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Railway Transport Planning and Management

Edited by Stefano de Luca, Roberta Di Pace and Chiara Fiori

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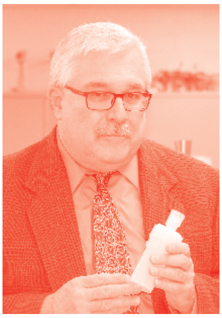



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Meet the editors

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Contents

Preface

Railways are the backbone of any transportation system and essential elements for environmental sustainability and the social equity of transport.

Currently, railway engineering is facing different and complex challenges due to the growing demand for travel, the new technologies, and new mobility paradigms that are significantly changing the "railway world."

Today, it is more important than ever to better understand revolutions in technology to develop and test effective and efficient approaches to address and integrate technologies and infrastructures within the planning, design and management of transportation systems.

All these issues require a clear knowledge of the pros and cons of the traditional transportation planning methodologies, existing technologies, and robust theoretical frameworks and should be supported by reliable and transferable validation tests.

This book examines railway systems from different perspectives of planning, management, performance analysis, and sustainable solutions (e.g., the use of hydrogen as fuel).

The book is organized into five chapters.

Chapter 1 proposes a methodology for selecting a transport strategy for railway passenger transport development. Specifically, the chapter applies Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) analysis and Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis integrated with multiple-criteria decision-making (MCDM). The proposed methodology is composed of five stages. The first stage formulates the alternatives of the policies for railway managers. The criteria in each PESTLE group are defined in the second stage (twenty-four criteria are studied). In the third stage, the SIMUS method based on linear programming is applied to rank the alternatives and assess the criteria in PESTLE groups. In the fourth stage, different multi-criteria approaches (distance-based, utility-based, and outranking methods) are implemented to get a final ranking. In the fifth stage, PESTLE analysis is combined with SWOT analysis for strategic planning. In particular, the chapter presents the integration of PESTLE with technical, economic, technological, and environmental (TETE) analysis. Finally, the chapter presents a case study on the Bulgarian railway network and evaluates and compares three strategies of railway transport development.

Chapter 2 describes the cognitive biases that may be found in the railway transport planning and management domain. Cognitive biases in the planning of railway projects lead to cost overruns and failure to achieve performance and fulfill safety objectives, as is noted in the economics, business management, and risk management literature. Unbiased decision-making is a key aim of systems engineering, encouraging careful consideration of stakeholder needs, design alternatives, and programmatic constraints and risks. Nevertheless, systems engineering practices dealing with railway transport planning and management fields do not pay attention to the human and organisational factors at the initial stages of planning. Results show that the Guide to Railway Investment Process (GRIP) (2019) has no provision for incorporating measures to address deficiencies raised by accident or safety analysis reports because the RSSB Taking Safe Decisions Framework does not include all the heuristics and the biases that usually occur and that may be used for taking decisions.

Chapter 3 proposes an analysis of the methods used in diagnostics of railway lines. Complex diagnostics of railway lines involves techniques based on discrete and continual data acquisition. While discrete measurements belong to conventional methods, the modern continual ones use automated robotized instruments with continuous recording. Even if observations have become more time-efficient, the processing epoch has become longer to evaluate a large amount of data. Railway line diagnostics are realized by methods to determine relative track parameters such as track gauge, elevation, and track gradients. Absolute, geodetic techniques determine directional and height ratios of the track, defined in a global coordinate and height system.

Chapter 4 investigates new methods for monitoring the dynamic processes of rolling stock/rail interaction and shows a new technical solution for measuring the wheel/rail interaction forces on a significant part of the sleeper. The adoption of the Finite Element Method (FEM) confirms the ability of piecewise continuous recording of vertical and lateral forces from the wheel/rail interaction by measuring the stresses in two sections of the rail. It also determines the optimum location of strain gauges and the effective length of the measuring zone. Additionally, the experiment confirms the effectiveness of the method to determine the vertical and lateral wheel/rail interaction forces and, at the same time, increases the statistical reliability of the data, improves the measurement accuracy, and reduces the time and cost as compared with current testing methods. Finally, the developed method is recommended to determine the wheel/rail interaction forces and identify defects on the wheels when diagnosing rolling stock on operational and travel regimes.

Chapter 5 focuses on hydrogen as a rail mass transit fuel. It provides an overview of methods to generate hydrogen, power drives (fuel cells and hydrogen internal combustion engine), location of the hydrogen generators and H2 transmission to users, safety and codes, and hydrogen-fueled trains. It also gives some examples of possible decarbonized trains in Australia, the United Kingdom, the United States, and Saudi Arabia together with an emission and fuel costs comparison.

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Chapter 1

An Integrated Approach of Strategic Planning and Multi-Criteria Analysis to Evaluate Transport Strategies in Railway Network

Svetla Stoilova

Abstract

This chapter presents a methodology for selecting transport strategy for railway passenger transport development. The strategic planning, as Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) analysis and Strengths - Weaknesses – Opportunities - Threats (SWOT) analysis integrated with Multiple-criteria decision-making (MCDM) have been applied as a tool to make decision. The proposed methodology consists five stages. The first stage formulates the alternatives of the policies for railway manager. The criteria in each PESTLE group have been defined in the second step. The total number of 24 criteria has been studied. In third stage, the SIMUS method based on linear programming has been applied to rank the alternatives and assess the criteria in PESTLE groups. The fourth stage represents the ranking by application the different multi0criteria approaches as distance based, utility based and outranking methods to make decision. The combination the PESTLE analysis with SWOT analysis for strategic planning is done in the fifth stage. The integration of the PESTLE with technical, economic, technological and environmental (TETE) analysis in presented. The application of methodology has been demonstrated with an example for Bulgarian railway network. Three strategies of railway transport development have been evaluated and compared. It was found that the most important are the political (0.29), social (0.25) and technological (0.25) groups in PESTLE analysis.

Keywords: PESTLE, SWOT, MCDM, multi-criteria analysis, SIMUS, TOPSIS, EDAS, MOORA, COPRAS, PROMETHEE, railway transport planning

1. Introduction

The development of railway transport is related to strategic planning and selection of one or another strategy for the development of the railway infrastructure, railway services and rolling stock. The railway managers need to choose the most appropriate development strategy between set of alternatives. This is a complex process in which it is necessary to take into account a set of factors that have to accounted both the expectations of users of railway services and the capabilities of railway operators and the possibilities of investment in railway transport. The strategic planning methods are a powerful tool for analyzing groups of criteria. Such approaches are Strengths – Weakness – Opportunities – Threats (SWOT), Political, Economic, Social and Technological, Legal and Environmental (PESTLE), PESTEL, and others. The SWOT method is a useful procedure to determine the internal and external influences on the investigated system. The PESTLE or PESTEL analysis is more waste and helpful and as compare to the SWOT analysis. It provides the environmental factors to tackle the problems. An integration between these techniques also it is possible. The strategic planning approaches help managers formulate and analyze criteria in each of the groups. Appropriate techniques for assessing the criteria and their influences, as well as for selecting a suitable alternative for development, are the methods of Multi Criteria Decision Making (MCDM). The different multi-criteria decision-making methods have been applied to study various transport problems. In general, the multi-criteria methods can be summarized as follows: Pair-wise comparisons; Distance based; Utility based; Outranking; Linear programming based. Some of multi-criteria methods can be used only to determine the weights of criteria; others serve ranking the alternatives, by setting the weights of the criteria; third solved weights of criteria by applying expert's assessment and scale of evaluating, and also ranking the alternatives. The Sequential Interactive Modeling for Urban Systems (SIMUS) method is a different multi-criteria approach applied linear programming and does not used the weights of criteria for ranking the alternatives. The use of one or another method depends on the decision maker according the problem to be solved.

The aim of this research is to increase the level of decision making by integrating the advantages of strategic planning as PESTLE and SWOT analysis with the advantages of the multi-criteria methods to assess the influence of criteria and evaluate the alternatives of strategic planning. The proposed techniques could help transport managers in their analysis and decisions when chose a suitable strategy in railway transport development. In this study different multi-criteria analysis techniques have been experimented and discussed as a tool for integration with PESTLE-SWOT approach.

This chapter represents a case study for Bulgarian railway network and railway passenger transport. The Bulgarian railway network is a part of TEN-T network. The current situation shows that the average technical speed of passenger trains is one of the lowest in Europe. The railway infrastructure is in process of rehabilitation in order to increase the safety and technical speed of railway sections and lines. The existing rolling stock have low quality and capabilities and have to be renewed and modernized. The existing structure of trains by types could be improved through implementation of new type of trains. Three strategies for improvement of the Bulgarian railway transport development have been assess in this chapter based on proposed integrated approach PESTLE - SWOT- MCDM.

The structure of the chapter is as follows: Section 2 shows literature review; Section 3 provides the methodology of research. Different multi-criteria approaches are included in methodology. The linear programming approach as SIMUS method, the distance-based approach as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and evaluation based on distance from average solution (EDAS) methods, the utility-based approach as multi-objective optimization on the basis of ratio analysis (MOORA) and COmplex PRoportional ASsessment method (COPRAS) methods, and outranking approach as Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method are represented. The integration of PESTLE-SWOT-MSDM is shown. Section 4 shows the obtained results for Bulgarian railway network and discussion. Finally, Section 5 provides the conclusions.

2. Literature review

The methods of strategic planning as SWOT, PEST and its modification as STEEP, PESTLE, PESTEL, STEEPLE or others have been applied in the following ways:

- Analysis the sub-criteria in SWOT, PESTLE, or other modification of strategic planning methods groups;
- Combination of PESTLE and SWOT analysis in order to expand the analysis of defined sub-criteria. This approach serves also for identifying the internal and external factors that influence a given system.
- Integration of the PESTLE (SWOT) analysis with multi-criteria analysis methods to determine the weights of sub-criteria in each PESTLE (SWOT) group. This approach is used to identify the sub-criteria that have the main impact of the investigated system.
- Ranking of alternatives based on SWOT (PESTLE) sub-criteria. The determination of the weights of sub-criteria and the ranking is performed by using multi-criteria analysis methods.

Some authors used the strategic management techniques as SWOT, PESTLE or others as a tool to analyze the studied system with purpose to strategic planning. The weights of the criteria in these cases are not determined. The PESTLE analysis has been implemented to analyze of the suborbital flight operation [1]; to determine the weak signals classification to detect threats and opportunities from web [2]; to analyze the renewable energy sector environment [3]. The integration of PESTLE and SWOT analysis is presented in [4] to analyze the Renewable Energy for Island Countries. The PESTEL analysis has been used for assessing the situation of Polish transport enterprises [5]. Some authors consider only the problem with the formulation of the SWOT factors. The SWOT analysis have been conducted to of railway freight transport [6]; of China's High-speed Rail [7]; to develop city public transport strategies [8]; to study the automobile reverse logistics [9]; to analyze the underground pedestrian systems [10].

The PESTLE framework has been also integrated with the methods to decision making and multi-criteria analysis. In [11] the integration of PESTEL analysis and AHP method has been applied to select an optimal location of logistic hubs. The green building industry in Turkey has been assessed by using PESTLE analysis and fuzzy model of the macro-environmental assessment, [12]. The PESTLE analysis and Multi Attribute Value Theory (MAVT) method have been integrated to study Carbon Capture and Storage process, [13]. The unconventional modes of transport have been analyzed based on PESTLE, and an AHP-TOPSIS approach, [14]. The SWOT/PESTLE analysis has been applied to investigate the water system in Serbia [15]; for Port Energy Management System to define the positive or negative effect, [16].

The city's transportation system strategies were evaluated and prioritized based on SWOT analysis and fuzzy complex proportional assessment (COPRAS) method [17]. An integrated SWOT – FUZZY PIPRECIA model was formed to analyze and improve logistics performances for transport of goods [18]. Some of the researchers combined the SWOT analysis with Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP) methods. This approach has been used to study the strategy of development of railway transport in West Africa [19]; to study different mode of transport to determine the transport strategy [20]; to analyses the Long-

Distance Passenger Transportation on a Highway Network [21]; to investigate urban planning [22]; for energy automobile industry [23]. Other authors used an integration of more multi-criteria methods with SWOT analysis, [24–26]. In these cases, one method is used to determine the weights of criteria, and another method is applied to assess the alternatives.

3. Methodology

The methodology of the research consists fifth stages, **Figure 1**:

- First stage: Formulation the alternatives of the policies for railway operator.
- Second stage: Definition of the criteria in PESTLE groups. The initial decision matrix represented the values of each criterion for each alternative is formed.
- Third stage: The SIMUS method is applied to rank the alternatives and assess the criteria in PESTLE groups. The criteria significance is dependent on the set of alternatives to evaluate. It is a similar concept to using Shannon entropy, to evaluate criteria weights.

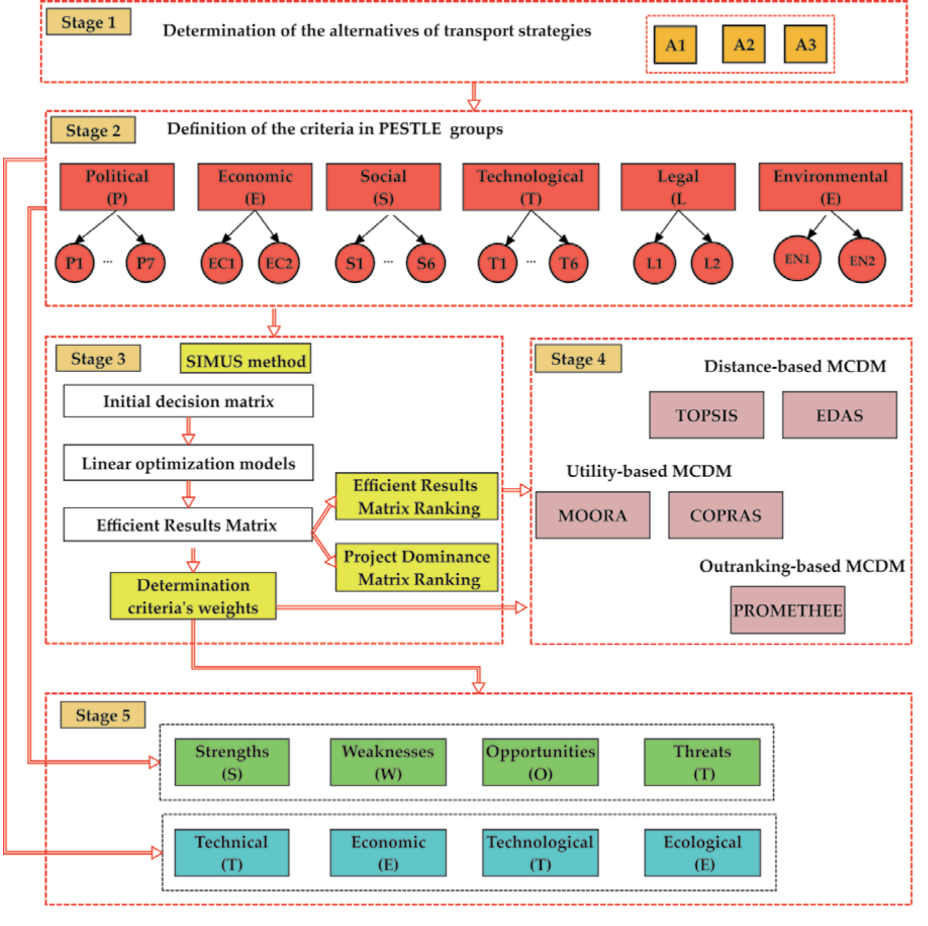

Figure 1.
Scheme of methodology.

- Fourth stage: Ranking by application the following distance based multi-criteria methods: TOPSIS and EDAS, utility based multi-criteria methods: MOORA and COPRAS; and outranking approach PROMETEE. These multi-criteria methods have different techniques versus SIMUS method. They have been selected to compare the results of PESTLE – SIMUS approach with the integration of PESTLE with other multi-criteria approach. Because these methods use the weights of criteria, they have been taken into account as equal to these determined by SIMUS method.

- Fifth stage: Combination the PESTLE analysis with other analysis for strategic planning. This serves to determine the weights of the main groups criteria of the compared types of analysis. The methodology consists two types of combination: (a) combination the PESTLE analysis with the SWOT analysis. For this purpose, the interpretation of the PESTLE criteria as SWOT criteria is formed. (b) Combination the PESTLE analysis with the technical, economical, technological and ecological (TETE) group criteria.

3.1 Determination of the alternatives

The alternatives represent strategies of the railway manager about the development the railway transport. The case for Bulgarian railway is considered as follows: there are three alternatives, or strategies, the first of which is to maintain the state of affairs as it is; the second, to replace the rolling stock only on some lines of the network, which is a partial improvement; the third, partial improvement on some lines with replacement of some of the rolling stock and also partial improvement of the railway infrastructure.

The characteristics of the alternatives are presented as follows:

A1 – Reconstruction on railway infrastructure. This mean rehabilitation of railway sections and railway lines to increase transport speeds and safety. This process is carried out in accordance with national transport programs.

A2 - New rolling stock on some lines. It means a staged update of rolling stocks, decommissioning of depreciated and obsolete rolling stock. This strategy takes also into account the reconstruction of railway infrastructure.

A3 –Introduction of new services. In this research, a strategy for the service “car on the train” named also motorail trains is proposed. The motorail trains offer service at which passengers can take their car along with them on their journey. The passengers are carried in the train, while the cars are loaded separately in specialized wagons of the same train. This strategy takes also into account the reconstruction of railway infrastructure.

3.2 Defining the criteria in PESTLE groups

The PESTLE analysis consists Political, Economic, Social, Technological, Legal and Environmental factors that have an impact on the investigated alternatives. A PESTLE analysis helps to understand the business and strategically position of the investigated system. In this study the criteria in PESTLE groups can be defined as quantitative and qualitative. The quantitative criteria are set with their values for each of the studied alternatives. The quality criteria are set in the following ways: with a scale for evaluating the performance of the criterion or by using the answer “yes” or “no”. In the first case, the following rating scale is proposed: 0, 1, 2 or 3. The value “0” indicates non-fulfillment of the respective indicator; a value of “1”, “2” or “3” means low, medium or high performance respectively. In the second case, if the answer is “yes” - “1”is written, otherwise - “0”.

In this study the following criteria in PESTLE groups are proposed:

Political (P) with the following criteria:

P1 - Increasing the quality of railway infrastructure. This means some reconstructions in railway infrastructure to increase the operating speed of the trains. The possible values of this criterion are 1 or 2. The values of "1" means increase of the admissible speed of the railway. The value of "2" means that the investigated alternative allows an increase in the permissible speed also by the rolling stock. The objective of this criterion is of maximum.

P2 - Development of the TEN-T network. This means the development the core TEN-T network in Bulgaria through the implementation of European programs and projects for the development of railway junctions, railway nodes, railway section, harmonization the Bulgarian 'railway system with the European ones. The possible values of this criterion are 1 or 2. The values of "1" means increase of the development of the railway infrastructure core TEN-T network in Bulgaria. The value of "2" means development the harmonization of the railway system with European railway. The new rolling stocks allows the introduction of new systems for electronic on-board system of locomotives and the development of the European railway traffic management system. The objective of this criterion is of maximum.

P3 – Modernization of the rolling stock. This means purchasing the new locomotives, new type of wagons and electric multiple units to operate in some railway routes. The possible values of this criterion are 1, 2 or 3. The values of "1" means carriage with existing rolling stocks, some modernization in locomotives could to be done. The values of "2" means implementation of the new locomotives and electric multiple units to operate in the main railway routes; the values of "3" means implementation of new type of wagons for carriage the cars. The objective of this criterion is of maximum.

P4 - Increasing the quality of road infrastructure. The road transport is competitive with the railway transport, especially on parallel routes. Improving the quality of road infrastructure makes it possible an increase of the speed of cars and busses. The possible values of this criterion are 0 or 1. Value 1 shows benefit of carriage for road operators. Value "0" shows benefit of carriage for railway operators. The quality of railway transport services increases when offering comfortable, high-speed and safe transport. The objective of this criterion is of minimum.

P5 - Delayed purchase of rolling stock. This means a delay in the scheduled purchasing time due to financial and other reasons. The values of this criterion are 0 or 1. The value "0" is set for alternatives which do not depend on the purchase of new rolling stock. The value of 1 indicates lack of purchase of rolling stock or delay in the purchase plan. The objective of this criterion is of minimization.

P6 - National policy for priority railway transport development. This means that the state should prioritize railway transport by assisting in the financing of railway infrastructure projects and the renewal of rolling stock. The values of this criterion are 0 or 1. The value "0" is set when the national policy is aimed at infrastructure projects for railway rehabilitation. The value "1" means that the expanding national policy by investing in the modernization of rolling stock and trains. The objective of this criterion is of minimum.

P7 - Development of intercity railway transportation. This means development the network of intensity trains with increasing speed. The values of this criterion are 0 or 1. The intercity trains suggest comfort, security and high-quality service between major cities in the railway network. The value "0" is set when only some reconstructions in railway line is met. The value of "1" means the high quality of intercity railway service. The objective of this criterion is of maximum.

Economic (EC) with the following criteria:

EC1 - Operating costs (EUR/day). The operating costs depend on the number of trains. They include the costs for train movement (electricity), costs for maintenance and repair of rolling stock, costs for locomotive crew, depreciation costs and other operating costs, and also the infrastructure charge. The costs for investments for rolling stock, as well as for reconstruction are not taken into account. The objective of this criterion is of minimization.

EC2 - Additional fees for loading and unloading operations. These fees are connected with motorail trains for loading and unloading the cars. The values of this criterion are 0 or 1. The value "0" is set when no service is offered with motorail trains. The value "1" means presence of motorail services. The objective of this criterion is of minimum.

Social (S) with the following criteria:

S1 – Security. The values of this criterion are 1, 2 or 3, which show the level of security. The reconstructions on railway infrastructure, the modernization the rolling stocks, the introduction the motorail services increase the level of security of transport. The larger number indicates the availability of more security in railway service. The objective of this criterion is to maximize security.

S2 – Reliability. This criterion is assessed as 1, 2 and 3. The renovation of the railway lines increase the reliability. The modernization of the rolling stock increases also the reliability of transport. The motorail trains also increase additionally the ratability od railway transport taken into account that the cars carried by trains reduce the traffic on the road infrastructure. The larger number indicates the availability of more reliability in railway service. The objective of this criterion is of maximum.

S3 – Comfort. This criterion is assessed as 1, 2 and 3. Travel comfort is expressed by ensuring the convenience of traveling in clean, renovated or renewed rolling stock. The comfort also increases when the motorail service is added because the drivers could use their free time to rest. The larger number indicates the availability of more comfort in traveling. The objective of this criterion is of maximum.

S4 – Additional services. The values of this criterion are 0, 1 or 2. The new rolling stock has equipment with modern information systems, and WIFI networks in the trains. The motorail trains offer the carriage the cars of the passengers. The larger number indicates the availability of more additional services. The objective of this criterion is of maximization.

S5 - Position in the transport market (quality). This criterion can have values 1, 2 or 3. The position of the railway transport on the market of transport services increases, with the improvement of the condition of the rolling stock and the railway infrastructure. The larger number shows a higher position in the transport market. The objective of this criterion is of maximization.

S6 – Transport in certain months. The values of this criterion are 0 or 1. The motorail services usually applied during the summer months, mine are associated with an increase in tourist travel. The objective of this criterion is of minimum.

Technological (T) with the following criteria.

T1 - Frequency, pair trains/day. The number of trains increase when the new rolling stocks is added. The objective of this criterion is of maximization.

T2 – Average operating speed, km/h. This criterion is determined according all fast and high-speed trains in the railway network. The increase of the operational speed is achieved with the reconstruction of the infrastructure and also the modernization of rolling stock. The value of average operating speed increases when there are conditions for some trains to run at high speed. The objective of this criterion is of maximization.

T3 – Directness. This criterion means services with a reduced number of intermediate stops. This criterion may have the following values: 0 or 1. The value "0" means lack of direct trains with increased speed. The introduction of direct express intercity trains, which have reduced stops in only a few places along the route, allows to increase the directness of the journey, to reduce its duration between stations, as well as for the entire route. The value “1” means presence of direct trains with increased speed. The objective of this criterion is of maximization.

T4 - Total travel time. This criterion includes the time for travel and the tome for acceptance and loading of cars in specialized wagons in motorail train composition. This criterion may have the following values: 0 or 1. The value “1” means increased total time due to motorail service; the value “0” is set when such service is not available. The objective of this criterion is of maximization.

T5 – Frequency of motorail trains. This criterion shows the number of pairs motorail trains per day. The objective of this criterion is of maximization taken into account that such service increases the transport satisfaction of the passengers of railway services. The objective of this criterion is of maximization.

T6 – Transport door-to-door. This means the possibility for passengers to travel with their own car from their home to the start railway station, then to load the car on the specialized wagon, and at the final railway station the car is unloaded and the passenger continues his journey with his own car to the final destination. This criterion may have the following values: 0 or 1. The value “1” means service door-to-door; the value “0” is set otherwise. The objective of this criterion is of maximization.

Legal (L) with the following criteria.

L1 - Possibility of increase the level of European Rail Traffic Management System (ERTMS) system. This criterion may have the following values: 0 or 1. ERTMS is a train signaling and traffic management system, created to assist interoperability by using a unique signaling and communication standard throughout Europe. There are three levels of the application of ERTMS depending on the need for existing railway infrastructure. The value “1” shows increase the level of ERTMS taking into account the level of communication system in locomotives and moving block technology. The objective of this criterion is of maximization.

Environmental (EN) with the following criteria.

EN1 - CO2 emissions. The values of CO2 emissions are calculated according the electricity generation for movement of the trains, t/MWhe.

EN2 - Saved CO2 emissions. This criterion takes into account the CO2 emissions saved by cars when transported in a specialized wagon. The value depends on the number of motorail trains.

3.3 SIMUS method

The SIMUS method is based on Linear Programming, Weighted Sum and Outranking, [27]. This approach considered the criteria as objectives in Linear optimization models. The first step of the method consists of the forming the initial decision matrix with alternatives in the columns and criteria in the rows. In the next step the normalization of the initial decision matrix is made by applying some of the normalizing procedures. In the third step, the linear optimization models are formed taken into account each criterion as objective and the optimal scores for the alternatives are determined. The results are placed in an Efficient Result Matrix (ERM). This matrix is considered as a new decision matrix, composed of the optimal values. The next step consists ranking the alternatives. The SIMUS uses two different multi-criteria procedures to rank the alternatives - Weighted Sum method and outranking approach. The first approach is called ERM ranking and is based on ERM matrix; the second ones is called Project Dominance Matrix (PDM) ranking and uses a new matrix which is formed based on ERM matrix. The results of both methods give the same ranking. This allows the result to be validated. The SIMUS method give also the marginal utilities for each criterion, and allow to determine the robustness of the solution. For this purpose, the ERM matrix is used to determine the weights of criteria. Determining the weights of the criteria allows the decision maker to assess their impact on the investigated system. The values of criteria are not used when ranking the alternatives.

3.4 TOPSIS method

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is based on the principle that best alternative should have the shortest distance from the ideal solution and farthest distance from the negative ideal solution. TOPSIS consists the following steps, [28]:

Step 1: Determination the decision matrix $(\boldsymbol{x_{ij}})_{\boldsymbol{nxm}}$ consisting of n alternatives and m criteria. Calculation of normalization matrix $(\boldsymbol{r_{ij}})_{\boldsymbol{nxm}}$. The values of normalization matrix are:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}, i = 1, \dots, n; j = 1, \dots, m \tag{1}$$

where: $i = 1, \dots, n$ is the number of alternatives; $j = 1, \dots, m$ is the number of criteria.

Step 2: Calculate weighted normalized matrix $(v_{ij})_{mxn}$. The elements of this matrix are:

$$v_{ij} = r_{ij}.w_j; \sum_{j=1}^{m} w_j = 1 \tag{2}$$

where: w_j is the weight of criterion j.

Step 3: Calculate the ideal best v_j^+ and ideal worst v_j^- value for each criterion j.

$v_j^+ = \min_i v_{ij}$ for non-benefits criteria; $v_j^+ = \max_i v_{ij}$ for benefits criteria.

$v_j^- = \max_i v_{ij}$ for non-benefits criteria; $v_j^- = \min_i v_{ij}$ for benefits criteria.

Step 4: Determination the Euclidean distance from the ideal best D_i^+ solution and the Euclidean distance from the ideal worst D_i^- solution.

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^+\right)^2}; D_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2} \tag{3}$$

Step 5: Calculate Performance Score C_i that presents the relative closeness of each alternative i with reference to negative ideal measure D_i^- as follow:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}; 0 \le C_i \le 1 \tag{4}$$

The ranking of the alternatives is based on the C_i values. The best alternative based on the Performance Score has the highest assessment value.

3.5 EDAS method

EDAS method determines the optimal alternative based on the higher distance from the nadir solution and lowest distance from the ideal solution. The EDAS method consists the following steps, [29]:

Step 1: Determination the decision matrix $(x_{ij})_{nxm}$ consisting of n alternatives and m criteria.

Step 2: Determination the average solution according to all criteria.

$$AV_j = \frac{\sum_{i=1}^{n} x_{ij}}{n} \tag{5}$$

Step 3: Determination the positive (PDA_{ij}) and the negative distance (NDA_{ij}) from average matrices

$$PDA_{ij} = \frac{\max\left(0, \left(x_{ij} - AV_j\right)\right)}{AV_j}, \text{for beneficial criteria} \tag{6}$$

$$PDA_{ij} = \frac{\max\left(0, \left(AV_j - x_{ij}\right)\right)}{AV_j}, \text{otherwise} \tag{7}$$

$$NDA_{ij} = \frac{\max\left(0, \left(AV_j - x_{ij}\right)\right)}{AV_j}, \text{for beneficial criteria} \tag{8}$$

$$NDA_{ij} = \frac{\max\left(0, \left(x_{ij} - AV_j\right)\right)}{AV_j}, \text{otherwise} \tag{9}$$

Step 4: Determination of the weighted sum of positive (SP_i) and negative (SN_i) distance:

$$SP_i = \sum_{j=1}^{m} w_j PDA_{ij}; SN_i = \sum_{j=1}^{m} w_j NDA_{ij} \tag{10}$$

Step 5: Normalization of the weighted sum of positive (NSP_i) and negative (NSN_i) distance as follows:

$$NSP_i = \frac{SP_i}{max_i(SP_i)}; NSN_i = 1 - \frac{SN_i}{max_i(SP_i)} \tag{11}$$

Step 6: Determination the appraisal score. The ranking is according to the decreasing values of appraisal score. The optimal alternative based on the appraisal score has the highest assessment value.

$$AS_i = \frac{1}{2}(NSP_i + NSN_I); 0 \le AS_i \le 1 \tag{12}$$

3.6 MOORA method

The multi-objective optimization on the basis of ratio analysis (MOORA) method uses both beneficial and non-beneficial objectives (criteria) for ranking the alternatives. This method is based on ratio system. The MOORA method is utility-based method and consists the following steps, [30]:

Step 1: Determination the decision matrix $(x_{ij})_{nxm}$ consisting of n alternatives and m criteria.

Step 2: The ratio represented the normalized performances x_{ij}^* of i-th alternative on j-th criterion is determined as follows:

$$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}, i = 1, \dots, n; j = 1, \dots, m; 0 \le x_{ij}^* \le 1 \tag{13}$$

Step 3: Determination the normalized performances in the case of maximation (for beneficial criteria) and the normalized performances in the case of minimization (for non-beneficial criteria). The optimal alternative based on the ratio system has the highest assessment value. The y_i value can be positive or negative. When the criteria weights are taken into account, they are added in the Eq. (13).

$$y_i = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{m} x_{ij}^* \tag{14}$$

Where: y_i is the total assessment of alternative j which can be positive or negative; g is the number of criteria to be maximized, $(n - g)$ is the number of criteria to be minimized.

3.7 COPRAS method

The COPRAS method uses simple evaluating procedure to determine the influence of maximizing and minimizing criteria on ranking the alternatives. The best alternative is based on both the ideal and the anti-ideal solutions. The COPRAS method is utility-based method and consists the following steps, [31]:

Step 1: Determination the decision matrix $(x_{ij})_{nxm}$consisting of n alternatives and m criteria.

Step 2: Normalization of the decision matrix. The elements are calculated as follows:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{15}$$

Step 3: Determination of the weighted normalized matrix $(\hat{x}_{ij})_{nxm}$. For this purpose, the elements of the normalized matrix are multiplicated by the weight to the corresponding criterion.

Step 4: Determination of the maximizing index $P_i$and minimizing index R_i

$$P_i = \sum_{i=1}^{k} \hat{x}_{ij}; R_i = \sum_{i=k+1}^{n} \hat{x}_{ij} \tag{16}$$

Where: k is the number of criteria which is to be maximized, $(n - k)$ is the number of criteria to be minimized.

