edges leads to significant delays and operational complications, necessitating costly management strategies or investments in infrastructure expansion.

The heterogeneity of railway traffic further exacerbates the capacity problem. Simultaneous handling of passenger and freight trains on the same limited infrastructure generates numerous conflicts. Differences in operational characteristics, such as speeds, priorities, acceleration, and braking times, lead to an asymmetric distribution of delays and significant variance in travel times (Dick et al., 2019; Dingler et al., 2014). The inclusion of these characteristics in analytical models is crucial for accurately estimating capacity and energy efficiency under various operating conditions (Rahoma et al., 2021; Gołębiowski et al., 2021). Consequently, even a minor, initial delay of a single train (e.g., freight) can propagate in a cascading manner throughout the network, affecting the punctuality of higher-priority passenger trains. This low system resilience makes precise timetable planning with appropriate headways necessary (Jamili, 2018). The complexity of real-time traffic management prompts researchers to seek solutions utilising, among others, machine learning for dynamic train rescheduling and conflict resolution (Kovari et al., 2023; Matowicki et al., 2025).

In the subject literature, infrastructure expansion is indicated as one of the most effective remedial methods, including the construction of new passing loops, extending existing ones, or, as a target solution, the addition of a second track (Shih et al., 2014). Strategic planning in this area is crucial, particularly when combined with the implementation of integrated periodic timetables to remove network bottlenecks (Franke, 2023). However, due to the high costs of full double-tracking, increasing attention is being paid to the analysis of so-called partial double-tracking. Such a strategy enables a significant improvement in capacity and service quality with minimal investment outlays, provided that the sections where expansion will yield the most essential operational benefits are precisely identified (Bažant et al., 2020). Furthermore, a meticulous assessment of infrastructure conditions and maintenance costs is vital for the rational selection of these modernisation variants (Gołębiowski et al., 2020). The identification of these critical segments and the evaluation of the actual gain from various modernisation variants, however, require the application of tools capable of detailed modelling of traffic dynamics, which goes beyond the capabilities of simple analytical models (Bešinović et al., 2018; D'Acierno et al., 2019).

2.2. Approaches to planning and evaluating investment variants

Following the identification of key challenges and bottlenecks, the next stage in the planning process involves selecting the most effective investment strategy supported by a wide range of decision-support methods (Jacyna, 2022). This decision is rarely straightforward and requires a systematic comparison of various modernisation variants. In the scientific literature and design practice, two primary methodological streams have emerged for evaluating infrastructure projects: Cost-Benefit Analysis (CBA) and Multi-Criteria Decision Analysis (MCDA).

Cost-Benefit Analysis (CBA) is a traditional and widely accepted assessment tool that focuses on a project's economic efficiency (Penyalver et al., 2018; Mátrai, 2013). Its foundation lies in comparing the discounted investment costs with total monetised benefits, such as passenger time savings or reduced operational costs for operators. Despite its popularity, this method has significant limitations. Critics argue that CBA often results in an incomplete evaluation, as it is unable to adequately capture and value non-economic aspects, such as environmental impact, social cohesion, safety, or strategic political goals (Dean et al., 2019; Tudela et al., 2006).

Multi-Criteria Decision Analysis (MCDA) methods serve as a response to these limitations. They enable the evaluation of investment variants based on a wide range of criteria, including both quantitative (measurable) and qualitative (descriptive) factors, which reflect project complexity and the diverse expectations of stakeholders (Aoun et al., 2021; Hickman et al., 2018). Within the MCDA framework, several specific techniques have been developed for the systematic evaluation and prioritisation of investments, ranging from the modernisation of traffic control systems and intermodal terminal layouts (Szczepański et al., 2021) to the selection of an optimal investment portfolio (Del Caro Daher et al.,2020; Yücel et al., 2019; Panek et al., 2025).

Comparative studies indicate that project rankings obtained using CBA and MCDA do not always converge. This stems from the fact that MCDA, by accounting for a broader context, may better reflect the final decisions made by public authorities (Khaki et al., 2011). For this reason, modern approaches to investment evaluation often advocate for the integration of both methods. Such a hybrid approach allows for utilising the economic rigour of CBA within the flexible structure of multi-criteria analysis, thereby enhancing the transparency and comprehensiveness of the decision-making process (Gühnemann et al., 2012; Florczak-Strama et al., 2016). Moreover, increasing emphasis is being placed on the participatory nature of the assessment by involving representatives of various stakeholder groups in the process of defining criteria and their weights, which further legitimises the final selection (Cornet et al., 2018). This process must also account for risk assessment in traffic planning, including the probability of uncertain phenomena affecting safety and operations (Gołębiowski, 2022).

2.3. Methods of railway capacity and traffic flow analysis

One of the most critical technical parameters determining the efficiency of planned railway investments is capacity. In the scientific literature, it is defined as the maximum number of trains that can be operated through a specific infrastructure element (such as a line or station) within a given time frame while maintaining set service quality standards. Two prominent families of methods are used for its estimation: analytical and simulation methods, which differ in their level of detail, scope of application, and the accuracy of obtained results (Khadem et al., 2022).

Among analytical methods, the method described in Code 406 of the International Union of Railways (UIC) is of fundamental importance. Its operation is based on the concept of timetable compression, which involves removing all buffer times to determine how densely train paths can be arranged on the graphical timetable (Landex et al., 2008; Lindner, 2011). This method is widely used by infrastructure managers in Europe to assess capacity utilisation, both on railway lines and, to a certain extent, in stations (Weik et al., 2020). Despite its widespread application, including on high-speed lines, research indicates its limitations (Ľupták et al., 2025). The standard implementation of UIC 406 does not fully account for dynamic network effects and complex traffic dependencies within large railway nodes, which may lead to an underestimation of actual constraints (Lindner, 2009). In response to these shortcomings, researchers propose extensions to the method, including integration with operational and economic factors, as well as mathematical models that investigate the effect of route parameters on average speed (Krzykawski et al., 2024). Additionally, they suggest adapting the method for strategic planning on a network-wide scale (Khadem et al., 2010; Grimm, 2012).

The second group consists of simulation methods, which allow for overcoming the static nature of analytical approaches. They utilise specialised software, such as OpenTrack or RailSys programs, to create dynamic, microscopic models of the railway network. These tools, by simulating the movement of each train while considering its traction parameters, infrastructure characteristics, and control system operations, enable a highly detailed analysis of traffic processes (Wang et al., 2014; Pascariu et al., 2021). Case studies, including one for the Italian Rome–Florence high-speed line, demonstrate that simulations enable the precise identification of bottlenecks and the testing of various operational scenarios under near-real-world conditions (Prencipe et al., 2018). Modern approaches often integrate analytical and simulation methods, for example, by combining UIC 406 principles with the simulation of advanced control systems, which allows for a comprehensive and reliable assessment of capacity in the context of planned investments (Wang et al., 2015).

2.4. Application of microsimulation tools in railway transport planning

Analytical methods, despite their utility, encounter limitations in analysing complex and dynamic traffic phenomena. This gap is successfully filled by microsimulation tools, which currently constitute the standard in detailed planning and performance evaluation of rail transport systems, including shunting stations and intermodal terminals (Szczepański et al., 2023; Nehring et al., 2021). Software such as OpenTrack or RailSys enables an in-depth analysis of the impact of investments on key indicators, including punctuality, reliability, and capacity (Huan et al., 2022; Rakhmangulov et al., 2017).

These tools enable the creation of detailed digital models that represent not only the infrastructure but also traffic management rules, rolling stock characteristics, and the current timetable. Thanks to this, it is possible to simulate various operational scenarios, including timetable optimisation to improve punctuality and testing traffic management strategies under disrupted conditions (Huang et al., 2022).

However, the most crucial advantage of microsimulation in the context of this study is the ability to test investment variants before incurring any financial costs. It is possible to precisely examine how changes in a station's track layout, the construction of a passing loop, or the modernisation of signalling and control systems affect line capacity or its resilience to delays (Dunbar et al., 2017; Arslan et al., 2021). Research shows that simulations not only verify the validity of a given solution but also optimise its parameters, such as the location and length of a new double-track section. The application of microsimulation thus allows for making informed, data-driven decisions that maximise the return on investment, which is particularly relevant given limited public funds. In more advanced applications, simulation models are integrated with optimisation algorithms or combined with macroscopic models, allowing for comprehensive traffic management on a network-wide scale (Licciardello et al., 2020; Kettner et al., 2004).

3. Research problem and methodology

3.1. Formulation of the research problem

The fundamental problem constituting the starting point for this research is the insufficient capacity of the single-track Poznań – Piła railway line in the context of the forecasted growth in transport demand. The existing infrastructure, characterised by long single-track sections, constitutes a bottleneck that limits the possibility of introducing a competitive, cyclical service offer and negatively affects the punctuality and stability of railway traffic. This necessitates the consideration of investments in line expansion.

