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Identifying priority directions for carbon emission reduction in railway transport using multi-criteria analysis

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Abstract. In the short and medium term, the decarbonisation of diesel traction cannot rely solely on full electrification and the rapid replacement of rolling stock, which creates a need for renewable diesel fuels. The aim of the study was to develop a multi-criteria procedure for ranking renewable diesel fuels for railway diesel traction and to identify the priority option for reducing carbon emissions. The article considered four renewable diesel fuel alternatives, namely fully hydrotreated vegetable oil (HVO) fuel, pure biodiesel fuel, a blend containing 20% biodiesel and 80% fossil diesel fuel, and synthetic paraffinic diesel fuel, proposes a formalised selection procedure based on a combination of the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods, and established a matrix of seven criteria: environmental performance, technical compatibility, operational suitability, economic feasibility, feedstock availability, infrastructure compatibility, and regulatory alignment. The weights of the criteria were determined using the AHP, consistency was verified, and the alternatives were ranked using the TOPSIS. The results indicated the superiority of the paraffinic fuels fully HVO fuel and synthetic paraffinic diesel fuel, which are suitable for use without retrofitting existing rolling stock. These fuels demonstrated the best combination of low total greenhouse gas emissions throughout the fuel life cycle and high technical compatibility. Pure biodiesel fuel and the blend containing 20% biodiesel were ranked lower due to their lower technical and operational suitability, higher sensitivity to storage and fuel-handling conditions, and a weaker overall emission-reduction effect in the case of the blend containing 20% biodiesel. The proposed approach can be used by railway operators, infrastructure managers, transport authorities, and researchers as a decision-support tool for the phased transition from fossil diesel fuel to renewable liquid fuels in the railway sector

Keywords: decarbonisation; transport technologies; renewable diesel fuels; diesel traction; biodiesel fuel; fuel compatibility; operational suitability

Introduction

Decarbonisation of rail transport is a key priority of modern transport policy. Under the climate agenda, the rail sector is regarded as a fundamental component of a low-carbon transport system. Achieving decarbonisation targets requires reducing dependence on fossil diesel fuel on non-electrified lines. Despite the high energy efficiency of rail transport compared with other modes of transport, diesel traction remains critically important for both train operations and shunting. This is particularly relevant where electrification is absent, or where its further expansion is economically or technologically constrained. In the short term, decarbonisation cannot rely solely on large-scale traction replacement, the deployment of hydrogen or battery-powered trains, or the complete restructuring of infrastructure. Therefore, the use of renewable liquid fuels appears to be a reasonable transitional option, because it can reduce the carbon footprint without radical intervention in the existing rolling stock fleet.

Recent studies confirm that railway decarbonisation depends on infrastructure constraints, operational profile, investment needs, as well as full life-cycle emissions. M. Kapetanović *et al.* (2024) evaluated traction alternatives for regional railways and showed that well-to-wheel greenhouse gas emissions must be considered when

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comparing non-electrified railway options. A. Aredah *et al.* (2024) compared alternative powertrain technologies for freight trains in their work and demonstrated that technical feasibility should be assessed together with operational and environmental consequences. A. Hernandez *et al.* (2024a) proposed a framework for evaluating railway decarbonisation alternatives, including alternative fuels and the deployment of battery-electric systems. A. Hernandez *et al.* (2024b) conducted an analysis of freight railway decarbonisation using the logic of emission reduction costs. As a result, the researchers show that the decarbonisation of diesel traction cannot be reduced to a single technological pathway.

At present, the most realistic fuel alternatives for diesel traction in the rail sector are paraffinic fuels such as HVO100, a renewable diesel fuel produced by hydrotreatment of oils and fats, and XTL, a synthetic liquid fuel, as well as biodiesel fuels, including B100 and B20. W. Szeto & D. Leung (2022) reviewed the production, properties, engine performance, and emissions of hydrotreated vegetable oil and emphasised its potential as a substitute for fossil diesel. C. McCaffery *et al.* (2022) examined HVO and HVO/biodiesel blends in an off-road heavy-duty diesel engine and provided evidence on the emissions and physicochemical characteristics of such fuels. H. Xu *et al.* (2022) showed that biodiesel and renewable diesel pathways may differ substantially in life-cycle greenhouse gas emissions depending on feedstock and production route. Y. Pradana *et al.* (2024) reviewed cold-flow limitations and improvement methods for biodiesel application. These findings are important for railway operation, because fuel quality deterioration may directly affect rolling stock reliability, filtration, maintenance frequency, and the stability of the transport process.