Step 5: Determination of the relative weights of each alternative. The best alternative is based on the highest the relative weights.

$$Q_i = P_i + \frac{\sum_{i=1}^{n} R_i}{R_i \sum_{i=1}^{n} \frac{1}{R_i}} \tag{17}$$

3.8 PROMETHEE method

The Preference ranking organization method for enrichment evaluation (PROMETHEE) method is outranking approach in multi-criteria analysis. The explanation and mathematical calculation steps of the PROMETHEE method are summarized below [28]:

Step 1: This step computes, for each pair of possible decisions and for each criterion, the value of the preference degree.

Step 2: This step consists of aggregating the preference degrees of all criteria for each pair of possible decisions.

Step 3: This step includes the computing of the outranking flows. For each possible decision the positive outranking flow $\varphi^{+}(a_i)$ and the negative outranking flow $\varphi^{-}(a_i)$ are computed. The positive outranking flow expresses how much each alternative is outranking all the others. The negative outranking flow expresses how much each alternative is outranked by all the others.

Step 4: In this step the net outranking flows $\varphi(a_i)$ of a_i in the alternatives set m of a possible decision are determined as a difference between $\varphi^{+}(a_i)$ and $\varphi^{-}(a_i)$. The optimal alternative is determined by the maximum value of net outranking flows, which corresponds to the alternative with highest priority.

For net outranking flow, the following conditions are valid:

$$\varphi(a_i) \in [-1; 1]; \sum_{i=1}^{n} \varphi(a_i) = 0 \tag{18}$$

3.9 Combination the PESTLE analysis with other analysis for strategic planning

The fifth stage of methodology consists a combination of the PESTLE analysis with other analysis for strategic planning as SWOT technique. In this chapter is

PESTLE	Criteria	S	W	O	T	PESTLE	Criteria	T	E	T	E
	P1			x			P1	x			
	P2			x			P2	x			
P	P3			x		**P**	P3	x			
	P4				x		P4	x			
	P5				x		P5		x		
	P6			x			P6			x	
	P7			x			P7			x	
E	EC1		x			**E**	EC1		x		
	EC2		x				EC2		x		
S	S1	x				**S**	S1	x			
	S2	x					S2	x			
	S3		x				S3			x	
	S4		x				S4			x	
	S5		x				S5			x	
	S6			x			S6			x	
T	T1		x			**T**	T1			x	
	T2		x				T2			x	
	T3		x				T3			x	
	T4		x				T4			x	
	T5		x				T5			x	
	T6			x			T6			x	
L	L1			x		**L**	L1	x			
E	EN1	x				**E**	EN1				x
	EN2			x			EN2				x

Table 1.
Interactions between PESTLE, SWOT and TETE analysis.

studied also the integration between PESTLE and technical, economic, technological and environmental (TETE) group criteria. This serves to determine the weights of the main groups criteria of the compared types of analysis. **Table 1** represents the interactions between PESTLE and SWOT analysis on the one hand and between PESTLE and TETE analysis on the other hand. The symbol "x" indicate that the criterion of PESTLE is also a criterion in SWOT or TETE analysis.

4. Results and discussion

The proposed methodology is applied for Bulgarian railway network. The following categories of intercity passenger trains have been studied: fast trains, accelerated fast trains and express trains. The fast trains serve intermediate stations between cities, big transport and important administrative centers. The accelerated fast trains have mandatory seat reservations and serve major cities and transport nodes. The direct express trains have a lower number of stops in comparison to accelerated fast trains. They also have mandatory seat reservations. The alternative A1 consists two categories of trains – fast and accelerated fast trains, while alternatives A2 and A3 offers three categories of trains – fast trains, accelerated fast trains and direct express trains.

Alternative A1 is close to the current situation in which some reconstructions in railway lines are carried out according to the operational program transport for Bulgaria. The trains are composed of wagons, only some intercity trains are electric multiple units. In current situation the average technical speed of movement of passenger trains in Bulgarian railway network is one of the lowest in Europe. The movement of trains is achieved at 75 ÷ 80 km/h, and in certain areas it is limited to 40–60 km/h in order to ensure traffic safety. The express trains and accelerated fast trains in alternatives A2 and A3 are composed of novel electric multiple unit trains. Alternative A3 offer new service with motorail trains in direction Sofia - Plovdiv – Burgas (this is part of the core TEN-T network). In this case, new rolling stooks for carriage of cars are taken into account.

4.1 Application of the SIMUS procedure

4.1.1 Ranking the alternatives

The third stage of methodology includes application the SUMUS method to select the appropriate alternative. **Table 2** consists two parts. The first part represents the initial decision matrix for SIMUS procedure. This matrix consists the values of quantitative and qualitative criteria in PESTLE groups. The values of criteria P5, P6, P7, EC1, S6, T3, T4, T6 and L1 are determined using scale 0, 1. The values of criteria P1, P2, P3, S1-S5 and T5 are determined using a scale of 0, 1, 2, 3.

The number of trains for alternatives A2 and A3 increases due to the replacement of old rolling stock with new one. The alternative A2 and A3 there are an increase in electricity consumption due to increased maximum speed 100–120 km/h in the direction Sofia - Plovdiv – Burgas (this is part of the core TEN-T network). The carbon dioxide emissions for the production of electricity by the power plants also decrease.

The second part of **Table 2** shows the normalized matrix, the type of actions for each criterion, the type of the operator for the restrictive conditions, the limits called "Right Hand Side" (RHS). The normalization has been performed by using the Sum of All Values method. In general, the normalization could be made based on some of different ways. The values of the RHS are obtained from the left normalized values and the type of action. In the case of minimum, RHS is equal to

Criterion	Initial matrix			Normalized matrix			Action	Type	RHS
	A1	A2	A3	A1	A2	A3			
P1	1.00	2.00	2.00	0.20	0.40	0.40	max	≤	0.40
P2	1.00	2.00	2.00	0.20	0.40	0.40	max	≤	0.40
P3	1.00	2.00	3.00	0.17	0.33	0.50	max	≤	0.50
P4	1.00	0.00	0.00	1.00	0.00	0.00	min	≥	0.00
P5	0.00	1.00	1.00	0.00	0.50	0.50	min	≥	0.00
P6	0.00	1.00	1.00	0.00	0.50	0.50	max	≤	0.50
P7	0.00	1.00	1.00	0.00	0.50	0.50	max	≤	0.50
EC1	50807.00	51957.00	61491.00	0.31	0.32	0.37	min	≥	0.31
EC2	0.00	0.00	1.00	0.00	0.00	1.00	min	≥	0.00
S1	1.00	2.00	3.00	0.17	0.33	0.50	max	≤	0.50
S2	1.00	2.00	3.00	0.17	0.33	0.50	max	≤	0.50
S3	1.00	2.00	3.00	0.17	0.33	0.50	max	≤	0.50
S4	0.00	1.00	2.00	0.00	0.33	0.67	max	≤	0.67
S5	1.00	2.00	3.00	0.17	0.33	0.50	max	≤	0.50
S6	0.00	0.00	1.00	0.00	0.00	1.00	min	≥	0.00
T1	36.00	38.00	40.00	0.32	0.33	0.35	max	≤	0.35
T2	65.00	80.00	80.00	0.29	0.36	0.36	max	≤	0.36
T3	0.00	1.00	1.00	0.00	0.50	0.50	max	≤	0.50
T4	0.00	0.00	1.00	0.00	0.00	1.00	min	≥	0.00
T5	0.00	0.00	3.00	0.00	0.00	1.00	max	≤	1.00
T6	0.00	0.00	1.00	0.00	0.00	1.00	max	≤	1.00
L1	0.00	1.00	1.00	0.00	0.50	0.50	max	≤	0.50
EN1	23511.00	25225.00	25225.00	0.32	0.34	0.34	min	≥	0.32
EN2	0.00	0.00	2808000.00	0.00	0.00	1.00	max	≤	1.00

Table 2.
Initial decision matrix. Normalized "sum" matrix.

the minimum value of the row; in the case of maximum, the RHS value is equal to the maximum value of the row in normalized matrix. The type of operator depends on the type of objective function. In the case of maximum, the operator is "≤"; in the case of minimum, the operator is "≥".

The linear optimization models are performed by using the data in **Table 2**. For example, the first optimization linear model is formed for the first objective Z1 (criterion P1) as follows:

$$Z1 = 0.20x_1 + 0.40x_2 + 0.40x_3 \rightarrow \text{Min}, \tag{19}$$

where: x_i represents the score of each alternative, i = 1,2,3.

The restrictive conditions for the optimization model are formed by using the others rows of the ERM matrix. For example, for criterion P2, the restrictive condition is:

$$0.20x_1 + 0.40x_2 + 0.40x_3 \leq 0.40 \tag{20}$$

The restrictive conditions are formed successively using all other rows in the Normalized Sum Matrix. The final restrictive condition for the first optimization model is performed by criterion EN2 (objective Z24) based on the data in the last row in the Normalized Sum Matrix, as follows:

$$1.00x_1 + 0.00x_2 + 0.00x_3 \geq 0.00 \tag{21}$$

For all variables the following condition is set:

$$0 \leq x_1, x_2, x_3 \leq 1 \tag{22}$$

Similar optimization linear models are performed for all other criteria. The results for the scores are recorded in Efficient Results Matrix. The next step of the SIMUS procedure includes the normalization of the ERM matrix. Then two approaches are used for ranking the alternatives - weighted sum method and outranking approach. In the first approach the sum method has been applied to normalize the ERM matrix. The results are presented in the first part of **Table 3**. The second part shows the steps of the ranking. First the sum of column is determined. The number of satisfactions of each alternative by each objective are determined and recorded as participation factors (PF). The normalization of the participation factor is carried out by dividing the number of criteria. The final results of the alternatives are calculated by multiplying the sum of the columns by the normalized participation factor. The alternatives are ranked in descending order. **Table 4** shows the ERM matrix and the determination of the weights of criteria. The first part of the table indicates the ERM matrix and the values of the objective function for each optimization. The second part of **Table 4** shows haw to calculate the weights of criteria. For this purpose, first the maximum value of the row for ERM matrix$\left(\max_j ERM_{ij}\right)$ is determined. The global weights (w_i) are determined by dividing the maximum value $\left(\max_j ERM_{ij}\right)$ by sum of all maximum values. These values indicate the importance of each objective. The results show very close values of the criteria. The weights of the main groups $\left(w_g\right)$ criteria are presented in the last column of the **Table 4**. It can be seen that the main importance has the criteria in political (0.29), social (0.25) and technological (0.25) groups.

Table 5 shows the results of ranking according the outranking approach of SIMUS method. The number of columns and the rows in PDM is equal to the number of alternatives. The ERM matrix is used for compiling PDM ranking. Starting from the highest value in the first row the difference between values in the same row of normalized ERM is calculated. The procedure is repeated with all the values. The net dominance is calculated as the difference between row sum and column sum. The alternatives are ranked according to the maximal value of the net dominance. The results presented in **Tables 3** and **5** show that the ranking formed using both procedures is the same. Alternative A1 is the most suitable.

The main advantages of the SIMUS method are that it does not use expert's assessment and does not use the weights of criteria for ranking the alternatives. There is no subjectivism in decision making. SIMUS applied Linear Programming that does not use any type of weights, that's why they are not needed in the SIMUS procedure. The results of optimization are Pareto efficient. The weights of criteria can be determined in the end of optimization to determine its impact on the studied system. Two approaches are used to rank the alternatives; thus, verifying the results.

Criterion	Objective	Alternatives		
		A1	**A 2**	**A3**
P1	Z1			1.00
P2	Z2			1.00
P3	Z3			1.00
P4	Z4			1.00
P5	Z5	1.00		
P6	Z6			1.00
P7	Z7			1.00
EC1	Z8		1.00	
EC2	Z9		1.00	
S1	Z10			1.00
S2	Z11			1.00
S3	Z12			1.00
S4	Z13			1.00
S5	Z14			1.00
S6	Z15		1.00	
T1	Z16	1.00		
T2	Z17	0.11	0.89	
T3	Z18			1.00
T4			1.00	
T5	Z19			1.00
T6	Z20			1.00
L1	Z21			1.00
EN1	Z22			1.00
EN2	Z23			1.00
Sum of Column (SC)		2.11	4.89	17.00
Participation Factor (PF)		3	5	17
Norm. Participation Factor (NPF)		0.13	0.21	0.71
Final Result (SC x NPF)		0.26	1.02	12.04
ERM Ranking			A3 - A2 - A1	

Table 3.
Normalized efficient results matrix. Ranking. (The values equal to 0 are not shown).

4.2 Application of the TOPSIS, EDAS, MOORA, COPRAS and PROMETHEE methods

The fourth stage of methodology includes ranking by application the following multi-criteria methods: distance based: TOPSIS and EDAS, utility based: MOORA and COPRAS; and outranking approach PROMETEE. All these methods require the weights of the criteria to be set. What because, the weights determined on the basis of the ERM matrix of the SIMUS method are used as input to the studied methods. The results of the criteria weights show that they have almost equal values. For this

	Criterion	Objective	A 1	A 2	A 3	Objective function values	$\max_j \text{ERM}_{ij}$	SIMUS w_i	SIMUS w_g
P	P1	Z1	0.00	0.00	1.00	0.40	1.00	0.042	0.29
	P2	Z2	0.00	0.00	1.00	0.40	1.00	0.042	
	P3	Z3	0.00	0.00	1.00	0.50	1.00	0.042	
	P4	Z4	0.00	0.00	0.93	0.00	0.93	0.039	
	P5	Z5	1.00	0.00	0.00	0.00	1.00	0.042	
	P6	Z6	0.00	0.00	1.00	0.50	1.00	0.042	
	P7	Z7	0.00	0.00	1.00	0.50	1.00	0.042	
E	EC1	Z8	0.00	0.93	0.00	0.29	0.93	0.039	0.08
	EC2	Z9	0.00	0.98	0.00	0.00	0.98	0.041	
S	S1	Z10	0.00	0.00	1.00	0.50	1.00	0.042	0.25
	S2	Z11	0.00	0.00	1.00	0.50	1.00	0.042	
	S3	Z12	0.00	0.00	1.00	0.50	1.00	0.042	
	S4	Z13	0.00	0.00	1.00	0.67	1.00	0.042	
	S5	Z14	0.00	0.00	1.00	0.50	1.00	0.042	
	S6	Z15	0.00	0.98	0.00	0.00	0.98	0.041	
T	T1	Z16	1.23	0.00	0.00	0.39	1.23	0.052	0.26
	T2	Z17	0.12	0.94	0.00	0.37	0.94	0.040	
	T3	Z18	0.00	0.00	1.00	0.50	1.00	0.042	
	T4	Z19	0.00	0.98	0.00	0.00	0.98	0.041	
	T5	Z20	0.00	0.00	1.00	1.00	1.00	0.042	
	T6	Z21	0.00	0.00	1.00	1.00	1.00	0.042	
L	L1	Z22	0.00	0.00	1.00	0.50	1.00	0.042	0.04
E	EN1	Z23	0.00	0.00	0.83	0.28	0.83	0.035	0.08
	EN2	Z24	0.00	0.00	1.00	1.00	1.00	0.042	
Total							23.80	1.00	1.00

Table 4.
Efficient results matrix (ERM). Weights of criteria.

Dominant alternatives	A1	A2	A3	Row sum	Net dominance
A1	—	2.0	2.1	4.1	−17.7
A2	4.8	—	4.9	9.7	−9.3
A3	17.0	17.0	—	34.0	27.0
Column sum	21.8	19.0	7.0	—	—
PDM Ranking			A3 - A2 - A1		

Table 5.
Project dominance matrix (PDM). Ranking.

reason, they may not be taken into account. **Table 6** shows the results of application the distance based multi-criteria methods: TOPSIS and EDAS methods. Eqs. (1–12) have been applied. It can be seen that the ranking of alternatives is similar to those

Alternative	TOPSIS				EDAS					
	D_i^+	D_i^-	C_i	Rank	SP_i	NSP_i	SN_i	$NSNl$	ASi	Rank
A1	2.910	1.843	0.388	3	4.135	0.318	13.486	0.000	0.159	3
A2	2.198	2.323	0.514	2	6.518	0.501	3.505	0.475	0.488	2
A3	1.843	2.910	0.612	1	13.019	1.000	6.681	0.000	0.500	1

Table 6.
TOPSIS, EDAS – results.

Alternative	MOORA				COPRAS			
	$\sum_{j=1}^{g} x_{ij}^*$	$\sum_{j=g+1}^{m} x_{ij}^*$	y_i	Rank	P_i	R_i	Q_i	Rank
A1	3.048	2.074	0.974	3	3.048	2.074	10.262	3
A2	8.472	1.833	6.639	2	8.472	1.833	15.686	2
A3	13.285	4.963	8.322	1	13.285	4.963	20.500	1

Table 7.
MOORA, COPRAS - results.

Alternative	$\varphi(a_i)$	$\varphi^+(a_i)$	$\varphi^-(a_i)$	Rank
A1	0.292	0.500	0.208	3
A2	0.104	0.292	0.188	2
A3	−0.396	0.188	0.583	1

Table 8.
PROMETHEE - results.

by SIMIS method. **Table 7** represents the results of MOORA and COPRAS methods. Eqs. (13–17) have been used. The ranking is also similar to those received by SIMUS approach.

Table 8 shows the net outranking flows, the positive outranking flow $\varphi^+(a_i)$ and the negative outranking flow $\varphi^-(a_i)$. The preference function for the criteria assessed by 0 or 1 is usual function. Other criteria have linear preference function. The ranking is the same as others procedures. The PROMETHEE method use preference functions for the criteria, type of their optimization and outranking approach. This makes it more effective in decision making compared to distance-based and utility-based approaches. Since the decision maker has to set the weights of the criteria, this makes the discussed distance-based, utility-based and outranking methods also dependent on subjective evaluation. Of course, the cases where the weights are determined by Shannon entropy or another method based on the information of data, must to be excluded.

The most suitable alternative according all represented approached is alternative A3. This means that introduction of new service “car on the train” named also motorail trains is proposed. This strategy takes also into account the reconstruction of railway infrastructure.

4.3 Combination the PESTLE analysis with SWOT analysis and TETE

In this chapter is studied the integration between PESTLE and SWOT analysis and also the integration between PESTLE and TETE analysis. This serves to determine the weights of the main groups criteria of the compared types of analysis. **Table 9** represents the dependencies between the criteria. The weights of predefined criteria in PESTLE group are recorded in the relevant places in SWOT or TETE group. Thus, the weights are determined for SWOT and TETE criteria. Finally, the main criteria for groups are calculated. It can be seen that the main importance for SWOT groups have Weakness (0.42) and Opportunities (0.38) groups criteria. The main impact for TETE groups criteria has technical (0.29) and technological (0.51) groups criteria.

Figure 2 illustrates the impact of the criteria according compared analysis. The established dependencies between the criteria in the use of different types of strategic analyzes help the decision maker to expand the analysis of the influence of factors on the studied system.

		SIMUS w_i	S	W	O	T			Te	Ec	Tn	En
P	P1	0.042	—	—	0.042	—	**P**	P1	0.042	—	—	—
	P2	0.042	—	—	0.042	—		P2	0.042	—	—	—
	P3	0.042	—	—	0.042	—		P3	0.042	—	—	—
	P4	0.039	—	—	—	0.039		P4	0.039	—	—	—
	P5	0.042	—	—	—	0.042		P5	—	0.042	—	—
	P6	0.042	—	—	0.042	—		P6	—		0.042	—
	P7	0.042	—	—	0.042	—		P7	—		0.042	—
	EC1	0.039	—	0.039	—	—		EC1	—	0.039	—	—
E	EC2	0.041	—	0.041	—	—	**E**	EC2	—	0.041	—	—
S	S1	0.042	0.042	—	—	—	**S**	S1	0.042		—	—
	S2	0.042	0.042	—	—	—		S2	0.042		—	—
	S3	0.042	—	0.042	—	—		S3	—		0.042	—
	S4	0.042	—	0.042	—	—		S4	—	—	0.042	—
	S5	0.042	—	0.042	—	—		S5	—	—	0.042	—
	S6	0.041	—	—	0.041	—		S6	—	—	0.041	—
T	T1	0.052	—	0.052		—	**T**	T1	—	—	0.052	—
	T2	0.040	—	0.04		—		T2	—	—	0.040	—
	T3	0.042	—	0.042		—		T3	—	—	0.042	—
	T4	0.041	—	0.041		—		T4	—	—	0.041	—
	T5	0.042	—	0.042		—		T5	—	—	0.042	—
	T6	0.042	—	—	0.042	—		T6	—	—	0.042	—
L	L1	0.042	—	—	0.042	—	**L**	L1	0.042	—	—	—
	EN1	0.035	0.035	—		—		EN1	—	—	—	0.035
E	EN2	0.042		—	0.042	—	**E**	EN2	—	—	—	0.042
		1.00	0.12	0.42	0.38	0.08			0.29	0.12	0.51	0.08

Table 9.
PESTLE – SWOT – TETE relations and weights.

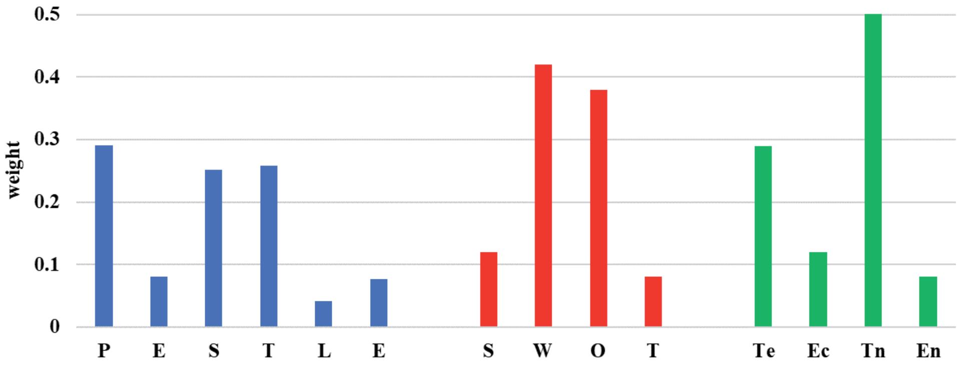

Figure 2.
PESTLE, SWOT, TETE weights.

5. Conclusions

This chapter proposes a methodology for assessment of the strategies of development the railway passenger transport using integration of PESTLE and SWOT criteria and MCDM methods. Different multi-criteria methods, as linear programming-based, distance-based, utility-based and outranking have been applied to rank the alternatives. All studied methods except SIMUS use weights of criteria in the procedures of ranking the alternatives. The SIMUS method only applies linear optimization, while the other applied methods use formulas to determine the distance to the ideal solution or utility. It is also a hybrid MCDM method because the ranking is based on weighted sum method and outranking approach. SUMUS also give the weights of the criteria as a result by the optimization and thus there is no subjectivism. The defined weights are valid for the set data.

The main advantages of the PROMETHEE method as an outranking method compared to the distance-based, utility-based multi-criteria methods are the following: it uses a preference functions for each criterion; normalization of the initial decision matrix is not used; availability of software that allows easy sensitivity analysis; the type of optimization can be taken into account - maximum or minimum.

The main advantages of the EDAS method are that it does not use normalization of the initial matrix for decision making; the criteria can be of maximum or minimum, i.e., of costs or benefits. This method determines the best alternative using the distance from average solution instead of calculating the distance from ideal and negative ideal solutions as in the compromise MCDM methods such as TOPSIS. The method is quite comprehensible and easy to apply. The TOPSIS method uses criteria that must be of one type - benefits. The subtraction-based conversion procedure for non-beneficial criteria is needed, which converts criterion type using the differences between criterion values and the maximum value in the criterion column. Thus, can completely distort the results of the analysis. The utility-based methods MOORA and COPRAS also use matrix normalization for decision making, the criteria can be of costs or of benefits. COPRAS separately evaluates influence of maximized and minimized criteria. It could be concluded that the SIMUS method is the most suitable multi-criteria method as based on linear programming it can assessed different quantitative and qualitative criteria and alternatives considering all criteria. There is also software that can solve SIMUS procedure.

The research propose PESTLE – SWOT – SIMUS approach as the most suitable to assess the alternatives and criteria. The advantages of application the SIMUS technique with PESTLE – SWOT criteria consists in the lack of subjectivism in decision making because the weights of criteria are not used, consideration the criteria as objectives in Linear programming optimization models. The PESTLE criteria are presented as objectives and the ranking of the alternatives of strategic planning is conducted without the use of subjective expert evaluation. The results of SIMUS ranking are compared with distance based, utility based and outranking multi-criteria approaches to make decision. These methods use weights of criteria in their procedures. In this research these weights have been set based on the results given by SIMUS method. The weights of criteria in PESTLE groups have been determined based on the results given by linear optimization in SIMUS, and the set of alternatives to evaluate. This approach depends of the data, there is not a subjectivism. It was found that the most important are the political (0.29), social (0.25) and technological (0.25) groups in PESTLE analysis. By establishing dependencies between PESTLE and SWOT groups criteria, the weights of Strengths - Weaknesses – Opportunities – Threats has been determined. It was found that the main importance in SWOT groups have Weakness (0.42) and Opportunities (0.38) groups criteria. The independences between PESTLE criteria and technical, economic, technological and environmental (TETE) criteria were determined. It was found that the main impact for TETE groups criteria has technical (0.29) and technological (0.51) criteria. It could be summed based on PESTLE and TETE analysis that the technological criteria have of great importance when choosing a strategy for railway development. The most suitable strategy for Bulgarian railway passenger transport has been proposed, including the service with motorail trains.

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Conflict of interest

The author declares no conflict of interest.

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Chapter 2

From Nobel Prizes to Safety Risk Management: How to Identify Latent Failure Conditions in Risk Management Practices

Sanjeev Kumar Appicharla

Abstract

The aim of the Chapter is to introduce readers to the Cognitive Biases found in Railway Transport Planning and Management domain. Cognitive biases in planning of railway projects lead to cost overruns, fail to achieve performance and fulfil safety objectives as well is noted in the economics, business management and risk management literature as well. Unbiased decision making is a core goal of systems engineering, encouraging careful consideration of stakeholder needs, design alternatives, and programmatic constraints and risks. However, Systems engineering practices dealing with Railway Transport Planning and Management fields do not pay attention to the human factors and organisational factors at initial stages of planning where driveability of European Railway Traffic Management System (ERTMS) Trains emerges as a concern in real time operations is noted in the Railway Transport Planning and Management domain. Therefore, there is a case for studying the Cognitive Biases in this domain. The System for Investigation of Railways (SIRI) Cybernetic Risk Model (2006), (2017) is a Systems engineering response to the internal research brief by RSSB, a GB Railways Safety Body. The SIRI Cybernetic Risk Model (2017) incorporating the "Heuristics and Biases" approach was published by the UK Transport Select Commission as a Written Evidence in 2016 on the occasion of the Inquiry theme of Railway Safety. The validity of the SIRI Risk Model (Swiss Cheese Model) is further illustrated through the 2019 historical survey of railway accidents and the two recent RAIB investigations of track worker fatal accident and signalling related near miss event in the form of Swiss Cheese Model. The data and information in the RAIB Reports (17/2019) and (11/2020) is supplemented by further research and the author's own past studies of accident analyses. The results of the study show that the Guide to Railway Investment Process (GRIP) (2019) (now deleted by Network Rail) has no provision for incorporating measures to address to deficiencies raised by the accident reports or safety analysis reports as the RSSB (2014) Taking Safe Decisions Framework does not include all Hueristics and the biases they lead in the information used for taking decisions. Thus, the Duty Holder Investment process fails to meet the requirements of the mandatory regulatory requirements of the Common Safety Method-Risk Assessment (CSM-RA) Process. The results of the Case Studies in the Chapter remain the same despite the proposed changes in the Shapps-Williams Reform Plan (2021) as the safety related matters are not yet addressed by the plan. The author hopes when the lessons that are learnt from the Case Studies are embedded in

railway organisations then we may see improvements in the railway planning and management practices by considering the risk factors at the conceptual stage of the projects and meet the requirements of ISO Standard 27500 (2016) for Human Centred Organisation. National Investigations Bodies (NIB) also may be benefitted.

Keywords: As low as reasonably practicable (ALARP) decision making, AI Internal Audit, Bounded rationality, Bow Tie Modelling and Assurance Management, Heuristics and Biases, Less Than Adequate Human, and Organisational Factors Analysis in Risk Assessments, Risk Management

1. Introduction

Thoughts without content are empty,
Intuitions without concepts are blind.
-Immanuel Kant (1724–1804) cited by [1]

Journal of Rail Transport Planning & Management aims to stimulate the quality of service for railway passengers and freight customers by improving the knowledge on effectiveness and efficiency of capacity management, timetabling, management, and safety of railway operations [2]. It is a matter of regret that the Journal of Rail Transport Planning & Management does not yet have any research paper dedicated to the role of cognitive biases in transport planning and management despite the fact that these are under investigation for the past decade and half. Role of cognitive biases in transport planning was investigated by Prof Bent Flyvberg leading to cost over-runs due to forecasting errors and a method of Reference Class Forecasting was advanced to mitigate the Optimism Bias [3]. This method was based upon the 2002 Nobel prize winning economics theory. Prof Bert De Reyck et al., after their study of "Optimism Bias "in Network Rail Projects, the Railway Infrastructure Manager, recommended that the correction of "Optimism bias" needs extension to all stages of the Guide for Railway Investment Process (GRIP) Process [4]. Despite the consideration of "Optimism bias "in Network Rail Projects, and some of the biases (like Hindsight, Outcome or loss aversion) in the RSSB (2014) Taking Decisions Framework, the similarity and other heuristics are not described therein. Further, the normative definition of "Rational" decision is not given as well [4, 5].

Apart from mitigating effects of Optimism bias through uplift of the cost budget, the infrastructure projects planning domain need to pay attention to the human and organisational aspects to consider the latent failures in risk management practices as well. For example, the failure of Crossrail to open in time and meet safety objectives despite the fact uplift of the cost budget was provided is a sign of planning failure [6–9].

Apart from these concerns, the ERTMS train driveability due to changes in speed profile as noted in the case of Swedish railway, planning and delivery of safety critical projects and scheduling of track maintenance tasks during the planning and operational stages are concerns of management and safety of railway operations [10].

This chapter is intended to draw readers attention to these aspects through very brief Case Studies of a safety incident and a fatal accident. In this section, we examine the role of Cognitive biases from the study of literature in economics and cognitive science domains to support the SIRI Model to be described in the Section 2 of this paper. In doing so, we advance two experiments to provide an intuitive basis for these concepts.

Insensitivity to prior probability of outcomes, Insensitivity to sample size, mis-conceptions of chance, Insensitivity to predictability, Illusion of Validity, mis-conceptions of regression are some of the biases due to the representativeness heuristic, one of the three heuristics that are employed in making judgements under uncertainty [11].

Within the Cognitive System Engineering disciple (see [12]), Systems reliability discipline (see [13]), and Organisational research disciplines (see [14]), it is accepted that decision makers are prone to use mental short cuts in complex solving tasks. Technically speaking, these short-cuts are known as Heuristics ([15], p. 37; [16], p. 66; [17], pp. 316–324). There are five types of Nobel prize winning schools of thought in relation to rationality: first, absolute rationality, which is enjoyed by primarily by economists, risk assessors and engineers like Nobel laureate Prof G.S Becker who argued that decision takers act rationally to optimise specific goals like wealth etc. ([17], p. 315; [18]). Second, Theory of Bounded or "limited" rationality which lays emphasis on limits on the capacity of human mind to take rational decisions in real world and rationality is limited by neurological conditions, memory, attention, lack of training in statistics and probability, and lack of education etc. [15–17]. Prof H.A. Simon argued against absolute rationality observing that limitations upon human information processing gives to rise to a tendency known as "satisficing behaviour" to settle for a satisfactory alternative than explore all alternatives for taking an optimal course of action [15–17]. Third one is the "Heuristics and Biases" Approach of the Behavorial school. Nobel laureate Prof Daniel Kahneman and Prof A. Tversky argued when make judgements concerning the likelihoods of uncertain events, "people rely on a limited number of heuristic principles, which reduce complex tasks of assessing probabilities and predicting values to simpler judgemental operations. In general, these heuristics are quite useful but sometimes lead to severe and systematic errors" ([11]; [15], pp. 36-52). Apart from these American schools, there is fourth type of rationality called, German school of rationality, and is named "Ecological rationality". Erwin Dekker and Blaž Remic argue that there are two types of ecological rationality advanced by Gerd Gigerenze and 2002 Nobel laureate Prof Vernon Smith [19]. The details of ecological rationality may be pursued with this article [19]. Fifth, type of rationality cited by Prof Daniel Kahneman is that based upon emotions of regret and disappointment. As per Prof Daniel Kahneman, these models have had less influence than Prospect theory of Risk ([11], p. 288).

The heuristics as per the classical "H&B" are discussed here below:

1.1 Representativeness (similarity) heuristic

First, Representativeness, which is usually employed when people are asked to judge the probability that an object or event A belongs to class or process B.