In view of the above, the following main research question was formulated: How do selected point and segment infrastructure investments affect the improvement of capacity and traffic reliability on the Poznań – Piła railway line?

Furthermore, to provide the study with a broader, applied nature, a generalised problem was also defined: How to identify the optimal investment strategy (sequence and scope of expansion) as a function of varying traffic load and structure?

3.2. Criteria for evaluating investment variants

To conduct an objective evaluation of the analysed infrastructure variants, a set of evaluation indicators was defined. These were selected to reflect the most essential aspects of railway line operation from both the passenger's and the infrastructure manager's perspectives. Indicator values are derived from the aggregated results of a series of stochastic simulations performed in the OpenTrack software. The following evaluation measures were defined:

1) **Traffic Reliability and Stability – Secondary Delays**
   This is the most critical indicator for assessing system resilience. It measures the ability of a given infrastructure (with a specific timetable) to absorb and dampen random disturbances. Unlike primary delays (introduced into the model), secondary delays arise from interactions between trains and capacity constraints. The indicator is calculated as the arithmetic mean of the difference between a train's delay at the final station and its initial delay. A negative value indicates that the system possesses reserves capable of neutralising disturbances, whereas a positive value indicates that it amplifies and propagates delays.
2) **Capacity Reserves (Infrastructure Occupation)**
   This is a technical indicator that allows for the empirical identification and quantification of the load on the network's most critical elements. It is measured as the average percentage occupation of the most heavily burdened single-track section

within the analysed time horizon. This indicator allows for verifying whether a bottleneck has been eliminated or merely shifted to another location.

3) **Investment Outlay – Length of Built Tracks**
For a simplified assessment of the economic efficiency of individual variants, the length of the newly built track, expressed in kilometres, was adopted as a comparative cost indicator. This is an objective measure which, assuming similar terrain conditions, accurately reflects the scale and proportions of financial outlays for individual linear expansion variants.

3.3. Objectives, assumptions and limitations of the analysis

The main methodological objective of this work is to conduct a multi-stage, comparative evaluation of infrastructure modernisation variants, enabling the identification of the optimal investment strategy.
To ensure the reproducibility of the research and to clearly define its scope, the following assumptions and limitations were adopted:

- The analysis does not account for the detailed maintenance costs of the new infrastructure, focusing instead on investment costs represented by the length of the built track.
- It was assumed that the rolling stock (its traction parameters), as well as general rules and traffic control systems (apart from the logic resulting from the change in track layout), remain unchanged across all variants.
- The modelling considers the impact of the human factor (e.g., drivers' driving style) to a limited extent by defining a Performance Distribution assigned to individual train categories. These assumptions remain constant across all investment and traffic variants.
- Two separate timetables were subjected to analysis (TV-1 and TV-2). In accordance with the adopted methodology, each of these timetables was identical for all infrastructure variants tested in each research stage, ensuring full comparability of results.

3.4. Research stages and methods used

The research process was designed as a multi-stage analytical procedure allowing for systematic and objective comparison of the scenarios under consideration. This methodology integrates the process of model construction and calibration, scenario definition, and two main phases of stochastic simulation, followed by a final analysis. The entire process is presented in Figure 1.

4. Research tool

4.1. Characteristics of the OpenTrack programme

In this study, OpenTrack software was utilised to evaluate investment variants on the railway line. It is a specialised tool designed for the microscopic and stochastic simulation of railway systems. Originally developed at the Swiss Federal Institute of Technology in Zurich (ETH Zürich), it is currently maintained and further developed by OpenTrack Railway Technology Ltd. Its primary purpose is to support planning processes, capacity analysis, timetable stability assessment, and the evaluation of investment projects.
As a microsimulation tool, OpenTrack models the movement of each train as a distinct object, accounting for its individual dynamic parameters as well as interactions with the infrastructure and other trains on a continuous time basis. Thanks to its capability of introducing random disturbances, the software enables not only the analysis of ideal scenarios but also the examination of the railway system's resilience and reliability under near-real-world conditions.

4.2. Functionalities relevant to infrastructure planning

OpenTrack offers a range of modules and functionalities that are directly applicable to the planning and evaluation of infrastructure investments. The general diagram of the programme's operation and the links between the individual modules are presented in Figure 2.
For this study, the following program modules were of primary importance:

- **Infrastructure Editor**: Enables detailed representation of the railway line geometry, including track alignment, turnouts, crossings, as well as the longitudinal profile (gradients) and cross section (superelevation). It enables the precise placement of signals, boards, indicators, and other components of the railway traffic control system. This is an essential element for the correct modelling of signal dependencies and line block systems.

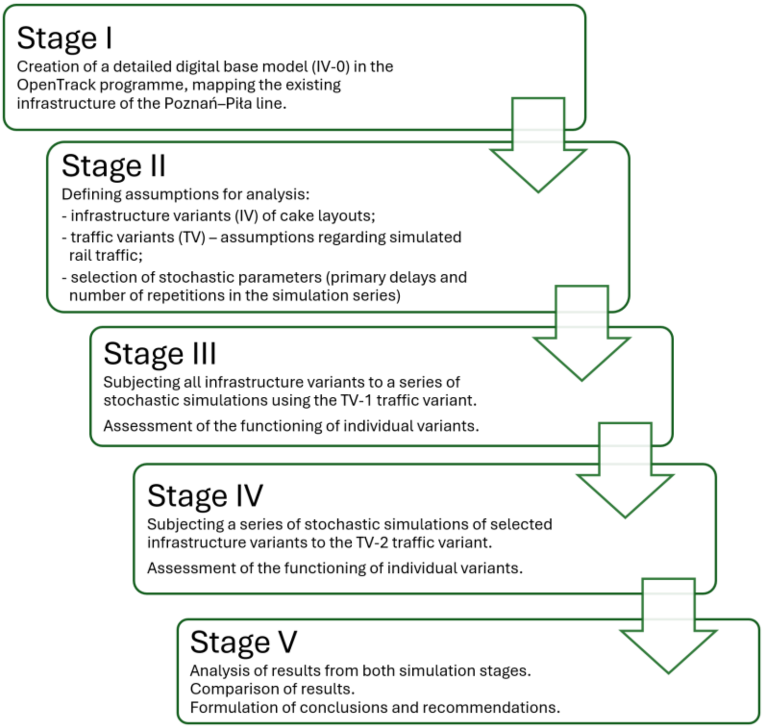

Fig. 1. Methodology of the analysis

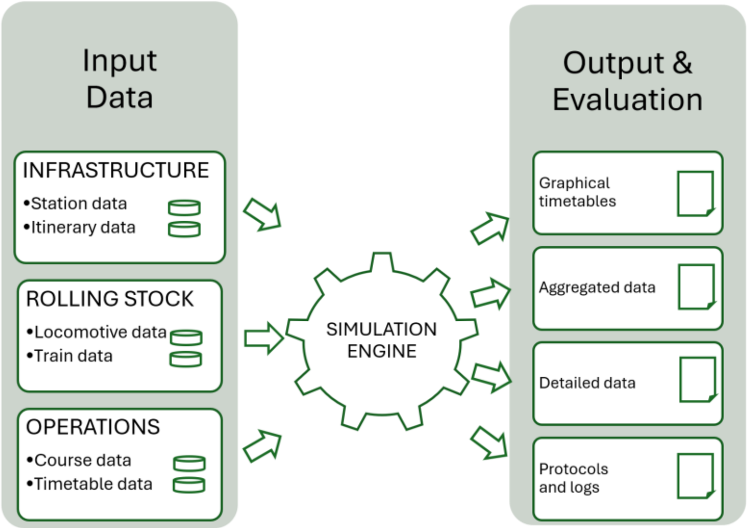

Fig. 2. Diagram of the Opentrack programme's operation

- **Timetable Editor:** Used for inputting the planned timetable, defining train paths, departure and arrival times, commercial stops, and minimum dwell times.
- **Simulation Engine**: Constitutes the computational module of the program, which, based on the input data regarding infrastructure, rolling stock, and the timetable, calculates train movements, identifies potential conflicts, calculates delays, and gathers detailed statistical data regarding the simulation run.

The ability to modify the infrastructure model, for example, by adding a new track, changing a signal's location, or introducing a double-track section, allows for the creation and comparison of various investment variants.

4.3. Railway network modelling

The modelling process in OpenTrack involves creating a so-called digital shadow of the analysed section of the railway network. The work begins by defining the main axial points (kilometrage), on which individual track elements (so-called edges) and nodes (e.g., turnouts) are then placed. Each track element has defined attributes, including length and the maximum permitted speed. Rail traffic control systems are also modelled, consisting of the placement of signals and their interconnection. The programme also allows for the definition of complex station layouts, which is essential for detailed analyses of railway station operations.

