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A TOOL FOR ANALYZING THE PASSAGE OF A TRAIN WITH SPECIFIC TECHNICAL PARAMETERS ON A RAILWAY LINE CONSIDERING VARIOUS MODELS OF MOVEMENT RESISTANCE

Summary. This study presents the results of research aimed at developing and verifying a computational algorithm that allows maximizing the mass transported by a train on a given railway line. The algorithm evaluates traction capability based on various models of train motion resistance described in the literature. Seven motion resistance models were implemented and compared to experimental data collected from a real train run on a selected non-electrified railway line. This comparison enabled the adjustment of model parameters to better reflect real traction conditions. The proposed method allows railway operators to estimate the maximum permissible train mass for specific line characteristics, ensuring operational safety and energy efficiency. The analysis confirmed that the choice of motion resistance model significantly affects the estimated traction performance. The optimized model (CNTK (2)) showed the best agreement with empirical results, demonstrating its applicability for operational analyses. The developed algorithm can be adapted to any location within the railway network, provided that an appropriate motion resistance model is applied. Ultimately, the method may support the development of digital tools for optimizing freight train parameters, improving cost efficiency, and enhancing the sustainability of rail transport.

1. INTRODUCTION

The motivation of the present article is the desire to present a tool that enables the analysis of a train's passage along a railway line with specific technical parameters. The authors decided to focus on the problem of the maximum weight that a given locomotive can carry on a given railway line, considering its individual technical parameters. The article presents an algorithm that enables the calculation of the resistance to motion generated by the train and the analysis of the train's ability to pass along a selected railway line. The authors aim to draw attention to the fact that road transport is gaining importance at the expense of rail transport, which may impact the development of railway infrastructure. The work is open and considers only the most significant components that affect the parameters of the analyzed problem. Ultimately, the article serves as a quick analysis of the possibility of a train passing on a given railway line and as a starting point for further development of the application, both in terms of content and programming.

For a long time, there has been a noticeable shift in the importance of road transport at the expense of rail transport. Customers frequently choose road transport for financial reasons, often overlooking the

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advantages of rail freight. The main strengths of road transport are its relatively low price, shorter delivery time, and greater flexibility in meeting customer needs. With the ongoing development of transport, both infrastructure and rolling stock have evolved − ranging from asphalt roads to modern railways, and from trucks to advanced locomotives.

Each infrastructure investment presents specific challenges that must be addressed during both the design and modernization of transport routes. Planned projects should improve the parameters of linear and nodal infrastructure, facilitating the movement of as many goods as possible in the shortest possible time. The role of both rail and road infrastructure is to ensure adequate network capacity and continuity, enabling efficient transport between destinations.

These issues motivated the author to analyze railway network parameters, particularly the maximum permissible parameters for transporting a single train on a given route—namely, the train's length and mass that a locomotive can haul safely along the line. The current study remains exploratory in nature, focusing on the most significant components affecting the maximum transportable mass. The greatest challenge in addressing this problem lies in obtaining the necessary reference data.

2. MATERIALS AND RESEARCH METHODS

2.1. Legal regulations resulting from the construction and modernization of railway lines

The subject of transport policy is the state, together with other administrative units, acting as creators of the rights and conditions for the functioning of this branch of transport. In terms of regulating the selection of the appropriate road for the development of the transport network, on September 24, 2019, the Council of Ministers adopted a resolution on the adoption of the "Strategy for Sustainable Development of Transport until 2030" (SRT2030). In short, this strategy assumes several main goals:

- increasing the transport accessibility of the country,
- improving the safety of all traffic participants,
- improving the efficiency of the transport sector [1].

The second document, officially approved by the Council of Ministers on June 29, 2005, and binding, is the State Transport Policy for the years 2006-2025. It confirms the implementation of objectives at the national level, taking into account the strategic objectives outlined in the white paper. This document outlines more precise methods for achieving the objectives stated in the above-mentioned higher-ranking documents. The instruments for implementing the transport policy will be:

- law,
- development planning and financing of the transport sector,
- activities of public administration at all levels.

Forecasting the long-term financial planning of investment implementation, along with the programming of operational and investment activities, forms the basis for the assumptions in this document, which result from the tasks to be performed within its framework. The goals are to be achieved through support from EU funds. Unfortunately, there is still no indication of which investments are considered priorities or bring them closer to the objectives set out in this document [2].

An important international document concerning all Member States of the European Union is the White Paper issued by the European Commission in Brussels on March 28, 2011. The intention of publishing the White Paper is "creating a single European transport area − striving to achieve a competitive and resource-efficient transport system" [3]. The described document adopts a clear position on the development of ecological forms of transport, one of which is rail transport, while road transport, which has the largest percentage share in the movement of people and goods, is to play the role of only the "last mile" function. Unfortunately, the document does not specify which railway lines should be built or modernized. The only information it contains concerns what needs to be done, but it does not contain proposals on how to achieve the goals, which makes it much more difficult for all entities to take any action in this regard. Uniform action in this area appears to be evident on a European scale, but the effects of the assumptions outlined in the white paper and their verification will still have to be awaited. In the context of the European Union's policy, there is a portal for European Funds that enables the use of funds allocated for the implementation of goals set, among others, in the white paper. Based on the comparison, it can be concluded that the objectives specified in the national documents (i.e., the Transport Development Strategy regarding the expansion of the railway infrastructure network) align with those described in the White Book of Transport of the European Commission body. The authors of the documents detail the expansion of the existing communication routes under the existing European AGTC agreement. The authors of the documents detail the expansion of the existing communication routes under the existing European AGTC agreement [4].