For example, in the GB Railways domain, I. Muttram, CEO Railtrack plc, London, stated" the dreadful accidents at Southall, Ladbroke Grove and Hatfield long term do not lie outside the bounds that are predicted by long term statistical analysis [20]. The same sentiment was echoed in another paper by John Corrie as well [21].

However, both papers from domain experts failed to note the role of risk in management systems [15, 20, 22]. In 1990, the transfer of rail safety regulation to the HSE invited, as a political fallout of the Kings Cross Underground Fire accident, opposition from the industry due to being classified as a high hazard industry and as a result of this opposition (a safety director in the HMRI opposed to the UK HSE Approach to safety regulation resigning) and the responsibility transferred to the DfT Office of Rail Regulation in April 2006 took place [23, 24]. The HMRI -Yellow Book process forms the Operational Reliability Process (A) and Systems Management Process based upon the IEC 15288 (2002) standard with human and organisation factors included constitutes Process B as noted in the systems engineering standard IEC 15288 [25–27].

Prof J. Barnett and Andrew Weyman drew attention to this heuristic in relation to the 'string' of large-scale UK railway accidents that happened in the late 1990s and early 2000s (Southall in 1997; Paddington in 1999; Hatfield in 2000 and Potters Bar in 2002). The series of accidents led to a speculation of a trend associated with railway privatisation. Statistically, Prof J. Barnett and Andrew Weyman argued that the small number of cases over a short time frame makes it impossible to draw firm conclusions; but the "belief in small numbers" leads to this conclusion of a statistical trend post privatisation. This belief is not limited to lay people but was seen in the case of scientists and engineers as well. Prof J. Barnett and Andrew Weyman noted, "The structural and regulatory impacts, from the Public Inquiries into the 'string' of large-scale UK railway accidents led to far-reaching and enduring effects" [28]. Industry observers noticed that it lacks will to move away from Blame Approach(see [29, 30]) and industry participants (2021) fail to recognise the fact that Yellow Book does not meet the requirements of the mandatory risk assessment process and hence withdrawn [23, 29–31].

Let us study the following case of standard problem of Bayesian Inference to understand the concept of Base Rate Neglect (base rate frequency):

"A taxicab was involved in a hit and run accident during the night. Two cab companies, the Black and the Green, operate in the city. 85% of the cabs in the city are Black and 15% are Green. An eye -witness account stated that the taxi -cab was Green. The court asked for the reliability of the witness under the same circumstances that existed on the night of the accident to be checked. The test results showed that witness identified each one of the two colours 80% of the time correctly and failed 20% of the time. What is the probability that the cab involved in the accident was Green rather than Black knowing that this witness identified it as Green?" [11].

The answer, when two information items of base rate (15%) and unreliable testimony (80%) of a witness are combined with the help of Bayes rule is that there is a 59% chance that the cab was Black (see TEDx talks @17.24) ([32], p. 166; [11]). The common answer to the standard Taxi-cab discussed here is that there is 80% chance that it is Blue is noted by Prof Daniel Kahneman [11].

How to combine the causal base rate information (the cab witnessed was Blue) and statistical base rate information (the number of blue cabs is 15%) through the Bayesian inference is not known commonly. Further, Prof Daniel Kahneman concluded that neglect of statistical base rate in such examples, the causal base rate will be used to feed a stereotype [11]. The colour of the cab involved in the hit and run case is not an indicator of causal factor is noted by the author. This message was reinforced by Prof Daniel Kahneman vide a personal communication to the author.

1.2 Availability heuristics

The ease with which outcomes can be brought to mind (recalled and visualised) increases their subjective salience and perceived likelihood (probability) of occurrence [28]. Infrequent and high-impact events can often be easily brought to mind, leading people to overestimate the likelihood of such an event. Biases due to retrievability of instances, Biases due to effectiveness of search set, Biases of imaginability, and Illusory correlation are due to the availability heuristic. The definition and details of the availability heuristic and its two aspects can be learnt from accessible Nobel prize document (2002) [33]. Biases of imaginability and biases due to retrievability of instances are relevant to the domain of risk management as we recall our fond memories with ease and are averse to entertain our pitfalls in our moral behaviour.

1.2.1 "Out of sight out of mind bias"

This arises from Availability heuristic in the form of omission of commonly known factors (see Kahneman et al., 1982 cited in [11]) and gains its validity from the risk analysis experiment (fault tree analysis of car starting scenario) (See Fischoff et al., 1978) is cited by ([15], p. 89). In the context of the GB Railways safety risk management, omission of Human and Organisational Factors from RSSB risk assessments is noted in the author's review of railway risk assessment data published by the Office of Rail and Road Regulation regarding the Crossrail risk assessment [6].

The same omission can be found in the doctoral theses of Dr. Bruce Elliott who does not even mention human factors and their integration into Systems engineering process and who has been for over two decades practising Systems engineering in the domain and has been one of the authors of the Yellow Book. Yellow book authors do not even consider the role of human information processing and heuristics in their Engineering Safety Management Strategy [25, 34].

Despite this glaring evidence, the professional body for safety, reliability, and risk management practitioners professional engineering society for safety and reliability, The Safety and Reliability Society (SaRS) in the UK, does not blink an eye lid when it reflects over the decade of experience in applying Common Safety Method for Risk Assessment [31].

1.2.2 Definitions of active and latent errors

The following are the definitions for hidden (latent) and active errors given by Rasmussen and Pedersen (1984) cited in [15], pp. 173–217; [30], pp. 26–43.

Definition: Human errors whose effects are felt almost immediately are called active errors [15]. For example, a train driver may fail to break short of the stopping distance provided at the stop signal or a pilot may fail to recognise the loss of control in flight situation [13, 15, 30, 35].

Definition: Latent errors, are error, whose adverse consequences may lie dormant within the system for a long time, only becoming evident when they combine with other factors to breach system (production) defences [15]. For example, failure to provide for an engineering safe guard as in the case of the Herefordshire level crossing accident [13, 15, 36].

Sanjeev Appicharla (2015b) identified approximately eighteen biases (this is not a conclusive list) from literature and stated them in the 2015 publication [37]. However, the sources of these biases were not traced to the heuristics in the 2015 publication and were made a part of the MORT Assumed Risk Branch is to be noted [37]. Thus, it requires this chapter to provide a correction of the error by mapping them to the Rasmussen's "Step-ladder model of" decision making [6].

1.3 Adjustment from an anchor heuristic

In classical paradigm, the third heuristics is the Adjustment from an anchor: Experimental subjects and people in real world situations are often unduly influenced by outside suggestion. People can be influenced even against their intentions when they know that the suggestion is made by someone who is not an expert [38]. In experimental situations, and real-world situation, subjects and decision takers make estimates by starting from an initial value that is adjusted to yield the final answer [11].

When subjects are asked to estimate the % of the African nations in the United Nations, and were given the starting point by spinning a wheel of fortune in the subject presence. Prof Daniel Kahneman and Prof Amos Tversky report that the median estimates were 25 ad 45 for groups that received 10 and 65, respectively starting points. Further, they state that payoffs for improving accuracy did not reduce the anchoring effect. Further in experiments involving intuitive calculating the result of 8! and result of 1x2x3x4x5x6x7x8 within five seconds, they found their predictions of higher number for descending sequence than the descending sequence. The actual answer is 40,320 in both cases [11]. Some of the examples in this category are Insufficient adjustment, Biases in evaluation of conjunctive and disjunctive events, anchoring in the assessment of subjective probability distributions are biases due to this heuristic [11].

To give a flavour of the idea of some of these biases in perceptual and cognitive context, let us look at the following two experiments. First one is about perceptual bias.

1.3.1 First experiment: perceptual bias"what you see is all there is"

Cognitive bias: WYSIATI is the acronym for "What you see is all there is", a cognitive bias as per 2002 Nobel Laureate, Prof Daniel Kahneman ([11], p. 417). Do you see an old or young woman? Or both? Please note your intuitive response!!

The author found that there was no consensus between System safety experts in viewing of the picture below at the 2011 UK IET International Safety Conference [40] (**Figure 1**). Further, only 3 out of 19 engineers with experience over 30 years saw both old and young girl in an experiment conducted in a Webinar for the author's college alumni [12].

1.3.2 Second experiment: investment decision

Prof Daniel Kahneman describes the following experiment. Imagine that you face the following pair of concurrent investment decisions. First examine both decisions, then make your choices ([11], p. 334).

Decision (i) choose between:

A. sure gain of £240.

B. 25% chance to gain £1,000 and 75% chance to gain nothing.

Decision (ii) choose between.

C. sure loss of £750.

D. 75% chance to lose £1,000 and 25% chance to lose nothing ([11], p. 334).

Prof Daniel Kahneman (2012) stated, "Most people, and large majorities prefer A to B and D to C. As in many other choices that involve moderate or high probabilities, people tend to be risk averse in the domain of gains and risk taking in the domain of losses" ([11], p. 334).

Figure 1.
The picture shows an old crone or a 19th century young girl, depending upon the perspective of person looking at the picture: The picture is sourced from Prof Charles Handy [39] cited in [40].

1.4 Importance of decision making in organisations

1.4.1 Insights from Nobel prize winners

1978 Nobel Laureate in Administrative Sciences, Prof H. A Simon asserted, on the theme of Decision making in Organisations, that there is a kind of Euclidean parallel between a decision-making tasks and manufacturing of and distributing organisation's products. Decision making task is a kind of two stage process: in the first stage, the search for the knowledge that can provide premises that logic of decision-making process requires. Second, identifying roles which can be assigned responsibility for goals to be realised with the constraints and side conditions that a decision must satisfy. Organisations develop effective process for manufacturing and distribution of products and same importance has to be accorded for the first stage of decision-making task ([41], p. 43).

Prof Charles Handy stated, on the vocabulary of organisations, whilst equating vocabulary to the ecology, thus: "March and Simon (1965) mean things like structure of communication, rules and regulations, standard programmes (inventory control & purchasing), selection and promotion criteria. The "vocabulary" forms the premises for decision -making itself. In short, the ecology sets the conditions for behaviour" ([39], p. 138).

Prof Daniel Kahneman, in his 2012 work, emphasised the Euclidean parallel between a decision-making tasks and life cycle stages of factory in manufacturing of and distributing organisation's products as well. Thus, organisation can be regarded as a factory that manufactures judgements and decisions. Given the analogy, the corresponding stages in the production of decisions are the framing of the problem that is to be solved, the collection of relevant information leading to a decision, reflection and review ([11], p. 426).

1.4.2 "Heuristics and Biases" (H and B) approach in system engineering discipline

1.4.2.1 Decision making process in the GB railway domain

Risk in management systems is a theme in the safety research literature dating back to the 1990s [15]. Risk in management systems was a research project carried out by RSSB as well [42]. The findings from these research programmes do not find their mention in the RSSB (2014) Taking Safe Decisions document is a matter of regret and this is not addressed till date [5]. In 2010, finding omission of systematic errors in risk judgements by Dr. George Bearfield, the then RSSB Safety Risk Assessment Manager when discussing Taking Safe Decisions Framework, Sanjeev Appicharla raised the issue of "Satisficing" behaviour "in a Letter to the Editor of the System Safety Club News Letter [14, 43]. Later, Sanjeev Appicharla published his findings of application of System engineering Methodology at RSSB and the cognitive biases that came to attention during the application. Sanjeev Appicharla found that Group -think bias was a major factor in decision over safety standards decision at RSSB, the GB Railways, Industrial level decision making body, and the concept of latent failures was not part of the organisation's vocabulary (see Handy's comment later in the text) at that time and still the case remains the same [29]. Section 2.2.3 of the RSSB (2014) Taking Safe Decisions document discusses the principles of good decisions, thus: "The choice of which option to pursue should be informed by evidence and analysis but ultimately the decision taker needs to make a judgement. When making judgements, people tend to be prone to a number of cognitive biases that have the potential to result in illogical or flawed decisions. Some of these are of particular relevance to safety management in the railway industry. An awareness of these can be useful for ensuring that decisions are rational and based on objective criteria. Annex 2 presents further information about psychological influences on decision taking" [5]. The author finds that Annex 2 describes some of the psychological traps that are particularly relevant to risk management in the GB rail industry such as Hindsight Bias, Loss aversion and Narrow Framing on the part of members of public but does not discuss "optimism bias" and "Out of sight out of mind" biases discussed in this chapter.

Modern control systems engineers and managers rely upon engineering judgements based upon "the transfer function method" to decide upon stability, observability and controllability of a system performance. One of the methods for signal information processing is the Kalman filter [44], (chapters 12 and 13). System safety experts like Prof Jens Rasmussen, Prof Jens Reason and Prof Nancy Leveson extended the idea of "management" concept of organisational theory as representing a control function to the analysis of risk management in socio-technical systems [15, 45, 46]. The linear process of decision making described by Nobel laureate Prof H.A. Simon in setting the Agenda, Representing the Problem, Identifying the Alternatives, and Selecting a course of Action and concepts of "Bounded Rationality" and "Satisficing" behaviour of firms and individuals had influenced System safety experts like Prof James Reason and Prof Jens Rasmussen as well [15, 16, 45] Prof Jens Rasmussen, a Cognitive Systems Engineering Expert, realised the rising influence of the "H and B" approach and the role "Management Oversight and Risk Tree "developed by W. Johnson and his team in identifying "less than adequate "or "potential inadequate conditions" that can lead to hazardous operations accidents or incidents [47]. Thus, it is inferred by the author, that linearisation heuristic in the study of system failures is no longer helpful as system failures can no longer be explained as a failure of human operator or technology failure but study of all stakeholders involved and organisational factors are to be included as well [29, 48].

Prof J. Barnett and Andrew Weyman, risk management experts, noted thus; "One of the key themes of the risk literature over the last 50 years is the widely encountered claim that compared to experts, lay people often over or underestimate risk. Or more specifically, that they are prone to deviate from the axioms of formal logic orientated around utility maximisation. ...casting risk assessment and its management as a technical, objective process has led many scientists and policymakers to conclude that insights on heuristics simply reflect a component of broader knowledge deficit and lack of sophistication in lay understandings of risk; however, this is not an area where there are necessarily marked distinctions between lay and expert decision makers. In fact, both are susceptible to decision bias effects and prone to apply heuristics, particularly, when dealing with unknown and uncertain issues that lie at or beyond the boundaries of their knowledge (see Kunreuther et al., 2010; MacGillivray, 2014). Expert use of heuristics runs the risk of being problematic when making decisions about complex phenomena, particularly where these are without precedent or unknown to science. Under these circumstances, science and engineering disciplines have little option other than to resort to often quite sophisticated but, nonetheless, rules of thumb, educated guesses, intuitive judgement and relatively crude theoretical models, for example selecting a subset of variables for manipulation in models designed to predict uncertain future outcomes, or assessing the degree of fit with some wider classification.

Ultimately, all scientific theories and models are heuristics – they are all simplified, although often complex and rigorously tested, approximations to reality. In engineering, failure models for complex systems are inevitably limited to the imagination of their architects. Similarly for natural phenomena, weather forecasters focus on those variables they consider to be primary influences.

Under most circumstances these models satisfice. If they did not, they would not be used. It is only when unforeseen novel interrelationships and alignments of variables occur that their limitations tend to become manifest and recognised (Reason, 1997)" cited in [28].

Prof McDermott A. Thomas et al. stated "Unbiased decision making is a core goal of systems engineering, encouraging careful consideration of stakeholder needs, design alternatives, and programmatic constraints and risks. However, as systems engineers, we must understand that while our discipline encourages rational decision making, the human decision-making process is largely irrational. Systems engineers have a role to guard against either individual or group related biases in the decision process. The first step is coming to recognize and understand common biases, why they occur, and how they affect group decision making. The formal foundations of human cognition and related cognitive bias should be part of systems engineering training – they are fundamental concepts in the development of core systems engineering competencies related to critical and systems thinking, group facilitation, and team dynamics [INCOSE, 20I8]. Challenging individual bias in team decisions should not be seen as undue criticism, but as part of the holistic process to arrive at sound decisions. Mentoring of team leads to help them learn to recognize common biases and call them out is critical" cited in [49].

1.4.2.2 AI systems

Andrew Smart et al., at Google noted on the lessons learnt from the aviation industry, thus: "Globally, there is one commercial airline accident per two million flights [Clarence Rodrigues and Stephen Cusick, 2011]. This remarkable safety record is the result of a joint and concerted effort over many years by aircraft and engine manufacturers, airlines, governments, regulatory bodies, and other industry stakeholders [Clarence Rodrigues and Stephen Cusick, 2011]. As modern avionic systems have increased in size and complexity (for example, the Boeing 787 software is estimated at 13 million lines of code [Paul A Judas, Lorraine E Prokop. 2011]), the standard 1-in-1,000,000,000 per use hour maximum failure probability for critical aerospace systems remains an underappreciated engineering marvel [Kevin Driscoll, Brendan Hall, Håkan Sivencrona, and Phil Zumsteg, 2003]. However, as the recent Boeing 737 MAX accidents indicate, safety is never finished, and the qualitative impact of failures cannot be ignored—even one accident can impact the lives of many and is rightfully acknowledged as a catastrophic tragedy. Complex systems tend to drift toward unsafe conditions unless constant vigilance is maintained [Nancy Leveson, 2011]. It is the sum of the tiny probabilities of individual events that matters in complex systems—if this grows without bound, the probability of catastrophe goes to one. The Borel-Cantelli Lemmas are formalizations of this statistical phenomenon [Kai Lai Chung and Paul Erdös. 1952], which means that we can never be satisfied with safety standards. Additionally, standards can be compromised if competing business interests take precedence. Because the non-zero risk of failure grows over time, without continuous active measures being developed to mitigate risk, disaster becomes inevitable" cited in [50].

1.4.2.3 ALARP decision making

Ale, B.J. et al. noted, thus: "For the purpose of Cost Benefit Analysis (CBA, the RSSB 'value of preventing a fatality' (VPF) was£ 1.826 million in June 2014. In terms of the RSSB Guidance on the use of cost–benefit analysis for ensuring safety, CBA should only provide an input to the overall decision rather than giving a definitive result. Notwithstanding the extensive guidance provided by RSSB to operators, a degree of uncertainty remains with respect to the safety decision because as in other situations in the common law system, the adequacy of a duty holder's safety measures will ultimately be determined by the Courts after an accident. While in the case of railways in the United Kingdom, guidance on risk-decisions and CBA is provided by the industry, the guidance for dams is provided by a Government Agency. However, in both cases, the risk assessment and CBA information inform the safety decision, they do not form the sole basis for the decision [51]. For further basis of the "H and B" Approach readers may consult "Allais "paradox question discussed in Appicharla to which the Prospect Theory is an attempt to resolve it [37]. RSSB (2014) (see **Figure 2** of the RSSB paper) summarises the information that informs decisions, the criteria that are applied, and the distinction between decisions that are taken to meet legal obligations and those that are taken voluntarily to meet commercial objectives [5]. However, as noted in Appicharla latent errors are not part of the decision criteria is to be noted [14, 29]. This fact comes to attention in the review of risk analysis of the RSSB Safety Risk Model where the organisational and managerial factors are omitted (a Bow-Tie model is acknowledged in the 2012 Review carried for the Regulator) [52]. Bow Tie models do not deal with the human errors in system's lifecycle is fact learnt from Sir Charles Haddon Cave's investigation as well [53]. Sanjeev Appicharla considered "H and B" Approach as a part of the "Assumed Risk "branch of the Management Oversight & Risk Tree it [37]. However, realising that the regulator would not publish the full human factors analysis of the ERTMS/ETCS Design and Development for the fear of legal challenges (informed privately) because of the Evidence submitted to the Regulator, Sanjeev Appicharla (2016-2017) decided to develop a Dynamic representation to include them as disturbances using the control theoretic representation (see Section 2).

Prof Roger Kemp asked, "Against this background (of Knightian discrimination between risk and uncertainty, emphasis added)", it is relevant to ask whether the UK safety regulatory system relying on quantified risk assessment and a calculated value of prevented fatality is really as scientific as we like to think – or can we argue that the maths is a convenient smokescreen behind which the regulator exercises qualitative engineering judgement, as in most other European countries? [23]. Prof Roger Kemp concluded, "Until the middle of the twentieth century, risks were

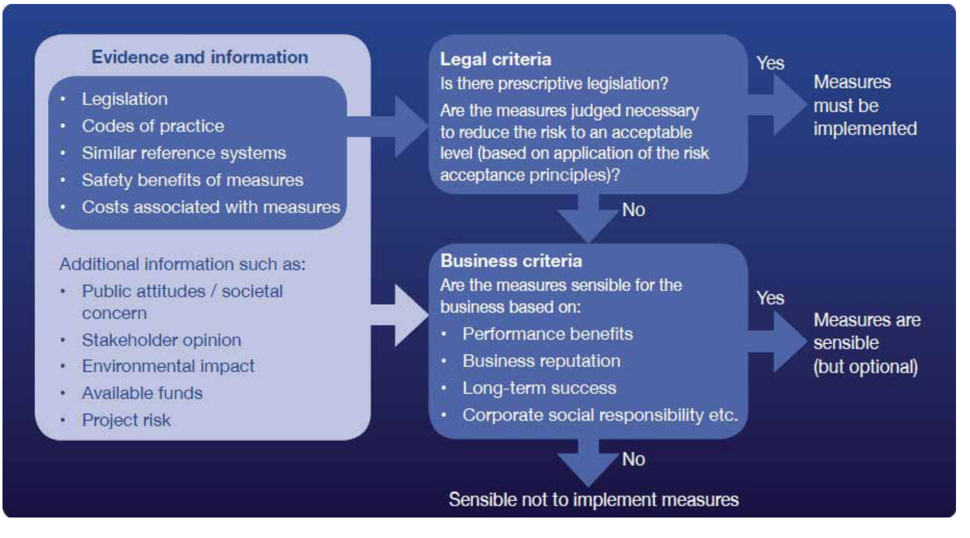

Figure 2.
Evidence and information that support industry decisions and the legal and commercial criteria applied. The picture is sourced from [5].

largely related to deterministic failures of mechanical components; they were easy to identify and were managed by 'engineering common sense' and learning from previous experience. The second half of the twentieth century saw the introduction of quantified risk assessment that gave a (sometimes spurious) assurance that risks had been calculated, assessed and managed against criteria of acceptable risk. In the twenty-first century we are seeing more risks in complex systems, which are less amenable to traditional analysis, and where the boundaries of the 'system' being analysed are fluid. This will require a different type of risk management system that will be a far cry from the number-crunching of the twentieth century" [23]. Doubts about current risk assessments were raised by Prof Anson Jack and his doctoral student as well [54]. Less than adequate mental models of the risk scenarios may lead to knowledge-based mistakes and this may be unrepresented in the current risk assessments [55].

2. The SIRI cybernetics model: validity and desirability of the SIRI safety risk model

Profs J. Reason and E. Hollangel and J Paires noted, thus: "The understanding of how accidents occur has during the last eighty years a rather dramatic development. The initial view of accidents as the natural culmination of a series of events or circumstances, which invariably occur in a fixed and logical order (Heinrich, 1931), has in stages been replaced by a systemic view according to which accidents result from an alignment of conditions and occurrences each of which is necessary, but none alone sufficient (e.g., Bogner, 2002)" cited in [56]. Further, they noted, "If we relax the requirement that every accident must involve the failure of one or more barriers, the inescapable conclusion is that we need accident analysis methods that look equally to individual as to organisational influences. In other words, models of "human error" and organisational failures must be complemented by something that could be called socio-technical or systemic accident models… It is now broadly recognised that accidents in complex systems occur through the concatenation of multiple factors, where each may be necessary but where they are only jointly sufficient to produce the accident. All complex systems contain such potentially multi-causal conditions, but only rarely do they arise thereby creating a possible trajectory for an accident. Often these vulnerabilities are "latent", i.e. present in the organisation long before a specific incident is triggered. Furthermore, most of them are a product of the organisation itself, as a result of its design (e.g., staffing, training policy, communication patterns, hierarchical relationship) or as a result of managerial decisions ([15], p. 2). On the use of the Swiss Cheese Model has been used for three different purposes. The first is as a heuristic explanatory device (communication); the second is as a framework for accident investigation (analysis); and the third is as a basis for measurements [56].

Prof John Adams and Prof Michael Thompson in their summary to the UK HSE Research Report 035, noted the subjective nature of risk. Further, they characterised HSE as a hierarchical risk manager, and faces a challenging task of managing societal concerns of risk. Given that risk is subjective in nature, in the report, they concluded that attempts to manage risk that a) ignore the rewards of risk taking, and/or b) exclude significant stakeholders, and/or c) fail to appreciate the type of risk it is sought to manage, are unlikely to succeed [57]. Readers may consult Reason et al. for details on the development of the Swiss cheese model and how its criticisms are clarified [56].

The standard UK HSE risk assessment and human error models in the form of feedback strategy are presented below (See **Figures 3** and **4**).

2.1 Swiss cheese model as a heuristic explanatory device

"The SCM is a heuristic explanatory device for communicating the interactions and concatenations that occur when a complex well-defended system suffers a catastrophic breakdown. In particular, it conveys the fact that no one failure, human or technical, is sufficient to cause an accident. Rather, it involves the unlikely and often unforeseeable conjunction of several contributing factors arising from different levels of the system. It also indicates what defines an organizational accident, namely the concurrent failure of several defences, facilitated, and in some way prepared, by sub-optimal features of the organisation design. In this regard it has proved very successful. It is a simple metaphor—easily remembered and passed on—that encompasses what is often a very complex story. A Google search on 'Swiss cheese model of accidents' yielded around 18,400 hits covering a wide range of hazardous domains. Many of these involve passing on the model to various professional communities. A high proportion of these messages are aimed at health carers" [56].

2.2 Management oversight and risk tree for identification of potentially less than adequate management conditions

Prof Jens Rasmussen et al. discussed role of less than adequate' management decisions play in risk management of loosely coupled systems and the usefulness of "large number and complexity of causal trees included the Management Oversight and Risk Tree developed by William Johnson (1980) (see [29] to help identify resident pathogens in management practices derived from analysis of past incidents

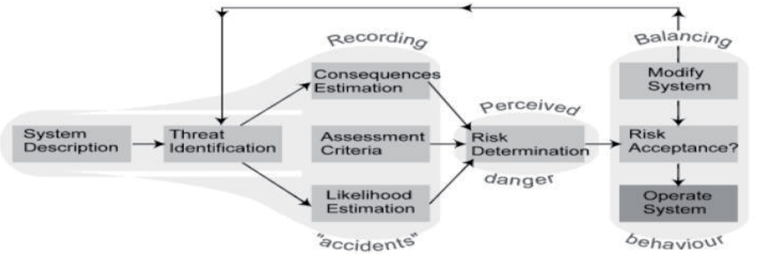

Figure 3.
The risk assessment process (Figure 1.3 in UK HSE 035, 2002 [57]) (see MB3 in the MORT M branch **Figure 5***: MORT tree) [58].*

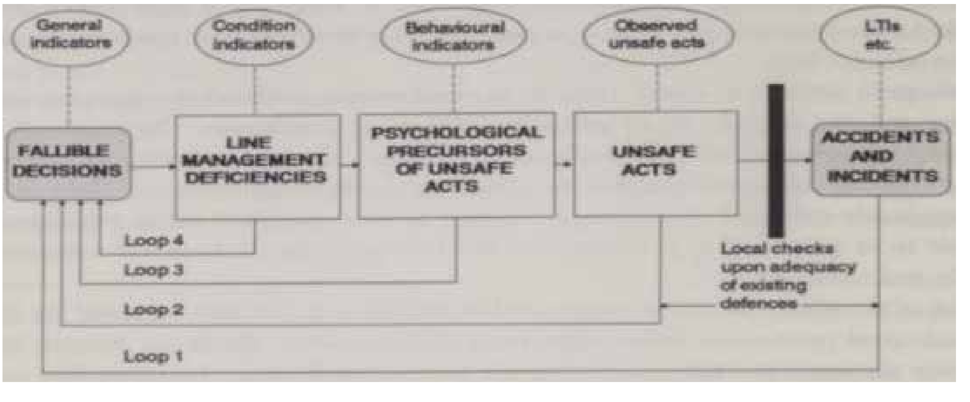

Figure 4.
Swiss cheese model (1990) version [56].

([16], p. 155; [47]). So, the author believes there is a justification to combine the concepts of 'resident pathogens' and "less than adequate' management decisions to yield a model of actual behaviour trace in terms of System safety engineering and management. This is supported from the comment in the British Standard on Root Cause Analysis, BS EN 62740:2015, on the MORT Technique, thus" "unless the organisation to which it (MORT, emphasis added) is applied is a high reliability organisation (a sort of learning organisation, emphasis added) very large number of weaknesses are found which make it difficult to implement changes. Thus, it is inferred by the author that SIRI Cybernetic Model (2017) is a model of actual behaviour trace in terms of System safety engineering and management as described by Prof Jens Rasmussen and help provide clarity where changes are feasible [47].

The "Heuristics and Biases"(H&B) approach made its appearance in the Section 2.2 of Prof Nancy Leveson's 2015 paper on how biases are inherent in the risk assessments [46]. Prof Nancy G. Leveson after discussing "confirmation bias", "the availability heuristic", "the likelihood of risk is underestimated", and "defensive avoidance" concluded, "Successful creation and use of leading indicators will require ways to control the psychological biases involved in assessing risk" [46]. MORT User Manual provides the accident analyst with the complete list of questions that need to be answered in analysis of the accident. The MORT User Manual (2009) is freely available for accessible online and can be downloaded [26, 58–60]. Overconfident operators can be seen in the domain despite lacking awareness of systems engineering concepts and making false claims about axle counters [61, 62].

However, if we take the comment of the British Standard on Root Cause Analysis, BS EN 62740:2015, "unless the organisation to which it (MORT, emphasis added) is applied is a high reliability organisation (a sort of learning organisation, emphasis added) very large number of weaknesses are found which make it difficult to implement changes. Thus, it is inferred by the author that SIRI Cybernetic Model (2016) is a model of actual behaviour trace in terms described by Prof Jens Rasmussen [47, 63]. Management oversight and risk tree (MORT) is extended into a dynamic risk model in the following manner (**Figure 5**).

The application of the MORT Fault Tree Analysis and other methods provided in the MORT User Manual such as Energy Trace Barrier (ETBA), Event and Causal

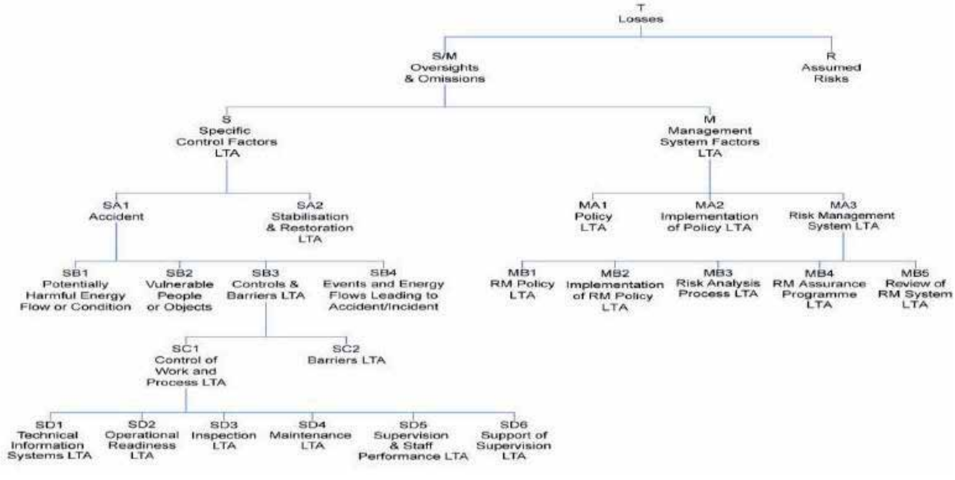

Figure 5.
MORT tree top [58].

Factors Analysis (ECFA) will enable identification of the operational reality, latent failure conditions and identify heuristics used and the resulting biases which may feed into the accident model. The process of applying the MORT analysis was described by Sanjeev Appicharla [36, 37, 40].

The focus of attention in the railway domain is absent from the classification noted by Prof Jens Rasmussen can be noticed from the inspection of the works published in the domain: Paul Hollywell, Mike Castles, Prof Anson Jack and Neil Barnatt, where the Cognitive Systems Engineering" discipline play their role by means of Swiss Cheese model (1990), Standard Risk Management Framework (1997) or Yellow Book type of Engineering Safety Management are applied but "Heuristics and Biases "approach are omitted [54, 64, 65].