However, the technical feasibility of these alternatives does not in itself determine their implementation priority. The existing literature covers individual aspects of the problem, including general decarbonisation pathways, engine and environmental characteristics of renewable diesel fuels, and operational risks connected with storage and fuel handling. At the same time, most studies do not provide a unified procedure for comparing HVO100, B100, B20, and XTL within one decision-making model for railway diesel traction. This creates the need to identify the most appropriate option among alternative fuels that differ in terms of life-cycle greenhouse gas emissions, technical compatibility, operational suitability, fuel supply infrastructure requirements, economic feasibility, feedstock availability, and regulatory alignment. Multi-criteria decision-making methods are suitable for this type of task. Multi-criteria methods make it possible to compare alternatives according to many criteria, for example: technical, environmental, economic, and regulatory ones. A. Abdulvahitoglu & M. Kilic (2022) applied an integrated AHP-TOPSIS approach to biodiesel fuel selection. W. Kriswardhana *et al.* (2025) reviewed the use of the AHP in transportation decision-making. Similar studies confirm the suitability of combining criteria weighting with ranking procedures in fuel comparison tasks.

The purpose of this study was to develop a procedure for ranking renewable diesel fuels for use in railway diesel traction in order to reduce carbon emissions. The tasks of the study were as follows: to analyse the existing renewable diesel fuel alternatives and to define the set of criteria for their evaluation; to develop a multi-criteria evaluation procedure for HVO100, B100, B20, and XTL based on the sequential application of the AHP and TOPSIS methods; to determine the criterion weights using the AHP method and to rank the renewable diesel fuel alternatives using the TOPSIS method.

Materials and Methods

Materials used in this study: scientific publications on railway decarbonisation and alternative traction technologies (Aredah *et al.*, 2024; Hernandez *et al.*, 2024a; Kapetanović *et al.*, 2024). Limitations on railway decarbonisation and traction were reviewed in F. Zenith *et al.* (2020), F. Barbosa (2023) and A. Hernandez *et al.* (2024b). Studies on HVO and renewable diesel fuels were represented by C. McCaffery *et al.* (2022), W. Szeto & D. Leung (2022), and J. Hunicz *et al.* (2025). The properties of biodiesel fuel and storage risks were considered in the works of E. Christensen & R. McCormick (2023), W. Ai *et al.* (2024), and Y. Pradana *et al.* (2024). Regarding multi-criteria decision-making and fuel selection, the publications by M. Behzadian *et al.* (2012), G. Yannis *et al.* (2020), and W. Kriswardhana *et al.* (2025) were considered. Regarding the application of transport fuel selection, G. Chaitanya *et al.* (2020), A. Abdulvahitoglu & M. Kilic (2022) and M. Kügemann & H. Polatidis (2024) were additionally considered. The application of alternative fuels for transport was also considered more broadly in the work of N. Aboushaqrah *et al.* (2022). The materials also include industry analytical reports and materials from operators (AERRL, 2022; European Union Agency for Railways, 2024; CER, 2025). Regarding the implementation of HVO, materials presented by Neste (2023), DB Cargo (n.d.) and LTG Group (n.d.) were reviewed. The description of the LTG Group (n.d.) project was used to verify the pilot context of HVO100. Data on railway biofuels were supplemented from sources of the International Union of Railways (2007), CONCAWE (2009), and the Federal Railroad Administration (2014). European policy documents were reviewed from the European Commission (2019; 2021). Regulatory and technical documents included standards of the BSI (2021; 2023a; 2023b) for paraffinic diesel fuel and diesel fuel. Additional standards for information on diesel fuel and EU regulation on renewable energy were also used (Directive of the European Parliament and of the Council No. 2001, 2018; Regulation of the European Parliament and of the Council No. 1119, 2021; BSI, 2024).

The study was based on data on the properties of renewable diesel fuels, including their technical compatibility with diesel engines, storage conditions, fuel handling requirements, regulatory constraints, and total greenhouse gas emissions across the entire fuel life cycle. The analysis also took into account the provisions of EU fuel standards, the findings of recent scientific studies, publicly available materials from railway operators, as well as materials obtained within the framework of the PhDs EU-Rail project. The study was conducted during 2025-2026. It covered the analysis of scientific publications, regulatory documents, technical standards, materials from railway operators, and project materials. The analysis of sources was conducted and structured into four thematic groups, namely: railway decarbonisation and alternative traction technologies; properties of HVO, XTL, and renewable diesel fuel; biodiesel storage and contamination risks; and multi-criteria decision-making methods. Generalisation and analysis of the sources were used to identify the main approaches to the decarbonisation of diesel traction and to the selection of alternative renewable diesel fuels. At the first stage, alternatives suitable for further comparison were selected, namely: HVO100, B100, B20, and XTL. At the second stage, the evaluation criteria were determined. As a result, the set of criteria included environmental indicators, technical compatibility, operational suitability, economic feasibility, feedstock availability, infrastructure compatibility, and regulatory compliance.