4.4. Application of OpenTrack in capacity and punctuality analysis

Once the model has been built and the timetable entered, OpenTrack is used as an analytical tool. Conducting a series of simulations for a given investment option allows for the collection of a rich set of evaluation indicators. In the context of capacity analysis, the programme allows verification of whether a given timetable is feasible on the assumed infrastructure and identifies areas of conflict and delays. By gradually expanding the timetable, it is possible to determine the maximum capacity of the line. In turn, punctuality and reliability analysis are based on stochastic simulations. The programme randomly generates initial delays for trains or equipment failures and then observes how these disruptions propagate throughout the network. The results, presented in the form of traffic graphs, secondary delay statistics or reports on the utilisation of individual infrastructure elements, provide an objective basis for comparing the analysed investment options in terms of their operational efficiency and resilience to disruptions.

5. Case study – Poznań–Piła railway line

5.1. Characteristics and history of the analysed section

The subject of this scientific article is railway line No. 354, located entirely within the boundaries of the Greater Poland Voivodeship, connecting the Poznań Główny branch post (PoD) with the Piła Główna station. The infrastructure manager of the line is PKP Polskie Linie Kolejowe S.A. The railway line is electrified along its entire length with 3 kV DC (direct current) and features a standard gauge of 1435 mm.

The history of the line dates back to the period of Poland's partitions. The construction of the line connecting the then Prussian Eastern Railway with the city of Poznań was completed on May 15, 1879. After the end of World War I, the line was transferred to Polish administration. In 1922, the second track was dismantled, along with the section from the Piła Kalina stop to the Dziembówko station. This section was subsequently rebuilt during the German occupation during World War II. The electrification of the line took place in 1990. In 2017, the line underwent extensive revitalisation, which involved, among other things, modifying track alignment to achieve a maximum speed of 120 km/h, as well as modernising existing and constructing new passenger stops and stations. In 2019, a contract was signed for a feasibility study regarding the addition of a 2-kilometre second track section to the Oborniki Wielkopolskie station (Wikipedia, 2025).

5.2. Infrastructural constraints

Railway line No. 354, with a total length of 92.985 km, is characterised by a variable number of tracks on the routes, which significantly affects train traffic conditions. Analysing its track layout, three sections can be distinguished:

- Double-track section: Poznań POD (km -0.237) – Oborniki Wielkopolskie Most (km 25.395),
- Single-track section: Oborniki Wielkopolskie Most – Dziembówko (km 82.098),
- Double-track section: Dziembówko – Piła Główna (km 92.538).

The list of operating points on railway line No. 354 is presented in Table 1.

Table 1. List of operational points on railway line No. 354. Source: own elaboration based on PKP PLK data

Name of point	Type of point	Kilometres
Poznań PoD	Branch post	0.001
Poznań Podolany	Passengers stop	3.261
Poznań Strzeszyn	Passengers stop	5.000
Suchy Las	Branch post	6.300
Złotniki Grzybowe	Passengers stop	8.157
Złotniki	Station	9.525
Złotkowo	Passengers stop	11.250
Golęczewo	Passengers stop	13.907
Chludowo	Passengers stop	16.747
Wargowo	Station	19.424
Bogdanowo	Passengers stop	24.228
Oborniki Wielkopolskie Most	Branch post	25.395
Oborniki Wielkopolskie Miasto	Passengers stop	26.331
Oborniki Wielkopolskie	Station	27.788
Rożnowo	Branch post	31.540
Parkowo	Passengers stop	35.887
Rogoźno Wielkopolskie	Station	42.514
Tarnowo Rogozińskie	Passengers stop	48.047
Sokołowo Budzyńskie	Passengers stop	51.912
Budzyń	Station	58.169
Ostrówki koło Chodzieży	Passengers stop	63.337
Chodzież	Station	70.439
Milcz	Passengers stop	77.356
Dziembówko	Station	82.098
Piła Kalina	Passengers stop	85.802
Piła Główna	Station	92.538

A single-track section from the Oborniki Wielkopolskie Most signal box (km 25.395) to the Dziembówko station (km 82.098) was selected for simulation analyses. The track layout is shown in Figure 3 and in the view from the Opentrack programme (Fig. 4).

There are four railway stations on the single-track section where trains can cross and overtake each other:

– Oborniki Wielkopolskie (27.788 km)
– Rogoźno Wielkopolskie (42.514 km)
– Budzyń (58.169 km)
– Chodzież (70.439 km)

5.3. Description of the analysed traffic variants

The basis for the simulation analysis is the definition of reliable traffic variants (timetables) that will be used to load the tested infrastructure variants. In this study, a representative time interval was selected and simplifications applied to the service model to ensure the objectivity and comparability of the variants.

A 4-hour afternoon peak period (14:00 – 18:00) was selected as representative for the following reasons:

- It covers a period of high, mixed traffic (regional, long-distance and freight passenger traffic), generating numerous interactions and conflicts.
- It is long enough to allow trains with the longest journey times (including freight trains) to pass through the entire section of the railway line under analysis.
- It allows the phenomenon of propagation and cascading of secondary delays to be observed, which is not possible in shorter time windows.
- It ensures an acceptable calculation time for a series of stochastic simulations.

The actual timetable (Table 2) is characterised by high irregularity and a significant number of shortened journeys (starting or ending at intermediate stations, e.g. Oborniki or Rogoźno).

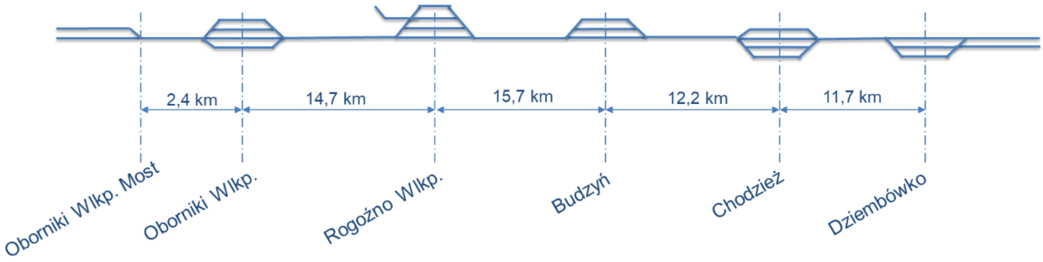

Fig. 3. Diagram of the track layout of a selected section of railway line No. 354

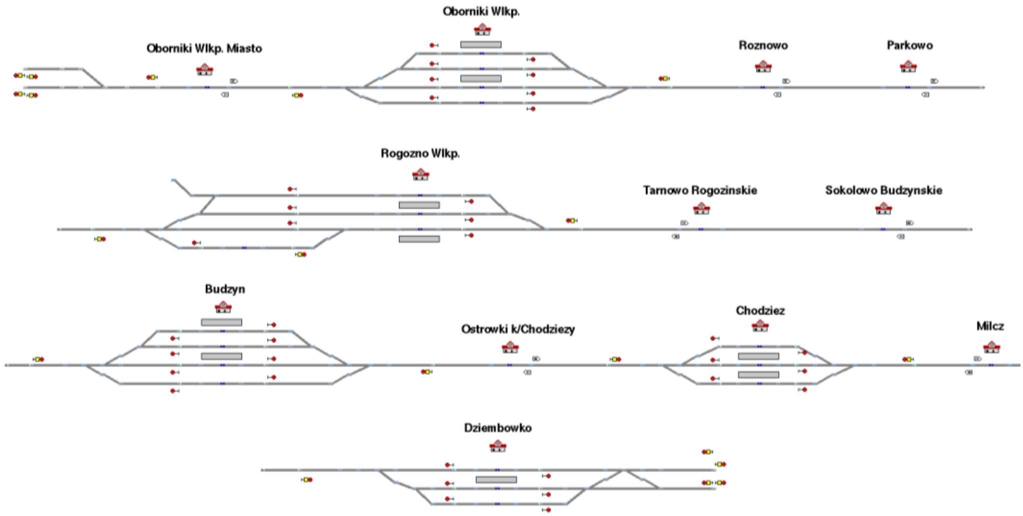

Fig. 4. Diagram of the track layout of the modelled section of railway line No. 354 in the Opentrack programme

Table 2. Number of trains running on the analysed section per day (2025 timetable). Source: own elaboration based on PKP PLK data

Train type	Entire route Oborniki – Dziembówko	Shortened route (starts/ends in Oborniki or Rogoźno)	Total
Regional	30	16	46
Long-distance	16	0	16
Freight	10	2	12
Total	56	18	74

The aim of this study is not to reconstruct historical punctuality but to systematically compare the potential and resilience of different infrastructure variants. To ensure the objectivity of this comparison, it is necessary to eliminate operational variables that may influence the results. Therefore, the following simplifying assumptions were made for all analysed scenarios (TV-1, TV-2):

- All trains run on the entire analysed section (Oborniki – Dziembówko).
- Shortened routes, which would disrupt cyclicality and make it difficult to compare the load on individual routes, have been abandoned.