Paul Hollywell attempted to create an accident model incorporating Human and Organisational Factors (HOF) factors to enable a systems approach to enhancing railway safety assurance [64]. But this model did not seek to integrate Hueristics and biases approach and how to apply learning lessons activity into a single model is to be noted. Prof Anson Jack and Neil Barnatt (2018) refer to criticism of Swiss Cheese Model by defending it and accept that Standard Risk Management Framework (1997) does apply to the railway domain but do not refer

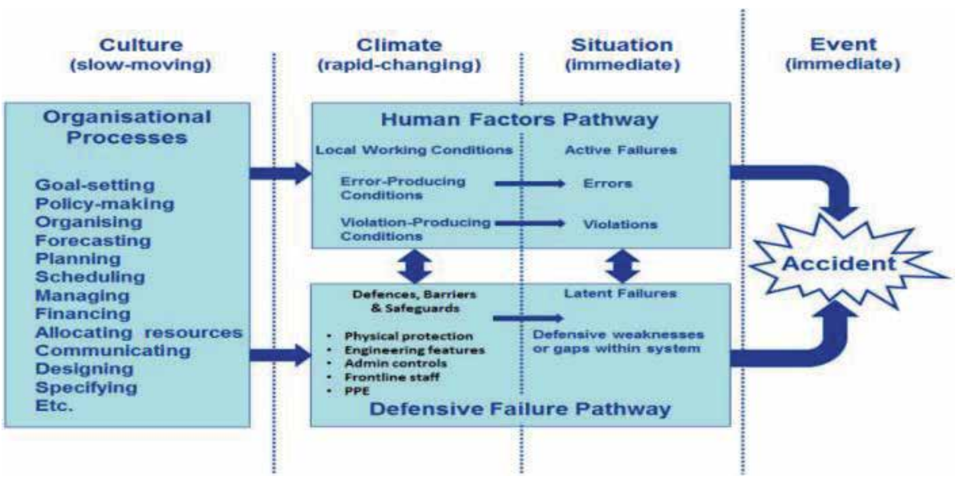

Figure 6.
A detailed model of organisational failures [64].

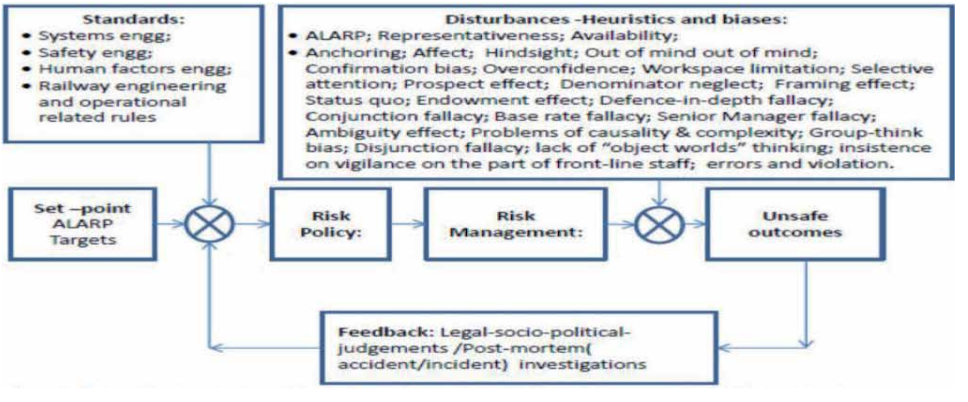

Figure 7.
SIRI cybernetic representation of societal accident risk management process [63].

to the "Heuristics and Biases" Approach. RSSB Ten Incident Classification System for Accident Investigation is not used for underlying management issues as the RAIB Report 03/2020 assumes from the presentation of the developer of the RSSB Scheme (2019) whose failure to understand the System Approach to Human Error can be seen in comparison to Paul Hollywell's model [64, 66, 67]. The requirement for Graphical model of accidents is required to depict structure, function and behaviour of systems was stated by Prof Jens Rasmussen (**Figure 6**) [68].

To claim internal and external validity of the SIRI Cybernetic model as a standard model, the argument is advanced based upon the UK HSE risk assessment, MORT and human error models shown here and metaphysics expressed by Nobel laureate in physics, Prof Erwin Schrodinger (**Figure** 7) [69].

3. Application of the SIRI cybernetic Model (2017)

Jean-Christophe Le Coze defined the context of risk management in the socio-technical society, thus: "A major dynamic of the contemporary world is globalization and the rise of a network society, a term coined to describe the changes over the past 20–30 years. The accidents of the 1980s occurred at a time when the notion of post-industrial society was a central description of Western societies that saw major transformations in cultural, political, economic and technological areas following the Second World War (Touraine, 1969; Bell, 1973). In the first decade of the twenty-first century, the concepts of network society or informational society have been suggested, most notably by Manuel Castells (Castells, 2001), to replace this previous scheme and to embrace current transformations. Information technology, privatisation, deregulation and financial and trade liberalisation have indeed shaped a new world for industries, leading to new opportunities as much as new challenges (Berger, 2005). Incorporating new technological developments into operations, adapting strategies to uncertain global markets, structuring organisations to obtain flexibility through subcontracting and matrix organisations, complying with new demands for accountability through international and intensified standardisation and indicators (for example, key performance indicators) or negotiating with a risk-averse civil society with stronger ecological concerns are some of the new trends of the past two or three decades that have been shaping high-risk systems environments. Our world now appears more interconnected, networked and complex than it has ever been and should as a result trigger a certain degree of reflexivity. It is something James Reason expressed following some of the critics of his contribution: 'Is Swiss Cheese past its sell-by dates?' (Reason et al., 2006). As the world evolves and as science evolves, so should the graphical models that serve as rally points for practitioners and researchers of socio-technological risks – and their analytical backgrounds" (Le Coze, 2013, 2015)" cited in [70].

The application of the SIR Model to the RAIB Reports 17/2019 and 11/2020 elicited following results. The results are presented in a very summarily manner due to space constraints.

3.1 RAIB summary of loss of safety critical signalling data on the cambrian coast line incident

On the morning of 20 October 2017, four trains travelled over the Cambrian Coast line, Gwynedd, without the "temporary speed restriction"-TSR data transmit by the signalling system to the onboard system. Trains approached a level crossing at 80 km/h (50mph), significantly exceeding the temporary speed restriction of 30 km/h (19mph). Since 2014, the temporary speed restriction was applied to give adequate warning time for level crossing users [71, 72]. At around 10:02 hrs, driver of the fourth train 2 J03 after passing through the TSR location approximately 80 km/h (50mph) while travelling between Barmouth and Llanaber reported a fault with the speed information displayed on the incab display on the train borne system [71, 72]. In the evening, on the October 2017, after the automated signalling computer restart, the temporary speed restriction data was not transmitted by data base system but a display screen to the signallers incorrectly showed the TSRs are being loaded for transmission to trains [71, 72]. Fortunately, despite the foregoing unsafe acts as per the Swiss Cheese Terminology, no harm occurred.

Since 2011 the Cambrian Coast line was commissioned with a pilot installation of the European Rail Traffic Management System (ERTMS) and it has been operating since then [71, 72]. This system replaced traditional lineside signals and signs with movement authorities transmitted to trains. These movement authorities include maximum speed of train, speed profile of the line, speed restrictions imposed by the interlocking and temporary speed restrictions due to working sites etc. These are displayed to the train driver and used for automatic monitoring and enforcement of train speed [73]. The RAIB (2019) Summary following causal factors were learnt, thus:

The causal factors identified by the RAIB were:

a. likelihood of a corrupted database (paragraph 46, Recommendation 5);

b. no indication of data base system failure provided to signallers (paragraph51, Recommendation 2) [71].

c. the temporary speed restriction data was stored in the volatile memory leading to loss of data during roll over (paragraph 62, no recommendation);

d. the required level of safety integrity for validation of temporary speed restriction data uploaded to the RBC following a rollover was not achieved by the design (paragraph 67, Recommendations 1 and 2);

e. the database system (GEST server software) was unable to detect and manage the corruption of its database (paragraph 75) [71]; and

f. the vulnerability of the signalling system to a single point of failure had neither been detected nor corrected during the design, approval and testing phases of the Cambrian ERTMS project due to a combination of the following [71]:

   i. Insufficient definition of the safety related software requirements for the GEST software (paragraph 81, Recommendations 1 and 2);

   ii. the hazard analysis process did not identify, and mitigate the risk of data base system failure (paragraph 88, Recommendation 2);

   iii. the validation process did not assure that the safety requirement for the correct display of temporary speed restrictions was implemented (paragraph 94, Recommendations 1 and 2); and

   iv. The database software (GEST server) was accepted into service without a generic product safety case (or equivalent);(paragraph 99, actions taken paragraph 149, Recommendations 1 and 2, Learning points 2 and 3).

The underlying factors in the Paragraph 144 identified by the RAIB were:

signalling supplier, Ansaldo STS, did not appreciate the latent failure of single point of failure within the GEST sub-system software (paragraph 113, Recommendation 2); and.

Client, Network Rail, input did not include effective systems engineering (emphasis added) role checks to identify the design process shortcomings (paragraph 116, Recommendation 1, Learning point 4) [71].

3.2 The application of the SIRI cybernetic model (2017) to the loss of safety critical signalling data

3.2.1 The SIRI cybernetic model (2017) stakeholder analysis

The description of the stakeholder organisations involved is given below. Marius Wold Albert (2019) of NNTU studied the same accident from the STAMP/CAST basis based upon the interim RAIB Report is to be noted [74].

The SIRI Cybernetic Model (2017) Analysis beings with identification of stakeholder organisations involved: As per the RAIB Report (17/2019), Network Rail owns and maintains the Cambrian lines infrastructure, and employs the Machynlleth signalling control centre staff, including signallers and signalling technicians responsible for operation and maintenance of the Cambrian ERTMS system. Arriva Trains Wales Ltd. operated the trains and employed the drivers affected by the loss of speed restrictions. Transport for Wales took over operation of these trains in October 2018. Ansaldo STS (now part of Hitachi STS) supplied the equipment for the Cambrian ERTMS installation and provides maintenance assistance to the local Network Rail signalling maintenance staff when requested. It employed the support engineer involved in restoring the train services after the incident. The Cambrian ERTMS project team designed, installed, commissioned and brought the Cambrian ERTMS system into operational use. It included representatives from both Network Rail and Ansaldo STS. Lloyd's Register Rail, now Ricardo Rail/Ricardo Certification, acted as the Independent Safety Assessor (ISA) of safety case documents issued by the Cambrian ERTMS project team. Network Rail chaired and employed the discipline experts which formed the System Review Panel (SRP). The SRP determined the acceptability of the safety case documents submitted to it by the Cambrian ERTMS project team, taking account of the issues that had been identified by the ISA (Clauses 9 to 15 [71]).

Simon Paye provided a large picture of the history that shaped the design and development of the ERTMS Standard and a map of stakeholders initially involved (SNCF, IRRI and UIC, and the European Commission) and their perception of the problems they intend to solve since 1986 [75]. Libor Lochman relied upon Simon Paye M. Sc Thesis to establish the background for the ERTMS [76].

Marius Wold in his M.Sc. Thesis in the Section 9.4 provided a control structure and operational structure of the GB Railways for the CAST Analysis [74]. From the website of the Network Rail Consulting, we learn that the European Rail Traffic Management System (ERTMS), Cambrian Early Deployment Scheme (EDS) was carried by them at the cost of £113 Million over a period of 42 months for their client UK Department for Transport [77]. Sanjeev Appicharla learnt from the research Incident Case Study on the ABCL Incident (2011) on the Cambrian ERTMS Railway that RSSB was involved as in granting a deviation to safety critical requirement, the UK HSE and the National ERTMS Programme of which RSSB was a part were involved in selecting the baseline D without identifying hazards involved [37, 78]. Sanjeev Appicharla provided an architecture context diagram which did not include a map of stakeholders initially involved (SNCF, IRRI and UIC, and the European Commission) despite having access to a copy of the original Commission Plan (1996). This latent error on the part of the author is to be noted (see Section 3.1) [37, 73].

3.2.2 The SIRI cybernetic model (2017) of safety standards

The RAIB Report (17/2019) accepts that the following standards are helpful in achieving safety and system assurance:

1. GEGN8650, 'Guidance on high integrity software-based systems for railway applications.

2. Network Rail standards?? These are unspecified by the RAIB.

3. CENELEC EN 501xx standards;

4. European technical standards for interoperability

5. ISO/TS 22163:2017(en) Railway applications — Quality management system — Business management system requirements for rail organisations: ISO 9001:2015 and particular requirements for application in the rail sector

The act of omission on the part of RAIB, RSSB, ORR, and the respective duty holder organisations forming the part of the safety regulation community or their European counter parts such as the UIC, the Rail Research Institutes or the UNISIG, or the Agency or the ISO Working Groups is that they fail to realise that the human and organisational factors(HOF) were omitted in the 2004 EU Railway Safety Directive and ROGS Regulations as well and retrospective analysis cannot be carried out if the Reference Architecture is followed dogmatically [71, 73, 79–81]. The RAIB has failed to raise the issue of lack of application systems engineering standard IEC 15288 after the initial report [82]. The RSSB standard GEGN8650 is recommended by the RAIB when examined thoroughly will reveal the many errors contained in it. One of the latent failure conditions is that the lack of awareness of the fact measurement of software integrity cannot be carried out (see Clause 2.3 Measuring Integrity when considering the NASA Langley Research (1993) Report [83, 84]. Inspection of the Network Rail (Infrastructure) Ltd. (NRIL) Health & Safety Management System does not contain any System safety method to manage the complexity of safety critical systems [85]. Inspection of NRIL System Operator (2018) Plan and RSSB Taking Safe Decisions (2014) reveal no information and decision criteria by which latent failure conditions identified by system safety research and RAIB accident investigation [67, 86]. On scrutiny of available documentation on the research by R. W Butler and G.S Finelli, empirical research on biases such as the UK HSE societal risk concerns, and regulatory lack of awareness of to enforce integration of human and organisational factors in activity of the system definition and perform risk analysis, risk assessment and evaluation accordingly and applying systems thinking based approaches is less than adequate by The Network Rail (Infrastructure) Ltd. (NRIL) Health & Safety Management System is inferred [6, 45, 74, 83, 87].

3.2.3 The SIRI cybernetic model (2017) of Swiss cheese model barrier analysis

The sequence of activity in Swiss Cheese Model analysis (ETBA in the MORT terms) starting with SA1 Incident/Accident and going downwards from the Barrier Analysis and below is shown in MORT User Manual [58]. Sanjeev Appicharla may be consulted to learn about the application of ETBA/MORT technique [37, 40]. The relationship between the latent failure conditions and the accident/incident is

1: harmful energy flow or adverse agent or environmental condition	**SB2: target: vulnerable person or thing**	**SB3: barriers & ccontrols to separate energy and target. For IM/RU SMS categories of factors, please refer to ROGS guidance [92] and MORT user manual (2009) [58]**
(System hazard: Kinetic hazard of ERTMS train moving into crossing space in excess of the permitted speed [59]. For component level hazards – please refer to Marius Wold Albert [74].	Worst case risk scenario of 30 or odd school bus of children [93].	Regulatory Decision-making layer: (Status quo bias)
		• LTA ALARP Decision Making [43, 51, 81] • LTA ORR Risk (SFAIRP) Policy [94] • LTA 2004 EU Railway Safety Directive [73] • LTA ORR ROGS Review LTA [92]
		Industry body layer: (Availability heuristic – out of sight out of mind bias) & Anchoring heuristic (single point failure):
		• LTA Railway Group Standards Planning: RSSB guidance note GEGN8650 LTA [84]. Infeasbility of SIL4 Assurance by testing [83] • LTA CENELEC safety standards (Duty holder Standards) & UNISIG Safety Analysis LTA [95] • LTA System definition (RSSB, 2011) [22] • LTA Risk Assessment (Application of IEC 61508 standard and related UK HSE Guidance LTA), (UK HSE RR 035), (National ERTMS Board, 2003), (RSSB SRM Review LTA), Yellow Book, RSSB Taking Safe Decisions [5, 25, 27, 52, 71, 78, 80, 95]
		Duty holder management and co-operation SMS layer
		• LTA Risk Management [43, 71, 77] • LTA RU/IM Safety Management System [42, 96, 97] • IM H& SE Document LTA [85, 86]
		Risk Assurance Management layer
		• LTA ERTMS Risk Assessment Review (Ricardo Rail/ Ricardo Certification Review LTA) [71]. • LTA System Assurance Management (Ricardo Rail/ Ricardo Certification Review LTA) [71].
		Operator layer
		• LTA Competence Management operator level [52, 71, 98–100]
		Learning lessons from past failures
		• LTA Accident Modelling and analysis of human and organisational factors, risk in management systems and LTA risk management framework [28, 37, 42, 47, 67, 96, 101, 102]

Table 1.
SCM/MORT ETBA analysis [56, 58, 71].

explored through the ETBA, and the MORT branches using the Cybernetic model and the Swiss Cheese Model to include social and organisational factors and the graphical representations requirements for the accident model. In the Swiss Cheese Model literature, we find that HFCAS, ACCIMAP, STAMP-CAST and PDCA-SHELL/PDCA cycle-based process models are used to identify the latent failure conditions [45, 88, 89]. The belated effort by the EU Agency for Railways to include HOF can be seen from the 2020 webinar [90, 91]. EU SAMRAIL and SAMNET Projects failed to improve safety culture and the less than adequate safety culture was affirmed again by a doctoral thesis (**Table 1**) [103–105].

3.3 Double fatality track worker accident

3.3.1 The RAIB summary of track worker accident

Approximately at 09:52 hrs, on 3 July 2019, a passenger train, which was travelling from Swansea to London Paddington, struck and fatally injured two track workers at Margam East Junction on the South Wales main line. The driver of the train 1 L48 09:29 Swansea to London Paddington sounded the train horn and applied the emergency brake when he sighted three track workers ahead on the Up Main line

SB1: harmful energy flow or adverse agent or environmental condition	**SB2: target: vulnerable person or thing**	**SB3: barriers & controls to separate energy and target with evidences. For IM/RU SMSM categories of factors, please refer to ROGS guidance [92] and MORT user manual (2009) [58]**
Kinetic hazard: train running into track section under maintenance [107].	Two track workers were struck and fatally injured [107].	Regulatory Decision-making layer: (Status quo bias)
		• LTA ALARP decision making UK HSE –035 [57, 81] • LTA RSSB Taking Safe Decisions [5, 43]; LTA ORR Policy [94]
		• LTA RSSB Safety Standards decision making [29]
		• LTA ORR/RU/ IM Change Management [67, 107, 108].
		• LTA ORR Risk Management Policy [37, 107–109]
		Industry body layer: (Availability heuristic – out of sight out of mind bias) & Anchoring heuristic (single point failure):
		• LTA RSSB System definition [22, 107, 108]. LTA RSSB Safety Standards decision making [29]
		• LTA IM Application of Standards [6, 45, 110]
		Duty holder management and co-operation SMS layer
		• LTA IM Risk Assessment Review [67, 107, 108].
		• LTA IM Risk Management System [67, 107, 108].
		• LTA IM Competence Management [67, 107, 108].
		• LTA IM System Assurance Management [67, 107, 108]
		Learning lessons from past failures
		• LTA Accident Modelling and analysis of human and organisational factors, risk in management systems [28, 37, 42, 47, 67, 96, 101, 102, 106]

Table 2.
SCM/MORT ETBA analysis [56, 58, 106, 107].

his line. A third track worker came very close to being struck. Prior to this sighting, his saw three track workers walking in the same direction as his train on the adjacent line. At the time of accident, the train was travelling at about 50 mph (80 km/h). The track workers walking on the adjacent Down Main line became aware of the train approaching and tried to warn their colleagues as the train passed them [106].

The three track workers on the Up Main line were working on a set of points, using a petrol-engine driven tool for loosening and tightening large nuts (commonly called a nut runner). CCTV images taken from a camera at the front of the train showed that two workers were stood in the four-foot, the one using the nut runner was crouching in the six-foot for tightening and loosening bolts. The three track workers did not become aware of the train until it was very close to them. By this time the train was travelling at around 50 mph The three workers, who were part of a group of six staff, who were carrying out a maintenance task on the track side. The group of track workers were not aware that the train was approaching until it was too late for them to move to a position of safety. The RAIB 11/2020 Report identified the causal factors, and underlying factors and or want of space there are not reported here but these can be accessed online [107].

3.3.2 The SIRI cybernetic model (2017) of stakeholder analysis

For want of space, the author requests readers to perform the other steps of the model analysis based upon the example given earlier see the RAIB 11/2020 Report [107].

3.3.3 The SIRI cybernetic model (2017) of safety standards

For want of space, the author requests readers to perform the other steps of the model analysis based upon the example given earlier.

3.3.4 The SIRI cybernetic model (2017) Swiss cheese model barrier analysis

See **Table 2**.

4. Conclusions

The paper showed failures in safety management led to safety risk problems in both tightly and loosely coupled systems. The rush to implement the AI algorithms must be checked in the domain for problems in auditing process in both non-AI and AI contexts as safety upsets in low accident rate industries such as aviation do occur revealing culture problems in such industries [35, 50].

The vocabulary of the organisational decision making as suggested by Prof H.A Simon did not cover risk assessments that were grossly underestimated due to imaginability bias. And the idea that bounded rational organisations do not seek to minimise harm are illustrated in both highly automated aviation work system and non-automated track work system(s) as well. Organisations need to strike a balance between loss aversion and excessive optimism attitudes to benefit the society where the goals involving emergent properties like driveability of ERTMS train are concerned [11, 41, 111].

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Chapter 3

Analysis of Methods Used to Diagnostics of Railway Lines

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Abstract

Complex diagnostics of railway lines involves techniques based on discrete and continual data acquisition. While discrete measurements belong to conventional methods, the modern continual ones use automated robotized instruments with continuous recording. Observations have become more time-efficient, but the processing epoch has become longer to evaluate a large number of data. Railway line diagnostics is realized by relative methods lead to determine relative track parameters as the track gauge, elevation, and track gradients and absolute, geodetic techniques determine directional and height ratios of the track, defined in a global coordinate and height system.

Keywords: railway diagnostics, ballastless construction, spatial polar method, terrestrial laser scanning, digital leveling

1. Introduction

Railway technical condition has a significant impact on the safety and traffic flow. One of the most important tasks of a railway responsible is to ensure regular maintenance that includes the diagnostics of the actual condition. The diagnostics prolongs the railway service life and contributes to preserve or improve the quality of geometrical and construction parameters of railway lines mainly dependent on materials used in its construction or reconstruction.

There are many ways to diagnose railway lines, starting from visual fault detection through video inspection and ending with the use of various automated diagnostics systems differed by their physical principles. The paper deals with diagnostics methods of railway track that the railway responsible required from civil engineers.

The diagnostics of the railway track done by civil engineers have to enable to determine the main railway parameters: operational safety, changes in the designed geometric directional and height parameters of the railway construction, the impact of quality degradation, material wear of constructional elements [1].

The diagnostics method are divided concerning the range of diagnostics needs and the possibilities of used methods. Generally, we distinguish diagnostics of absolute geometric position, diagnostics of relative geometric position, and diagnostics of constructional track parameters.

The geometric track position represents the projected directional and height parameters of railway lines. From the point of view of the assessment of traffic influences, we divide the geometric position into absolute and relative one. The absolute geometric track position refers to the projected one and relative track position refers to the mathematical functions of analytical geometry like curve, line, cubic parabola, etc. In practice, the absolute directional position of the track is given by the horizontal distance between the track axis and a railway benchmark, and the absolute height position of the track is given by the vertical distance between the top of the non-elevated rail and the benchmark. The relative directional position of the rails represents the positional differences of rails from the projected values. The relative height position of the rails contains a longitudinal change of height of both rails, the mutual height position of rails called rail cant, and the change of the mutual height position of the opposite heads called rail collapse [2, 3].

The track arrangement includes track gauge, gauge change as widening or shrinking, transverse inclination of the rails, size of connection gaps, parallelism of connections, division of sleepers, fastening of rail tracks.

2. Influence of railway traffic and climate changes on railway condition

Traffic effects appear as vertical and horizontal forces acting on the railway track with the character of static and dynamic loading. Long-term traffic effects cause changes in the geometric position and arrangement of the track, changes of the constructional elements, which will be reflected in track deformations, material wear, and material fatigue, and changes in the subsoil, which cause deformations and degradation of physical railway characteristics.

Climate conditions especially temperature, water, and snow influences cause changes in rail length. Low temperature causes the creating of cracks of wooden sleepers and changing the elasticity of some materials. High temperature worse quality properties of non-metallic materials as plastic and rubber elements. Waterfalls cause corrosion of metal parts of the construction, mold, and rot of wooden sleepers, and overall deterioration of subsoil. Long-term precipitation causes increasing the level of groundwater. Snowfall reduces traffic cross-section and makes it inoperable. The effects of traffic and climate changes on the railway line depend on:

- traffic loading and speed,
- type and intensity of railway traffic,
- the quality of the material of the constructional elements of the railway line,
- the quality of the railway construction,
- condition of railway vehicles,
- the scope and quality of maintenance and repairs.

Traffic harms the absolute and relative directional track position. Concerning the absolute directional position, the horizontal forces cause moving the rail in their direction, which caused the change of axial distances of multi-track lines or the change of the distance to objects located around the track. The absolute directional track position can be found out by using measuring devices or geodetic methods.

Concerning the relative directional position, the horizontal forces cause a change in the curvature expressed as ratio 1/r, which appears as changes in the size and direction of the acting forces. Directional deformations are determined by measuring the uplift above the curve chord. The difference between the projected and the actual measured value shall not exceed the value predetermined in national technical standards. The most common directional deformations include:

- disorders in the subsoil,
- improperly designed geometric position of the track,
- climatic conditions,
- influence of railway vehicles,
- insufficient maintenance or repairs.

Defects in directional position are expressed in discomposed driving, deterioration of comfort, increasing the stress of constructional elements, greater wear of the material, and finally the deterioration of quality traffic route. Corrections of errors in the directional track position are performed mechanically by automatic or mechanical tamper [4, 5].

The vertical forces acting on the railway cause elastic or flexible permanent deformation of the height position of railway tracks, which is reflected in the reduction of level one or both of the tops of the rails. The height deformations can appear as continual or short changes of a track. The continual changes of track height are generally evaluated as absolute errors of height position, with uneven drops of the rails causing a change of cross-section and the change of the mutual relative position of the track and the traction line. The absolute height position of the track is measured either manually (by a simple measuring device) or by geodetic height measurements. Changes in relative height may affect all or some of the monitored parameters of geometric position (track depression, elevation, or collapse). The longitudinal height changes of the rails arise in places of increased vertical forces (joints) or failures in the subsoil sediments. The deformations can be single-sided on a rail or double-sided-symmetrical on both rails in the same place and double-sided-cross on both rails with a shifted start. Cracks and drops of joints affect driving comfort and cause an increase of vertical forces (shocks). The longitudinal height of the rails is determined by geodetic methods or by measuring wagons. The mutual height changes of both rails negatively affect the loading on the rails. Demolition is the most monitored parameter in terms of operational safety.

Track collapse is calculated from the height difference measured at the length of the respective base and calculate as the slope (in form 1: n). The not permitted inclination is assessed as an error only if the length of the slope is minimal 2.0 m. The most common causes of changes in the height position of the rails are the following:

- uneven compaction of the trackbed,
- disorders in the subsoil,
- changes in the properties of the subsoil,
- loose fasteners,
- contact gaps,
- uneven distribution of sleepers,

- incorrect cant
- acting the railway vehicles (unevenness loading),
- poor maintenance and repairs

Troubleshooting at the height of the rails is done manually by small range devices or mechanically by automatic machine jacks. The negative effect of the traffic on the track arrangement appears as an extension or reduction of the track gauge. These changes affect the movement of railway vehicles on the running track, which causes changes in the loading of constructional elements. Track gauge is controlled in discrete points using gauges, or continuously by measuring devices. Besides the value of the track gauge also the course of the change of the gauge between two different values at a distance of 1,0 m is assessed. The reasons for the widening of the gauge include poor installation of the rail grate, lateral wear of the rails, wear and loosening of fasteners, uneven pushing of the bases, construction of railway vehicles, bending of sleepers, and insufficient maintenance and repairs. The reduction in gauge causes rolling of railheads, deformation of sleepers, uneven wandering of the rails. Repair of the incorrect gauge is performed according to the type of fastening and sleepers by flipping the clamps, folding the clamps, or by turning flat rib bases.

3. Diagnostics of relative constructional and geometric track position

The main aim of diagnostics of the relative track geometric position is to find negative influences of force and dynamic effects of railway vehicles. Two types of relative diagnostics are used: partial diagnostics. Partial diagnostics is detecting changes in one or more parameters from the geometric arrangement rails. Complex diagnostics allows simultaneous measurement of all crucial parameters by one device on which the measuring means are located. According to the used measuring equipment and technologies, we divide diagnostics into analog devices based on manual manipulation, which detects permanent changes, and electronic devices, which allow registering the elastic deformations that occurred under traffic loading.

3.1 Partial diagnostics

Partial diagnostics of the track was the most used method in the past for control the geometric position of the rail. Nowadays, it is often applied as a complementary method to visual diagnostics because of its unquestionable advantages such as speed of use in operational conditions, simple manual manipulation, and immediate output of results. Partial diagnostics is used to measure track gauge, relative mutual directional, and height position of rails. The most suitable equipment for these purposes seems to be a gauge measuring device, which measures permanent deformations of the track without any influences of the other parameters. Depending on the technology, the gauge measuring device can be used for discrete data recording or continual measurement with graphical and numerical output [6, 7].

The constructional principle of the analog gauge measuring device used for discrete diagnostics is based on direct or indirect measurement of a specific parameter while other track parameters are possible to estimate by using numerical calculations. The continual measurement of track geometrical parameters has a wider base of measuring devices based on the electronic principle of data recording. These devices usually measure the track gauge and the relative height position at the same time. In addition to the measured parameters, the constructional track parameters are evaluated in post-processing.

3.2 Complex diagnostics

Complex diagnostics of relative geometric track parameters control the mutual position of the left and right rail, track gauge, relative gauge changes, the longitudinal relative height position of both rails, rail cant, and track collapse evaluated above the relevant base. In addition to these static values, also dynamic influences and other parameters belong to microgeometry and material diagnostics of rails are evaluated. Devices for complex diagnostics work continually, although the measurement is performed pointwise with measurement steps of 250 mm, measured values are included in the outputs of the evaluation of individual parameters and the condition of the line. Physical principles of complex diagnostics devices enable contact or contactless measurement, the result of which is in the form of graphical record, numerical record, local evaluation, sectional and overall evaluation of railway conditions, which output is in the digital or video form. Besides, the proposal of maintenance measures is a part of the output of complex diagnostics. The most complex diagnostics of the railway line is realized by Measuring wagon and is involved in regular maintenance programs, which prepare belong to the competence of railways management [5].

3.3 Diagnostics of constructional elements

Diagnostics of constructional elements of railway belong to the necessary part of the process of railway diagnostics. Great attention is paid to rail condition, its time changes, and deformation, while the other rail parameters are diagnosed only visually, due to their less impact on the safety and fluentness of traffic. More detailed diagnostics is applied only in case of abnormal occurrence of destructive phenomena [8, 9]. Diagnostics of constructional elements of the track is divided into:

- geometrical diagnostics of rail profiles,
- material diagnostics of rail profiles,
- diagnostics of microgeometry of rail profiles,
- diagnostics of sleepers, small rails, and fasteners.

The size of wear of railhead (**Figure 1**) caused by railway traffic, horizontal deformation at the rail leading edge, and vertical deformation at the head of a rail are determined during geometrical diagnostics of rail profiles. The wear of the railhead is caused by wheel friction as the railway vehicle moves along the rail. The geometric shape of the railhead is gradually changed by the influence of traffic loading.

Material diagnostics of rail profiles aim to detect inner faults that occurred during railway traffic. Material defects can appear at the surface of the rail part, close below the surface, and inside the rail. Material diagnostics prefers non-destructive methods without any restriction in railway traffic as visual, capillary, or ultrasonic detections. The ultrasonic method is the regular diagnostics method and is performed by manual devices, measuring vehicles, or wagon detectors.

The diagnostics of sleepers focuses on concrete sleepers to search for cracks, which worsen its qualitative properties, damages of the surface of the basement,

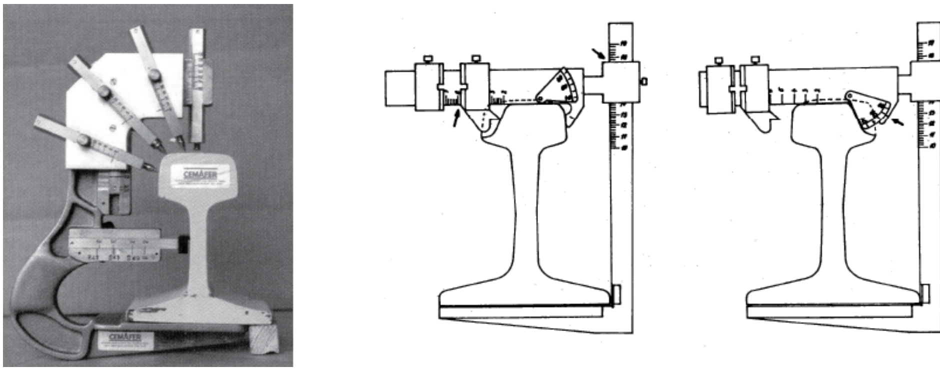

Figure 1.
The manual device for measuring the rail wear on-site (source [10]).

developed by incorrect repair technology and faults of holes need for sleeper screws. The visual inspection of sleepers focuses on the cracks laying on the surface of the basement, mechanical damage of the surface of the basement caused by railway traffic at the points of contact with other constructional elements, deformations of the shape of sleepers, rot, and mold, etc. Steel sleepers are controlled from the point of view of developing the cracks, shape deformations, changes of the shape and size of holes, and material corrosion.