The analysis of the above documents, both national and European, reveals that the growth of rail transport is becoming increasingly important for entities involved in transport development planning. Both financial and environmental aspects speak for the growth and development of rail transport.

The primary barrier, which is a long-term and costly process for immediate improvement, is the issue of modernizing point and linear infrastructure elements [16]. The low technical parameters of the currently operated railway routes necessitate the designation of detours, particularly for freight trains, which often extend the delivery time of goods to a specific customer, while also incurring additional economic, organizational, and technical costs for the railway carrier [6]. An example of such planning activities aimed at improving freight line performance is the feasibility study for the new Katowice–Ostrava line conducted under the Central Communication Port program [7].

For the purposes of this article, a sample railway line was selected (Fig. 1) and the problem of locomotives' passage on this line was analyzed. The line is 7,851 km long with a maximum speed of 30 km/h. The selected line is non-electrified. There are six category A level crossings on this line. Below is a diagram of the chosen region's network, managed by the selected infrastructure manager.

2.2. Train movement analysis – UIC formula

To achieve the planned goal, the following research approach was adopted. First, a literature review was conducted to identify and compile the formulas necessary to calculate train motion resistance. Based on these formulas, an algorithm was developed and implemented in an Excel spreadsheet, and subsequently in a dedicated software tool to facilitate its use in railway operations.

Basic physical formulas were used to analyze the train's movement. To be able to apply basic physical formulas, one needs to collect the basic physical quantities necessary to use the formula. Basic physical quantities necessary to perform the task, i.e. weight of the locomotive, gross weight of the wagons, maximum elevation on the section of the railway line, distance between the centers of the running surface of the railhead in the curve, wheelbase of the locomotive and wagons, minimum curve radius, coefficients of the rotating masses of the locomotive and empty wagons or loaded, the length of the locomotive and wagons are presented in the table below.

To ensure that the analysis tool could be used easily, it was developed using a formula, which results in some limitations:

- Concerning the operating characteristics of the TEM2 locomotive engine adopted in accordance with the materials submitted by the manufacturer,
- The formula does not consider the variable speed of the railway line; a fixed maximum speed limit on a given railway line should be assumed.
- Braking force is not included,
- The current model is limited only to the characteristics of the diesel locomotive.

The following algorithm was employed to calculate the resistance to motion.

The real traction resistance depends on the exact parameters of the ground, such as track condition, braking system, and temperature, among others. Generally, resistances are determined using the following formula:

$$W_d = W_S(s) + W_L + W_T + W_D \text{ [kN]}, \tag{1}$$

where:

$W_S(s)$ – resistances depending on the vertical track profile,

W_L – resistances depending on the horizontal profile resulting from the movement along curves,

W_T – driving resistance in tunnels,

W_D – resistance dependent on wind pressure and aerodynamics, arising when vehicles pass each other.

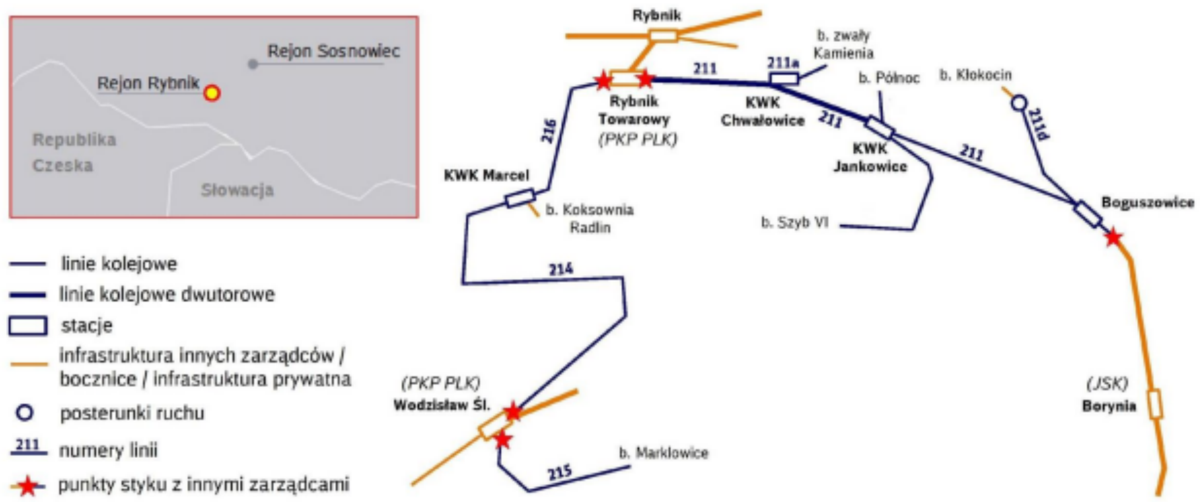

Fig. 1. Analyzed lines managed by the selected infrastructure manager [8]