The weighting and scoring stages were carried out by the authors. A documentary and analytical approach was used in combination. The judgments were also formed on the basis of the research aim and the synthesis of scientific literature, including fuel standards, railway operator materials, and the technical applicability framework. The weights of the criteria were formed through pairwise comparisons using the Saaty scale. In each of the pairwise comparisons, the relative importance of one criterion over another was determined according to its contribution to the decarbonisation objective, as well as the practical feasibility of introducing the fuel into existing railway diesel traction. Environmental performance was considered the leading criterion. The scores for criteria C2-C7 were determined after comparing each fuel alternative with the criterion content. The scoring procedure was carried out according to a five-point rule, namely: 5 indicated full or near-full suitability, clear compliance with the relevant standard, and no need for substantial changes; 4 indicated high suitability with minor transition or control measures; 3 indicated medium suitability requiring additional monitoring or agreed application rules; 2 indicated low suitability with substantial technical, operational, economic, or infrastructure limitations; and 1 indicated very low suitability and practical unsuitability under the assumed railway operating conditions. For all criteria C2-C7, a higher score corresponded to a more favourable solution. To determine the weights of the evaluation criteria, the AHP and the Saaty scale were applied (Saaty, 1980). The pairwise comparison matrix was formed for seven criteria. The weights were calculated as the normalised principal eigenvector of the pairwise comparison matrix. The consistency index was calculated:

$$CI = (\lambda\_max-n)/(n-1), \quad (1)$$

where λ_{max} – the maximum eigenvalue of the pairwise comparison matrix; n – the number of criteria in the pairwise comparison matrix.

The consistency ratio was calculated:

$$CR = CI/RI, \quad (2)$$

where CI is the consistency index calculated using formula (1); is the average random consistency index for pairwise comparison matrices of the corresponding size, the values of which are given in the AHP method tables.

For $n = 7$ the adopted value is $RI = 1.32$. For the given matrix: $\lambda_{max} \approx 7.0505$; $CI \approx 0.00842$; $CR \approx 0.00638$. Since $CR < 0.10$, the pairwise judgments can be considered consistent and may therefore be accepted as valid for further analysis. The next stage is the application of the TOPSIS method. The following notation is used: x_{ij} – denotes the value of alternative i under criterion j. TOPSIS normalisation is calculated using the formula (3):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad (3)$$

where r_{ij} – the normalised value of the j-th criterion for the i-th alternative; m – the number of alternatives; x_{ij} – the initial value of the i-th alternative under the j-th criterion; i – the index of the alternative; j – the index of the criterion; Σ – the summation sign over all alternatives; √ – the square-root operation.

The weighted normalised values are calculated using the formula (4):

$$v_{ij} = w_j \cdot r_{ij}, \quad (4)$$

where w_j – the weight of the j-th criterion determined using the AHP method; r_{ij} – the normalised value of the i-th alternative under the j-th criterion; i – the index of the alternative; j – the index of the criterion.

The ideal and anti-ideal points for the cost criterion C1 (*WTW* – total greenhouse gas emissions over the entire fuel chain) are defined as follows):

$$v_j^+ = min_i^{vij}, v_j^- = max_i^{vij}, \quad (5)$$

where v_j^+ – the ideal value of the criterion; v_j^- – the anti-ideal value of the criterion; v_{ij} – the weighted normalised value of the i-th alternative under the j-th criterion; i – the index of the alternative; j – the index of the criterion; min_i – the minimum value among all alternatives; max_i – the maximum value among all alternatives.

For the benefit criteria C2-C7, the ideal and anti-ideal points are defined as follows:

$$v_j^+ = max_i^{vij}, v_j^- = min_i^{vij}, \quad (6)$$

where v_j^+ – the ideal value of the j-th criterion; v_j^- – the anti-ideal value of the j-th criterion; v_{ij} – the weighted normalised value of the i-th alternative under the j-th criterion; i – the index of the alternative; j – the index of the criterion; max_i – the maximum value among all alternatives; min_i – the minimum value among all alternatives.

The distance to the ideal point is calculated using the formula (7):

$$D_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2}, \quad (7)$$

where D_i^+ – the distance of the i-th alternative to the ideal point; v_{ij} – the weighted normalised value of the i-th alternative under the j-th criterion; v_j^+ – the ideal value of the j-th criterion; i – the index of the alternative; j – the index of the criterion; n – the number of criteria; Σ – the summation sign over all criteria; √ – the square-root operation.

And the distance to the anti-ideal point is calculated using the formula (8):

$$D_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}, \quad (8)$$

where D_i^- – the distance of the i-th alternative to the anti-ideal point; v_{ij} – the weighted normalised value of the i-th alternative under the j-th criterion; v_j^- – the anti-ideal value of the j-th criterion; i – the index of the alternative; j – the index of the criterion; n – the number of criteria; Σ – the summation sign over all criteria; √ – the square-root operation.

The closeness-to-ideal index is calculated using the formula (9):

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-}, \quad (9)$$

where S_i – the closeness-to-ideal index of the i-th alternative; D_i^+ – the distance of the i-th alternative to the ideal point; D_i^- – the distance of the i-th alternative to the anti-ideal point; i – the index of the alternative.