4. Diagnostics of the track absolute geometric position

The diagnostics of the absolute geometric position of the track is practically based on the control of the change of the track spatial position concerning the designed parameters included in the project documentation. The absolute track diagnostics is usually realized by geodetic methods that enable the determination of the spatial position of the track axis concerning the railway benchmarks defined in global European or national coordinate and height systems. Depending on the used geodetic method, the control of the spatial track position can reveal either directly a spatial change or only a change in directional or height position of the track. Generally, the spatial change of a point is defined by the spatial vector defined by three main components: size, direction, and time. Defined by the three main components, which are the magnitude of the direction and the time of action [11–13]. The detection of these parameters can capture geodetic methods, based on the contact and contactless principle, such as terrestrial laser scanning, digital photogrammetry, spatial polar method, kinematic GNSS method, etc. Altitude changes are monitored by the method of precise leveling, and the polar method provided by robotic total stations is currently suitable for detecting displacements of the railway structure in 2D space. The use of the geodetic method for monitoring a railway line depends on the accessibility of the track, length of the railway closure, accuracy requirements, the expected size of the spatial change, which depends on the construction of the railway superstructure, etc.

5. Application of diagnostics method on a ballastless railway line

Ballastless railway line (BRL) is a modern railway construction that ensures safety and traffic comfort while increasing demands for traffic speeds above

160 km/h, which is accompanied by an increase in traffic loading. The BRL refers to the construction of a railway superstructure in which the spreading function of the trackbed is replaced by reinforced materials and which is placed on a concrete or asphalt base plate. The ballastless construction has proven to be a practical and advantageous construction system of the railway superstructure in many countries. An essential reason to build such a railway superstructure is the high track stability associated with fluent vehicles movement and traffic comfort, especially for passengers. The railway responsible appreciates significantly lower requirements for track maintenance, which is accompanied by smaller financial demands. This high driving comfort can only be obtained, in the case of the classic superstructure design, in conjunction with very high operating costs. According to [1] the ballastless railway construction can reduce the following cost items:

- demands on revision and inspection of geometric track position,
- climate influence on railway superstructure and subsoil,
- vegetation care,
- demands on track reconstruction,
- minimization of cleaning track bed,
- increasing time interval of track renewal.

In Slovakia, the ballastless railway construction is built on modernized railway sections especially in tunnels, which have the required subsoil properties, with minimal settlement and bridges without subsidence. In summary, the construction of BRL is suitable due to the reduction of the excavation area, durability and stability of the track position, and minimal demands on maintenance.

The diagnostics of geometrical track position was realized railway section with ballastless construction RHEDA 2000®. The total length of the ballastless construction is 4480 m and passes through various types of track subsoil as tunnel (**Figure 2**), open-air (**Figure 3**), and bridges (**Figure 4**). Due to the difference in subsoil stiffness in the particular line sections, the system of the ballastless railway line was modified to reflect the thickness and reinforcement of the concrete structure.

The critical part of ballastless construction is the transition section laying between ballastless and standard railway construction because of the change of

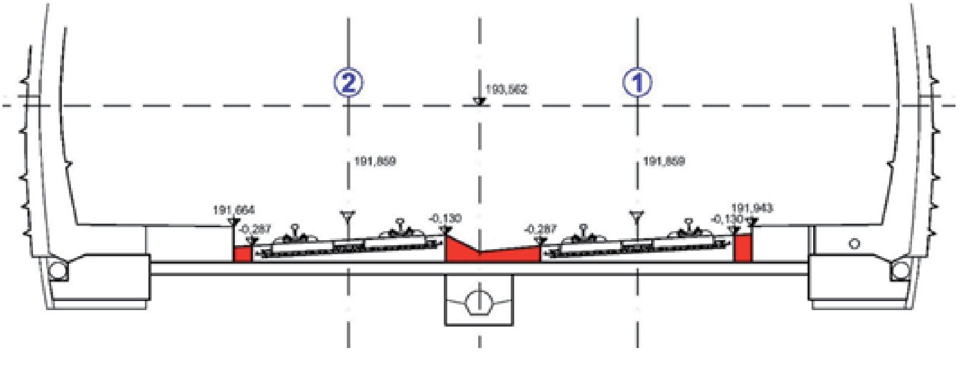

Figure 2.
Ballastles railway line in a tunnel.

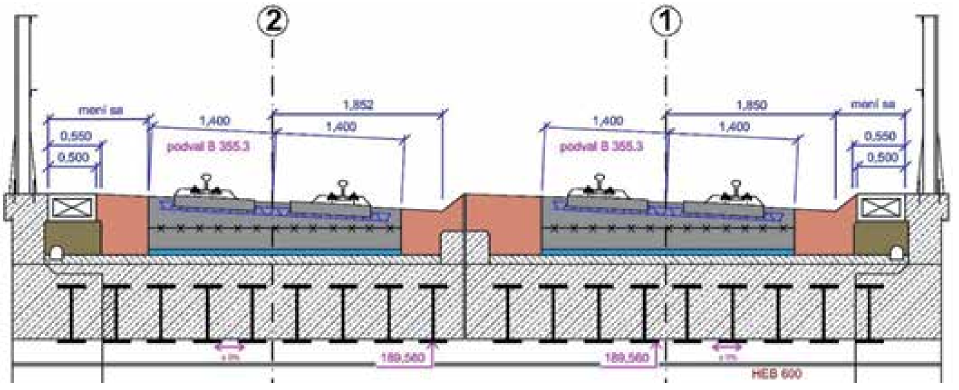

Figure 3.
Ballastles railway line on bridges.

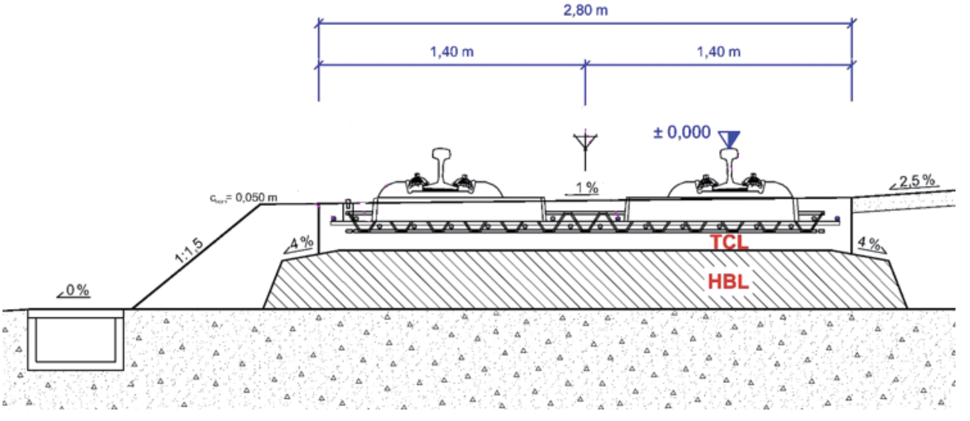

Figure 4.
Ballastles railway line in open-air.

construction stiffness. During the diagnostics process, great attention was paid to this part of railway construction to determine deformations.

5.1 Evaluation of partial and complex diagnostics of BRL

Partial diagnostics of geometrical track position was performed by manual gauge devices ROBEL and GEISMAR to find out gauge changes and track elevation at each mounting node. Complex diagnostics of the structural and geometrical track position was realized by the electronic measuring system KRAB™-Light. The track geometric parameters are measured by contact sensors and recorded in each 250 mm step. The result of diagnostics is obtained in postprocessing:

- track gauge is measured by a potentiometric sensor on the left separate wheel (**Figure 5**),
- the directional position is given by horizontal uplift of the right rail,
- height position is given by vertical uplift of the right rail,
- track elevation measured by inclinometer (**Figure 6**),

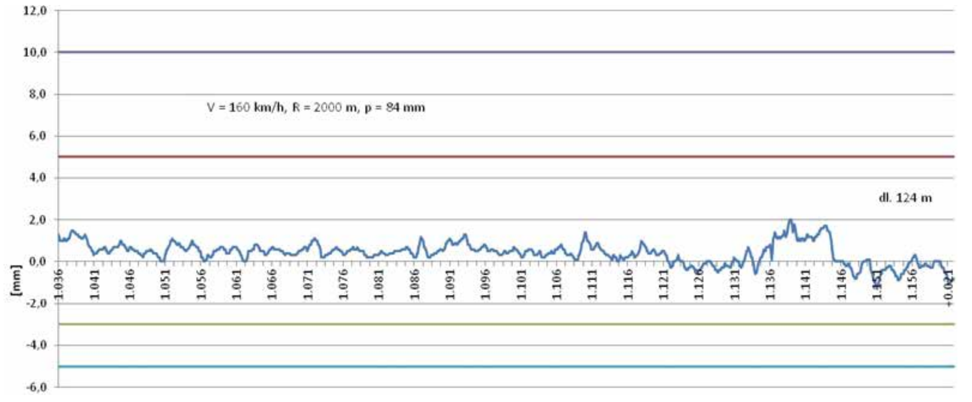

Figure 5.
Changes in track gauge defined in mm.

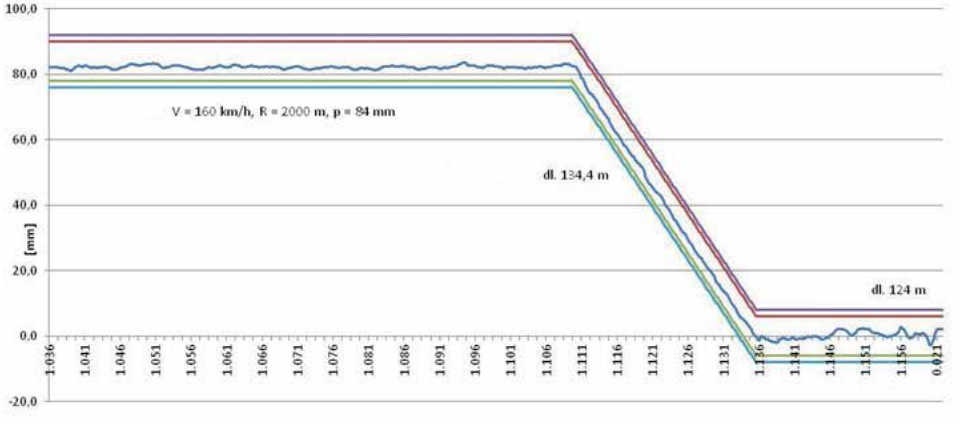

Figure 6.
Track elevation defined in mm.

- quasi-collapse on a short base,
- the longitudinal inclination of the track obtained only by special inclinometer configuration,
- distance traveled obtain by an incremental rotary sensor.

5.2 Evaluation of geodetic diagnostics of BRL

The project of diagnostics of ballastless railway line suggested using geodetic methods to define the spatial, height, and positional track changes.

5.2.1 Analysis of spatial observations

The positional observations of BRL were realized by a video-assisted robotic total station utilizing Trimble VISION technology, which means that it sees everything without a trip back to the instrument and selects targets with just a tap of the controller screen. So, measurements are drawn to the video image and the surveyor can be certain to never miss a shot he needs. The total station involves also FineLock technology to detect targets without interference from the surrounding prism and SurePoint accuracy assurance to correct instrument pointing. The primary precision of the total station is defined by angle accuracy of 0.3 miligons, distance accuracy in standard prism mode is 1 mm + 2 ppm and in tracking mode, it is 4 mm + 2 ppm. So, the technology is destined to be used for both discrete and continuous measurements of the ballastless railway.

Geodetic observations of ballast-less track were realized in standard prism mode to find out spatial track change of ballastless construction in particular points and in tracking mode to evaluate spatial changes from continual observations. The measurements were realized in observational epochs with a period of half a year and spatial changes were evaluated from the differences of the actual and first epoch of spatial vectors.

The organization of the observational epoch consisted of a particular measurement of both rails under traffic closure. The particular points were signalized on each eighth sleeper (5 m) by the marks drawn on the concrete sleeper. Diagnostics of geometrical track position assumes also to determine the longitudinal and transversal changes of the track axes, which are monitored in particular measurement epochs. For this reason, the geodetic observations were pointed to the right rail of the railway line the axes position was defined in post-processing by offset regime. For the purpose to eliminate a pointing error, coordinates of the particular points were converted into a projected system by using track-projected parameters. The analysis of track positional changes belongs to the statistical hypothesis testing based on the postulate of null hypothesis [14]:

$$H_0 : \Delta Z = 0, \Delta z = -\varepsilon_{\Delta z} \tag{1}$$

where ΔZ is the real positional displacement of a point and Δz is measured displacement. If the null hypothesis is confirmed the real displacement is not proven and it is only a function of real observational error $\varepsilon_{\Delta z}$

$$\Delta Z = \Delta z + \varepsilon_{\Delta z} \tag{2}$$

and the measured displacement in the i-th and first epoch of measurement Δz:

$$\Delta z = z_i - z_1 \tag{3}$$

Suppose, the measured values are normally distributed $N\left(\Delta Z,\ \sigma^2_{\Delta z}\right)$ and also the measuring errors will be normally distributed, the confidential interval for measured displacement can be defined as follows:

$$P(|\varepsilon_{\Delta z}| > t_\alpha \sigma_{\Delta z}) = P(|\Delta z| > t_\alpha \sigma_{\Delta z}) = \alpha, \tag{4}$$

where $\sigma_{\Delta z}$ is random standard deviation depended on random variances of both observation epochs:

$$\sigma_{z1i} = \sqrt{\sigma^2_{zi} + \sigma^2_{z1}} \tag{5}$$

In practice, the real value of displacement is unknown and hypothesis testing of the positional displacement can be established by the following inequalities:

If $|\Delta z| < \sigma_{\Delta z1i}$ the null hypothesis is confirmed and positional displacement is not evident.

If $\sigma_{\Delta z1i} \leq |\Delta z| < 2\sigma_{\Delta z1i}$ the null hypothesis is not confirmed and positional displacement is considered as possible.

If $|\Delta z| > 2\sigma_{\Delta z1i}$ the null hypothesis is not confirmed and positional displacement is evident.

5.2.2 Analysis of height observations

The height measurements were performed by precise leveling method with the level instrument, of which the unit standard deviation does not exceed value 0.40 mm in every observational epoch. The height differences were related to the reference network, which consists of permanently stabilized leveling marks, stabilized either on the base of the masts or in the concrete curb. The critical value for determining the height stability of the reference network was determined from the measured height change test and is determined as twice the mean value of the standard deviations found in the particular observation epochs. The process of control the stability of the height reference network consists of estimating the parameters of the regression line, constructed from the difference between the elevation in the first epoch and the i-th epoch, testing of outliers, and estimating the a posteriori accuracy of the network [15].

The analysis of height changes consists of assessing the elevation differences of the i-th and the first leveling. If the standard deviation of the leveling network of the length L in the i-th measurement is given by the relation:

$$\sigma_{hi} = \sigma_{0i}\sqrt{L} \tag{6}$$

the accuracy of the heights differences is defined by the standard deviation:

$$\sigma_{\Delta h} = \sqrt{\sigma_{hi}^2 + \sigma_{h1}^2} \tag{7}$$

out of which we define the probability α and the coefficient of the Student distribution t = 2:

$$\Delta h \geq 2\sigma_{\Delta h} \tag{8}$$

However, the critical limits which represents the reliability interval for the proof of the height changes of the particular points were defined according to the relation:

$$\Delta\overline{h} - 2\sigma_{\Delta h} \leq \Delta h \leq \Delta\overline{h} + 2\sigma_{\Delta h} \tag{9}$$

5.2.3 Analysis of laser scanning

Terrestrial laser scanning has become a very useful method for acquiring an accurate three-dimensional detail of a complex observed object or facility, but its application in engineering surveying has some limitations resulting from the uniqueness of a measured structure. Railway track belongs to the long line ground objects and so the technology of its laser scanning has to be conformed to this fact.

For the scanning procedure of rail track, we used pulsed dual-axis compensated laser scanner Leica ScanStation C10 with the prescribed accuracy of a single measurement in position ±6 mm and distance ±4 mm and angular accuracy is ±12″. These specifications designate standard deviation for target acquisition ±2 mm. The scanning system is based on a 3R green laser of wavelength 532 nm with a scanning range of 300 m [16].

ScanStation was situated on both sides of railway lines and its 3D position was determined by resection method related to the railway benchmarks. The scan

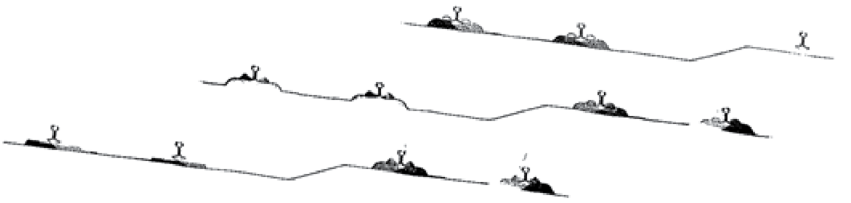

Figure 7.
Illustration of transversal profiles of both railway lines obtained by numerical analysis of clouds of data.

resolution was 3 cm at a range of 30 m while keeping the prescribed accuracy in position ±6 mm. The scan area was limited by the horizontal field of view from 0° to 180° and vertical field of view from −45° to +90°.

The point cloud processing belongs to the most time-consuming and very important part of data utilization. Each point in the point cloud is measured concerning the scanner position, and so the parameter transformation from local to the global national system is necessary to fit the point cloud to coordinate system. For this fact, the connection between laser scanning and terrestrial measurement is necessary, which is based on the 3D position of identical points of both systems. The combination both of measurement methods also helps to verify the positional data, which are utilized in the post-processing procedures. The positional control of the observed point cloud is also realized by the photogrammetric method, which enables the overlapping digital photos, made by a video camera, with corresponding scans.

The point cloud processing continues with the feature codes extraction directly from the point cloud and their export to feature code processing software. While scanning a site, the scanner captures everything in the selected field of view. Objects, which are not relevant to the surveyor have to be removed from the scan. This removal process is an interactive process and a skilled operator needs only a few minutes for extracting and deleting the useless objects. The process of determination of track changes consists mostly of applying mathematical procedures especially regression analysis and mathematical modeling to receive the faithful model of reality [17, 18]. The received mathematical model was finally used to reconstruct the railway track geometry and to evaluate the transversal and longitudinal profiles of a track section (**Figure 7**).

6. Conclusion

Evaluation of partial and complex track diagnostics consists of determining "Local errors" specified in railway sections, which differ by the subsoil construction. The Local errors are defined by values of deviation of the measured parameter from design one. Complex track diagnostics is evaluated by "Quality number", which is determined as the ratio between both observed standard deviation and theoretical one. Based on the value of the quality number, the level of maintenance of the railway line is recommended or repair work is specified.

The standard deviation of determining track changes measured by geodetic methods gives the view on a-posteriori accuracy of the observed track parameter. It involves the error of multitrack target position regarding track axis (±2 mm) and precision of displacement estimation process (±2–3 mm). The longitudinal displacement of the ballastless track was not evaluated, because the precision of multitrack target positioning in the longitudinal direction of the track is out of the assumed value of longitudinal displacement. Concerning the discrete observations, the main problem seems to be in permanent signalization of the particular points on the ballast-less track construction to minimize the error of reflector target positioning.

Precision analysis of digital leveling realized on ballast-less track consists in both analyses of vertical reference network and precision analysis of the track measurements. The first one brought the view on the stability of reference system and the standard deviation, as the main characteristic of used leveling method. Precision analysis of track measurements consists of defining the standard deviation of height differences and the confidential interval, which qualifies the evident vertical displacements of track construction. The precision analysis of geodetic observations realized on ballast-less track construction was performed in conformity with the appropriate technical standards. Accuracy of used digital leveling satisfies the demands, which are defined for observation of such an unconventional track construction.

The application of laser scanning brings to surveyors a great possibility to display the real world in much more detail than it was in past, and it brings also new approaches to utilize the scanning outputs by a using variety of software. For civil engineering, the most common output from laser scanning is the digital terrain model, which can be applied in map-making, designing, deformations diagnostics, construction inspection, or historical objects reconstruction.

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Chapter 4

New Approach Measuring the Wheel/Rail Interaction Loads

Yuri P. Boronenko, Rustam V. Rahimov and Waail M. Lafta

Abstract

This chapter suggested new methods for monitoring the dynamic processes of rolling stock/rail interaction. This study develops a new technical solution for measuring the wheel/rail interaction forces on a significant part of the sleeper. The theoretical part of this study, using FEM, confirm the ability of piecewise continuous recording of vertical and lateral forces from the wheel/rail interaction by measuring the stresses in two sections of the rail. Also, the optimum location of strain gauges and the effective length of the measuring zone have been determined. The experimental part of this study has been carried out on the stands and the railway track to confirm the effectiveness of the method to determine the vertical and lateral wheel/rail interaction forces, increase the reliable statistical data, improve the measurement accuracy, reducing the time and cost compared with current testing methods. The developed method is recommended to determine the wheel/rail interaction forces and identify defects on the wheels when diagnosing rolling stock on operational and travel regimes.

Keywords: wheel/rail interaction, rolling stock/track effects, vertical force and lateral force of rolling stock, rail strain gauge, effective rail zone, wheel/rail loads

1. Introduction

The rapid development of heavy traffic is one of the priorities to increase the efficiency of rail transportation, which allows the formation of freight trains of increased weight and length. However, this will increase axle loads and issues related to controlling rolling stock/rail interaction forces.

The first experimental assessments of the force impact of rolling stock on a rail track were carried out in the late 19th and early 20th centuries [1–3]. In 1925, an experimental method on the rolling stock/rail impact was developed, the forces acting on the track, stresses, and deformations in the track elements have been investigated [4]. Direct measurement of the wheel/rail interacting forces is difficult; therefore, their determination is usually carried out indirectly by measuring shear deformations, and relative displacements using strain gauges and the subsequent application of algorithms for processing the data obtained [5–9].

Early research confirmed that since the maximum stresses arise at the edges of the rail base, the vertical and lateral forces have been initially determined from their correlation dependencies on the half-sum and half-difference of edge stresses [7, 10]. Later, these studies were developed in the works of M.F. Verigo, O.P. Ershkova [11], S.S. Krepkorosky, A.K. Shafranovsky [12, 13] and others [14–16].

The main disadvantage of this method is that the received results depend on the elastic properties of the path [4]; therefore, the error ratio reaches 30% [7].

E.M. Bromberg and O.P. Ershkov were developed, theoretically substantiated and practically implemented a more accurate experimental method for measuring vertical and lateral forces ("three-point" method) [11, 17] by simultaneously registering stresses at three points, **Figure 1**), measuring stresses at the edges of the rail base (strain gauges 1 and 2) and in the outer section of the headrail (strain gauge 3) [7, 14, 15, 18].

The absence of computers (during that period) limited the development of the "three-point" method. Subsequently, the method was replaced by the analog Schlumpf method [19–21] for measuring the rolling stock force effect on the rail. According to this method, the lateral forces are measured by the deformations of the rail web by four strain gauges (numbers 6–9 in **Figure 1**). The essence of this method lies in the linear dependence of the magnitude of the lateral forces on the difference in bending moments acting on points mutually symmetric to the neutral axis of the rail neck [7, 14, 22].

Researches revealed that the shortage of the Schlumpf method [22, 23] is inaccurate results on the measurement of wheel/rail interaction forces when the acting point of the vertical force displace relative to the longitudinal plane of the rail due to the lateral displacement of the wheelset in the track. The values of the lateral forces in the wheel/rail contact depend on the position of the contact spot on the railhead; therefore, errors are inevitable in determining their values. According to VNIIZhT research [14], the greatest error in measuring lateral forces by this method is 7–9%; according to the VNIKTI results [22], the method can error up to 40%. While, according to the VNICTT research [24], the error can reach 100%. Subsequently, Schlumpf's method was improved and modernized by many researchers, to which a significant number of theoretical and experimental studies are devoted, for example, G.F. Agafonova [25], E.I. Danilenko [26], V.S. Kossova [27], A.K. Shafranovsky [12, 13] and other sources [15, 22, 25, 27].

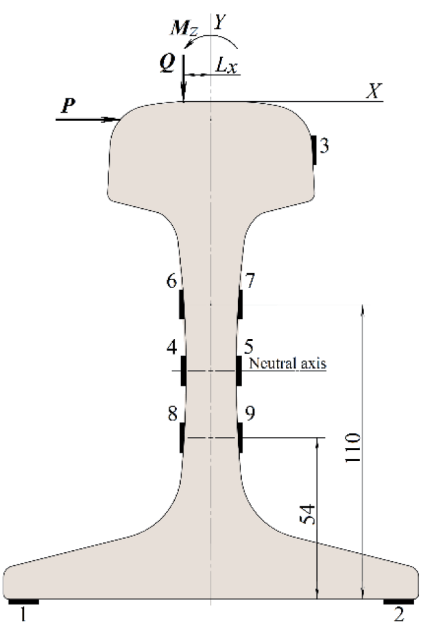

Figure 1.
Schemes of sticking strain gauges on the rail neck to determine the rolling stock/rail force: 1–9 - strain gauge numbers; Q is the vertical force; P - lateral force; M_z - bending moment; X, Y - directions of the axes of the coordinate system.

To determine the vertical forces in the wheel/rail contact, a method based on the measurement of deformations by using strain gauges (#4 and #5 in **Figure 1**), installed vertically from both sides in the same section on the neutral axis of the rail journal, is widely used [3, 6, 7]. This method for measuring vertical forces depends on the lateral force and the eccentricity of the vertical force [4].

For the correct measurement of the wheel/rail interaction forces, an experimental and computational method [27] have been developed to install strain gauges, similar to the Schlumpf method. This method's difference lies in the joint measurement of the vertical and lateral forces in the cross-section of the rail at different positions of the wheel on the rail [22–24]. To measure the forces acting on the railhead, in contrast to the Schlumpf method [21], the signals are recorded from each strain gauge separately. In this case, to obtain the output signals, the strain gauges numbers 6 to 9 in **Figure 1** have been connected to four measuring bridges connected to the recording devices through strain amplifiers [22, 23]. Several calibration experiments were carried out to confirm the readings of strain gauges and force effects, including various options for loading the measuring section of the rail. As a result of calibration experiments using linear superposition from strain gauges (S) readings, the influence matrix [G] has been formed. The pseudoinverse matrix $[G]^+$ to the matrix [G] is calculated, which makes it possible to obtain at each moment (t) the actual values of the force acting on rolling stock/rail interaction, according to the incoming signals from strain gauges using the matrix on Eq. (1) [22, 23]:

$$\{F(t)\} = \begin{Bmatrix} Q\ (t) \\ P\ (t) \\ M_z(t) \end{Bmatrix} = [G]^+ \cdot \{S(t)\}. \tag{1}$$

According to the calculations using the finite element method, it has been found that the restoration of lateral forces using the method of "Russian Railways-2016" [22, 27] gives an error of no more than 10%. In contrast, with the restoration of vertical forces, the relative error does not exceed 1.5%, and it has been noted that using the "RZD-2016" method compared with the Schlumpf method significantly increases the number of used strain gauges and measurement channels.

The researches of Yu.S. Romain [7] confirmed that to reduce the number of strain gauges and channels, measure the stresses not at four but three points of the rail, connecting them with three half-bridge circuits. As a result of theoretical and experiments calculations, the measurement error ratio was about 4% [7]. Later, numerous experimental studies in this field have been carried out, and the most important researches were proposed by D.R. Ahlbeck and H.D. Harrison [9, 28, 29] and by A. Moreau [30].

On the railways of North America and Europe, the "American Method" described by D.R. Ahlbeck and H.D. Harrison [9, 28, 29] is used to measure the wheel/rail interaction loads. According to this method, measurements of lateral forces are carried out by strain gauges located on the rail foot, as shown in **Figure 2**.

A linear dependence of the lateral forces measured by the "American method" on the displacement of the vertical force relative to the longitudinal plane of the rail has been revealed [31]. Moreover, this dependence gives an error in measuring the lateral force of no more than 4% [14]. Subsequently, experimental methods for measuring transverse forces based on measurements of deformations on the surface of the rail foot has been developed in [32, 33].

Also, there is another method for measuring lateral forces - the "method with measurements over the sleeper", similar to the Schlumpf method [19, 20], where four strain gauges are installed vertically on the rail neck above the axis of the

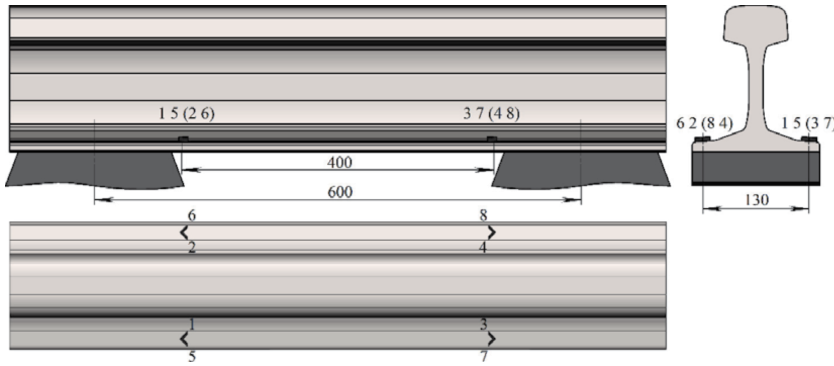

Figure 2.
Position of strain gauges for measuring lateral forces by the "American method": 1–8 - numbers of strain gauges.

sleeper to provide maximum rigidity to lateral loads and, consequently, to the maximum bend of the rail web. Since this method is very sensitive to changes in the position of the vertical force, then later this method was abandoned [31].

All the methods described above for measuring the vertical and lateral forces of the wheel/rail interaction are point-based. The forces are determined only when the wheel is positioned over the sections of the strain gauges; therefore, continuous registration of forces is impossible. The measurement results depend on the speed of movement and the sampling frequency of the measuring equipment. Multiple passes of the test rolling stock along the measuring track section are required to obtain a statistically reliable amount of experimental data. Further development of methods for measuring the forces acting in the wheel/rail contact, which significantly increases the volume of recorded data, is a strain-gauge measuring scheme of "piecewise-continuous" registration [14].

Currently, the system for measuring the vertical force acting in wheel/rail interaction is consists of two complexes of strain gauges installed on the rail neck at an angle of 45° symmetrically relative to the middle of the sleeper gap, where signals from eight strain gauges are summed [9, 29, 31, 34, 35]. With this system, we can measure the difference in displacement between two sections at some distance within the same spacing, and the actual position of the vertical load has not been considered in the results. This method eliminates the effect of lateral force, which causes shear, bending in the horizontal plane and torsion of the rail. Thus, a constant measured value for several tens of *centimeters* is obtained, providing more reliable measurements [31]. Subsequently, the method of "piecewise-continuous" registration of vertical forces was improved by many researchers, for example, in [34, 36, 37]. The effective zone of the "piecewise-continuous" registration scheme in one inter-sleeper gap is approximately 0.2 m.

A similar method of connecting strain gauges is used in the "French method" to evaluate lateral forces described by A. Moreau [30]. The method is based on measuring the stresses in the rail neck from the action of a bending moment in the horizontal plane created by a lateral force from a passing wheel. According to the "French method", the vertical force mounted on the rail neck has been checked using strain gauges (**Figure 3**) located symmetrically relative to the horizontal neutral axis of the rail, in two measuring sections of the rail in each space between sleepers.

A. Moreau suggested that the distance between two measuring sections of sleepers is 350 mm with a distance between the sleepers' axes of 60 cm [31]. The method can significantly increase the information recorded by the measuring circuit. The registration area of the lateral forces is several tens of *centimeters*. Further improvement of the method proposed by A. Moreau is reflected in the works [31, 35].

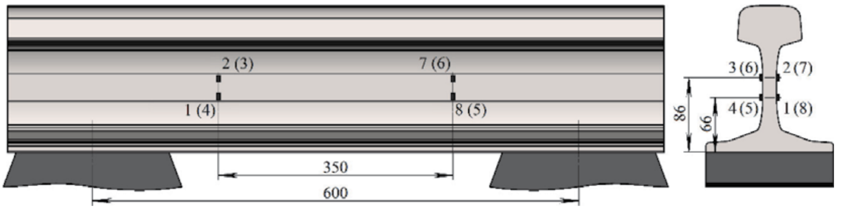

Figure 3.
Location of strain gauges for determining lateral forces by the "French method": 1–8 - numbers of strain gauges.