Table 1

Main vehicle and infrastructure parameters for motion resistance analysis

PARAMETER NAME	VALUE	UNIT
Locomotive weight	126.00	t
Gross weight wagons	868.00	t
Maximum elevation in the section	18.90	per mile
Half the distance between the centers of the running surface of the railhead in a curve	0.76	m
Spacing axis locomotives	4.20	m
Spacing axis wagon	9.00	m
Minimum arc radius on the section	300.00	m
Rotating mass factor of the loaded wagon	1.05	-
Rotating mass factor locomotives	1.25	-
Length locomotives	17.03	m
Length wagon	14.04	m
Number wagons	42.00	pcs
Length composition	606.76	m
Wagon weight	20.67	t
Composition mass with rotating mass factor	1129.66	t
Weight of the train for the first 100 m	294.28	t
Mass of the train for each additional 100 m	164.85	t
Number of cars for the first 100 m with a locomotive	5.91	pcs
Number of wagons for each additional 100 m of train length	7.12	pcs
Resistance resulting from overcoming the arc	5.38	kN
The rotating mass factor of the empty wagon	1.12	-

The resistances, depending on the vertical track profile, are determined using the formula:

$$W_s(s) = m \cdot g \cdot i(s) \text{ [kN]}, \quad (2)$$

where:
i(s) – route profile in meters of ascent or descent related to 1 km of route.
The value of i(s) depends on the distance traveled by the vehicles (units m/km or ‰).
m – train gross mass [Mg],
g – gravitational acceleration, 9.81 [$\frac{m}{s^2}$].

Resistance in curves of the track (Protopapadakis formula):

$$W_L = \frac{158.4 \cdot L_L + 103.4 \cdot L_0}{R_L} \left[\frac{\mathrm{N}}{\mathrm{Mg}}\right], \quad (3)$$

where:
L_L – half of the distance between the centers of the running surface of the railhead on the curve [m],
L_0 – wheelbase of the vehicle [m],
R_L – arc radius [m].

In practice, however, simplified expressions are used. The basic resistance according to the UIC formula is as follows:

$$W(v) = [2.5 + 0.025 \cdot (\frac{3.6 \cdot v}{10})^2] \cdot m \cdot g \text{ [N]}, \quad (4)$$

where:
v – speed $[\frac{m}{s^2}]$,
g – gravitational acceleration, 9.81 $[\frac{m}{s^2}]$,
m – train weight [t].

The assumptions for the calculations assumed constant coefficients of rotating masses, respectively, for the loaded train (1.05), for an empty train (1.12), and for the locomotive alone (1.25). The rotating mass factor is crucial because it accounts for the moment of inertia of the drive system during the acceleration of the rotating masses. There are several methods for its calculation; however, a simplified model with a constant coefficient was adopted in the work.

The work involves widening the arches in accordance with the criteria for constructing the railway track. The widening of the track depends on the type of rails, the radius of the curve or the type of sleepers used to build the railway track. The simplified calculation model allowed for the use of a fixed widening of 65 mm in the curves of the classic track, which has a width of 1435 mm [8]. Delivered by a locomotive modernization company, the external characteristics of the TEM2 locomotive engine enabled the direct conversion of tractive force into acceleration, and subsequently, acceleration into the distance traveled by the train. For these calculations, the most basic physical formulas for velocity and acceleration were used. Based on the adopted algorithm, the calculation sheet generates a graph illustrating the dependence of the TEM2 locomotive start-up on the resistance to motion that arises during the locomotive's start-up with a given load. A graph representing this relationship is presented in Fig. 2.

By entering detailed technical data into the sheet, we can also check whether, in critical conditions on the railway line (i.e., with the most significant inclination and the smallest curve radius on a given railway line), a given locomotive will be able to move for a given train, and thus, safely in all conditions, without restrictions, cross a given railway line.

The calculation will show what theoretical speed we should achieve when taking off with the train at the highest inclination on the line and the smallest radius of the curve under critical conditions (e.g., 9.6 km/h). However, if the locomotive does not have enough tractive force to move up the highest hill on the line, the sheet will also answer: "too little train force!"

2.3. Limitations in the created model

Due to the time constraints imposed on writing the work in question and the limited availability of scientific sources, it was decided to make some simplifications in the assumptions for the development of the algorithm. According to the information provided by a locomotive modernization company, due to the external characteristics of the TEM2 locomotive engine operation (Fig. 3), it was decided to leave the speed jumps depending on the force without recalculating the intermediate values. Due to the company's calculation secret, the interpolation of individual speed differences in relation to the tractive force has not been performed, which has a direct impact on the reduced accuracy of calculating the tractive force for individual speeds.