Thanks to this approach, each infrastructure variant is tested under identical, repeatable traffic conditions, allowing for the objective isolation of the impact of the infrastructure itself on the results.

For the analysis, three separate traffic variants (timetables) were defined, representing the current and future possible models of line operation, which are presented in Table 3.

Table 3. Assumed number of trains in the analysed 4-hour simulation period (14:00-18:00)

Train type	Number of trains in 4 hours		
	TV-0	TV-1	TV-2
Regional	16	8	16
Long-distance	4	4	4
Freight	2	2	4
Total	22	14	24
Comments	*Uneven intervals between regional trains, some with reduced service.*	*60-minute intervals in regional traffic in both directions.*	*30-minute intervals in regional traffic in both directions.*

Variant TV-0 (current situation) – This variant reflects the current irregular traffic during the afternoon rush hour (Table 3). It serves as a reference point for the other variants. It is characterised by uneven intervals between trains.

Variant TV-1 (60-minute interval in regional traffic) – This is the first target variant, representing the introduction of a cyclical transport offer (hourly interval) that is attractive to passengers. Despite the potentially lower total number of trains than in the peak of variant TV-0, this variant is more demanding for single-track infrastructure. A fixed, cyclical timetable means that train meeting points (crossings) occur regularly at the same, strictly defined locations. This variant tests the infrastructure's ability to handle regular, predictable traffic. The traffic graph for variants IV-0 and TV-1 is shown in Fig. 5.

Variant TV-2 (30-minute interval in regional traffic) – This variant represents a prospective timetable. Intensive regional traffic (30-minute interval) combined with increased freight traffic creates a significant number of potential conflicts. It is practically impossible to implement this timetable on the existing infrastructure (IV-0). This scenario was used to simulate only selected modernisation variants, allowing for a precise assessment of their capacity reserves (Fig. 6).

5.4. Description of the analysed investment variants

To conduct a comparative analysis, six infrastructure variants (IV) were defined, reflecting various strategies and scales of modernisation for the analysed railway line. The total length of the newly constructed open track, expressed in kilometres, was adopted as the comparative indicator of investment outlays for each variant. The defined variants are presented in Table 4.

Table 4. Description of investment variants

Name	Description	Length of new track
IV-0	Base variant (existing state)	-
IV-1	Construction of a new passing loop in the Sokołowo Budzyńskie stop	1.5 km
IV-2	Addition of a second track on the Rogoźno – Budzyń section	15.7 km
IV-3	Addition of a second track on the Oborniki – Rogoźno section	14.7 km
IV-4	Addition of a second track on the Oborniki – Budzyń sections	30.4 km
IV-5	Full double-tracking (Oborniki Most – Dziembówko)	56.7 km

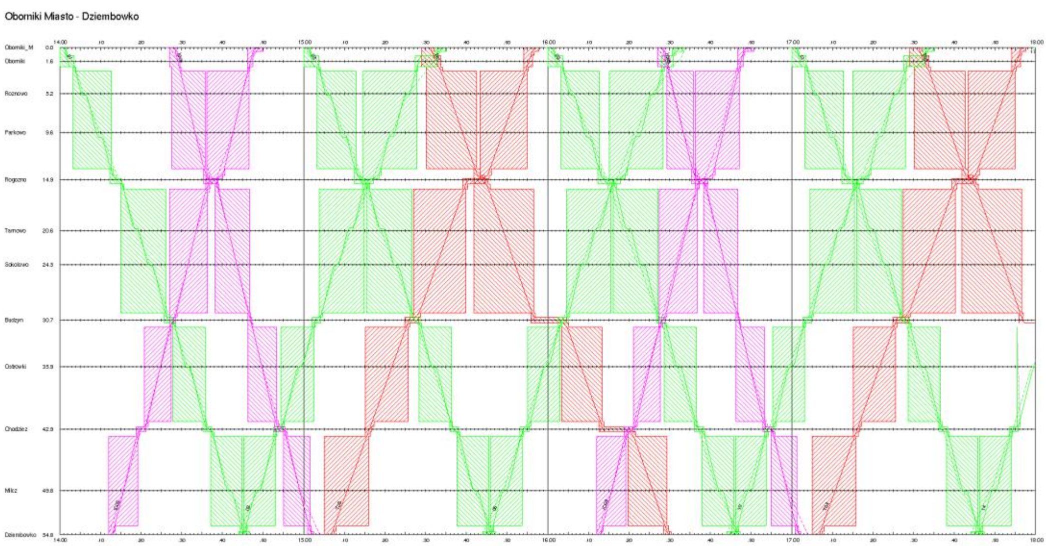

Fig. 5. Traffic chart for the assumed timetable for variants IV-0 and TV-1

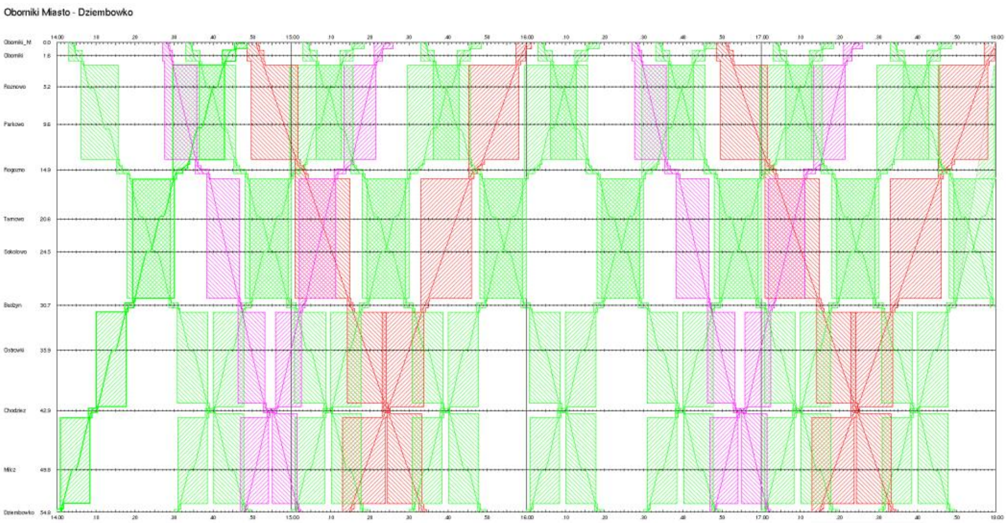

Fig. 6. Traffic chart for the assumed timetable for variants IV-5 and TV-2

5.5. Determining the number of repetitions in a simulation series

To ensure the reliability of stochastic studies, it is necessary to select an appropriate number of repetitions (N) to achieve statistical stability of the results. A purely mathematical approach, aiming for the convergence of indicators (such as secondary delay), often leads to an unjustified increase in calculation time, as fluctuations of a few seconds are insignificant in the context of the entire system's scale.

This paper adopts an engineering approach, which consists of finding the stabilisation point of the leading operational indicators. To this end, a series of N = 200 simulations was carried out for the base variant (IV-0), analysing selected statistical measures (Fig. 7).

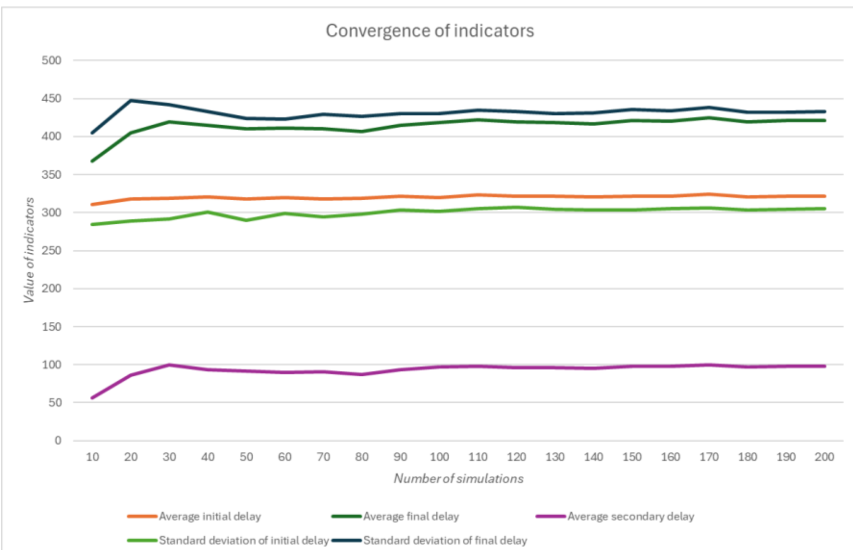

Fig. 7. Stabilisation of selected indicators depending on the number of simulations

Considering the achievement of stability of selected measures for all relevant variant analyses in this study, N = 100 repetitions was adopted as a value that fully guarantees the reliability of the results while optimising the analysis time.