All the above methods for measuring the wheel/rail force are based on the use of strain gauges installed on the rail, differ in the location of strain gauges and the specifics of processing the received signals. Other experimental research methods of measuring the forces arising at the point of contact of wheel/rail are also known [14, 36, 38–41].

An effective method for measuring vertical and horizontal forces transmitted by wheels to sleepers are also methods where registration is carried out using force-measuring elements mounted on rail pads [3, 4, 40]. Such vertical and horizontal power measuring elements using strain gauges in the bridge circuit were developed at VNIIZhT by LA Grachishnikov [3].

In researches [38, 41], measurements of vertical and lateral forces from the wheel/rail interaction have been carried out by measuring the deformation of the hole in the rail. In this case, to measure the interaction forces, cylindrical strain gauges mounted on two liners have been installed in the holes in the rail neck [38] in the neutral axis of the rail, where each force component can be measured separately [14, 39]. Similarly, a simple transducer was developed that allows one to separate the effects of the vertical force from the lateral ones by placing it in the holes made in the rail neck near the centre of the rail lateral torsion [41]. The main disadvantages of the methods are the low sensitivity of deformation signals to lateral forces and violation of the track integrity [34, 35].

The statistical studies on the Russian railways showed that the GOST R 55050–2012 [21] method and the Russian Railways (RZD-2016) method are used to measure the force effect of rolling stock on the track [21, 27, 42]. These methods are implemented using strain gauges mounted on the rail neck and measure the wheel/rail forces only when the wheel is positioned over the strain gauges sections, and continuous registration of forces in the wheel /rail contact is impossible. In this case, the results depend on the speed of movement and the number of tests; therefore, to obtain a statistically reliable amount of experimental data, multiple passes of the test rolling stock along the measuring section of the track are required. For this reason, there is a need to develop new technical solutions that make it possible to increase the length of the measuring zone, ensure the continuous registration of the force effect wheel/rail interaction during movement, and increase the measurement accuracy.

2. Research on the development of methods for recording the wheel/rail interaction

2.1 Calculation method and calculation model

For this study, a simplified computational model of the rail track has been built, which is a rail of the R65 type (according to GOST 8161–75) [43], 3200 mm long, laid on six sleepers, the distance between them is 544 mm, with boundary conditions characterizing the rigidity of the upper structure of the railway tracks, fasteners, and horizontal longitudinal stiffness of the rail, as shown in **Figure 4**.

As a boundary condition, kinematic connections have been assumed, which are elastic elements (Elastic Support/Foundation Stiffness), to consider the vertical and lateral stiffness of the relationship between the rail and sleepers and the longitudinal stiffness rail. In calculations, vertical and lateral forces added together in one section and successively have displaced along the rail. Different positions of the wheelset relative to the longitudinal axis of the rail during movement have been considered. **Figure 2** represents the Rail model that has been used where:

Q - the vertical force; P - lateral force.

$l_1 = l_2 = l_3 = l_4 = l_5$ - the distance between the supports.

a – represent the location of the vertical and lateral forces applied relative to the axis of symmetry of the inter-sleeper's gap.

C_x and C_y - transverse (horizontal) and vertical stiffness of the connection between the rail and the sleepers.

C_z - longitudinal stiffness of the rail.

Apply vertical loads on the rail's rolling surface; small areas of the contact patch with an area of 144 mm^2 were provided (**Figure 3**). Contact patch centre:

- It is in the middle of the railhead.
- Displaced 11.7 mm outward from the middle of the railhead.
- Displaced 11.7 mm inward from the middle of the railhead.

Apply a lateral force to the rail's side edge; the ridge contact patch areas with an area of 35 mm^2 were provided (**Figure 3**). The centre of such a platform was at a distance of 13 mm from the railhead level.

The ANSYS Workbench software package, version 18, has been used for calculations using the finite element method. The finite element mesh that has been

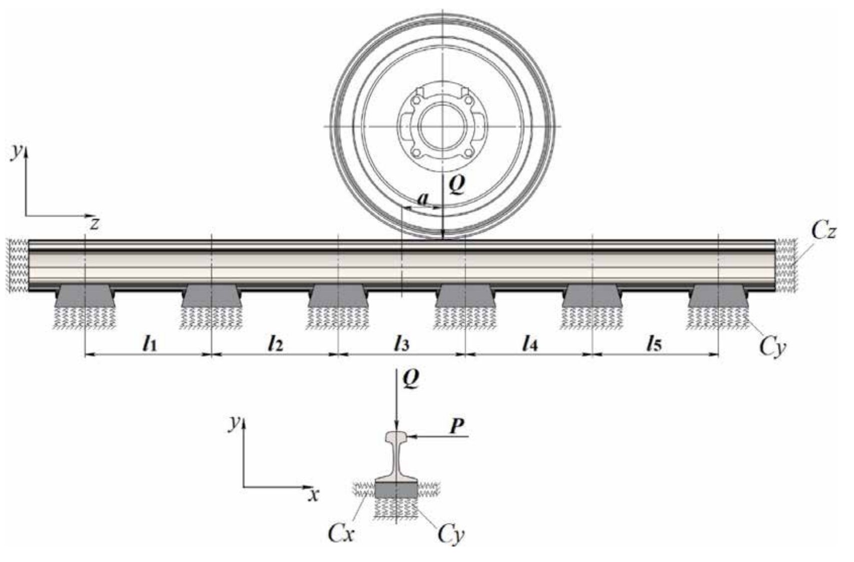

Figure 4.
Design diagram of the rail, where: Q - the vertical force; P - lateral force; $l_1 = l_2 = l_3 = l_4 = l_5$ - the length of the sleepers (distance between the supports); a - the coordinate of the application of vertical and lateral forces relative to the axis of symmetry of the inter-sleepers' gap; C_x and C_y - transverse (horizontal) and vertical stiffness of the connection between the rail and the sleepers; C_z - longitudinal stiffness of the rail.

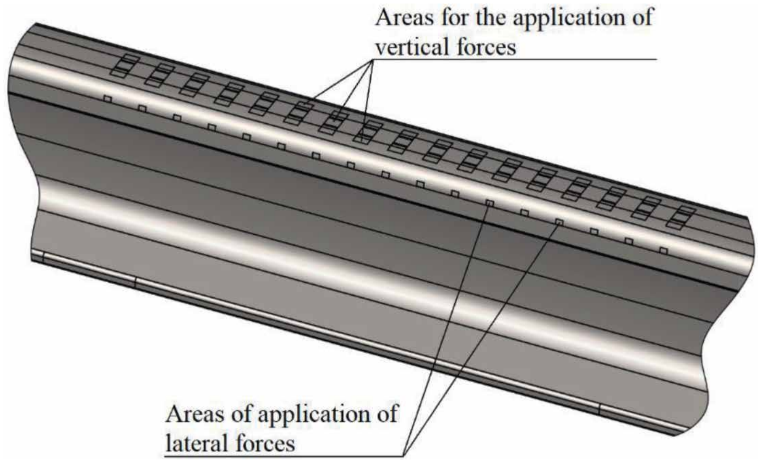

Figure 5.
Platforms on the rail surface for applying vertical and lateral forces.

applied to the rail model includes 117535 elements and 435738 nodes. Finite elements of the Solid186 type with a size of 7.5 mm have been used. The Solid186 feature has a quadratic shape with twenty nodes with three degrees of freedom at each node: displacements in the nodal coordinate system's x, y, and z directions.

The gap between the sleepers was divided into 17 sections to determine the dependence of the stresses arising on the surface of the rail neck, on the acting forces in the wheel/rail contact (from section −8 to section 8), the distance between which is 34 mm (**Figure 5**).

2.2 Research on the development of a method for registering vertical forces acting from a wheel on a rail

The analytical method of calculation substantiated the possibility of registering vertical forces from the wheel to the rail by measuring the shear stresses in two sections of the rail over a significant part of the sleep space [44, 45]. The results of the analytical calculation made it possible to conclude that the difference in shear forces in 2 symmetrical sections at a distance between the measuring sections remains constant and equal to the vertical force from the wheel to the rail (**Figure 6**).

$$P = Q1 - Q2 = \frac{I.b}{S}\left(\tau_{zx}^{L} - \tau_{zx}^{R}\right) \tag{2}$$

Where, τ_{zx}^{L} and τ_{zx}^{R} - shear stresses, measured respectively in sections to the left and right of the acting force; S - the static moment of the lower part of the section relative to the point at which the stresses are determined; b - is the width of the rail neck in the measured section; I - the moment of inertia of the rail.

Since the calculation formulas (2) do not include parameters that depend on the distance between the sleepers and the characteristics of the supports, this circumstance makes it possible to determine the vertical force from the wheel to the rail on a significant part of the sleep distance, thereby increasing the volume of reliable statistical data obtained and increasing the accurate measurements.

Virtual measuring points were set symmetrically on both sides of the rail on the neutral axis, and the values from these points were summed up to check the

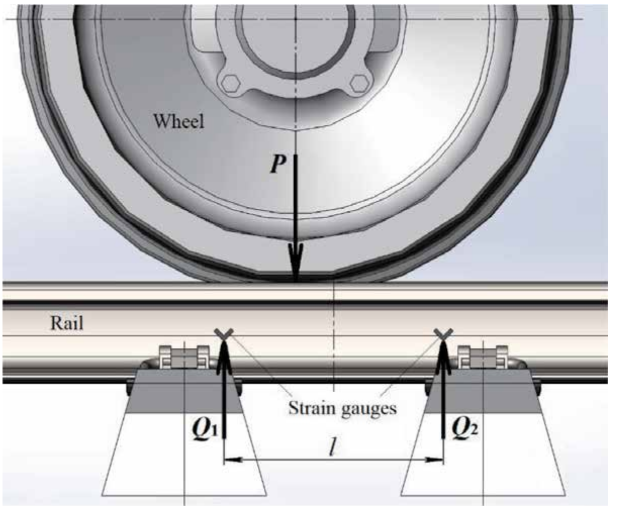

Figure 6.
Scheme of piecewise continuous registration of vertical forces: P - vertical force from the wheel to the rail; Q_1, Q_2 - transverse forces; l - the distance between strain gauges.

possibility of restoring forces by measuring shear stresses in two sections and exclude the influence of lateral and longitudinal forces.

Using the FEM, the vertical force Q was applied at a point on the railhead surface for each section and alternately shifted along the rail from section −8 to 8. As a result, the reconstructed values of vertical forces were determined from the difference in shear stresses $\tau_{zx(+i)}$ - $\tau_{zx(-i)}$ arising in 2 symmetric sections of the rail when the vertical force moves along the rail, which are shown in **Figure 7**.

When comparing the calculation results of the vertical forces, it has been found that the main difference between the results obtained by the finite element method and the data found according to the beam theory was the absence of a force jump. Using FEM, a smooth increase in the values of the restored forces is observed over a length approximately equal to 3/4 of the rail height, then the growth slows down and reaches a maximum in the centre of the inter-sleeper gap. The forces at the centre of the span remain practically constant. The constant-scale zone for the restoration of the vertical force turns out to be significantly smaller than it follows from the calculation according to the beam theory.

The best accuracy of the vertical force is provided when measuring shear stresses in sections 6 (−6) with a length of the measuring zone of about 200 mm (**Figure 7, d**). With an increase in the length of the measuring zone, the deviation increases. The accuracy of restoring the vertical force along sections 4 (−4) and 5 (−5) is significantly lower (**Figure 7, b, c**), but in the middle part of the measuring zone of any of these figures, the constancy of the restoring force is ensured. The resulting discrepancies can be eliminated by calibration. The maximum length of the measuring zone, where the constancy of the vertical force is ensured, is approximately 0.3 ... 0.5 of the distance between the sections, which makes it possible to increase the volume of reliable statistical data obtained and improve the measurement accuracy.

Thus, the results obtained in the calculations by the finite element method confirmed the sufficient efficiency of restoring the vertical force in the wheel/rail contact from the measured shear stresses in two sections of the rail.

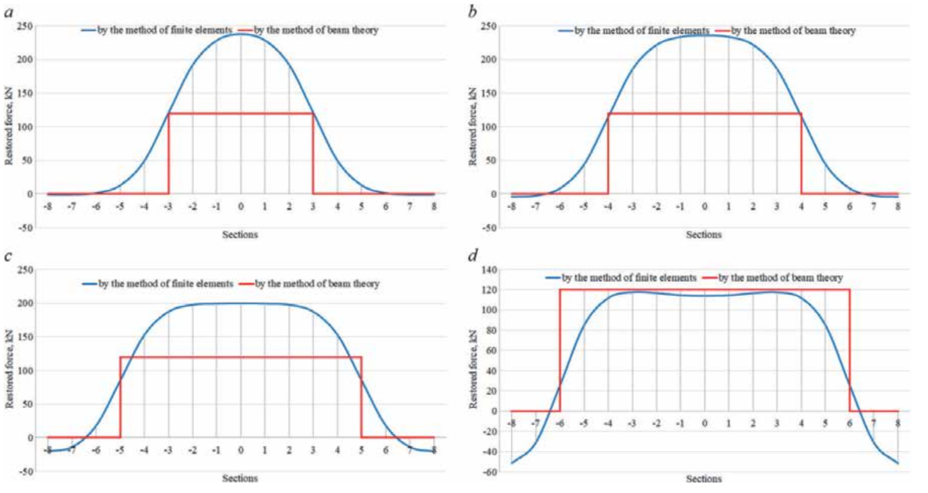

Figure 7.
The reconstructed values of the vertical force from the difference in the values of the shear stresses arising in the investigated sections of the rail when the vertical force moves from section −8 to section 8: a - section 3 (−3); b - sections 4 (−4); c - sections 5 (−5); d - sections 6 (−6).

2.3 Influence evaluation on the accuracy of displacement measurements of the wheel from the axis of symmetry and the occurrence of lateral forces

When the rolling stock moves along the rail track, a transverse displacement of the wheel pair in the track occurs, which leads to the displacement of the "wheel/rail" contact patch in the transverse plane of the rail; as a result, the vertical force also changes its position. In this case, the occurrence of lateral force is possible when the wheel flange hits the rail. Therefore, additional calculations were carried out for the following cases: displacement of the point of application of the vertical force relative to the longitudinal axis of the rail; lateral force generation.

As a result of the calculations, taking into account the movement of the wheel/rail contact patch in the transverse plane and the occurrence of lateral force, it was found that the lateral displacement of the wheel relative to the longitudinal plane of the rail by 11.7 mm and the occurrence of lateral force do not significantly affect the measurement accuracy of the vertical forces by the difference between the values of shear stresses in two sections of the rail. In this case, the effect of the lateral displacement of the wheelset on the result is no more than 1.6%, and the lateral force is no more than 1.38%.

For further experimental verification, it has been recommended to install strain gauges in sections 6 (−6), provided that the distance between the axles of the sleepers is 544 mm and the length of the sleeper gap is 408 mm. The stiffness characteristics of the rail base and rail can influence the results of the experiment. The discrepancy between the vertical force coming from the wheel to the rail and the restoring force is proposed to be eliminated by calibrating the strain gauge circuits.

2.4 Experimental studies to determine the loads from a wheel/rail contact

Experiments were carried out on a fragment of an R65 type rail made according to GOST 8161–75 [43] with a length of 665 mm, fixed on two supports measuring 200 × 140 × 20 mm; distance is 544 mm.

Pre the experiment, a precision marking of a rail fragment between the supports was carried out on 17 sections, the distance between 34 mm.

Then, strain gauges were glued to both sides of the rail web. Strain gauges are placed on the neutral axis of the rail in sections 6 (−6) to determine the vertical force by measuring the stresses in two sections of the rail. To determine the forces on the rail, strain gauges have been installed on the neutral axis of the rail in section 0. The arrangement of strain gauges is shown in **Figure 8**.

Strain gauges are connected to two full parallel bridges with a four-wire connection to register signals in sections −6 (6). Strain gauges are connected according to a full-bridge circuit with a four-wire connection to register signals in section 0.

$$P = Q_1 - Q_2 = \frac{K_p(\varepsilon_1 + \varepsilon_2)}{2} - \frac{K_p(\varepsilon_3 + \varepsilon_4)}{2} - \frac{K_p(\varepsilon_5 + \varepsilon_6)}{2} + \\ + \frac{K_p(\varepsilon_7 + \varepsilon_8)}{2} = \frac{K_p}{2}(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 - \varepsilon_5 - \varepsilon_6 + \varepsilon_7 + \varepsilon_8), \tag{3}$$

Where Q_1 - Q_2 is the difference in shear forces.

K_p is a coefficient that depends on the characteristics of the material and the profile of the rail. During operation, this factor can change due to wear on the railhead.

The change in the output voltage for the considered circuit of parallel operation of two bridges is determined by the expression:

$$\Delta U = k(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 - \varepsilon_5 - \varepsilon_6 + \varepsilon_7 + \varepsilon_8)(1 - \eta)U, \tag{4}$$

or

$$\Delta U = k \cdot \varepsilon_\Sigma (1 - \eta)U. \tag{5}$$

$$\varepsilon_\Sigma = \varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 - \varepsilon_5 - \varepsilon_6 + \varepsilon_7 + \varepsilon_8;$$

Where η is a term characterizing the nonlinearity of the bridge; k - coefficient of sensitivity of strain gauges; U is the voltage of the measuring bridge.

From equality (3) and (5), we obtain the formula for determining the vertical force from the readings of strain gauge bridges:

$$P = \frac{K_p}{2}\varepsilon_\Sigma = \frac{K_p}{2}\frac{\Delta U}{Uk(1 - \eta)}. \tag{6}$$

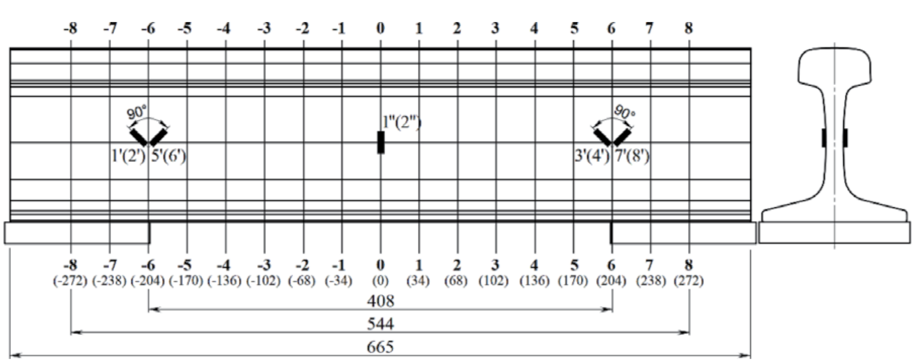

Figure 8.
Layout of strain gauges on the rail neck (numbers from −8 to 8 indicate section numbers, numbers in brackets for each section indicate distances from the middle part between the supports): 1′-8′, 1″-2″- strain gauge numbers.

During experiments, a static vertical load P equal to 0 kN, then from 100 kN to 200 kN with a step of 25 kN was applied to a rail fragment sequentially, along the investigated sections (**Figure 8**), through a loader at the DYNASET-200 stand. Up to 100 kN to 0 kN with the same step until the moment of complete unloading. The experiment process at the DYNASET-200 stand is shown in **Figure 9**.

Based on experiments results, the dependences of the vertical force on the position of the load application point have been determined according to the proposed method (**Figure 10**).

The experiment results showed that the average value of the restored forces over the length of the measuring zone of 204 mm according to measurements in sections 6 (−6) was 199.15 ± 0.98 kN with a load of 200 kN. The error ratio, in this case, was equal to 0.42%.

The experiments were carried out to determine the vertical static force from the wheel to the rail according to the proposed method based on the measured stresses in two rail sections.

The results showed that the discrepancies in the recovery of the force value of 200 kN at the point of application of the vertical force located in the longitudinal axis of the rail, in section 0 according to measurements in sections 6 (−6) relative to the measuring circuit located in section 0 and recording readings according to GOST R 55050–2012 [21], was 0.47% (0.95 kN).

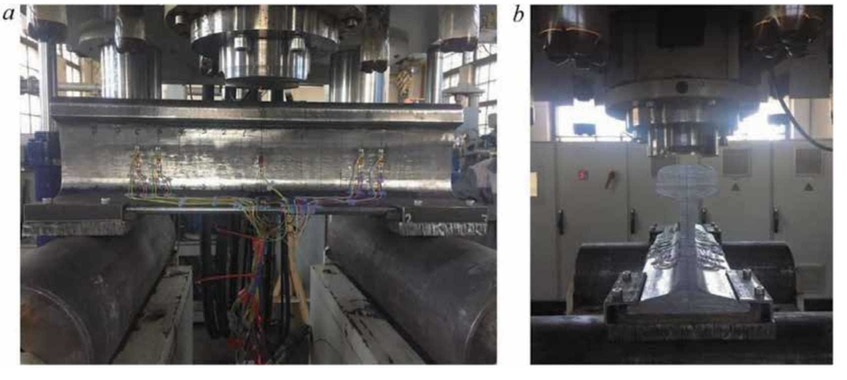

Figure 9.
A fragment of a rail on the DYNASET-200 stand during the experiment: a) front view: b) left view.

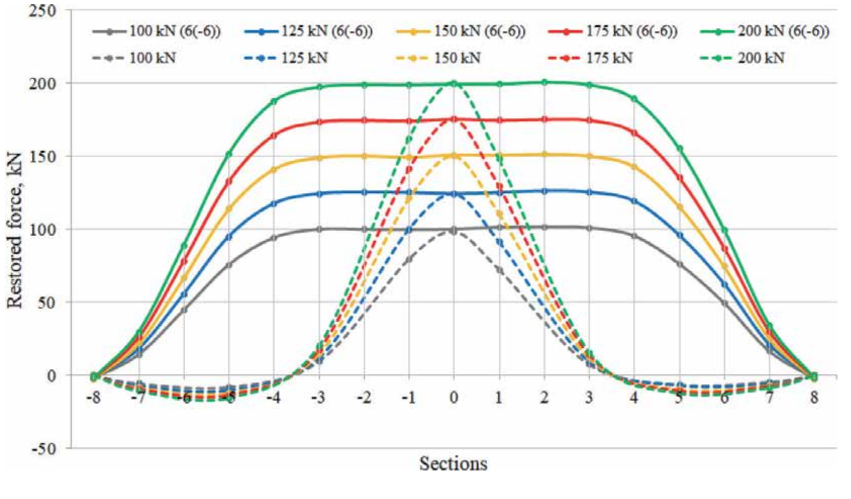

Figure 10.
Dependence of the restored forces recorded by the measuring circuits located in sections 6 (−6).

Thus, the experimental studies confirmed the effectiveness of recovering vertical forces by measuring stresses in two sections of the rail under the action of a vertical load located in the longitudinal plane of the rail [46, 47].

Then, the proposed measurement technology has been tested to determine the wheel/rail interaction loads [48, 49]. Due to the nature of the track on the site, strain gauges have been installed at 363 mm.

Over a length of the measuring zone of approximately 220 mm, the deviations of the scale factor from the mean value do not exceed 3%, which is in satisfactory agreement with the FEM calculation. It is also possible to increase the length of the measuring zone up to ±440 mm when using a variable scale factor. The measurement comparison results are shown in **Figure 11**.

It is clear that, at the moment when the wheel was passing the middle of the measuring section, the results coincide with the measurements according to GOST R 55050–2012, and the proposed method gives many values of the rolling stock/rail interaction force.

Thus, the results above confirmed the ability of the new method to determine the vertical force acting in the wheel/rail interaction, increase the information received by 20–40 times with the same number of measuring circuits and improve the measurement accuracy compared with the current method using according to GOST R 55050–2012 [50].

2.5 Development of a method for determining lateral forces in the wheel/real interaction

To develop a new method for measuring the lateral force from the wheel/rail interaction theoretically, the method of registering vertical forces between the wheel/rail by measuring stresses in two sections of the rail [44, 50] and the "French method" of lateral forces registration has been adopted as prototypes, The method of registering vertical forces between the wheel/rail by measuring stresses in two sections of the rail increased measurement accuracy of the vertical effect of the rolling stock on the path on a significant part of the sleeper gap. The "French

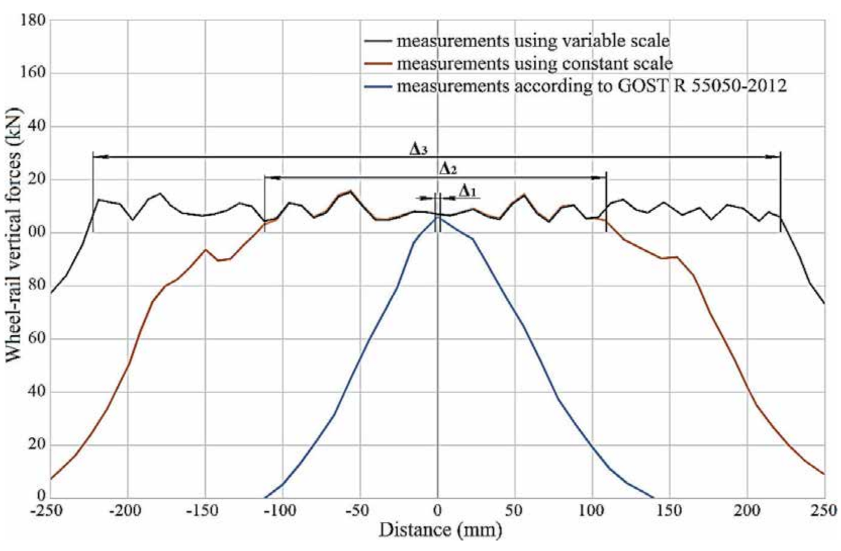

Figure 11.
The measurement of the vertical force acting from the wheel to the rail when passing the measuring section at a speed of 100 km / h (length of the measuring zone with an error of no more than 3% $\Delta_1 \approx 8$ mm), according to the method of two sections with a constant scale ($\Delta_2 \approx 220$ mm) and variable scale ($\Delta_3 \approx 440$ mm).

method" of lateral forces registration, described in [31, 30], with the installation of strain gauges vertically on the rail necks, symmetrically relative to the horizontal neutral axis of the rail.

At the first stage, the results accuracy of the "French method" was investigated on the track of a traditional 1520 mm gauge design [30]. For this, eight virtual measuring points have been installed on both sides of the rail neck in two vertical cross-sections located in the inter-sleep space. Ly_1 - Ly_2 values were changed while maintaining the symmetrical arrangement of the measurement points relative to the neutral axis of the rail (**Figures 12**). The (Ly_1 - Ly_2) in the vertical direction between the measurement points varied from 5 to 90 mm with a step of 5 mm. The distance in the horizontal direction was varied from 274 to 544 mm with a step of 10 mm.

In this case, the lateral force P is determined, similarly to the Schlumpf method [19], by the expression.

$$P = \frac{M_{O_1} - M_{O_2}}{L_{y2} - L_{y1}} = \frac{\Delta M}{\Delta L_y}, \tag{7}$$

Here M_{O_1}, M_{O_2} are the bending moments relative to the points O_1 and O_2 (**Figure 12**) from the action of the vertical force Q and lateral force P.

As a result of multivariate calculations using the finite element method, the dependences of the main, normal, and tangential stresses arising in the investigated sections of the rail under the action of vertical and lateral forces have been obtained.

The calculations showed that with such an arrangement of measuring points, it is impossible to accurately determine the value of the lateral force (railway track with R65 rails and laying concrete sleepers 1800 pcs / km) [51].

The maximum error ratio of expression (7) was no more than 13.8%, caused by the nonlinear dependence of the stresses σ_y on the displacement of the contact point in the transverse direction. Therefore, it has been decided to abandon the "French" approach to measurements with the asymmetrical installation of measurement points relative to the neutral axis of the rail.

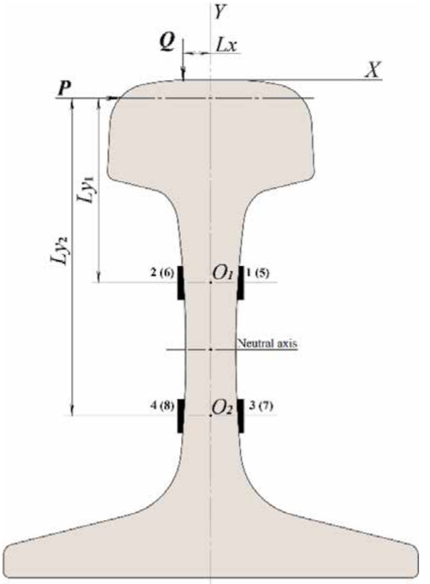

Figure 12.
Arrangement of symmetrical points for measuring voltages; 1–8 - numbers of points of measurements; Q is the vertical force; P - lateral force; X, Y - directions of the axes of the coordinate system.

At the second stage, multivariate calculations have been carried out to measure normal stresses at the points without maintaining the symmetrical arrangement of the measurement points relative to the neutral axis of the rail. The best results determine lateral forces from the wheel/rail interaction given by the location of the measurement points below the neutral axis of the rail (**Figure 13**).

At the designated points, the values of normal stresses σ_y are determined. The differences in normal stresses (σ_y) do not depend on the displacement of the vertical force across the rail, and expression (7) has been used to determine the lateral force, as in the Schlumpf method. The value of ΔL_y is constant. The arising stresses linearly depend on ΔM; therefore, expression (7) has been replaced with the equivalent:

$$P = \frac{\Delta M}{\Delta L_y} = K\Delta\sigma_y. \quad (8)$$

Where K is a scale factor that depends on the inertial characteristics of the rail section; $\Delta\sigma_y$ is the difference between normal stresses arising at points (**Figure 13**), which is determined by the formula:

$$\Delta\sigma_y = \left(\Delta\sigma_{y34} + \Delta\sigma_{y78}\right) - \left(\Delta\sigma_{y12} + \Delta\sigma_{y56}\right) \quad (9)$$

where $\Delta\sigma_{y12}$, $\Delta\sigma_{y34}$, $\Delta\sigma_{y56}$ and $\Delta\sigma_{y78}$ are the values of the difference between the normal stresses at the measuring points 1 2; 3 4; 5 6 and 7 8, respectively, determined by the formulas:

$$\Delta\sigma_{y12} = \sigma_{y1} - \sigma_{y2}; \Delta\sigma_{y34} = \sigma_{y3} - \sigma_{y4}; \Delta\sigma_{y56} = \sigma_{y5} - \sigma_{y6}; \Delta\sigma_{y78} = \sigma_{y7} - \sigma_{y8}. \quad (10)$$

The values of $\Delta\sigma_y$ has been determined according to formula (9) in the central part of the sleeper do not depend on vertical force application relative to the middle of the railhead. However, they have some deviations along the measuring zone, from section −8 to section 8; with an increase in length, the deviation increases.

Thus, the values of $\Delta\sigma_y$ was obtained when multiplied by a scale factor, make it possible to determine the magnitude of the lateral force during the wheel/rail interaction.

The analysis of the results using FEM confirms that such an arrangement of measurement points using a constant scale factor provides a standard deviation

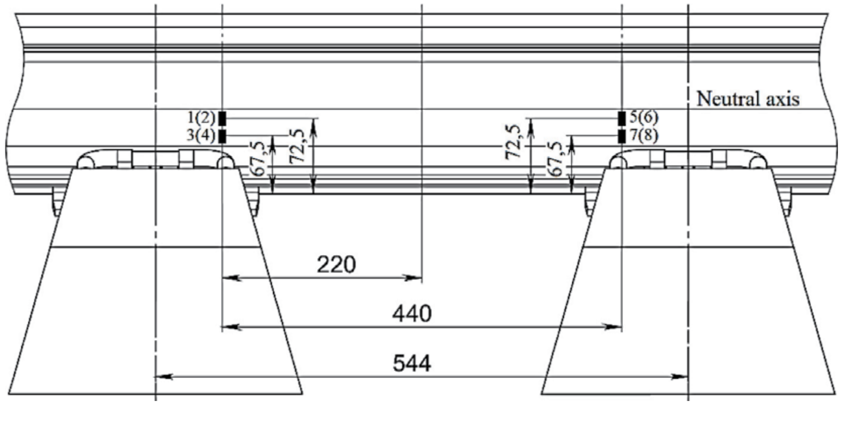

Figure 13.
Layout of stress measurement points below the neutral axis of the rail: a - view from the inside of the track; b - outside view; 1–8 sampling point numbers.

when determining the wheel/rail interaction lateral force of no more than 4% along the length of the measurement zone of approximately 140 mm. The values of the wheel/rail interaction lateral force when a vertical force of 120 kN and a lateral force of 45 kN have been applied are shown in **Figure 14**.

From the above results, lateral forces of the wheel/rail interaction along the length of the 140 mm measuring zone with a relative error of not more than 4.0% have been determined by installing eight strain gauges in the inter-sleeper span below the neutral axis of the rail and perpendicular to the longitudinal axis of the rail. Strain gauges are installed on both sides of the rail web in two vertical cross-sections, the distance between which is 440 mm, provided that the distance between the sleepers' axes is 544 mm to eliminate the influence on the measurement accuracy of lateral forces from the wheel/rail interaction and the displacement of vertical forces relative to the longitudinal plane of the rail. The sections are located symmetrically at a distance of 220 mm from the vertical central transverse plane of the sleepers. Strain gauges with a 1–5 mm base are glued at heights of 67.5 and 72.5 mm from the rail base. The developed method for measuring lateral forces by measuring normal stresses in two rail sections is recommended to be verified experimentally.