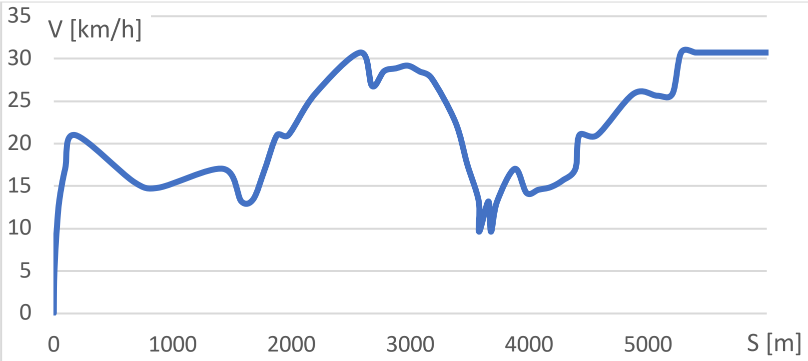

Fig. 2. Diagram of the dependence of the TEM2 locomotive start-up on the resistance to motion arising during the start-up of the locomotive with a given load

In the formula, we assume a constant speed along the entire railroad. The formula does not predict braking force. All restrictions on the railway line included in the List of Permanent Warnings cannot be considered, either. The algorithm, however, allows for the possibility of checking whether a given train on a specific line can operate under certain railway line parameters or whether it will have insufficient tractive force to overcome the challenges of a particular railway line. The use of a different locomotive requires a separate characteristic of the tractive force depending on the speed. In particular, it will be problematic to add electric locomotives to the formula. If it is necessary to calculate the system for an electric locomotive, its external characteristics must be reworked. Currently, on the railway lines belonging to the selected infrastructure manager, there is no need to calculate external characteristics for electric locomotives; therefore, this issue is not included in the formula.

In the case of unfavorable input data, particularly in extreme conditions on the speed graph, a range of 0.5–5 km/h can be obtained. Such a result should also be interpreted to determine whether the train can pass safely with the given input data. If the conditions allow safe conduct of the experiment, you can try to determine it experimentally.

All the above tables were automatically recalculated after the appropriate train parameters were entered in accordance with the limitations listed above.

3. ANALYSIS OF THE RESULTS

Tests were carried out on a real object to confirm the correctness of the adopted hypotheses and achieve the purpose of the work; for this purpose, the correct operation of the formula on individual sections of line No. 211 was checked (Fig. 1). The TEM2-134 locomotive, belonging to one of the Polish carriers. There were 42 empty coal wagons on the train (Fig. 4). The measurement consisted of reading the mileage of the railway line from hectometer posts and simultaneously reading the speed from a Hassler-type speedometer.

Additionally, it was decided to download the recorded parameters using an onboard device installed on the locomotive in question. The comparison of the results of the three methods is presented in the chart below (Fig. 5).

There are slight differences between the theoretical trip calculated in the numerical model and the measured practical trip. Differences may be due to:

- speed reading measurement error,
- measurement error of the Hasler-type speedometer,
- a locomotive which, after years of operation, may no longer have the assumed parameters of the characteristics adopted for the implementation of the theoretical journey,
- lack of ideal weather conditions for wheel-rail contact, which is one of the basic assumptions of the spreadsheet.

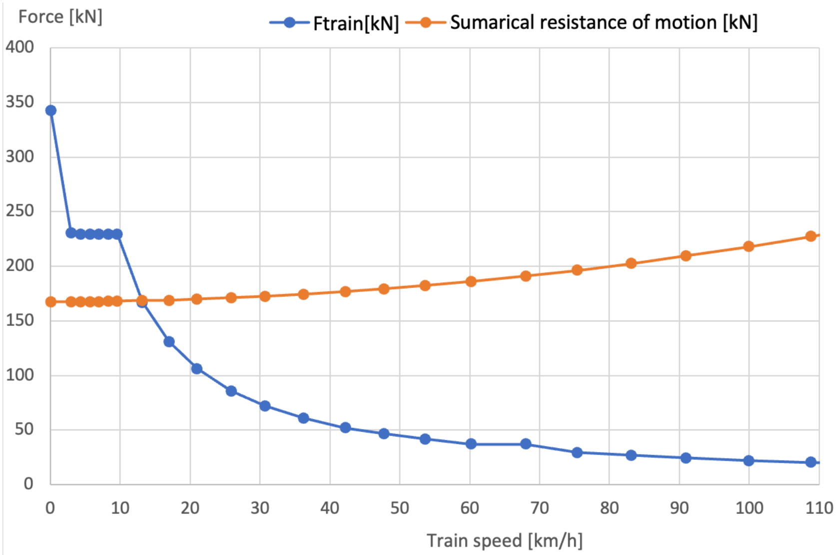

Fig. 3. Diagram of the dependence of the TEM2 locomotive start-up on the resistance to motion arising during the start-up of the locomotive with a given load

Fig. 4. Train number A7573W during technical preparation for transport

The most significant measurement error was the one carried out based on the operation of the onboard system. The onboard recording system saves measurement data once a minute, omitting all values that occur between these times. To illustrate the situation, in one minute at a speed of about 25 km/h, the train travels about 500 m, which is a very inaccurate measurement system when changing the profile of the railway line, rounded up to even 100 m.

It is important to note that during the practical run, we did not reach a speed lower than assumed in the theoretical run, which allows us to accept the spreadsheet as reliable.