The values of are taken from formulas (7), (8). The higher the value of the higher the rank of the alternative. The AHP–TOPSIS sequence makes it possible first to establish the relative importance of the criteria and then to obtain an integrated ranking of alternatives on the basis of a single evaluation matrix. For the final TOPSIS matrix, the following *WTW* values, representing total greenhouse gas emissions over the entire fuel chain, were used: HVO100 from waste oils – 16.0; B100 from rapeseed – 50.1; and XTL from waste wood – 15.6. Fossil diesel fuel was taken as the reference value at 94. For B20, the value of 85.2 was obtained by calculation as a first approximation based on the biodiesel content in the blend. The model uses one quantitative criterion, WTW, and six criteria evaluated on a scale from 1 to 5. The scores for criteria C2-C7 were formed on the basis of the analysed scientific publications, fuel standards, technical documents, railway operator materials, and the technical applicability framework.

The *WTW* value for B20 was determined using the formula (10):

$$WTW(B20) = 0.20 \cdot WTW\_B100 + 0.80 \cdot WTW\_Diesel, (10)$$

where *WTW(B20)* – the total greenhouse gas emissions of the B20 fuel blend over the entire fuel chain; *WTW_B100* – the total greenhouse gas emissions of pure biodiesel fuel over the entire fuel chain; *WTW_Diesel* – the total greenhouse gas emissions of fossil diesel fuel over the entire fuel chain; 0.20 – the share of biodiesel fuel in the B20 blend; 0.80 – is the share of fossil diesel fuel in the B20 blend; *WTW* – denotes the well-to-wheel assessment boundary and refers to total greenhouse gas emissions over the full fuel chain, from fuel production to final use.

And the relative reduction compared with fossil diesel fuel was determined as follows:

$$\eta = (1 - WTW_{alt} \,/\, WTW\_Diesel) \cdot 100\%, \quad (11)$$

where η – the relative reduction in greenhouse gas emissions compared with fossil diesel fuel; *WTW_alt* – the total greenhouse gas emissions of the selected fuel alternative over the entire fuel chain; *WTW_Diesel* – is the reference value for fossil diesel fuel; 100% – the multiplier used to express the result as a percentage.

Thus, the methodological basis of the study was built on the sequential application of the AHP and TOPSIS methods, which made it possible first to substantiate the relative importance of the evaluation criteria and then to obtain an overall ranking of alternative fuels for railway diesel traction.

Results and Discussion

The study considers four renewable diesel fuel alternatives for use in railway diesel traction:

1) Alt 1 – HVO100 (paraffinic diesel fuel produced in accordance with EN 15940);

2) Alt 2 – B100 (biodiesel based on fatty acid methyl esters, produced from vegetable oils and fats in accordance with EN 14214);

3) Alt 3 – B20 (a diesel fuel blend containing 20% biodiesel);

4) Alt 4 – XTL (synthetic paraffinic diesel fuel produced in accordance with EN 15940).

The selection of alternatives was based on fuel standards and data on renewable diesel fuel and railway decarbonisation pathways. W. Szeto & D. Leung (2022) and C. McCaffery *et al.* (2022) support the technical relevance of HVO and HVO/biodiesel blends, while M. Kapetanović *et al.* (2024) used full fuel-chain assessment in railway traction comparison. These alternatives were selected because they have either practical relevance to the railway sector or have already been considered in pilot applications, and because they are covered by clearly defined fuel standards. Typical values of life-cycle greenhouse gas emissions were used in the assessment. This means that the evaluation considered not only the fuel itself, but the entire production pathway from feedstock to final use.

At the stage of preliminary selection, both the fuel type and the conditions under which it can realistically be used in diesel traction were examined. In particular, consideration was given to whether the fuel could be used without modification of the rolling stock, how sensitive it is to the characteristics of the fuel system, what risks may arise during the transition from one fuel to another, and what storage conditions are required. Such preliminary selection makes it possible to identify the options that are generally suitable for further consideration, but it does not determine which fuel should be implemented. The final decision should be made on a rational basis using the results of a multi-criteria assessment that takes into account both environmental impact and operational reliability under railway operating conditions (Table 1).

Table 1. Renewable diesel fuel alternatives and their technical applicability framework

Alternative	Standard and class	Technical applicability in diesel traction	Typical compatibility risks	Typical storage risks
Alt 1	EN 15940; paraffinic diesel fuel	Can be used without retrofitting; suitable both in neat form and in blends	Insufficient lubricity if not controlled, need for batch quality verification, possible issues with seals and elastomers in older rolling stock	Tank flushing and cleaning are required during the transition; filter clogging may occur at the initial stage
Alt 2	EN 14214; biodiesel based on fatty acid methyl esters	Use without retrofitting is limited; suitability depends on fuel quality and operating conditions; additional monitoring is required	Risks of incompatibility with certain materials, deposit formation, and filter clogging during the transition	Sensitivity to oxidation, water accumulation, microbiological contamination and deterioration of properties at low temperatures
Alt 3	EN 590 base fuel; high-FAME diesel considered within EN 16709	Intermediate option; requires a specifically defined blend composition and agreed application rules	Dependence on the quality of the biodiesel component; risks for filtration and seals are lower than for B100, but remain present	Sediment formation may occur at low temperatures; water content, microbiological condition and sampling procedures must be controlled
Alt 4	EN 15940; synthetic paraffinic diesel fuel	Can be used without retrofitting; the main limitations are related to availability, price and certification	Similar to HVO100: lubricity, batch quality control and risks for older fuel-system materials	Similar to HVO100: cleaning and control are required during the transition; the main difficulties are related more to supply than to fuel properties