2.6 Experimental studies to determine lateral loads from the interaction of a wheel with a rail

Experiments have been carried out on a fragment of a railway track with R65 rails according to GOST 8161–75 [43], 3000 mm long, laid on wooden supports (beams) measuring 100 × 200 × 2000 mm, the spacing of which is 544 mm. A precision marking of the R65-type rail was carried out between wooden beams in 9 sections, the distance between which is 34 mm to prepare for the experimental tests. Precision rail markings are shown in **Figure 15**.

Then, on both sides of the rail web in two vertical cross-sections with the distance between them 440 mm, strain gauges with a nominal base of 3 mm have been glued. The sections have been arranged symmetrically at a distance of 220 mm from the vertical central transverse plane between the wooden beams. At the same

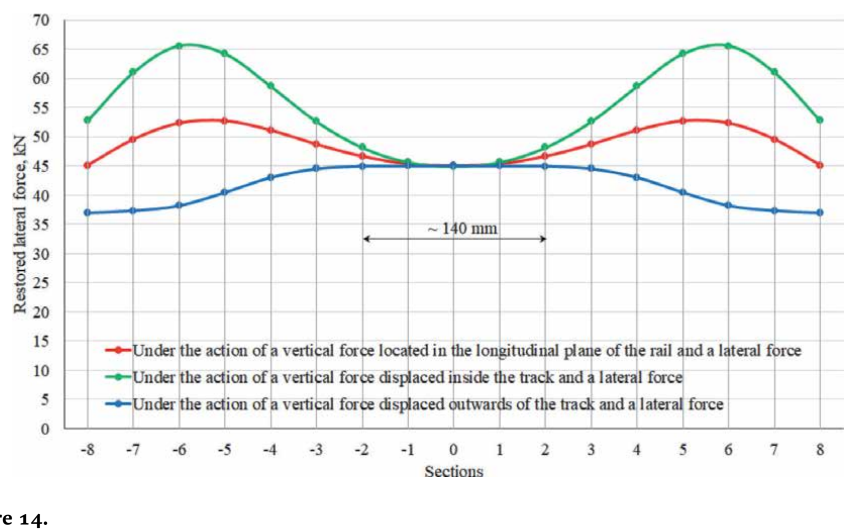

Figure 14.
The values of the lateral force from the difference in the values of the normal stresses arising in the investigated sections of the rail when the vertical and lateral forces move from section - 8 to section 8. (The lateral force in the rail calculate according to Eq. 5*, and when vertical force 120KN and lateral force of 45 kN acted on the rail).*

time, in contrast to theoretical studies [51], where the distance between the measurement points is recommended to be 5 mm, in experimental studies, the distance between the centres of the strain gauges was 7 mm. When the wheel moves along the rail and sleepers, deformations occur, recorded by the installed strain gauges. The vertical normal stress σ_{yi} arising on the rail web is proportional to the deformations.

$$\sigma_{yi} = \frac{E}{1-\mu^2}\left(\varepsilon_{yi} + \mu\varepsilon_{xi}\right), \tag{11}$$

Where E is the modulus of elasticity; μ is Poisson's ratio; ε_{yi} - linear deformations caused by normal stresses σ_{yi} on the rail web; ε_{xi} - linear deformations on the rail web caused by rail bending.

The difference between normal stresses, expressed in terms of deformations, has the following form:

$$\Delta\sigma_{y12} = \sigma_{y1} - \sigma_{y2} = \frac{E}{1-\mu^2}\left(\varepsilon_{y1} - \varepsilon_{y2}\right); \tag{12}$$

$$\Delta\sigma_{y34} = \sigma_{y3} - \sigma_{y4} = \frac{E}{1-\mu^2}\left(\varepsilon_{y3} - \varepsilon_{y4}\right); \tag{13}$$

$$\Delta\sigma_{y56} = \sigma_{y5} - \sigma_{y6} = \frac{E}{1-\mu^2}\left(\varepsilon_{y5} - \varepsilon_{y6}\right); \tag{14}$$

$$\Delta\sigma_{y78} = \sigma_{y7} - \sigma_{y8} = \frac{E}{1-\mu^2}\left(\varepsilon_{y7} - \varepsilon_{y8}\right); \tag{15}$$

$$\begin{aligned}\Delta\sigma_y &= \left(\Delta\sigma_{y34} + \Delta\sigma_{y78}\right) - \left(\Delta\sigma_{y12} + \Delta\sigma_{y34}\right) \\ &= \frac{E}{1-\mu^2}\left(\varepsilon_{y3} - \varepsilon_{y4} + \varepsilon_{y7} - \varepsilon_{y8} - \varepsilon_{y1} + \varepsilon_{y2} - \varepsilon_{y5} + \varepsilon_{y6}\right).\end{aligned} \tag{16}$$

Where ε_{yi} is deformations caused by normal stresses σ_{yi} recorded by the i-th strain gauge.

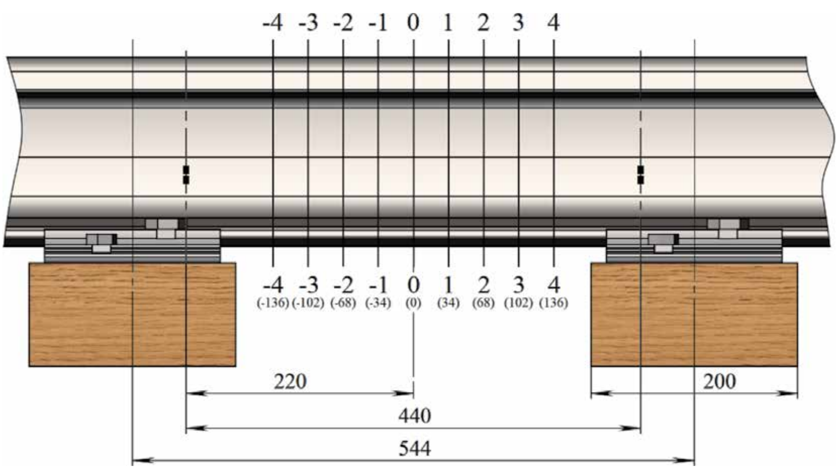

Figure 15.
Sections of the investigated rail fragment between the sleepers (numbers from −4 to 4 indicate the section numbers, the numbers in brackets for each section indicate the distance from the middle part between the wooden beams).

The magnitude of the lateral force, expressed in terms of deformations ε_{yi}, has the form:

$$P = K \bullet \Delta\sigma_y = K \bullet \frac{E}{1 - \mu^2} \left(\varepsilon_{y3} - \varepsilon_{y4} + \varepsilon_{y7} - \varepsilon_{y8} - \varepsilon_{y1} + \varepsilon_{y2} - \varepsilon_{y5} + \varepsilon_{y6}\right) \tag{17}$$

The summation and subtraction of strain signals included in the formula (17) are performed using a complete measuring bridge with a four-wire connection. The expression determines the change in the output voltage of the measuring bridge:

$$\Delta U = \left(\frac{\Delta R_3}{R} - \frac{\Delta R_4}{R} + \frac{\Delta R_7}{R} - \frac{\Delta R_8}{R} - \frac{\Delta R_1}{R} + \frac{\Delta R_2}{R} - \frac{\Delta R_5}{R} + \frac{\Delta R_6}{R}\right)(1 - \eta)U, \tag{18}$$

R is the resistance of the strain gauges; ΔR_1 - ΔR_8 - change in resistance of strain gauges T1 – T8, respectively; η - parameter characterizing the nonlinearity of the measuring bridge; U is the voltage of the measuring bridge.

The resistance change is proportional to the deformation.

$$\frac{\Delta R_i}{R} = k_{\text{т}} \varepsilon_{yi}, \tag{19}$$

Where k_T is the coefficient of the strain gauge sensitivity of the strain gauges. Then the change in the output voltage will be determined by the formula:

$$\Delta U = k_{\text{т}} \left(\varepsilon_{y3} - \varepsilon_{y4} + \varepsilon_{y7} - \varepsilon_{y8} - \varepsilon_{y1} + \varepsilon_{y2} - \varepsilon_{y5} + \varepsilon_{y6}\right)(1 - \eta)U \tag{20}$$

From expressions (17) and (20), we obtain the formula for calculating the lateral forces arising from the interaction of the wheel and the rail:

$$\begin{aligned} P &= K \frac{E}{1 - \mu^2} \left(\varepsilon_{y3} - \varepsilon_{y4} + \varepsilon_{y7} - \varepsilon_{y8} - \varepsilon_{y1} + \varepsilon_{y2} - \varepsilon_{y5} + \varepsilon_{y6}\right) = \\ &= K \cdot \frac{E}{1 - \mu^2} \cdot \frac{\Delta U}{k_T U (1 - \eta)} = K_{\text{гр}} \cdot \frac{\Delta U}{U(1 - \eta)}, \end{aligned} \tag{21}$$

Where $K_{гр} = K \quad \frac{E}{k_m \quad (1 - \mu^2)}$ - it is proposed to determine experimentally.

To register signals and determine lateral forces during the wheel/rail according to expression (21) is necessary to install eight strain gauges vertically on both sides of the rail neck, connected to a complete measuring bridge with a four-wire circuit with recording equipment.

At the first stage, a central vertical static load Q, equal to 25 and 50 kN, have been applied sequentially (**Figure 15**), followed by a decrease in the load until the moment of complete unloading.

At the second stage of the experiment, a vertical static load Q, equal to 25 and 50 kN, was applied along the rail sections with a displacement relative to the longitudinal rail axis by 20 mm outward and inward from the middle of the railhead. At all stages of the experiment, simultaneously with the vertical load on rail fragment, a horizontal transverse load P equal to $0.2Q$ and $0.4Q$ have been applied at a distance of 20 mm from the railhead level.

According to the experiment results [52], the dependences of the lateral force on the point of load application have been determined using the proposed method (**Figure 16**).

The average values of the restored lateral forces over the length of the measuring zone 136 mm have been obtained, shown in **Table 1**.

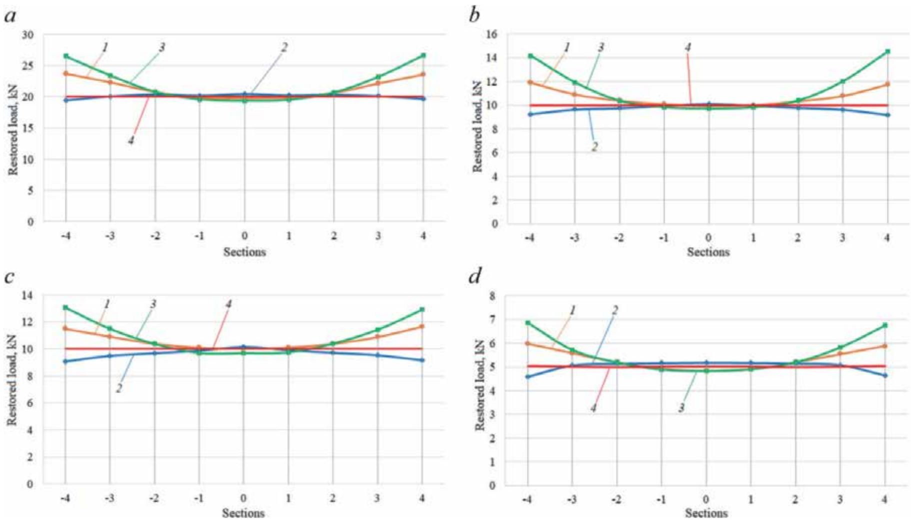

Figure 16.
Dependences of the restored lateral forces on the point of load application: a - under the action of a vertical force of 50 kN and a lateral force of 20 kN; b - under the action of a vertical force of 50 kN and a lateral force of 10 kN; c - under the action of a vertical force of 25 kN and a lateral force of 10 kN; d - under the action of a vertical force of 25 kN and a lateral force of 5 kN; 1 - under the action of a vertical force in the longitudinal plane of the rail and a lateral force; 2 - under the action of a vertical force with an outward displacement of the track and lateral force; 3 - under the action of a vertical force with an inward displacement of the track and lateral force; 4 - actual load.

Parameter	Loading Scheme			
	A	B	C	D
Recovered loads, kN:				
mean	20.16	10.04	10.02	5.06
maximum value	20.79	10.38	10.39	5.20
minimum value	19.35	9.71	9.68	4.84
Confidence interval width, kN	0.72	0.34	0.36	0.18
Standard deviation, kN	0.47	0.24	0.28	0.15
Relative error, %	2.37	2.43	2.82	3.01

A - with a vertical force of 50 kN and a lateral force of 20 kN;
B - with a vertical force of 50 kN and a lateral force of 10 kN;
C - With a vertical force of 25 kN and a lateral force of 10 kN;
D - With a vertical force of 25 kN and a lateral force of 5 kN.

Table 1.
Statistical data obtained from the length of the measuring section (136 mm).

The experimental studies carried out on the railway track confirmed the results of theoretical studies and the effectiveness of the method of piecewise continuous recording of lateral loads from the wheel/rail interaction by measuring the normal stresses in two rail sections [53].

3. Conclusions and recommendations

1. Theoretically and experimentally approved the possibility of piecewise continuous recording of vertical and lateral forces from the wheel/rail

interaction by measuring the stresses in two rail sections on a significant part of the sleeper gap.

2. As a result of comprehensive studies using analytical calculations on beam theory, the finite element method and experiments on stands and railway tracks, it has been approved that the best option for determining the vertical forces in wheel/rail contact by measuring shear stresses in two sections of the rail when installing strain gauges on the neutral axis of the rail in two sections at a distance of 204 mm from the centre of the sleeper gap (the distance between the measuring sections is 408 mm). This ensures the determination of the vertical force with a relative error of not more than 4% over the length of the measuring zone, approximately 1/3 of the distance between the sleepers (approximately 220 mm), and with the use of a variable scale factor, this length increases to 440 mm.

3. As a result of comprehensive studies using the finite element method and experiments on the railway track, it has been found that the best option for determining lateral forces from the wheel/rail interaction by measuring normal stresses in two sections of the rail and install eight strain gauges at heights of 67.5 and 72.5 mm from the rail base in two vertical cross-sections, the distance between them is 440 mm, located symmetrically relative to the vertical central transverse plane of the sleepers gap. This arrangement of strain gauges provides a standard deviation of the restored lateral force of no more than 4% along the length of the measuring zone of about 140 mm.

4. Thus, methods and devices have been developed for determining the vertical and lateral forces acting from the wheel on the rail by measuring the stresses in two sections of the rail [54, 55], which ensure the registration of the force effect of the rolling stock on the railway track on a significant part of the sleeper gap, allowing to increase the volume the obtained reliable statistical data, improve the measurement accuracy, reduce the number of trips of the tested rolling stock along the experimental measuring sections, thereby reducing the time and cost of tests in comparison with test according to GOST R 55050-2012 and "RZD-2016".

5. The developed methods for measuring the forces of wheel/rail interaction by measuring stresses in two sections of a rail has been recommended to be used when determining the wheel/rail interaction forces, as well as for identifying defects on the rolling surface of wheels when diagnosing rolling stock while a train is in motion [56, 57].

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Chapter 5

Hydrogen as a Rail Mass Transit Fuel

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Abstract

There is a continually growing need for mass transport and along with customer desire for greater comfort and speed, its consumption of energy will grow faster still. The fiscal cost of energy plus global warming has spurred efficiency improvement and thoughts now concentrate on fuels. In the UK for major lines for trains, this is electricity generated in a benign fashion in large facilities nominally remote from the train and track. Electric trains tend to be lighter, hence more efficient and demand less maintenance than their diesel counterpart. Similar arguments, including pollution emissions apply to city mass transit systems. For medium density and lower density routes, whether fuel cells or the next generation of IC or GT engines are employed, hydrogen is a prime energy candidate and here we examine its feed, production, distribution, and application, including generator location. Hydrogen from steam hydrocarbon reformers have even been installed in ships. Other countries have similar desires to those of the UK, including Saudi Arabia, but their problems are different and outline examples from Australia and Saudi Arabia are included.

Keywords: cost of train emissions, fuel cells, hydrogen fuel, hydrogen generator location, hydrogen production, hydrogen trains

1. Introduction

1.1 Background

Much energy generated ultimately ends as a heat release to the environment. If any associated carbon dioxide is produced, it retains this heat plus any received from other sources such as the sun and this raises ambient temperatures. To minimise the production of carbon dioxide and other emissions, the use of rail for passenger and freight transport is being promoted and rail itself is being decarbonised thus reducing transport energy per passenger-km and benefitting use of trains.

In 2019, rail services globally consumed 0.6 million BPD of oil [1] equivalent to 0.6% of global oil use, and 280 TW-h of electricity (1.2% of global amount). They were responsible for 0.3% of direct carbon dioxide emissions. Rail passengers accounted for slightly less than 10% of global passenger-kilometres, consuming 3% of transport sector energy, reducing mass transport energy use and any carbon dioxide emissions.

The ideal fuel for trains is electricity, as electric trains are lighter, more fuel efficient and have less maintenance needs than trains using other propulsion fuels. Electric motor drives are designed for rapid acceleration and electric trains usually issue less emissions in the vicinity of the track. If the electricity used is "renewable", e.g. from wind, then carbon emissions are virtually eliminated. Nuclear power fits into this category, with the latest designs having long periods between refuelling activities. Ammonia is also a possible fuel supply as it does not contain carbon.

The problem with electric propulsion systems is their cost (CAPEX). This is acceptable for high speed and high usage routes but not for lower usage routes. This applies also to mass transport inner city traffic. For medium sized trains operating on tracks with low density traffic, the trains are usually diesel driven in the UK and are ideal for conversion to use hydrogen as a fuel. There are other applications including shunters and low power drives on large engines which normally use 25kV AC electricity supply through pantographs but still need low speed mobility when operating away from overhead power supply cables.

For the UK, approximately 40% of energy consumption is used for transport of which 1.9% (0.9% of total) is used for trains: see **Table 1**. This gives the parameters used for the UK (total), that for trains only and those for passengers and freight. For year 2018/2019, passenger services used 3.976 TW-hr of electricity and 469 million litres of diesel. The numbers for freight movements were 75 GW-hr and 153 million litres of diesel [2]. For year 2019/2020 passenger trains used 4.186 Tw-hr of electricity and 476 million litres of diesel. Freight services used 70 GW-h of electricity and 172 million litres of diesel [3]. In this later period, CO_{2e} for passenger traffic fell to 35.1 gm/passenger-km from 36.6 and CO_{2e} for freight was 27.5 gm/Te-km rising from 25.3 gm/Te-km where CO_{2e} is the weighted average of CO_2 + CH_4 + N_2O and is a measure of greenhouse gas emissions. Passenger numbers fell slightly (~1.3%). This shows the general increase in rail movements also confirming the movement from hydrocarbon fuels to electricity for rail passenger services and thence ultimately to zero carbon emissions when the electricity is generated using renewables. Last period's freight statistics are a little disappointing, continuing the steady decline from a peak in 2013/2014 but there is a new generation of electric freight engines in the offing and an increase in freight energy consumption can indicate a faster service and a rising economy.

Country	Energy	Unit/year	2019	2018	2017	2016	2015
UK	Total supplied	EJ	7.84	7.96	7.99	8.01	8.11
	Energy/capita	GJ/cap	116.1	118.6	119.8	120.9	123.1
	Carbon dioxide	Million Tonne	387.1	396.9	404.1	415.8	439.7
Trains	CO_{2e} passenger	gm/pass-km	35.1	36.6	40.8	43.8	46.4
	Percent change	%	−4.10	−10.30	−6.85	−5.60	−4.32
	CO_{2e} freight	gm/Te-km	27.5	25.3	26.4	26.2	27.1
	Percent change	%	8.70	−4.35	0.76	−3.32	11.74
Passenger	Electricity	TW-h of fuel	10.592	10.061	9.222		
	Liquid fuel	TW-h of fuel	4.738	4.668	4.916		
Freight	Electricity	TW-h of fuel	0.177	0.190	0.168		
	Liquid fuel	TW-h of fuel	1.712	1.523	1.625		
	Total used	EJ	0.0619	0.0591	0.0573		
	Fraction of total	% of UK Total	0.790	0.743	0.717		
	Carbon dioxide	Million Tonne	3.675	3.512	3.450		
	Fraction of total	% of UK Total	0.949	0.885	0.854		

Table 1.
Energy and Emission Statistics for UK.

The above statistics have been developed against a background that only 38% of UK track is electrified with over 70% of rolling stock being pure electric, highlighting the concentration of its use [4, 5]. Current proposal is that a further 11,700 STkm of track will be electrified leaving only 2,400 STkm of track for all other non-electric users. This implies that only 3–4% of trains require conversion to hydrogen fuelled units. For a total fleet of 14,000 vehicles this equals 420 to 560 vehicles to be considered for conversion. If no further route electrification occurs, then 4,200 vehicles could be considered for conversion thus giving a lower and upper bound range for hydrogen needs.

For the EU (see **Table 2**), there are approximately 64,000 power units of which the top three owners are Germany, UK (included in these numbers) and France whose combined numbers have over 55% of the units. Adding the next two (Poland and the Netherlands) they hold nearly 70% of the total traction stock [6]. Despite EU's endeavours, there is little commonality between the railways of each nation despite having the same rail gauge and loading gauge (UK is different for the latter). For fast trains there has been some success as they are electric units with most using 25 kVAC/50 Hz supply (Germany and Austria are different having 15 kVAC @ 16.67 Hz supply) permitting fast continuous transit, for example, from Italy to the UK. Signalling and control systems are different leading to complications particularly for items involving computer software.

Where practicable, precise statistics are used. Where not available, overall national data is employed. **Tables 1** and **2** (based on [7]) gives the total energy consumption, the per capita energy consumption and the carbon dioxide generated for the three largest EU train users with overall EU and world data to provide comparisons. Train energy consumption is small though decarbonisation of this energy supply is still laudable.

Currently hydrogen comprises 2% of Europe energy mix and the target is to raise this to 14% by year 2050. The estimated investment necessary to achieve this is 470 bn € [8]. France produces one million tonne per year of hydrogen of which 94% comes from fossil fuels [9]. They can inject up to 6% (v/v) hydrogen into their gas grid at this moment and they plan to raise this figure to 10% by 2030. France's railways, particularly SNCF, do not see hydrogen as an affordable and accessible fuel to replace the hydrocarbon services and prefer a combination of electricity and batteries (hybrids where necessary). To compress, store and transport one million tonnes per year of hydrogen will need significant amounts of energy. Their estimate is that to produce this quantity of hydrogen using electrolysis will need 2000 to 4000 by 3Mwe wind turbines or 6+ EPR nuclear stations. However total rail use would be only 3% of this number and only 1% of this is from fossil fuels [10] which need replacing. This is acceptable if there is a hydrogen grid in place which may not be realistic (see later). Despite this, the French railways are committed to decarbonisation of their resources and SNCF wish to eliminate emissions by year 2035. The parties project a 20% increase in traffic over this period (passenger and cargo) and are negotiating the supply of new hydrogen fuelled trains. Alstom can build these trains in France.

France has approximately 30,000 km of track (16.400 km are double tracks) of which 15,100 km are electrified (9,200 km at 25 kVAC and 5,900 at 1.5 kVDC) with 2,600km suitable for fast use. 80% of SNCF routes are electrified but 50% of TER (the regional supplier of rail transport) still use diesel units [11]. In terms of carriage, only 20% of rail trips are by diesel units whereas 40% of TER trips are by diesel units. These numbers give the potential task for decarbonisation.

For year 2019 Germany had 38,465 km of track (41,365 km in year 2015) of which 20,726 km (19,857 km in 2015) were electrified and 18,500 km were double track. 79.3 billion passenger-km and 75.5 million Te-km of freight were

Country	Energy	Unit/year	2019	2018	2017	2016	2015
Germany	Total	EJ	13.14	13.44	13.78	13.62	13.40
	Energy/cap	GJ/cap	157.3	161.7	166.8	165.7	163.8
	Carbon dioxide	Million Tonne	683.8	731.3	760.9	770.5	755.6
Train	Electricity	TW-h of fuel		54.27			Q/η
	Liquid fuel	TW-h of fuel		2.75			
	Total	TW-h		57.0			
	Fraction of total	% of Germany		1.526			Energy
	Carbon dioxide	Million Tonne		10.563			
	Fraction of total	% of DB+ Total		1.444			CO_2
France	Total	EJ	9.68	9.87	9.70	9.76	9.92
	Energy/cap		148.6	151.9	149.6	151.0	154.0
	Carbon dioxide		299.2	307.2	318.1	312.1	306.7
Train	Electricity	TW-h of fuel		22.25	19.25	18.75	19.00
SNCF	Liquid fuel	TW-h of fuel		1.64			
Train	Electricity	TW-h of fuel		9.75			
TER	Liquid fuel	TW-h of fuel		3.96			
	Total	TW-h		37.60			
	Fraction of total	% of France		1.37			
	Carbon dioxide	Million Tonne		7.292			
	Fraction of total	% of France		2.374			
EU	Total	EJ	68.81	69.81	69.91	69.14	68.32
	Energy/cap		134.3	136.4	136.9	135.7	134.7
	Carbon dioxide	Million Tonne	3,330.4	3,466.5	3,527.1	3,498.5	3,486.9
World	Total	EJ	583.90	576.23	560.42	550.60	543.17
	Energy/cap		75.7	75.5	74.2	73.8	73.6
	Carbon dioxide		34,169.0	34,007.9	33,279.5	32,936.1	32,787.2
Train	Electricity	EJ		1.529			1.315
	Liquid fuel	EJ		1.479			1.748

Country	Energy	Unit/year	2019	2018	2017	2016	2015
	Total energy	EJ		3.009			3.062
	Fraction of total	% of world		0.522			0.564
	Carbon dioxide	Million Tonne		186.83			195.97
	Fraction of total	% of world		0.549			0.598

Table 2.
Energy and emission statistics by country.

carried. There is a steady elimination of diesel units, as electrification of track is undertaken and a determination to replace diesel units where electrification is not attractive, with hydrogen powered units. Currently 1300 diesel units are scheduled to be replaced.

Despite the above, 90% of Germany's railways are already electric and 27.5 TW-h of electricity were consumed [12]. The share of various energy sources in Deutsche-Bahn's traction power mix in FY2020 were as follows [13]:

i. Renewable = 61.4%

ii. Black coal = 11.2

iii. Nuclear = 12.0

iv. Natural gas = 8.1

v. Lignite = 7.0

vi. Other = 0.3

1.2 Hydrogen statistics

The production of hydrogen currently consumes approximately 6% of global natural gas and coal and simultaneously produces roughly 830 million tonnes (Te) of carbon dioxide in this process [1]. Global demand for pure hydrogen is around 70 million Te/year and is used mostly for oil refining and chemical manufacture including products such as methanol, acetic acid derivatives and fertilisers. Here we are contemplating using it for propulsion of trains both using internal combustion devices and in fuel cells.

The use of hydrogen as a fuel has been a goal for some time and much research has been performed in trying to produce hydrogen from water by various means, e.g., [14] with the resulting dilute gases burned in heat recirculating burners [15]. These can achieve high efficiency electricity generation with minimum pollution [16]. When higher energy densities are obtained from using renewables, their widespread use may occur but for now and the immediate future the main available methods for generating hydrogen are:

i. Steam – hydrocarbon reforming ideally from natural gas

ii. Gasification – frequently from coal

iii. Electrolysers – splitting water using electricity.

There are other techniques but until affordable methods of carbon capture and storage exist then these will remain as the major producers and for (i) and (ii) emit carbon dioxide. With natural gas in (i), a hydrogen cost of 8.3 US$/GJ has been estimated and this will increase to 11.5 US$/GJ with carbon capture (updated from Ref. [17]). A minimum purchase price of 13.4 US$/GJ is anticipated for imported green hydrogen and this is currently believed to be too low for western European countries to compete.

For coal as a feedstock in (ii), the numbers become 11.8 US$/GJ and 15 US$/GJ respectively, but all these numbers are sensitive to feed cost. Disposal costs need to be added and deep disposal of carbon dioxide (e.g. in former oil and gas producing wells) is currently favoured. This can imply transport of carbon dioxide over some distance (some studies for this have been developed see e.g., [18]) which all adds cost. As electrolysers use electricity, renewables are available now to generate this, including nuclear for onshore applications and offshore if located within reasonable transmission cable distance (e.g. the Beatrice platform in the North Sea when it was a production platform). Electrolysers on offshore platforms using offshore renewables will be considered when sufficient electrolysers can be fitted into the space available. Some ideas using them are presented here (e.g. for those offshore locations where sea area is available) but costs offshore are high, being potentially some 12 times more expensive than equivalent tasks onshore. This factor reflects a combination of lower productivity and higher unit costs for offshore work.

Previous promising technologies such as plasma arc pyrolysis, solar reforming and anaerobic bacterial action have been studied and generally discounted but certain of these could be attractive in the smaller size applications.

Ammonia generated in world scale units from natural gas would be more easily distributed than hydrogen at high pressure as the vessels for ammonia storage would be designed for significantly lower pressures than those for hydrogen. The ammonia can be broken down locally [19] to produce hydrogen for fuel cells or consumed directly in IC engines. Ammonia has safety issues due to the reactions of people when exposed to it and its use is only advantageous in weight sensitive applications.

In this chapter, the following definitions are employed. Grey hydrogen is hydrogen produced from hydrocarbons where no attempt has been made to recover any carbon dioxide produced in the process. Sometimes it is subdivided further with grey hydrogen being reserved for natural gas feedstock, brown hydrogen used when it is produced from oils and black hydrogen when produced from coal. Blue hydrogen is hydrogen produced from natural gas in a process where any carbon dioxide formed is captured and stored in a suitable location. Green hydrogen is hydrogen produced from a source, e.g. water, where no carbon compound is involved in the process. Electricity to provide the energy for splitting the water molecule must come from a renewables' source.

1.3 Target hydrogen capacity for trains

Typical hydrogen unit will be replacing the local DMU and shunters [20]. There are approximately 1022 sets with individual power in the range 300–799 bhp. By taking average values we get a total requirement of 35.2 kg/hr./train which for 1022 sets gives 35.6 Te/hr. of hydrogen or 865 Te/day neglecting any quiet periods. Only one to two world scale grey hydrogen plants would be needed to produce this quantity of hydrogen: its distribution is the important factor.

The prototype trains from Porterbrook or from Alstrom have fuel cells with capacities of 100 kWe and 200 kWe respectively. They both have batteries to help smooth out the power demand. If these cells have an installed efficiency of 35%, the overall hydrogen demand will be 8.58 kg/h and 17.16 kg/h respectively. A hydrogen plant for the former would have a capacity of 0.21 Te/day/train – well within current technology for electrolysers.

If the full electrification programme for the UK is implemented, then only 3 to 4% of trains would use hydrogen as a fuel which in turn would generate a hydrogen demand of 14.6 Te/hr. or 350 Te/day. The quantity of hydrogen that needs to be produced depends on many factors outside the remit of train evaluation.

2. Some methods to generate hydrogen

2.1 Steam-hydrocarbon reformers

This process has been used for a long time: catalysts were developed to use what was once lower cost naphtha to make H_2 + CO synthesis gas. Subsequently it was used to make "Town Gas". In the UK, the Town Gas requirement continued until the completion of the natural gas grid to domestic households with one of the last reformers in operation being the Foster Wheeler design at Southall in west London. To-day the feedstock in the UK for hydrogen is usually natural gas.

There are many arrangements of steam-hydrocarbon reformers but the critical component, the furnace, falls into one of three basic patterns. There is the original ICI "down fired" design in which the catalyst tubes are suspended from the roof in lanes with the burners located between the lanes firing downwards. The second common design has the tubes in a single line with a multitude of small burners located in the side walls firing horizontally either side of the tubes to give uniform radiant heating. The third common design is the Foster Wheeler Terrace Wall design. This consists also of a single row of vertical tubes but the walls are displaced at an intermediate level to accommodate the burners which fire vertically upwards. There are usually two terraces of burners per side and their flames adhere to the wall giving a uniform radiating surface. All three furnace designs have approximately the same effectiveness. The marginal differences in performance of each is reflected in their application with client preferences frequently dictating the selection.

In the reforming process the purified feed hydrocarbon (the catalyst can suffer from sulphur poisoning) is heated from ambient temperature in external heat exchangers and/or the convection bank of the main furnace to approximately 350 °C and mixed with superheated steam. The preheat process continues with heating the mixed gases to approximately 600°C before entering the catalyst tubes in the radiant section where the reforming action occurs. The tubes have typically internal diameters of 3.5–4.0 inches (88.9–101.6 mm) and contain the catalyst pellets. The gases leave the tubes at 900–950°C and now contain a mixture of hydrogen, carbon monoxide, carbon dioxide, feed slippage and excess steam with their pressure falling from roughly 32 bar abs to 28 bar abs. The tube materials are high alloy, e.g. spun cast 25 Cr-35 Ni and are 13 to 15 metres long depending on the process needs.