4. ANALYSIS OF THE IMPACT OF AVAILABLE TRAIN MOTION RESISTANCE MODELS

Due to the various models of motion resistance available in the literature, it is essential to select the model that best reflects the actual conditions obtained during the experimental studies. For this purpose, seven of the most typical train motion resistance models were modeled: the UIC model [9], the Strahl model [10], the DB (1) model in the Sachs & Sauthoff version [13, 14] and the DB (2) model (for sliding bearings) [13], the Davis model from 1926 [12, 14], the Franck model [11], and the CNTK (1) model for the Polish railway infrastructure [10, 11].

Fig. 5. Diagram of the dependence of the TEM2 locomotive start-up on the resistance to motion arising during the start-up of the locomotive with a given load

The final step was to modify the parameters of the CNTK (2) model to achieve maximum convergence of the numerical model with the experimental results.

The above models describing the motion resistance were taken into account to ensure that the train obtains sufficient traction force throughout the entire speed range.

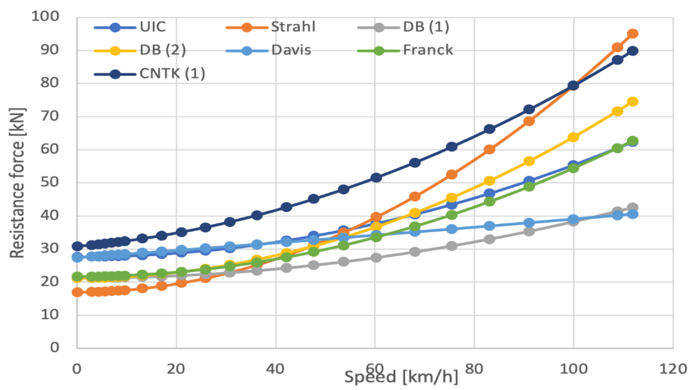

Fig. 6. Summary of motion resistance characteristics for selected models given in the literature as a function of Speed

Fig. 6 shows that, depending on the model used, the motion resistance values can vary significantly. For example, for a speed of 112 km/h, the Davis model indicates a value of 40.56 kN, while the Strahl model yields a motion resistance value of 95 kN. For freight transport, and particularly for journeys with maximum load, the differences are more significant at lower speeds (i.e., around 20 km/h). For this speed, results range from 20 kN (Strahl) to 35 kN (CNTK (1)). For the resulting set of curves (Fig. 6), a driving simulation was conducted, taking into account all the above motion resistance models. For models in English units, conversions to SI units were included, considering the speed in km/h and the weight in tons. Generally, it should be stated that up to a speed of 100 km/h, the relatively highest values of motion resistance were obtained for the CNTK (1) model. It should be noted that for speeds relevant to freight transport (i.e., up to 60 km/h), the differences between the relationship according to CNTK (1) and UIC are significant. The Davis model is the only one that showed characteristics very close to linear. All the above-mentioned dependencies on the motion resistance were used to analyze the convergence of the numerical model results with the measurement results during the ride, as shown in Figs. 7 and 8.