Source: compiled by the authors based on International Union of Railways (2007), CONCAWE (2009), Federal Railroad Administration (2014), L. Komariah *et al.* (2022), BSI (2021; 2023a; 2023b; 2024), W. Ai *et al.* (2024), Y. Pradana *et al.* (2024)

The alternatives and technical frameworks presented in Table 1 serve as a suitability filter. However, they do not determine the priority of implementation. To address this, a multi-criteria AHP-TOPSIS procedure was developed, taking into account not only life-cycle greenhouse gas emissions, but also technical compatibility, operational suitability, economic factors, feedstock availability, infrastructure compatibility, and regulatory aspects. A set of seven criteria was established for evaluating the alternatives: C1 – environmental performance; C2 – technical compatibility; C3 – operational suitability; C4 – economic feasibility; C5 – feedstock availability; C6 – infrastructure compatibility; and C7 – regulatory alignment. The characteristics of these criteria are presented in Table 2. The environmental criterion, C1, was assessed on the basis of life-cycle greenhouse gas emissions across the entire fuel chain, from fuel production to final use. This indicator is expressed numerically as grams of carbon dioxide equivalent per unit of fuel energy. For criteria C2-C7, a rating scale from 1 to 5 was applied, following the principle that a higher score indicates a better result.

Table 2. Criteria and evaluation rules

Criterion	Designation	Evaluation format	Optimality rule	Criterion content
Environmental performance	C1	Total greenhouse gas emissions across the entire fuel chain, gCO_2e/MJ	Lower is better	Total greenhouse gas emissions from fuel production to end use
Technical compatibility	C2	1-5 scale	Higher is better	Compliance with the relevant standard, possibility of use without retrofitting, compatibility with the fuel system
Operational suitability	C3	1-5 scale	Higher is better	Performance at low temperatures, storage behaviour, filterability, risk of additional maintenance
Economic feasibility	C4	1-5 scale	Higher is better	Fuel cost, price volatility, transition costs
Feedstock availability	C5	1-5 scale	Higher is better	Origin of feedstock, its availability, and potential for wide-scale use
Infrastructure compatibility	C6	1-5 scale	Higher is better	Suitability of tanks and fuel-handling infrastructure; need for flushing, cleaning and quality control
Regulatory alignment	C7	1-5 scale	Higher is better	Compliance with standards and certification requirements, possibility of official accounting and practical application

Source: developed by the authors based on BSI (2021; 2023a; 2023b; 2024), W. Szeto & D. Leung (2022), C. McCaffery *et al.* (2022), H. Xu *et al.* (2022), M. Kapetanović *et al.* (2024), A. Aredah *et al.* (2024), A. Hernandez *et al.* (2024a)

A wide range of technical, environmental, and economic indicators was taken into account when developing the evaluation criteria. It was decided not to include these indicators separately in the final model; instead, they formed the basis for scoring criteria C2-C7. This approach made it possible to preserve the substantive value of the assessment while ensuring comparability of the alternatives under conditions of limited publicly available data. The criteria are described below. The environmental component of the model is based on total greenhouse gas emissions across the entire fuel chain, from feedstock to final fuel use. This indicator was selected as the main measure of decarbonisation, since exhaust emissions alone do not reflect the full climate impact of a fuel. The indicator is expressed in gCO_2e/MJ and characterises the total greenhouse gas emissions, in CO_2-equivalent, attributed to a unit of fuel energy over the entire fuel life cycle.

Parameters such as nitrogen oxides (NOx) emissions were also considered important for assessing local pollution and operating conditions, particularly during shunting operations and in areas sensitive to air quality. However, they were not treated as separate criteria because no single set of comparable data for railway equipment under identical test conditions was available. Lubricity, density, viscosity, and compatibility with fuel-system materials were considered as components of technical compatibility (Knothe, 2005; Lapuerta *et al.*, 2011; ISO 12156-1:2018, 2018). Low-temperature properties, filter replacement frequency, failures of fuel equipment, and performance under cold-weather conditions were considered as components of operational suitability (Christensen & McCormick, 2023; Ai *et al.*, 2024; Pradana *et al.*, 2024).