The main reactions within the tubes are: $CH_4 + \mathrm{H_2O} + \mathrm{heat} = 3\,\mathrm{H_2} + CO$

And $CO + \mathrm{H_2O} = \mathrm{H_2} + CO_2 +$ a little evolved heat

The hot furnace flue gases leave the radiant section at a temperature above 1000°C and are cooled to approximately 150°C before entering the flue stack.

The reformer section of the furnace has a low thermal efficiency (~48% LHV depending on the fuel and temperature profiles needed) and its overall efficiency is raised to some 92% LHV by heating the process feed and raising high pressure steam in its convection bank. This steam is suitable for mechanical drives. These processes are well known and the technology rests with the mechanical design to handle these high temperatures.

Excess steam is needed in this operation to minimise carbon formation and its deposition on the catalyst. This steam is condensed out as water and recycled.

2.2 Gasification

In gasification, the feed supply is burned in air or oxygen under sub-stoichiometric conditions to produce a $H_2/CO/CO_2/N_2$ mix if air is used for combustion or a minimum nitrogen mix if an ASU (air separation unit) is employed to produce the oxygen-only supply.

Early applications included gas production for domestic use. These often started with coal which was heated in retorts to produce coal gases and tars and the resulting coke was then used to make gas. The tars at that time had a market value. The gas production was essentially a series of batch processes with coke being introduced and a sub-stoichiometric quantity of air passed over it which ignited the coke and raised its temperature evolving a CO/N_2 mix. Then steam was added producing an $H_2/CO/CO_2$ mix which in turn lowered the solid materials' temperature. The process was then repeated until the coke feed batch was exhausted, the ovens cleaned out and recharged with any ash recovered in the cleanout process. The resulting gas streams were then combined.

Modern processes use coal or similar feed and are continuous and employ oxygen supply instead of air. The feed progressed from a top hopper downwards going through the above separate stages but in a single unit. The ash exits from the bottom. Any tars evolving are also gasified in the process. The off-gas needs cleaning and any carbon dioxide removed to leave clean hydrogen. The basic problem with coal is that it produces a larger quantity of carbon dioxide compared with steam-hydrocarbon reforming with natural gas. For example, methane produces 55.0 gm CO_2/MJ (2.5 kg CO_2/kg) compared with 88.4 gm CO_2/MJ (2.75 kg CO_2/kg) for coal.

One positive side effect is that the gasification process produces a large amount of heat which can be used to produce steam and this in turn produces power to drive the plant and even export electricity. The overall plant is expensive and tends to be used where coal is readily available at low cost.

2.3 Electrolysers

Electrolysers are used to split water into hydrogen and oxygen using electricity. Currently they are only available in the smaller sizes (1 to 5 MWe) but they are being scaled up with an 100 MWe electrolyser being designed in Japan.

There are two fundamental designs used for most electrolysers, viz. Proton Exchange Membranes (PEM) and Alkaline Electrolysers. In the former a solid polymer membrane is used with an applied current so that the protons being small, pass through the membrane to capture electrons from the electrical circuit to form hydrogen. PEM technology gives a flexible device and the quantity of hydrogen being produced can be adjusted over the required full operating range. The system is compact and reliable.

In an Alkaline Electrolyser, an alkaline electrolyte is used (usually potassium hydroxide – KOH) with a porous separation between the anode and the cathode. Hydroxyl ions pass through the separator in the liquid solution to form oxygen and water. At the other electrode hydrogen is generated along with the hydroxide ion by the external electrical source. Alkaline electrolysers are efficient and reliable.

Catalysts are being developed to improve the efficiency of both processes. Both technologies are the subject of much research and development. The units are compact and can fit inside the envelope of a standard container and can be scaled up as multiple containerised units.

Electrolysers have efficiencies in the range 70 to 80% thus to produce 1 kg of hydrogen, 50 to 55 kW-h of electricity is needed. With the prototype trains needing 8.6 kg/h and 17.2 kg/hr. of green hydrogen, then 0.47 to 0.95 MW-h electricity from a renewable source is needed. For the 35.2 kg/hr./train of the typical train in the UK, approximately 1.9 MW-h of electricity is required therefore for 1022 trains 1980 MW-h of renewable electricity is needed. The trains do not operate for 24 hours by 7 days per week, so introducing a diversity factor of 0.65, 1286 MWe from a continuous source of electricity is required which is approximately the output from one large nuclear station. This assumes that adequate hydrogen buffer storage is available to smooth out the flow between peak demands.

2.4 Other methods

The energy density using various techniques is presented not to discourage research in any field but to highlight the difficulties faced when using “renewables”.

2.4.1 Ammonia

Steam-hydrocarbon reformers are used to produce synthesis gas to make ammonia. It can be made also from feed gas from gasifiers. Ammonia can burn and produce large quantities of NO_x but there is a widow in which pollution emissions are minimal. It has been used successfully with internal combustion engines and its choice is based frequently on its ability to be moved under atmospheric pressure. It can be split also to release its hydrogen for use with IC engines and fuel cells as with any other method to produce hydrogen.

2.4.2 Algae

Certain algae can produce hydrogen from water. Early work in the 1970’s demonstrated this method of hydrogen production using the sun’s light but the energy density was very low [21]. With current technology the energy density is still low at approx. 2 W/m^2 but development work with energy cells is in progress and its production meets all renewables criteria.

2.4.3 Intermediate products such as alcohols

These can be made from natural gas in steam-hydrocarbon reformers or by using renewables (e.g. beverage production) [22]. The methanol or ethanol produced could be shipped to site using trucks, trains, etc. and at the specified location either fed directly to a suitable fuel cell or reduced to hydrogen first and then fed to the fuel cell.

2.4.4 Other sources

There are many other sources of renewables including solar, geothermal, PV, wave and tidal. In the UK, many are not useable. Wave and tidal stream electrical generation is being developed but most schemes are simply too expensive. This belief may be revisited when the final bill for the Hinckley C EPR nuclear complex is received. Tidal schemes, for example, may have variable outputs but their variation is predictable in advance, unlike wind.

3. Power drives

3.1 Fuel cells

Hydrogen benefits from limited hydrocarbon emissions but when hydrogen is used with IC engines its efficiency is still relatively low. Its use with fuel cells can be much better depending on their design. With stationery devices waste heat recovery can improve the picture overall but its use on trains is somewhat limited. Space heating is one application for this heat as may be air conditioning if space and weight limitations permit.

Fuel cells are ideal where low pollution emissions are essential, in applications when disconnected from the grid, where frequent and comparatively rapid start-up is necessary and when fuel supply is continuous. Options to hydrogen as a fuel, include fuel cells using hydrocarbons (including alcohols) but they produce carbon dioxide and unless the alcohols are naturally brewed, they are usually made from natural gas.

Fuel cells using hydrogen are ideal for trains and research is ongoing to recycle time expired fuel cells as occurs with batteries. Many fuel cell configurations have been examined and each has a niche application: some are detailed below. In most train drives the cells are used with batteries which help to smooth out the load on the cells (**Table 3**).

3.2 Internal combustion engines

Along with electric drives, internal combustion engines are the most common train drives following the demise of steam. Hydrogen fuelled IC engines are modified versions of diesel or gas engines. Though relatively high efficiencies can be attained (in the range 25–40% overall), they suffer from the normal limitations of internal combustion engines in that high temperature pollutants, e.g. NO_x, are still produced even though no carbon dioxide or other carbon based pollutants would be

Fuel cell typical examples				
	Generic type	**Op. Temp. °C**	**Fuel**	**Efficiency %**
1	Proton exchange membrane fuel cells (PEMFC)	60 to 100	Hydrogen	
2	Direct methanol fuel cell (DMFC)	90–120	Methanol	10–25
			Modified versions can reach 40%	
3	Alkaline fuel cell (AFC)	<80	Hydrogen	up to 62
			Used by NASA in early days	
4	Phosphoric acid fuel cell (PAFC)	~200	Hydrogen	37–42
			Can run on impure hydrogen	
5	Solid oxide fuel cell (SOFC)	600–1000	Hydrogen	55–60
			Can run on natural gas or propane	
6	Molten carbonate fuel cell (MCFC)	650–1000	Hydrogen	45–55
			Can run on natural gas, propane or even diesel	

Table 3.
Typical fuel cell examples.

Hydrogen for trains	Advantages	Disadvantages
CAPEX for new rail	Less expensive than electrification	
Design of drivers	Less weight than battery driver	More complex than battery or electric drivers
Distance limitations		Electric driver has no limit
CAPEX of engines		More expensive than electric drives
OPEX	Quicker hydrogen fill than battery recharge	
Operational safety		Hydrogen needs very careful handling
Reliability	No overhead cables	Electrified routes have overhead pantographs
Maintenance		Much more maintenance of fuel cell drivers
Emissions	None, if blue or green hydrogen	Electric or battery drivers need to run on renewables to equate
Hydrogen production		Competes directly for renewable energy sources
Hydrogen transport	New pipeline grid for 100% hydrogen gives robust supply system	Limited quantities by road bottle trailers

Table 4.
Benefits and problems associated with the use of hydrogen for trains.

emitted. IC engines are far less sensitive to hydrogen impurity and usually exhibit very rapid responses to load change. If the exhaust is hot and clean, it can be used for indirect space heating using an intermediate fluid (**Table 4**).

3.3 The use of hydrogen for trains

The benefits and problems associated with using hydrogen as a fuel for trains is presented in **Table 4**.

4. Location of the hydrogen generators and H_2 transmission to users

4.1 Locations

A distributed system of electrolysers will need the major utilities with an adequate supply of water and electricity. If there are not adequate waste-water facilities, then a holding pond will be required where water can be treated before its discharge as well as the usual personnel-related facilities needed for a manned plant.

As the hydrogen economy in the UK develops, these regional facilities will contribute to the initial injection of hydrogen into the gas grid. This is likely to be limited to 10–20% by volume. In the UK, 78.8 billion cubic meters of natural gas was consumed in 2019. By replacing 10% by volume of this natural gas with energy equivalent hydrogen, approximately 15.5 million tonnes of carbon dioxide emission will be avoided each year.

It will be the political decisions of individual countries to determine how or even if. they proceed with the replacement of all or part of their existing natural gas infrastructure with hydrogen. If the hydrogen requirements for trains increases more rapidly than the new supply facilities, small boutique hydrolysers may be located at principal loading locations. This would give a cost savings on road transport of hydrogen, mitigate the safety risk and increase reliability of supply. Regional hydrogen projects will continue to be attractive in locations that have the facilities to accommodate the necessary carbon capture and storage, have industries nearby that can utilise the hydrogen – including trains – and are in areas that are attractive for the necessary grants and financial support.

4.2 Offshore

As the hydrogen economy develops, there will be a natural decrease in the production and use of hydrocarbons. In the North Sea, the production companies and offshore asset owners will be examining how they may make best use and financially benefit from the existing platforms and pipelines. Studies are already underway to determine the suitability of these types of assets in supporting hydrogen production. The basic steel structures (jackets and platforms) will need assessment and if in good condition, re-used perhaps with minor modifications and upgrades. The necessary infrastructure of accommodation, life support, safety and communications will still exist but may need refurbishment. The difficulties start with the removal of unwanted existing equipment and its replacement with the new facilities. These difficulties include total weight and its topside distribution and access.

As green hydrogen for the replacement of natural gas is a goal for substantive emissions reduction, renewable energy is required to produce the hydrogen. Offshore wind energy is one source. Turbines in the vicinity of selected platforms could provide power directly and exclusively for this process, eliminating the costly cable to shore. The production of hydrogen based on wind energy alone would be part of an overall industry business plan to supply hydrogen only when wind energy was available.

New compressors will be needed to send the produced hydrogen to shore as the molecular weight of hydrogen is much lower than natural gas. Its physical properties are different from hydrocarbons and every rotating component will need unique attention due to hydrogen's ability to escape through tiny apertures. The compressor drive will be several megawatts for systems that would be financially attractive.

The transport of the hydrogen to shore and into the existing natural gas grid is more problematic. Modern carbon steel pipes are frequently not compatible with hydrogen gas. Initial investigations and ongoing studies show that the more recently introduced high grade steels (above grade X52), are unlikely to be acceptable as long-term infrastructure elements. Some possibility exists to re-use those of lesser grade steels e.g. X42 and X52 but these pipelines will need more rigorous analysis and testing. This is time consuming and costly and required for each line.

Societa Gasdotti Italia has engaged DNV GL to study its 18,000 km HP regional and national pipeline network to determine potential hydrogen transportation options. "The study will guide SGI in identifying suitable sections of its gas network to safely convey blended mixtures of natural gas and hydrogen. The gas network operator's aim is to understand if and how 100% hydrogen can be safely carried across its network." [23]. Given the fundamental requirement of a grid to distribute gas safely to the domestic, commercial and industrial markets, and now significantly reduce these sector's emissions, any re-use of existing gas pipeline systems for hydrogen must be thoroughly investigated, risk assessed, proven and accepted by the pipeline industry.

A 100% hydrogen filled onshore pipeline will be more costly than an equivalent natural gas pipeline. The increases in materials and construction costs will arise from:

i. NACE compliant line pipe, to specification "*MR0175/ISO 15156, Petroleum and Natural Gas*" has stringent steel chemistry requirements. It is lower in carbon, sulphur and phosphorus content than standard linepipe. The pipe manufacturing requires expensive quality control activities including inspection and this will increase its cost/tonne by some 6–8%;

ii. Line pipe for the same design pressure will be considerably thicker due to the lower yield strength of the required materials. Whereas X60 to X65 or higher grade is suitable for use with natural gas; Grade B, X35 to X52 is needed for hydrogen. For comparison, API pipe for 24 inch, 100 bar design pressure will show an increase in cost/metre of pipe ~ 11–77% for this change in grade;

iii. Line pipe logistics and handling costs will increase by up to 50%, due to the increased pipe weight.

iv. Construction costs will be impacted due to the increased time for welding and increase in welding spreads required for thicker wall pipe. The increase in construction cost will be ~ 13–25%

For an onshore pipeline, like-for-like costs would increase in the range of 12–27%. For offshore lines the increases could be doubled, due to the impact of escalated costs for installation and support vessels together with the various risk factors associated with construction and installation and weather states. For a given energy throughput and permissible pressure drop, a larger pipe ID is needed for hydrogen than for natural gas. This will be expensive if one is near a cusp which demands a step-up in specification of installation equipment.

4.3 Coastal locations

This general location is attractive during the emerging hydrogen economy period when the pipelines to shore are still carrying natural gas. An existing gas plant site can be partially or completely converted to use this feedstock to make grey or blue hydrogen. The pipeline may also be used for the transport of captured carbon dioxide when it is redundant and if the spent gas field is suitable for carbon dioxide storage.

4.4 Inland locations 1: large hydrogen production hubs

Hydrogen is made either from natural gas or from water using electrolysers in large production hubs located near the shore. Electricity from offshore windfarms is one possibility as are nuclear sources. The hydrogen produced will be distributed and if the existing grid cannot be used, additional costs must be added for any onshore pipeline distribution cost. If the hydrogen is derived from natural gas, any carbon dioxide produced must be collected and sent by pipeline to the disposal well.

4.5 Inland locations 2: hydrogen production hubs local to train line(s)

Hydrogen production is located near the train loading station hence the production facilities will be based on electrolysers: also there may be a local market to use these generated gases. The hubs will contain hydrogen storage facilities which will cover minor outages and give warning of impending trouble that can be resolved with truck supply. The site will have any necessary compression facilities to give maximum supply pressure to the trains to reach their required storage pressures.

4.6 Distribution by pipeline, ship, train and vehicle and their economic consideration

The use of ships to transport hydrogen for trains needs to be studied in detail for specific situations. If the hydrogen is to be liquefied for tanker transport, the source of the energy required to both convert to a liquid and then back into gas before compressing onto the train bottles needs to be considered carefully. If this energy is not renewable, there is an immediate argument that this hydrogen use is more environmentally damaging than the use of diesel as the train's fuel.

Work has already begun in the UK to replace ageing user pipeline connections from cast iron and other materials to plastics, in readiness for hydrogen. This also has the added benefit of immediately reducing harmful emissions from the old pipework [24].

The potential for hydrogen use, either in modified diesel engines or fuel cells, is likely to exceed the economic or safe limit for delivery by road transport and initially diesel power will be retained. The current volume of hydrogen being used to power trains in the UK is negligeable and their 420 kg/day is easily delivered from existing production facilities in bottles via trucks. A supply of 475 Te/day of hydrogen needed after the system upgrade though would require increased production capacity as well as a more robust delivery system. If the demand by rail services is slow in developing, the more general hydrogen economy may have developed to the point where a national hydrogen grid exists. Transportation and distribution pipelines will then be able to supply train terminals. This supply may be directly by pipe connections as is used by a typical commercial or industrial user or by shuttle trucks from a nearby hydrogen terminal.

Depending on hydrogen quantity needed, it is practicable to have a waggon carrying a standard size container which would carry hydrogen at pressure. Full containers would be located at the refuelling station to permit a rapid turn-around. The empty container would be taken by truck to the hydrogen production facilities for re-charging.

Prior to this national hydrogen grid, there will be the development of facilities for blue hydrogen production where there is access to both the natural gas feedstock and the conditions for CCS. An example of this is the low carbon hydrogen project by Hynet which is located on the existing refinery in Ellesmere Port, England. This novel development will include new hydrogen-from-natural-gas production facilities, carbon capture and storage in the Liverpool Bay gas fields as well as a new pipeline for local distribution to regional users for their hydrogen.

4.7 Current availability in the UK

Hydrogen is currently available in the UK via road using tube trailers with standard capacities of 300 kg at 228 bar g or high pressure trailers up to 900 kg at 300 bar g. These trailers will be designed to be used on site as storage so that additional decanting into static storage tanks is not necessary. Being of a similar size to a standard 38 tonne, 12 m long, container trailer, these will be located strategically to train loading sidings.

For a typical hydrogen train with an approx. 17 kg/h of average day demand, operating for 16 hours per day and a route that had two trains running at any time, the requirement for fuel would easily be met with a trailer delivered every 12 to 48 hours. The usual considerations – cost of additional pressurisation, availability of HP trailers and any differential cost of transport – would determine trailer selection. With higher delivered pressure, hydrogen would be beneficial in reducing the on-site compression required during loading operations and reduce loading duration.

5. Safety and codes

Hydrogen is a colourless, odourless, tasteless gas which is highly flammable. Its limits of flammability in air (25 °C/atmospheric pressure) are 4.0% (lower limit) and 75% (upper limit). The values in oxygen are 4.0% (lower limit) and 94% (upper limit). It has a high energy density on a mass basis (LHV = 119.9 MJ/kg) but a poor one on a volumetric basis (LHV = 10.8 MJ/m^3). It is a small molecule and will pass in quantity through small leaks and is difficult to contain and a fuel-air mixture is easy to ignite. Controlling this flame can present challenges but its combustion at source will prevent any flammable accumulation and thus prevent any explosions. Hydrogen disperses readily and both raw gas and flame tend to rise rapidly. It is widely used in the oil industry which has a suite of codes and standards covering its safe handling.

As the non-oil hydrogen industry is still in its infancy, the starting point for the preparation of suitable codes and standards could be to consult those companies that currently produce and handle hydrogen as part of their normal business activities. These companies, along with the rail operators, should work with the Safety Boards and National Standards authorities in the development of the necessary suite of documents for hydrogen use. International communication and cooperation with those countries and companies using hydrogen for trains will facilitate the development of the required regulations. Formal risk assessment procedures will be needed to reflect the hazards introduced by hydrogen and should form part of the new standards and guidance.

Training and safety courses for those personnel handling hydrogen in large quantities is a pre-requisite. The mandatory earthing during the transfer and loading process, personal protection equipment requirements, reclassification of hazardous areas, use of special hoses and equipment and operator safety must all be covered. These subjects can be presented in training courses as well as being stated in the new standards. The certification of these operators through a recognised formal process should be considered as should the training and certification of the technicians and engineers involved in the maintenance and inspection activities. Any Emergency Response Planning in place for current rail operations must be reviewed and updated to reflect the new hazards.

6. Hydrogen fuelled trains

6.1 Application

The most recent report by ORR [4] states that those lines in the UK that will likely not be electrified for economic reasons, total 3,700 STkm This assumes that the 11,700 STkm currently ear-marked for electrification are so converted. In addition, from the 3,700 STkm, a case for conversion to electricity of another 1,340 STkm can be made. The potential for hydrogen if these services were converted using new internal combustion engines is estimated (assuming 25% mechanical efficiency) as 1450 Te/day.

This future quantity of hydrogen will not likely be allowed on the roads to be transported from the few existing or planned new built production locations. If a broad national hydrogen economy infrastructure plan is not in place as the train numbers increase, smaller hydrolyser plants will be considered, located at or near major train fuelling locations. These essentially packaged units, including the required water treatment facilities and hydrogen storage at the unit or the rail siding, will be powered by renewable energy making this green hydrogen production.

In the design of the facilities, there will be a degree of redundancy. There will be an on-line spare compressor for example together with several days hydrogen storage capacity to cover outages together with diesel generators to provide black start capabilities.

6.2 Porterbrook: Hydroflex

Porterbrook own and lease railway vehicles in the UK. They have developed with Hydroflex a hybrid train based on the Class 319 local train. The class 319 was developed originally in 1987 and is well proven in UK service. It has a steel body roughly 19.9 m long by 2.82 m wide by 3.58 m high. This experimental vehicle can operate from a third rail (750 V DC) or from an overhead supply (25 kV AC). It has a 100 kWe fuel cell and stores 20 kg of hydrogen in four pressure vessels at high pressure, delivering the hydrogen to the fuel cell at 8.5 bar g. Its operating range will be from 345 bar g to approx. 12 bar g. The fuel cell delivers its output to a Li-ion battery pack from where all drive power is taken. Early development work and research was performed at the University of Birmingham, UK.

6.3 Alstom Coradia iLint train

Alstom manufacture a variety of trains including the Hydrogen powered Coradia iLint. This vehicle is based upon a diesel engine chassis and the latter has been sold worldwide including to Canada. The hydrogen train is configured with 150 seats, a range of 1000 km and has a maximum speed of 140 km/hr. The hydrogen is stored in the roof of the vehicle at 5,000 psia (35 MPa) and the hydrogen is distributed to the train fuel cell at 1 MPa (145 psia). Two prototype iLint trains have been operated in Germany carrying passengers: possible orders for trains for regular service are being considered for lines in Germany and Austria.

7. Examples of possible decarbonised trains

7.1 Melbourne, Australia

These passenger trains have been refurbished and now are nearing replacement. They are used on metropolitan lines out of Melbourne city and consist of 3 cars per set but are usually run with 6 cars. Though normally using electricity (an ideal situation) it is included to cover the situation if electricity is not available.

Power consumption = 800 kW typical fully laden including air conditioning.
Passenger load = 420 seated (1530 “crushed”).
Speed = 40–60 km/hr. average.
Power supply (currently) = 1.5 kV DC collected using pantographs.
Carbon dioxide avoided = 615 Te/hr. for diesel @ 35% efficiency.
Hydrogen needed = 60 kg/hr. @ 40% efficiency.

7.2 Alstom hydrogen trains: Model for Oxford to Cambridge route

Distance = 170 km.
Power = 0.465 kW.
Fuel cell power = 200 kW.
Battery pack = 225 kW-hr.

Passenger load = 138 seats + 190 standing.
Average speed = 60 km/hr.
Hydrogen needed = 17 kg/hr. @ 35% efficiency.
Carbon dioxide avoided if using diesel (35% effic.) = 155 kg/hr.
NO_x avoided = 2.34 kg/hr.

7.3 BHP iron ore train : Western Australia

Test train on BHP private track for maximum achievable train length: Length = 7.32 km.
Track length = 275 km.
Eight (8) locomotives (with GE AC6000CW 6000 HP diesel electric engines) distributed as three (3) pair and two (2) single units along train length. AC traction.
Individual engine weight = 192–196 Te.
Fuel tank capacity per engine = 21,000 litres.
Number of waggons = 682.
Total gross weight = 99,724 Te.
Total ore weight = 82,000 Te wet ore.
Average speed = 46 km/hr. (excluding coupler breakdown time).
Maximum speed = 120 km/hr. individual engine.
Fuel consumption = 3,500 l/hr. diesel average (on test, engines idled for nearly five hours).[1]
Hydrogen needed @ 40% eff. = 21.5 Te/hr.

7.4 Fuel cell driven switcher: California USA

Experimental replacement of a diesel engine switcher with a zero emissions' fuel cell using hydrogen as a fuel and advanced battery technology. The overall aim is to improve local air quality.
Typical switcher fuel consumption = 50, 000 US gallons/year diesel.
This machine data is based on units used in marine ports which run at near continuous operation and power levels.
Fuel saved assuming 4,000 hours per year full load operation = 47.14 l/hr.
Carbon dioxide avoided = 520 Te/year.
Hydrogen needed @ 35% eff. = 58.3 Te/year.

7.5 Hydrogen fuelled trains in the Kingdom of Saudi Arabia

An example of a country that has an opportunity to showcase hydrogen fuelled trains is Saudi Arabia. The new city of Neom, a city of one million people located in the northwest of the kingdom, will maximise the use of renewable energy and hydrogen and that the hydrogen would be produced in sufficient quantities both to satisfy the city's needs and leave a sizeable surplus for export. The proposed export price of the hydrogen would be less than that envisaged for UK green hydrogen production. The new train lines would connect Neom to the rest of the country and would be able to show hydrogen fuelled trains with minimal emissions.

The takeover of the original railway operator, Saudi Railways Organisation (SRO) by Saudi Railways (SAR), announced in February 2021, should allow advancement of the national strategy for transport and logistics rail. The current Saudi Railway Master Plan (2010–2040) has several major projects which will connect major cities, ports and industrial areas. The new lines will total nearly 5000 km

[1] The total time was 10 hours 40 minutes but nearly 5 hours was spent repairing a broken coupler.

and will include rail links between all the GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates). The potential rail links with Neom will increase this length considerably.

The use of hydrogen for trains on these new lines would both satisfy the requirement to go green with the reduction of emissions from diesel drivers as well as being a very impactful advertisement for their hydrogen production and export industry.

8. Costing of pollution

Pollution has an economic cost [25]. Pollution from hydrocarbon fuel's costs depends on many factors including locale and the numbers here are based on UK inner city parameters [26]. They are indicative of many western industrial societies. The numbers used in this analysis are given below and should be adjusted for each location (**Table 5**).

The following examples show the variety and extremes of railway locomotives, their loads, the power they produce, approximate quantity of hydrogen that they would use and the volume of their hydrogen tank. For the smaller and medium sized drive units a stored pressure of 205 bar g is assumed (design = 225 bar g @ 150°C) and for the larger machines, the proposed stored pressure is 300 Bar g (design = 330 bar g @ 150°C). In the USA for trucks, a stored pressure of 600 bar g has been considered though at these pressures, compression power needed would be high and detract from efficiency even though more hydrogen storage per unit volume would be achieved. The economic success depends on capital cost, fuel cost and the pollution avoided cost by using hydrogen.

Cost parameters	US$	Unit
NO_x	9,062	$/Te
CO_2	1.24	$/Te
SO_2	18.74	$/Te
PM2.5	104,180	$/Te
NH_3	7,923	$/Te
Cost of hydrogen	4.65	$/kg
Diesel	1.432	$/litre
Electricity	171.10	$/MWe-h[2]
Pollution		
CO_2 produced from diesel	2.68	kg/l
LHV diesel fuel	36.9	MJ/l
	45.5	MJ/kg
NO_x	0.46	gm/kW-h (diesel)
Particulates	0.17	gm/kW-h (diesel)
S content of diesel fuel	Euro VI limits	—
CO_{2e} from passenger trains	35.1	gm/passenger-km
CO_{2e} freight trains	27.5	gm/Te-km

Table 5.
Cost allowance for individual polluting components.

Cost item/example	1	2	3
Cost CO_2	0.39	132	0.22
Cost NO_x	1.50	1864	300
Cost particulates	0	75	
Cost fuel (based on diesel)	144	42,169	68
Cost hydrogen	294	100,175	169

Table 6.
Cost comparisons: Emission and fuels – Costs in US$/hour operating.

8.1 Example 1 (7.1 above)

A 1500 Volt DC electric train supplied from overhead cables and using pantographs (description as above) is included as an example as an example of existing use of high voltage electrification. The electricity is most probably supplied from Yallorn power station which uses brown coal which would benefit from gasification.

8.2 Example 2 (7.2 above)

This was a test train used by BHP-Billiton in Western Australia to take iron ore from the mines to the coast. The distance the test train travelled was 275 km. The train used eight locomotives (GE AC6000CW) configured as three engine sets, each of two engines plus two independent engines under the control of a single driver operating the whole train. The individual engine weight was 192–196 Te, the train had 682 waggons stretching 7.32 km with the engines distributed along their length. The gross weight was 99,734 Te of which 82,000 Te was wet ore. The assumed total travel time was six hours. This feat has still the world record for load carried and train length.

8.3 Example 3 (7.3 above)

This is a retired shunter (switcher) engine used in Los Angeles – details as above. It was nearing retirement and is now proposed to be used as a basis of a study by replacing its diesel engine with a fuel cell running on stored hydrogen. The precise details are still the subject of further experimental study/analysis, but it is predicted to save 50,000 US gallons diesel each year. If the predictions are achieved and the results are applicable to all such engines in the port, potentially 12 million US gallons diesel each year will be saved. The prime aim is to eliminate undesirable emissions in the vicinity of the port. The cost numbers presented are based on UK metrics (**Table 6**).

Power station costs depend on other factors including the fuel itself and here it could be brown coal. Power stations concentrate their emissions making their disposal somewhat easier. If down hole location is selected, other geological problems must be addressed, including any bacterial actions.

There are other undesirable components produced by energy transformation and use but it is unlikely that they will justify the movement to hydrogen fuel on their own based on cost. Engine design is progressing with improvements in emissions taking place. The use of many of the renewables presents their own problems.

9. Conclusions

Hydrogen to power trains, replacing diesel fuel and reducing its related emissions, is a necessary consideration on the path to decarbonisation of any railway. As shown, a sizable use of IC engines with hydrogen or using fuel cells reduces these emissions. The route to make and supply the necessary hydrogen is dependent on many external factors. If there is a hydrogen gas grid in place, either a new build or refurbishment of an existing natural gas system then oversizing of hubs (giving economies of scale) is one attractive option. If new infrastructure is needed, and is not available to an acceptable timescale, then using many dispersed local electrolysers is also an option.

Another decision to be accepted is the degree of electrification to be used as any problems will be passed back to the source of the power required, which must be renewable. An electrified system using high voltage overhead supply with pantograph collection is expensive to instal but uses the minimum energy when compared with hydrogen power using fuel cells. The electricity supply can be from indigenous nuclear stations which also have high capital cost and low running cost. Hydrogen's cost, even if imported, will still be high. The route selected will be controlled by the political process and other factors such as the cost of money, the extent of electrification already in place and its age (sunk cost) and the ability and extent to use existing infrastructure to distribute hydrogen.

In the medium term, all governments considering a green hydrogen economy to reduce emissions, essentially from hydrocarbon fuels, must make those decisions on their chosen way forward. In the UK as well as those countries that have a natural gas infrastructure that supplies gas for home heating and industry, the choice to convert to hydrogen will help make transport decisions. As the hydrogen national grid will deliver to most of the country, it should carry the future volume requirements for rail especially if a large portion of the current diesel-powered trains are converted to electricity.

The bigger picture for hydrogen as a future fuel and significant emissions reducer can only be projected on the assumption that this is mostly green hydrogen. The related challenges will include the competition for renewable energy, the space – onshore or offshore – for the number of new wind turbines that will be needed in the new energy mix, the CAPEX, the disruption to the overall economy especially during the transition phase, and political capital needed to establish a true hydrogen economy.

Technology that is yet in its infancy, including industrial processes to supplant the old processes with high emission outputs such as steel making and cement manufacture, will need to be formalised, piloted, upscaled and implemented in a decreasing timeframe. Improvements in battery and fuel cell design will occur and help here.

For rail to widely use hydrogen, the first step should be the production of suitable codes and standards.

Abbreviations

BPD	Barrels per Day
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
EJ	Exa Joules
STkm	Single Track kilometres
TE	Metric Tonne
TW-h	Tera Watt hours

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Railway engineering is facing different and complex challenges due to the growing demand for travel, new technologies, and new mobility paradigms. All these issues require a clear understanding of the existing technologies, and it is crucial to identify the real opportunities that the current technological revolution may pose. As railway transportation planning processes change and pursue a multi-objective vision, diagnostic and maintenance issues are becoming even more crucial for overall system performances and alternative fuel solutions.

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