5.6. Determination of primary delay parameters

Stochastic analysis was used to assess the reliability and resilience of the analysed infrastructure variants. This requires the definition of realistic random parameters for initial delays with which trains enter the analysed section.

An analysis of empirical data from the Railway Transport Office (UTK) for 2024, presented in Tables 5 and 6, shows that on the analysed section of the line, the punctuality rate for long-distance (74.46%) and regional trains (89.01%) is significantly lower than the national average (91.64% in 2024). This proves that the current single-track infrastructure is highly susceptible to generating and propagating delays.

As the aim of this study is not to simulate historical delays, but to objectively compare the potential and resilience of new infrastructure variants (IV) when operating new, cyclical timetables (TV-1, TV-2), the use of historical, very high delay values (e.g. an average of 29 minutes for long-distance trains) resulting from the current inefficiency of the network does not seem appropriate. For this reason, this study adopts an approach of testing the resilience of variants against two controlled disruption scenarios representing a stably managed railway network:

1) **Scenario A**: average initial delay of 300 s (5 minutes). This value was chosen because 5 minutes is the standard international punctuality threshold. This scenario represents typical daily operational problems (minor breakdowns, extended stops) in a properly functioning railway system.
2) **Scenario B**: average primary delay of 600 s (10 minutes). This scenario represents a more significant, but still common, disruption (e.g., rolling stock failure, malfunction of rail traffic control systems).

To ensure consistency and repeatability of the analysis, an identical implementation method in OpenTrack was adopted for all train categories in both disruption scenarios. It was assumed that all trains entering the analysed section receive a random primary delay.

Table 6. Aggregate punctuality index for the analysed section (2024). Source: own elaboration based on UTK data

Parameters	Total	
	Long-distance	Regional
Number of train stops	8 374	24 397
Number of punctual trains	6 235	21 716
Punctuality rate	74.46%	89.01%
No. of trains delayed > 5 min	2 139	2 681
Percentage of trains delayed > 5 min	25.54%	10.99%
Total delay time > 5 min	61 908	47 001
Average delay (in min)	28.94	17.53

Table 5. Punctuality statistics for Oborniki Wielkopolskie Miasto and Chodzież stations (2024). Source: Own elaboration based on UTK data

Station	Operator	Number of stops	Number of punctual trains	No. of trains delayed > 5 min	Total delay time > 5 min	Average delay (in min)
Oborniki Wielkopolskie Miasto	PKP INTERCITY	4173	3159	1014	31183	30.75
	POLREGIO	3776	3101	675	12262	18.17
	Koleje Wielkopolskie	10282	9627	655	12143	18.54
	Total	**18231**	**15887**	**2344**	**55588**	**23.72**
Chodzież	PKP INTERCITY	4201	3076	1125	30725	27.31
	POLREGIO	3775	2955	820	13517	16.48
	Koleje Wielkopolskie	6564	6033	531	9079	17.10
	Total	**14540**	**12064**	**2476**	**53321**	**21.54**

6. Microsimulation results and their interpretation

6.1. Comparison of infrastructure variants for traffic variant TV-1

This chapter presents and interprets the results of a series of stochastic simulations (N = 100) for the TV-1 traffic variant (hourly cycle) and for all defined infrastructure variants (IV). The analysis was carried out in two disruption scenarios: scenario A (initial delay of 300 seconds) and scenario B (initial delay of 600 seconds). The quantitative results of the simulations are summarised in Tables 7 and 8.

The analysis of **secondary delays** (Tables 7 and 8) reveals significant differences in the performance of individual variants. The base variant (IV-0) is an unstable solution – in Scenario A, it adds an average of 106 seconds of delay to each train, while in the significant disruption scenario (Scenario B), this delay rises to as much as 193 seconds. The comparison of investments in variant IV-2 (construction of a second track on the Rogoźno–Budzyń section) and IV-3 (construction of a second track on the Oborniki–Rogoźno section) provides fascinating insights. Despite the similar section length, variant IV-2 reduces secondary delays by 94 s relative to the base variant, whereas variant IV-3 proves to be significantly less effective, reducing secondary delays by only 36 s. This demonstrates that the choice of modernisation location is critical for its success. Variant IV-4 actively dampens disturbances in Scenario A (-52 s); however, in Scenario B, it reaches the limit of its capabilities (+2 s). Only the full double-tracking variant (IV-5) possesses sufficient reserves to seamlessly absorb even major disruptions in both scenarios (-154 s and -134 s, respectively).

System reliability is also measured by its predictability, as indicated by the **standard deviation of the final delay**. The lower the value of this indicator, the more consistent the travel time is for the passenger. These results correlate with the stability analysis: the base system (IV-0) is the most unpredictable, with a standard deviation of 433 s in Scenario A, rising to 699 s in Scenario B. Every effective investment improves predictability. The best variant (IV-5) significantly reduces delay dispersion, lowering the standard deviation to 314 s (in Scenario A) and 627 s (in Scenario B), which translates to a more reliable service for travellers.

In the next step, an analysis of the infrastructure load itself was performed. It allows for the empirical identification of bottlenecks and the assessment of the uniformity of line utilisation. Tables 9 and 10 compile the results of percentage occupation (Reservation [%]) for individual sections, broken down into average (Avg.) and maximum (Max.) values recorded during 100 simulation runs. To better capture the characteristics of the entire system, basic statistical measures were also calculated for each variant based on the set of average occupations of all five sections.

Table 7. Simulation results for scenario A (average initial delay of 300 s)

Infrastructure Variant (IV)	Average initial delay	Average final delay	Average secondary delay	Standard deviation of initial delay	Standard deviation of final delay
IV-0	320	427	106	302	433
IV-1	318	370	51	302	395
IV-2	319	332	12	306	378
IV-3	312	383	70	291	399
IV-4	311	260	-52	291	355
IV-5	306	152	-154	290	314

Table 8. Simulation results for scenario B (average initial delay of 600 s)

Infrastructure Variant (IV)	Average initial delay	Average final delay	Average secondary delay	Standard deviation of initial delay	Standard deviation of final delay
IV-0	625	824	193	589	699
IV-1	624	735	107	592	674
IV-2	628	708	77	596	672
IV-3	610	769	154	583	693
IV-4	609	611	2	585	658
IV-5	603	467	-134	583	627

The data presented in Table 9 allow for a precise assessment of the base state and the effects of individual modernisations. In the base variant IV-0, the system is highly unbalanced, as illustrated by the high standard deviation of section occupation (17.70%). There are two distinct bottlenecks: the Oborniki – Rogoźno section (with an average occupation rate of 62.05%) and the Rogoźno – Budzyń section (with a rate of 64.37%). These result from the length of both sections and the absence of an installed automatic line block system, which would divide the section into shorter block sections.

Variant IV-1 (construction of a passing loop) intelligently addresses the main problem, reducing the average occupation of the Rogoźno – Budzyń section by over 25 percentage points (pp) (from 64.37% to 38.71%). Nevertheless, the "bottleneck" constituted by the Oborniki – Rogoźno section, with a maximum average occupation of 56.87%, remains unresolved.

Variant IV-3 (expansion of the Oborniki – Rogoźno section) acts as its mirror image. It solves the problem in the expanded section (occupation drop to 32.93%), but the main bottleneck in this case remains the Rogoźno – Budzyń section (63.87%).

Significant improvement is brought by Variant IV-4 (expansion of both sections). It eliminates both identified bottlenecks, lowering their occupation to a stable level of approximately 33%. This causes a shift of the critical section to the Chodzież – Dziembówko section; however, its maximum average load (47.41%) is already significantly lower. The system also becomes clearly more balanced (standard deviation drops to 11.16). Variant IV-5, which provides for full double-tracking, completely resolves the capacity problem as expected. The average section load drops to a mere 24.42%, the maximum average load is only 33.06%, and the system is the most balanced (standard deviation 9.00), which testifies to immense capacity reserves.

A comparison of the results from Scenario A (Table 9) and Scenario B (Table 10) provides conclusions regarding the resilience of individual variants to increased disturbances. In variant IV-0, average section occupation values paradoxically decrease; however, an increase in maximum values can also be observed in selected periods. This likely results from low section occupation at the beginning of the simulation due to the considerable primary delays assigned to trains. However, in the latter part of the simulation, periods of very heavy traffic occur on a given section. A similar phenomenon can be observed in variants IV-2 and IV-3. Variants IV-4 and IV-5, with a larger scope of investment, also demonstrate high resilience to increased disturbances. In their case, doubling primary delays (from 300 s to 600 s) does not have a significant impact on infrastructure load. This proves that these variants possess sufficient capacity reserves to fully absorb disturbances of this scale.