Criterion C2 reflects the extent to which a given type of fuel complies with current standards and can be used in existing diesel engines without modification. The criterion also takes into account the risks posed to the fuel system during the transition to a new fuel. The highest scores are assigned to the paraffinic fuels HVO100 and XTL. To better understand fuel lubricity and fuel-system materials, reference materials from G. Knothe (2005), ISO 12156-1:2018 (2018), and DieselNet (n.d.) were analysed. Their use is associated with fewer technical limitations (Szeto & Leung, 2022; MTU, 2023; Hunicz *et al.*, 2025). By contrast, B20 and especially B100 receive lower scores because of their higher biodiesel content, greater sensitivity of sealing materials, a higher risk of deposit formation, and stricter fuel handling and storage requirements. International Union of Railways (2007), Federal Railroad Administration (2014), and W. Ai *et al.* (2024) provide an understanding that fuels containing biodiesel require additional attention to fuel quality, filtration, and storage. L. Komariah *et al.* (2022) also confirm the relevance of microbiological contamination risks for diesel-biodiesel blends.

Criterion C3 reflects operational suitability, including fuel performance in different seasons, behaviour at low temperatures, suitability for long-term storage, filterability, and the impact on maintenance requirements. This criterion takes into account low-temperature properties, storage stability, and the risk of contamination. For a better understanding of how biodiesel is stored and what storage risks exist, the studies by E. Christensen & R. McCormick (2023), W. Ai *et al.* (2024), as well as Y. Pradana *et al.* (2024), were used. Regarding fuel quality deterioration and risks characteristic of railways, data from DieselNet (n.d.), International Union of Railways (2007), and Federal Railroad Administration (2014), were used. The study by E. Christensen & R. McCormick (2014) was used as an additional source of information on the long-term storage stability of biodiesel and biodiesel blends. According to these characteristics, HVO100 and XTL have an advantage, whereas B100 receives a lower rating because of its greater sensitivity to operating and storage conditions. B20 occupies an intermediate position (Münzer, 2023; BSI, 2024; Pradana *et al.*, 2024).

Criterion C4 reflects economic feasibility, including fuel price fluctuations, transition costs, fuel-system cleaning, filter replacement, and quality control costs (AERRL, 2022; Hernandez *et al.*, 2024b). Criterion C5 characterises feedstock availability, including the origin of the fuel, dependence on food-based feedstocks, and the potential for large-scale use of such fuel in a particular region (Directive of the European Parliament and of the Council No. 2001, 2018; AERRL, 2022; Xu *et al.*, 2022). Criterion C6 reflects infrastructure compatibility (International Union of Railways, 2007; CONCAWE, 2009). Criterion C7 reflects the availability of the relevant standard, certification, the possibility of officially accounting for the decarbonisation effect, and the practical suitability of the fuel for application in the railway sector. These elements were assessed using fuel standards for fatty acid methyl esters, which are the main components of conventional biodiesel, as well as for paraffinic diesel fuel and conventional diesel fuel (BSI, 2021; 2023a; 2023b). The standard for diesel fuel with a high content of fatty acid methyl esters and EU regulation on renewable energy were also considered (Directive of the European Parliament and of the Council No. 2001, 2018; BSI, 2024).

After identifying the alternatives and criteria, the evaluation rules for constructing the comparison matrix were established (Table 3). In the TOPSIS matrix, one quantitative criterion was used, namely total greenhouse gas emissions across the entire fuel chain, expressed as WTW (well-to-wheel), gCO_2e/MJ. The remaining six criteria were evaluated on a scale from 1 to 5 according to pre-established rules. The article developed a multi-criteria "AHP→TOPSIS procedure". At the first stage, the weights of the criteria were determined using the AHP method. A pairwise comparison matrix based on the Saaty scale was used. In the problem formulation, the environmental criterion receives the greatest weight; however, technical compatibility and operational suitability cannot be treated as secondary either, since they determine the actual feasibility of using the fuel under the conditions of the existing fleet. Economic feasibility and feedstock availability also have a significant influence due to supply conditions and market uncertainty. The infrastructural and regulatory components are important derivatives of the fuel class, supply practices, and the possibility of formal implementation.

Table 3. AHP pairwise comparison matrix on the Saaty scale

-	C1	C2	C3	C4	C5	C6	C7
C1 Environmental performance	1	2	2	2	3	4	6
C2 Technical compatibility	1/2	1	1	1	2	3	4
C3 Operational suitability	1/2	1	1	1	2	2	3
C4 Economic feasibility	1/2	1	1	1	2	2	3
C5 Feedstock availability	1/3	1/2	1/2	1/2	1	1	2
C6 Infrastructure compatibility	1/4	1/3	1/2	1/2	1	1	1
C7 Regulatory alignment	1/6	1/4	1/3	1/3	1/2	1	1

Source: authors' pairwise comparison based on the criterion system in Table 2 and the AHP scale proposed by T. Saaty (1980)

The weights were calculated as the normalised principal eigenvector of the AHP pairwise comparison matrix (Table 4, Fig. 1). The consistency ratio was below 0.10; therefore, the pairwise judgments were accepted for further TOPSIS analysis. For the adopted matrix, the largest weight belongs to C1, environmental performance. Technical compatibility, operational suitability and economic feasibility also remain significant, which reflects the practical constraints of introducing renewable fuels in existing diesel traction.