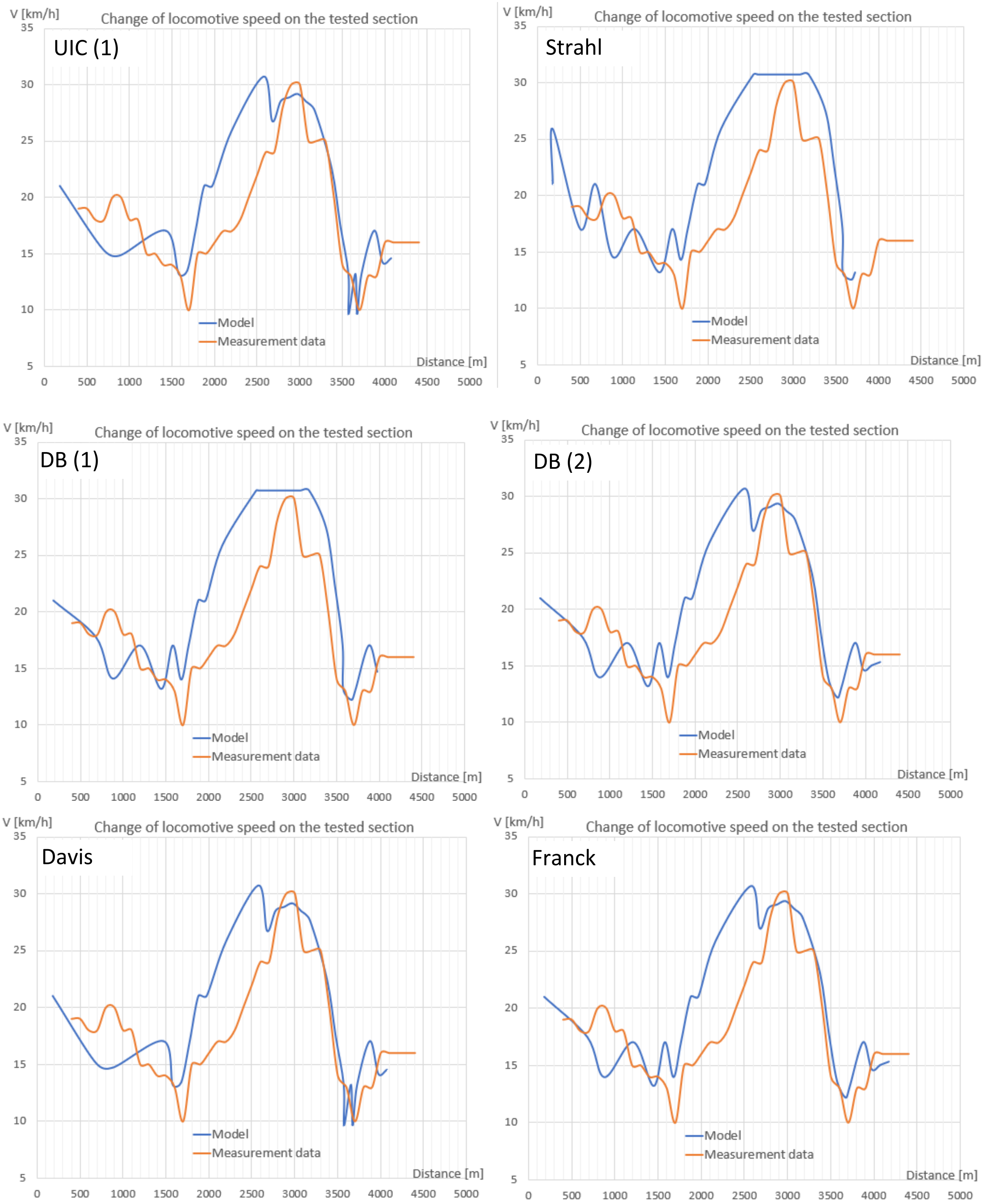

Fig. 7. Change of speed on the tested line for different resistance of train motion models

A µ1 measure was introduced to quantify the model's fit to the experimental data based on the difference in the area under the curve (i.e., integrating speed as a function of distance, as shown in Table 2). The difference between the values obtained from individual models and actual trip measurements, referenced to the baseline trip measurement and expressed as a percentage, allows for a quantitative comparison of the usefulness of individual motion resistance models in verifying train travel on a given route. It should be noted that speed was calculated not from 0 km/h but from the minimum value of 10 km/h. This allowed for more pronounced differences between the models (the area between the curve and the 10 km/h line was calculated, not from 0 km/h). This means that the lower the μ1 value, the better the model reflects the actual trip results. At the same time, an additional rV measure was introduced to avoid a situation in which the model for minimum speeds obtains speeds above the actual values. This measure considers the difference in the minimum speed from the passage compared to the minimum speed from the model in a specific section of the railway line.

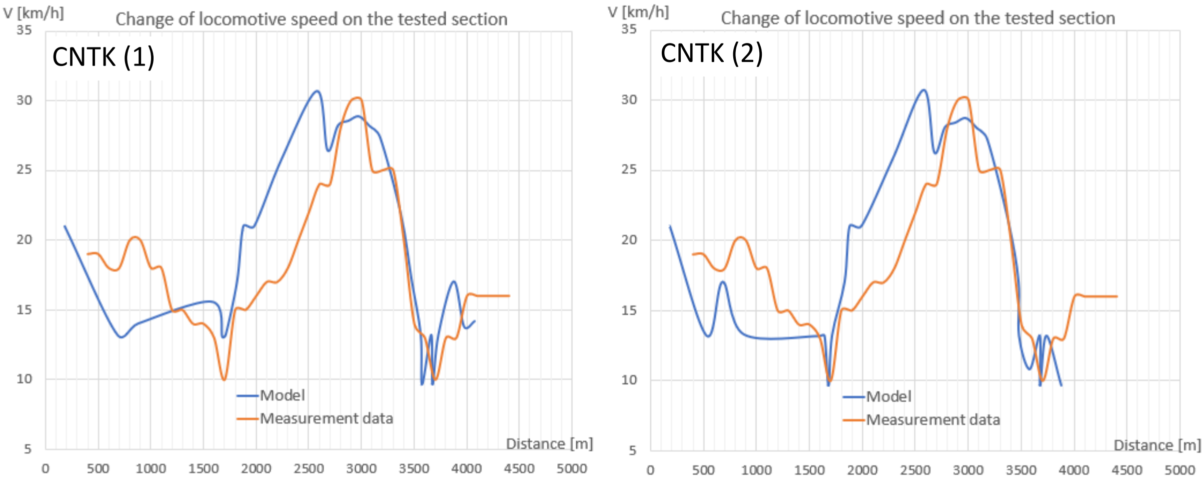

Fig. 8. Change of speed on the tested line for different resistance of train motion models (continuation from Fig. 7)

Table 2

Table of obtained values of model quality measures

Measure	UIC	Strahl	DB (1)	DB (2)	Davis	Franck	CNTK (1)	CNTK (2)
μ1	20.41	29.44	31.17	25.6	20.11	25.52	12.48	8.58
rV	-0.37	2.54	2.22	2.18	-0.37	2.16	-0.37	-0.37

Models for which the minimum speed on the tested railway line—particularly at critical locations—is higher than the actual recorded value (red rV measure) are considered unsuitable for verifying the feasibility of a train passage with maximum weight. Such cases may lead to erroneous simulation results, suggesting the possibility of successful passage under conditions in which the real vehicle would not be capable of traversing the critical section. This measure verifies whether the model provides minimum speeds below the actual ones (obtained from tests for passage on the selected railway line). Exceeding this value indicates that the model will tend to overestimate performance (speed) for critical locations, which could result in the train not actually passing through these locations after such verification.