Table 9. Infrastructure occupation results for timetable variant TV-1 and Scenario A (average primary delay 300 s)

	IV-0		**IV-1**		**IV-2**		**IV-3**		**IV-4**		**IV-5**	
	Reservation [%]											
Section	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**
Oborniki Miasto – Oborniki	14.80	23.15	14.34	24.26	15.84	24.50	16.06	24.89	16.71	25.53	8.32	14.48
Oborniki – Rogoźno	62.05	82.00	56.87	86.27	62.79	82.49	32.93	50.20	33.11	50.66	33.06	50.28
Rogoźno – Budzyń	64.37	86.13	38.71	61.65	33.07	51.12	63.87	85.82	32.88	51.32	32.81	50.64
Budzyń – Chodzież	46.41	66.33	44.97	69.10	46.54	65.06	45.80	65.60	46.24	66.78	23.67	39.74
Chodzież – Dziembówko	47.47	68.07	44.03	69.01	47.85	68.12	46.74	67.38	47.41	70.64	24.22	39.16
Max.	64.37	86.13	56.87	86.27	62.79	82.49	63.87	85.82	47.41	70.64	33.06	50.64
Avg.	47.02	65.14	39.78	62.06	41.22	58.26	41.08	58.78	35.27	52.99	24.42	38.86
Standard deviation	17.70	22.35	14.04	20.56	15.80	19.60	15.91	20.37	11.16	15.90	9.00	13.15

Table 10. Infrastructure occupation results for timetable variant TV-1 and Scenario B (average primary delay 600 s)

	IV-0		IV-1		IV-2		IV-3		IV-4		IV-5	
	Reservation [%]											
Section	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**
Oborniki Miasto – Oborniki	14.22	24.20	15.11	23.22	15.32	25.16	15.11	25.69	15.61	26.13	7.99	14.88
Oborniki – Rogoźno	57.01	85.35	61.08	84.30	58.88	86.07	31.19	53.52	31.77	53.91	32.28	54.16
Rogoźno – Budzyń	59.29	86.50	41.18	58.23	31.06	53.02	60.18	88.56	31.82	54.52	32.04	54.53
Budzyń – Chodzież	44.74	67.80	45.96	67.27	45.21	68.17	44.76	68.82	45.71	69.87	23.42	41.37
Chodzież – Dziembówko	44.73	68.45	47.01	69.56	45.73	68.89	43.89	67.65	45.92	69.55	23.77	40.72
Max.	59.29	86.50	61.08	84.30	58.88	86.07	60.18	88.56	45.92	69.87	32.28	54.53
Avg.	44.00	66.46	42.07	60.52	39.24	60.26	39.03	60.85	34.17	54.80	23.90	41.13
Standard deviation	16.07	22.58	15.02	20.44	14.85	20.43	15.08	20.82	11.20	15.92	8.83	14.41

Based on the results for timetable variant TV-1, infrastructure solutions were selected for further analysis (timetable variant TV-2). Infrastructure variants IV-0, IV-1, IV-2, and IV-3 were rejected, while two variants were qualified for further study under increased traffic load: IV-4 (expansion of two sections) and IV-5 (full double-tracking).

6.2. Comparison of infrastructure variants for traffic variant TV-2

Following the first phase of analysis for timetable variant TV-1, the second phase of research was conducted. Variants showing potential to handle more intensive traffic (TV-2) with a 30-minute frequency in regional traffic were selected for analysis. This analysis aimed to verify whether these variants possess sufficient capacity reserves to handle increased traffic stably and reliably.

Similar to the first stage of analysis, the most critical operational indicators for both investment variants are presented in Tables 11 (for primary disturbances of 300 seconds) and 12 (for primary disturbances of 600 seconds).

The results of the secondary delay analysis in this phase indicate that variant IV-4, which showed complete stability under lighter traffic (TV-1, 60-minute interval), becomes an unstable system under more intensive traffic conditions (TV-2, 30-minute interval). Already at nominal disturbances (Scenario A), it generates an average of +96 seconds of secondary delay, indicating operation at the limit of capacity and a lack of operational reserves. In Scenario B, this indicator remains at an equally high, unstable level (+99 s).

Table 11. Simulation results for scenario A (average initial delay of 300 s)

Infrastructure Variant (IV)	Average initial delay	Average final delay	Average secondary delay	Standard deviation of initial delay	Standard deviation of final delay
IV-4	390	489	96	333	498
IV-5	380	329	-51	338	358

Table 12. Simulation results for scenario B (average initial delay of 600 s)

Infrastructure Variant (IV)	Average initial delay	Average final delay	Average secondary delay	Standard deviation of initial delay	Standard deviation of final delay
IV-4	794	910	99	678	805
IV-5	771	795	24	677	724

In contrast, variant IV-5 (full double-tracking) remains fully stable in Scenario A and actively absorbs disturbances, reducing the primary delay (-51 s). Only with significant disturbances (Scenario B) does passage through the analysed railway line section cause an increase in delays (+24 s); however, its result is still drastically better than that of variant IV-4. The analysis of the standard deviation of the final delay confirms these conclusions. In both scenarios, variant IV-5 is significantly more predictable for the passenger, exhibiting lower standard deviation values of the final delay.

The differences in performance between the two variants are explained by the infrastructure occupation results presented in Tables 13 and 14.

In variant IV-4, a clear difference can be observed between the expanded double-track sections (Oborniki – Rogoźno and Rogoźno – Budzyń) and those that remained single-track. The average occupation of double-track sections is approximately 44% (for Scenario B), reaching maximum values of roughly 70% in selected time periods. On the single-track sections between Budzyń and Chodzież, and between Chodzież and Dziembówko, the maximum occupation in Scenario B exceeds 90%. These sections limit the capacity of the entire line, which directly generates the secondary delays shown in Tables 11 and 12. In variant IV-5, the maximum average occupation on any section does not exceed 49% (for Scenario A), which attests to sufficient capacity reserves. Comparison with Scenario B (Table 14) additionally shows that increased disturbances have almost no impact on the average section load.

To summarise, the analysis of timetable variant TV-2 demonstrated that although constructing a timetable for variant IV-4 is theoretically possible, the system operates at the limit of capacity and is highly unstable even with relatively low primary delays. The phenomenon of merely shifting the critical section, constituting the "bottleneck" of the railway line, to subsequent single-track sections was identified. The study demonstrates that, under the adopted assumptions, the only variant that guarantees both the required capacity and the necessary reliability to handle a 30-minute frequency is the complete expansion of the line to two tracks (IV-5).

Table 13. Infrastructure occupation results for timetable variant TV-2 and Scenario A (average primary delay 300 s)

Section	IV-4		IV-5	
	Reservation [%]			
	Avg.	Max.	Avg.	Max.
Oborniki Miasto – Oborniki	16.79	29.35	10.75	20.03
Oborniki – Rogoźno	37.44	64.57	46.96	74.56
Rogoźno – Budzyń	37.95	66.84	48.83	76.78
Budzyń – Chodzież	50.75	84.76	36.40	58.59
Chodzież – Dziembówko	44.52	75.38	35.68	57.61
Max.	50.75	84.76	48.83	76.78
Avg.	37.49	64.18	35.72	57.51
Standard deviation	11.44	18.81	13.58	20.34

Table 14. Infrastructure occupation results for timetable variant TV-2 and Scenario B (average primary delay 600 s)

Section	IV-4		IV-5	
	Reservation [%]			
	Avg.	Max.	Avg.	Max.
Oborniki Miasto – Oborniki	19.87	31.75	10.46	19.92
Oborniki – Rogoźno	43.76	70.05	45.14	75.98
Rogoźno – Budzyń	44.27	71.36	46.74	79.06
Budzyń – Chodzież	64.72	90.57	35.22	60.27
Chodzież – Dziembówko	63.86	90.02	34.65	59.68
Max.	64.72	90.57	46.74	79.06
Avg.	47.30	70.75	34.44	58.98
Standard deviation	16.44	21.38	12.97	21.07

7. Conclusions and recommendations

7.1. Summary of the results

The two-stage simulation analysis allowed for a quantitative assessment of the examined investment variants (IV).

In Stage 1 (timetable variant TV-1), it was demonstrated that the base variant (IV-0) operates in an unreliable manner. In both initial delay scenarios, it causes an increase in the delays, amounting to over 100 seconds of secondary delay. The introduction of a relatively inexpensive point investment (IV-1, construction of a passing loop) proved to be an efficient solution, reducing secondary delay by approximately 50%. It was also demonstrated that the choice of investment location is of great importance. Variant IV-3 (expansion of the Oborniki–Rogoźno section) yields significantly worse results than variant IV-2, which involves the expansion of the slightly longer Rogoźno–Budzyń section. A high degree of reliability and capacity to absorb disturbances (negative secondary delays) in this scenario was demonstrated only by the significantly more expensive variants IV-4 and IV-5.