Table 4. AHP criterion weights

Criterion	Weight
C1 Environmental performance	0.302
C2 Technical compatibility	0.175
C3 Operational suitability	0.157
C4 Economic feasibility	0.157
C5 Feedstock availability	0.086
C6 Infrastructure compatibility	0.071
C7 Regulatory alignment	0.052

Source: calculations based on the AHP pairwise comparison matrix in Table 3

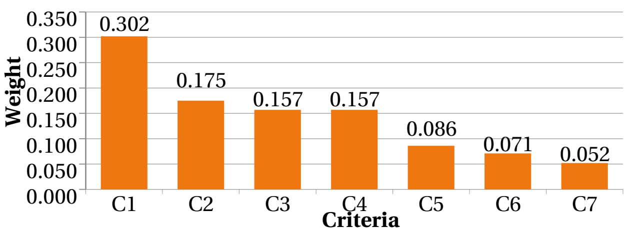

Figure 1. Criteria weights determined using the AHP method
Source: visualisation based on the AHP criterion weights in Table 4

The next stage is the application of the TOPSIS method (Table 5). Since the calculation procedure was described in the Materials and Methods section, this subsection presents the input matrix, the scores of alternatives, and the final ranking results. For the final TOPSIS matrix, the following *WTW* values, representing total greenhouse gas emissions over the entire fuel chain, were used: HVO100 from waste oils – 16.0; B100 from rapeseed – 50.1; and XTL from waste wood – 15.6. Fossil diesel fuel was taken as the reference value at 94. For B20, the value of 85.2 was obtained by calculation as a first approximation based on the biodiesel content in the blend. The model uses one quantitative criterion, WTW, and six criteria evaluated on a scale from 1 to 5.

Table 5. Evaluation matrix for TOPSIS

Alternative	*WTW* GHG emissions gCO_2e/MJ↓	*WTW* savings relative to 94 gCO_2e/MJ, %↑
Alt 1	16.0	≈83.0
Alt 2	50.1	≈46.7
Alt 3	85.2	≈9.3
Alt 4	15.6	≈83.4

Note: ↓ – the lower the value, the better; ↑ – the higher the value, the better
Source: compilation and calculation based on Directive of the European Parliament and of the Council No. 2001 (2018), with the B20 value calculated using formula (10)

The values of total greenhouse gas emissions across the entire fuel chain are as follows: 16.0 for HVO produced from used cooking oil, 50.1 for rapeseed-based biodiesel, and 15.6 for synthetic diesel fuel produced from wood waste. The reference value for fossil diesel fuel was taken as 94. The five-point assessment scale for criteria C2-C7 was based on systematically organised information, including compliance with standards, the possibility of use without modification, fuel behaviour at low temperatures, suitability for long-term storage, the risk of additional maintenance, transition costs, feedstock availability, compatibility with fuel infrastructure, and compliance with certification requirements (Table 6).

Table 6. Scores of alternatives under criteria C2-C7

Alternative	C2 (1-5) ↑	C3 (1-5) ↑	C4 (1-5) ↑	C5 (1-5) ↑	C6 (1-5) ↑	C7 (1-5) ↑
Alt 1	5	4	3	4	4	5
Alt 2	2	2	2	2	2	3
Alt 3	3	3	3	2	3	3
Alt 4	5	4	2	4	4	4

Source: scoring based on the applicability framework in Table 1 and the fuel-standard framework for EN 15940, EN 14214, EN 590 and EN 16709, International Union of Railways (2007), CONCAWE (2009), Federal Railroad Administration (2014), W. Szeto & D. Leung (2022), C. McCaffery *et al.* (2022), L. Komariah *et al.* (2022), W. Ai *et al.* (2024), Y. Pradana *et al.* (2024), J. Hunicz *et al.* (2025)

The high scores of Alt 1 – HVO100 in terms of technical compatibility, operational suitability, and infrastructure compatibility are explained by the fact that it is a paraffinic fuel of the EN 15940 class. This fuel can be used in existing equipment without modification, blended with diesel fuel, and introduced with relatively moderate transition-related risks (Szeto & Leung, 2022; Hunicz *et al.*, 2025; Neste, n.d.). Alt 2 – B100 received lower scores because of its higher biodiesel content, greater sensitivity to storage conditions, the risk of microbiological contamination, filter-related problems, and stricter requirements for fuel handling. Alt 3 – B20 occupies an intermediate position. At the same time, its effect on reducing total greenhouse gas emissions across the entire fuel chain is more limited, which prevents it from competing with paraffinic alternatives. Alt 4 – XTL is close to HVO100 in terms of its technical and operational properties. However, it is inferior to HVO100 in terms of economic feasibility. After normalising the values, applying the criterion weights, and calculating the distances to the conditional ideal and anti-ideal solutions, the following results were obtained (Table 7, Fig. 2).