It is worth noting that the best results were obtained for the CNTK model (1). The model curve was adjusted to better represent the actual driving behavior—specifically, from a model with the parameters $W(v) = a + b \cdot v + c \cdot v^2$ to a model with parameters (a+20), (b+1.1), and (c-20)—to further optimize the model. The results are presented in Table 2, where the modified model is marked as CNTK (2). The achieved consistency in driving behavior, especially at low speeds, is shown in Fig. 8.

Recent studies have confirmed the significant influence of reducing train mass on total motion resistance and traction energy consumption. Bulakh [17] demonstrated that lowering the gross mass of freight wagons by structural optimization can reduce traction energy demand by up to 12–15% on straight track sections, with a proportional decrease in overall motion resistance. These findings confirm the importance of precisely calibrating resistance models against the actual rolling stock parameters, as adopted in the presented algorithm.

It should be noted, however, that this correction may be effective only for the specific case analyzed. Its potential generalization to other railway lines within the operator's network should be preceded by a series of runs involving vehicles of different masses and profiles. Such validation would allow assessing the robustness of the adjusted model and its applicability to diverse operational conditions.

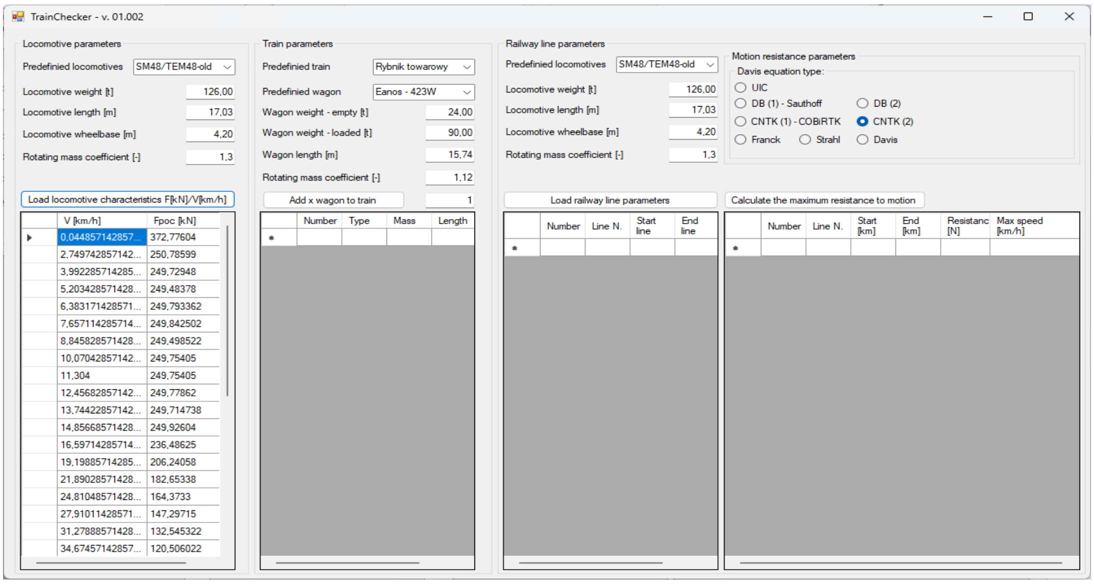

Fig. 9. TrainChecker software for automating the process of selecting the maximum load for a train ride on a selected railway line (railway lines, and other data are loaded from an xlsx file)

It should be noted that to automate the process, the authors are currently developing software (*TrainChecker*) that can determine the maximum tractive weight for a given line, which will increase freight transport profitability, reduce costs, and minimize negative environmental impacts (Fig. 9).

It should be emphasized that the literature contains a significant number of errors concerning the relationships between train running resistance. The discrepancies with the original data concern both the values of individual coefficients and the units used.

In summary, it should be noted that a tool for optimization was developed (i.e., increasing transport capacity on a given railway line with a given locomotive characteristic). It is also possible to use the algorithm as a tool for verifying a train's capability to pass with a given gross weight.

Simultaneously, the motion resistance models available in the literature were verified, and a model was selected that best represented the actual passage on the selected railway line. Additionally, the parameters of the selected motion resistance model were optimized to achieve a better representation of the vehicle's passage on the tested railway line section. A preliminary version of the software was developed for the resulting numerical model.