In Stage 2 (timetable variant TV-2), only selected infrastructure variants subjected to demanding traffic loads were tested. Variant IV-4 (expansion of two sections), despite functioning correctly in variant TV-1, proved very unreliable under conditions of dense regional traffic (secondary delay amounted to +96 s). With the assumed traffic, the Budzyń–Chodzież and Chodzież–Dziembówko sections proved to be the bottlenecks of the analysed line (average occupation >60%, maximum >90%).

The only variant that reliably handled TV-2 traffic was variant IV-5, providing for full double-tracking of the line. It demonstrated high stability (secondary delay of -51 s) and possessed the largest capacity reserves, as confirmed by the section occupation analysis.

7.2. Conclusions for planning the development of single-track infrastructure

The research showed that for specific, assumed timetables, partial expansion of a single-track line may not be sufficient. It does not systemically solve the capacity problem, but merely shifts it to subsequent, non-expanded sections, remaining an effective solution only up to a certain level of traffic load. At the same time, the analysis confirmed that the construction of a strategically located passing loop can be a very cost-effective transitional investment, capable of stabilising the network given moderate traffic growth and postponing the necessity of incurring multiply higher expenditures. The transition from a 60-minute to a 30-minute frequency causes a significant loss of reliability in partially single-track systems, which proves that for target, dense timetables, the only solution guaranteeing the required resilience to disruptions is the complete expansion of the line to two tracks.

7.3. Advantages and limitations of using microsimulation

The conducted research confirmed that the microsimulation technique is a valuable tool in the investment decision-making process. Its fundamental advantage is the ability to conduct stochastic analysis. The application of random delays and the analysis of indicators such as secondary delay or standard deviation allowed for the assessment of the reliability and resilience of variants, rather than just their theoretical capacity. At the same time, the study revealed methodological limitations and requirements. Conducting the presented analyses requires adopting several assumptions, particularly the timetable, as well as parameters describing the infrastructure, railway traffic control systems, and traction vehicle characteristics.

7.4. Possibilities for further research

The conducted analysis can be expanded and refined through several new research areas. In this work, two manually constructed, fixed timetables (TV-1, TV-2) were used to test individual infrastructure variants. An interesting direction would be the application of optimisation algorithms to find the optimal timetable for each variant, which would allow for the precise determination of their limiting capacity. Furthermore, the study focused on operational indicators and a simple cost indicator (track length); therefore, further work could include a broad multi-criteria analysis or cost-benefit analysis, considering detailed construction, maintenance, and external costs. Additionally, a valuable research direction would be the analysis of subsequent, including mixed, infrastructure solutions. Investment variants related to the construction of a new track can be expanded to include cases of expanding railway traffic control systems and their combinations with track layout expansion.

Acknowledgement
The project is co-financed by the Governments of Czechia, Hungary, Poland and Slovakia through Visegrad Grants from International Visegrad Fund. The mission of the fund is to advance ideas for sustainable regional cooperation in Central Europe.

References

1. Aoun, J., Quaglietta, E., Goverde, R. M. P., & D'Ariano, A. (2021). A hybrid Delphi-AHP multi-criteria analysis of Moving Block and Virtual Coupling railway signalling. Transportation Research Part C: Emerging Technologies, 129, 103250. https://doi.org/10.1016/j.trc.2021.103250
2. Arslan, O., Reichert, M., Sellaouti, A., & Hoffmann, S. (2021). Investigation of personal rapid transit station capacities using microscopic traffic simulation. 2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) (pp. 1–6). IEEE. https://doi.org/10.1109/MT-ITS49943.2021.9529288
3. Bažant, M., & Bulíček, J. (2020). Assessment of partial double-tracked railway lines with focus on capacity. Transport Means - Proceedings of the International Conference (pp. 283–288).
4. Bešinović, N., & Goverde, R. M. P. (2018). Capacity Assessment in Railway Networks. International Series in Operations Research and Management Science, 268, 25–45. https://doi.org/10.1007/978-3-319-72153-8_2
5. Cornet, Y., Barradale, M. J., Gudmundsson, H., & Barfod, M. B. (2018). Engaging Multiple Actors in Large-Scale Transport Infrastructure Project Appraisal: An application of MAMCA to the case of HS2 High-Speed Rail. Journal of Advanced Transportation, 2018, 9267306. https://doi.org/10.1155/2018/9267306
6. D'Acierno, L., Botte, M., & Pignatiello, G. (2019). A simulation-based approach for estimating railway capacity. International Journal of Transport Development and Integration, 3(3), 232–244. https://doi.org/10.2495/TDI-V3-N3-232-244
7. Dean, M., Hickman, R., & Chen, C.-L. (2019). Testing the application of participatory MCA: The case of the South Fylde Line. Transport Policy, 73, 62–70. https://doi.org/10.1016/j.tranpol.2018.10.007
8. Del Caro Daher, P. H., de Moura, D. F., de Morais Neto, G. C., & Leal, J. E. (2020). Sustainable Railway Solutions Using Goal Programming. Lecture Notes in Mobility, 129–157. https://doi.org/10.1007/978-3-030-19519-9_4
9. Dick, C. T., Atanassov, I., Kippen, F. B. III, & Mussanov, D. (2019). Relative train length and the infrastructure required to mitigate delays from operating combinations of normal and over-length freight trains on single-track railway lines in North America. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 233(7), 731–742. https://doi.org/10.1177/0954409718809204
10. Dingler, M. H., Lai, Y.-C., & Barkan, C. P. L. (2014). Effect of train-type heterogeneity on single-track heavy haul railway line capacity. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 228(8), 845–856. https://doi.org/10.1177/0954409713496762
11. Dunbar, R., Roberts, C., & Zhao, N. (2017). A tool for the rapid selection of a railway signalling strategy to implement train control optimisation for energy saving. Journal of Rail Transport Planning and Management, 7(4), 224–244. https://doi.org/10.1016/j.jrtpm.2017.09.002
12. Florczak-Strama, M., & Parkitna, A. (2016). Project appraisal in the transport sector. Advances in Intelligent Systems and Computing, 432, 63–73. https://doi.org/10.1007/978-3-319-28567-2_6
13. Franke, P. (2023). Planning of railway infrastructure development in combination with the construction of an integrated periodic train timetable. WUT Journal of Transportation Engineering, 137, 133–152.
14. Gołębiowski, P. (2019). Selected Aspects of the Train Timetable Construction of Passenger Trains with the Consideration of Platform Edges and Stabling Tracks Allocation Problem. Logistics and Transport, 41, 91–100. https://doi.org/10.26411/83-1734-2015-1-41-11-19
15. Gołębiowski, P. (2022). Risk assessment in railway traffic planning - assumptions for the method. WUT Journal of Transportation Engineering, 134, 109–123. https://doi.org/10.5604/01.3001.0016.3272