5. POSSIBILITIES AND BARRIERS OF IMPLEMENTATION IN THE EUROPEAN UNION AND WORLDWIDE

Based on the analysis, the presented computational method and analytical tool, enabling the assessment of the possibility of a train passage under specific technical parameters and with reference to selected models of motion resistance, have potentially wide applications not only in domestic conditions but also internationally. Their concept aligns with the strategic directions set out in the European Commission's "Greening Freight Package" aimed at promoting sustainable and energy-efficient rail freight [16]. In particular, it should be emphasized that this solution aligns with the directions of the European Union's transport policy, as outlined in its strategic documents, such as the White Paper on Transport, which indicates the need to increase the share of rail freight in the modal split. The analyzed algorithm and the software developed based on it may serve as instruments to support the implementation of these objectives by optimizing the operational parameters of freight trains in relation to the specific infrastructural conditions of individual railway lines. This approach corresponds with the recent findings of the European Union Agency for Railways, which highlight the role of digital tools in improving the safety and efficiency of rail operations [15]. From the perspective of European practice, it is worth noting that in Western European countries, where railway systems are highly integrated with digital technologies (e.g., Germany, France, Austria), the implementation of such solutions may proceed relatively smoothly. The tool could be integrated with existing traffic management systems (e.g., ETCS), which would provide additional synergistic effects. Similar perspectives have been emphasized by Djordjević et al. [18], who analyzed the operational efficiency of European freight corridors in the context of technological modernization. The authors indicated that the implementation of digital tools, such as automatic couplers, intelligent wagons, and predictive maintenance systems, significantly improves corridor throughput and reliability. These technologies, combined with optimization algorithms similar to the one presented in this paper, create synergistic effects that enhance freight train performance, reduce delays, and increase the competitiveness of rail freight in Europe. Furthermore, due to the growing importance of intermodal transport and the priority role of the TEN-T corridors, a method that allows for the quick and precise determination of the maximum gross train weight for given line conditions could become a valuable support in planning international freight flows.

However, the application of the analyzed method is not limited to the European Union. In North America, where heavy haul freight trains exceeding 10,000 tons in mass and 2 km in length dominate, the algorithm could serve as a tool for optimizing train load and configuration with respect to diverse line profiles, particularly on mountainous routes. In Asia, particularly in China and India, the dynamic development of both high-speed rail and bulk freight transport creates favorable conditions for implementing such analytical tools. They could support fleet management and transport planning in regions with highly variable infrastructure quality. Finally, in South America and Africa, where the process of railway infrastructure modernization is still ongoing, the method could be applied to verify the actual transport capabilities of lines with limited technical parameters.

Nevertheless, the potential implementation of the method is associated with several barriers. The most significant include the lack of a uniform and publicly available dataset, particularly regarding locomotive tractive characteristics, which are often treated as industrial secrets. The diversity of technical standards, including track gauges, permissible axle loads, or geometric parameters of lines, requires local adaptation of the algorithm. Moreover, the current version of the model has limitations, such as the absence of braking force calculations, variable speed considerations, or weather effects, which may restrict its direct applicability in operational environments without further development.

At the same time, considerable opportunities should be emphasized. Firstly, the algorithm aligns with the global trend of railway sector digitalization and the development of "smart rail," which drives the demand for analytical tools supporting decision-making processes. Its use could enhance the competitiveness of rail transport against road transport by lowering freight costs and improving the utilization of available capacity. From the perspective of the EU climate policy and global decarbonization goals, this tool may be considered a significant element supporting the achievement of environmental targets, and thus benefits from vast opportunities for public and European funding. The discussed method and developed tool represent a solution with strong application potential, the implementation of which in the European and global context could significantly contribute to the improvement of efficiency, safety, and competitiveness of railway transport. However, the full exploitation of this potential requires the further development of the algorithm, the elimination of existing simplifications, and the provision of reliable and standardized input data.

The proposed method is based on generally accepted resistance models. To apply this method to infrastructure other than the one being tested, one should use one of the resistance models specified by the authors (Figs. 6 and 8 – CNTK(2)) for a given railway infrastructure or implement their own model. Selecting a resistance model for a given railway infrastructure enables a more accurate determination of the maximum load for the railway line being tested.

6. CONCLUSIONS

This study aimed to present an algorithm capable of estimating the feasibility of train passage on infrastructure with specific technical parameters. This objective was achieved by developing a computational solution that enables the determination of motion resistance and verification of traction capacity. The algorithm was implemented as a spreadsheet to provide general accessibility and transparency of use, thus allowing railway stakeholders to perform preliminary assessments of train operation feasibility under defined conditions.

A critical contribution of the work is the verification of various train motion resistance models available in the literature. The comparative analysis demonstrated significant divergences in the predicted resistance values, particularly in the low-speed range, which is crucial for freight operations on lines with restrictive gradients and curvature. The assessment revealed that the CNTK (1) model provided the closest correspondence to experimental results, and further parameter adjustments (CNTK (2)) enhanced the accuracy of representation. This outcome highlights the importance of calibrating theoretical models against empirical data to ensure reliability in practical applications.

The developed method and software provide a practical foundation for decision-support tools used by railway operators and infrastructure managers. The results confirmed that the CNTK (2) model offered the best alignment with real-world data, emphasizing the importance of calibrating theoretical resistance models against empirical measurements. This ensures reliable application of the algorithm in assessing train-passage feasibility under varying infrastructural and operational conditions.

Future work should expand the algorithm to include braking force, variable speed profiles, and weather conditions. In addition, integrating the tool with digital railway systems could enhance its operational value and contribute to the broader European goals of increasing rail freight efficiency and reducing environmental impact.

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