16. Gołębiowski, P., & Kukulski, J. (2020). Preliminary study of shaping the railway track geometry in terms of their maintenance costs and capacity. Archives of Transport, 53, 115–128. https://doi.org/10.5604/01.3001.0014.1787
17. Gołębiowski, P., Jacyna, M., & Stańczak, A. (2021). The Assessment of Energy Efficiency versus Planning of Rail Freight Traffic. A Case Study on the Example of Poland. Energies, 14(18), 5629. https://doi.org/10.3390/en14185629
18. Grimm, M. (2012). The analysis of congested infrastructure and capacity utilisation at trafikverket. WIT Transactions on the Built Environment, 127, 359–367. https://doi.org/10.2495/CR120301
19. Gühnemann, A., Laird, J. J., & Pearman, A. D. (2012). Combining cost-benefit and multi-criteria analysis to prioritise a national road infrastructure programme. Transport Policy, 23, 15–24. https://doi.org/10.1016/j.tranpol.2012.05.005
20. Hickman, R., & Dean, M. (2018). Incomplete cost–incomplete benefit analysis in transport appraisal. Transport Reviews, 38(6), 689–709. https://doi.org/10.1080/01441647.2017.1407377
21. Hong, H. (2023). Research on key bottlenecks and solutions for improving transport capacity of existing urban rail transit lines. Proceedings of SPIE - The International Society for Optical Engineering, 12626, 126260Z. https://doi.org/10.1117/12.2674280
22. Huang, Z., Xu, H., & Chen, J. (2022). Simulation and Verification System Design for High Speed Railway Based on OpenTrack Secondary Development. Proceedings of SPIE - The International Society for Optical Engineering, 12081, 120812U. https://doi.org/10.1117/12.2623975
23. Jacyna, M. (2022). Wspomaganie decyzji w praktyce inżynierskiej: metody, algorytmy, przykłady. Wydawnictwo Naukowe PWN.
24. Jamili, A. (2018). Computation of practical capacity in single-track railway lines based on computing the minimum buffer times. Journal of Rail Transport Planning and Management, 8(2), 91–102. https://doi.org/10.1016/j.jrtpm.2018.03.002
25. Kettner, M., Sewcyk, B., & Hunold, J. (2004). Interlinking micro- and macroscopic railway traffic simulation models. Eisenbahningenieur, 55(2), 6–11.
26. Khadem Sameni, M., & Moradi, A. (2022). Railway capacity: A review of analysis methods. Journal of Rail Transport Planning and Management, 24, 100357. https://doi.org/10.1016/j.jrtpm.2022.100357
27. Khadem-Sameni, M., Landex, A., & Preston, J. (2010). Revising the UIC 406 method: Revenue generating capacity. Proceedings of the ASME Joint Rail Conference 2010, 2, 579–588. https://doi.org/10.1115/JRC2010-36281
28. Khaki, A. M., & Shafiyi, S. M. (2011). Comparison between the output of Cost Benefit Analysis and Multi-Criteria Analysis in Urban Transportation Investments. Australian Journal of Basic and Applied Sciences, 5(11), 667–677.
29. Kovari, B., Balogh, C. L., & Aradi, S. (2023). Multi-Agent Reinforcement Learning for railway rescheduling. SACI 2023 - IEEE 17th International Symposium on Applied Computational Intelligence and Informatics, Proceedings, 375–380. https://doi.org/10.1109/SACI58269.2023.10158653
30. Krzykawski, M., Burdzik, R., & Gołębiowski, P. (2024). Assumptions for the mathematical model investigating the effect of railway line route parameters on the average speed of railway vehicles. WUT Journal of Transportation Engineering, 140, 5–18. https://doi.org/10.5604/01.3001.0054.7732
31. Landex, A., Schittenhelm, B., Kaas, A. H., & Schneider-Tilli, J. (2008). Capacity measurement with the UIC 406 capacity method. WIT Transactions on the Built Environment, 103, 55–64. https://doi.org/10.2495/CR080061
32. Licciardello, R., Adamko, N., Deleplanque, S., & Ricci, S. (2020). Integrating yards, network and optimisation models towards real-time rail freight yard operations. Ingegneria Ferroviaria, 75(6), 417–447.
33. Lindner, T. (2009). Recommendations for enhancing UIC Code 406 problems, solution possibilities and limits arising by the application of an analytical compression method for doing capacity research. ZEVrail, 133(11-12), 510–519.

34. Lindner, T. (2011). Applicability of the analytical compression method for doing node capacity evaluations [Anwendbarkeit des Analytischen Kompressions-Verfahrens zur Leistungsuntersuchung von Knotenpunkten]. ZEVrail, 135(3), 76–81.
35. Ľupták, V., Dedík, M., Morihladko, P., Šulko, P., & Pečený, L. (2025). Assessment of the Railway Line Capacity on the Railway Network Using a New Innovative Method. Sustainability, 17(10), 4476. https://doi.org/10.3390/su17104476
36. Matowicki, M., Młyńczak, J., Gołębiowski, P., & Přikryl, J. (2025). Defining Railway Traffic Conflicts and Optimising Their Resolution: A Machine Learning Perspective. Transactions on Transport Sciences, 16, 44–48. https://doi.org/10.5507/tots.2025.010
37. Mátrai, T. (2013). Cost benefit analysis and ex-post evaluation for railway upgrade projects. Periodica Polytechnica Transportation Engineering, 41(1), 33–38. https://doi.org/10.3311/PPtr.7102
38. Nehring, K., Kłodawski, M., Jachimowski, R., Klimek, P., & Vasek, R. (2021). Simulation analysis of the impact of container wagon pin configuration on the train loading time in the intermodal terminal. Archives of Transport, 60, 155–169. https://doi.org/10.5604/01.3001.0015.6928
39. Nikolayzik, D., Maus, M., & Nießen, N. (2024). Investigation of Railway Network Capacity by Means of Dynamic Flows. Applied Sciences (Switzerland), 14(18), 8233. https://doi.org/10.3390/app14188233
40. Panek, A., Jacyna, M., Jachimowski, R., & Szczepański, E. (2025). Reliability and efficiency in technology selection in logistics facilities – multi-criteria decision support using the AHP method. Eksploatacja i Niezawodność – Maintenance and Reliability, 27, 1–21. https://doi.org/10.17531/ein/200684
41. Pascariu, B., Coviello, N., & D'Ariano, A. (2021). Railway freight node capacity evaluation: A timetable-saturation approach and its application to the Novara freight terminal. Transportation Research Procedia, 52, 155–162. https://doi.org/10.1016/j.trpro.2021.01.017
42. Penyalver, D., & Turró, M. (2018). A classification for the redistributive effects of investments in transport infrastructure. International Journal of Transport Economics, 45(4), 695–732. https://doi.org/10.19272/201806704008
43. PKP Polskie Linie Kolejowe S.A. (2024). Regulamin sieci 2024/2025. https://www.plk-sa.pl/klienci-i-kontrahenci/warunki-udostepniania-infrastruktury-i-regulaminy/regulamin-sieci/regulamin-sieci-2024/2025
44. Prencipe, F. P., & Petrelli, M. (2018). Analytical methods and simulation approaches for determining the capacity of the Rome-Florence "direttissima" line. Ingegneria Ferroviaria, 73(7-8), 599–633.
45. Rahoma, D. M. S., Heikal, A. Z., Zohny, H. N., & Kotb, A. S. (2021). Proposed models to calculate and optimise line capacity under different operation conditions for egyptian railway network. Journal of Applied Engineering Science, 19(1), 77–83. https://doi.org/10.5937/jaes0-27821
46. Rakhmangulov, A., Sładkowski, A., Osintsev, N., Mishkurov, P., & Muravev, D. (2017). Dynamic optimization of railcar traffic volumes at railway nodes. Studies in Systems, Decision and Control, 87, 405–456. https://doi.org/10.1007/978-3-319-51502-1_10
47. Shih, M.-C., Dick, C. T., Sogin, S. L., & Barkan, C. R. L. (2014). Comparison of capacity expansion strategies for single-track railway lines with sparse sidings. Transportation Research Record, 2448, 53–61. https://doi.org/10.3141/2448-07
48. Sogin, S., Lai, Y.-C., Dick, C., & Barkan, C. (2013). Comparison of capacity of single- and double-track rail lines. Transportation Research Record, 2374, 111–118. https://doi.org/10.3141/2374-13
49. Szczepański, E., Gołębiowski, P., & Kondracka, B. (2023). Evaluation of the technological process of wagon processing at shunting stations using the simulation model. Zeszyty Naukowe. Transport - Politechnika Śląska, 120, 249–267. https://doi.org/10.20858/sjsutst.2023.120.16
50. Szczepański, E., Jacyna, M., Jachimowski, R., Rostia, V., & Nehring, K. (2021). Decision support for the intermodal terminal layout designing. Archives of Civil Engineering, 67, 611–630. https://doi.org/10.24425/ace.2021.137188
51. Tudela, A., Akiki, N., & Cisternas, R. (2006). Comparing the output of cost benefit and multi-criteria analysis: An application to urban transport investment. Transportation Research Part A: Policy and Practice, 40(5), 414–423. https://doi.org/10.1016/j.tra.2005.08.002

52. Wang, H., Zhao, N., & Chen, L. (2015). An integrated capacity evaluation method for CBTC- system-equipped urban rail lines. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 229(3), 291–302. https://doi.org/10.1177/0954409713511448
53. Wang, Y., & Zhang, X. (2014). Research on Transport Capacity of Urban Rail Transit Based on Railsys. Lecture Notes in Electrical Engineering, 288, 235–241. https://doi.org/10.1007/978-3-642-53751-6_23
54. Weik, N., Warg, J., Johansson, I., Bohlin, M., & Nießen, N. (2020). Extending UIC 406-based capacity analysis – New approaches for railway nodes and network effects. Journal of Rail Transport Planning and Management, 15, 100199. https://doi.org/10.1016/j.jrtpm.2020.100199
55. Wikipedia. (2025). Linia kolejowa nr 354. https://pl.wikipedia.org/wiki/Linia_kolejowa_nr_354
56. Wojnar, G., & Irlik, M. (2022). Multicriteria train running model and simulator for railway capacity assessment. Transport Problems, 17(2), 199–212. https://doi.org/10.20858/tp.2022.17.2.17
57. Yücel, N., & Taşabat, S. E. (2019). The Selection of Railway System Projects with Multi Creteria Decision Making Methods: A Case Study for Istanbul. Procedia Computer Science, 158, 382–393. https://doi.org/10.1016/j.procs.2019.09.066