Table 7. TOPSIS results

Alternative	D^+	D^-	S	Rank
Alt 1	0.0012	0.2268	0.9948	1
Alt 4	0.0315	0.2254	0.8773	2
Alt 2	0.1395	0.1046	0.4286	3
Alt 3	0.2158	0.0458	0.1750	4

Source: TOPSIS calculations based on Tables 4-6

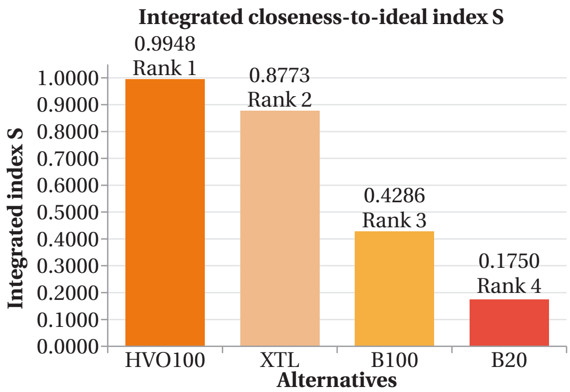

Figure 2. Integrated closeness coefficient to the ideal solution

Source: visualisation based on the TOPSIS results in Table 7

The best-performing option was HVO100. This alternative combines very low total greenhouse gas emissions across the entire fuel chain with high scores for technical compatibility, operational suitability, infrastructure compatibility, and regulatory alignment. In essence, it represents the most straightforward pathway for the initial stage of decarbonisation without significant modification of the rolling stock. XTL ranked second. In terms of technical compatibility, operational suitability, and infrastructure requirements, it is close to HVO100, but it is inferior in terms of economic feasibility. B100 ranked third because of the combination of higher total greenhouse gas emissions across the fuel chain and lower scores for technical compatibility. The lowest result was obtained for B20. Its moderate technical scores do not compensate for the limited overall decarbonisation effect under criterion C1.

The obtained ranking is consistent with the results of W. Szeto & D. Leung (2022), who showed that hydrotreated vegetable oil has properties that make it suitable as a substitute for fossil diesel fuel, as well as with C. McCaffery *et al.* (2022), who demonstrated the relevance of HVO and HVO/biodiesel blends for application in heavy-duty diesel engines. However, it should be noted that the present study differs from these and most similar works. This study focuses not only on fuel properties and engine emissions, but also compares fuel alternatives within a single decision-making model for railway diesel traction. The lower ranking of B100 and B20 is consistent with the findings of L. Komariah *et al.* (2022), W. Ai *et al.* (2024), and Y. Pradana *et al.* (2024), who considered storage stability, low-temperature behaviour, and microbiological contamination as important limitations of fuels containing biodiesel. In comparison with similar studies, the present research integrates technical compatibility, infrastructure suitability, economic feasibility, feedstock availability, and regulatory alignment into a single ranking procedure, which is an important factor. Additionally, a scenario was considered in which biodiesel derived from waste cooking oils was used instead of rapeseed feedstock for B100, with a corresponding reduction in total greenhouse gas emissions across the fuel chain for B20. Under this scenario, the integrated closeness index improved for Alt 2 and Alt 3; however, the ranking order did not change. It should be noted that the obtained ranking reflects the results under the scenario assumptions adopted in this study regarding feedstock origin and the level of emissions across the full fuel life cycle. This means that the overall result is valid within the adopted system of criteria and weights.

Conclusions

Renewable fuel alternatives for existing diesel traction engines were identified and classified, namely HVO100, XTL, B100, and the B20 blend. For each alternative, the technical scope of application, typical compatibility risks, and key storage characteristics were determined. It was found that, for paraffinic fuels, the main issues concern batch quality, supply conditions, and the transition to a new fuel type, whereas fuels with a high biodiesel content involve greater risks in terms of compatibility, operational stability, and storage. A seven-criteria evaluation model was developed, including environmental performance, technical compatibility, operational suitability, economic feasibility, feedstock availability, infrastructure compatibility, and regulatory alignment. The criterion weights were determined using the AHP method. The most important criterion was C1, environmental performance, while C2, technical compatibility, C3, operational suitability, and C4, economic feasibility, were also identified as major criteria. The TOPSIS ranking produced the following result: the paraffinic fuels HVO100 and XTL were identified as the preferred options, as they combine lower emissions across the fuel life cycle with high technical compatibility, appropriate operational suitability, and better manageability of infrastructure-related risks. The B100 and B20 alternatives proved less favourable because of a combination of factors, namely lower technical compatibility, greater sensitivity to storage conditions, stricter fuel handling requirements, and, in the case of the blended option, a weaker overall emission reduction effect. The proposed approach can be used as a decision-support tool for railways, railway operators, and researchers planning a phased transition from fossil diesel fuel to renewable liquid fuels. In further studies, it is necessary to focus on verifying the obtained ranking by taking into account real data on railway fuel consumption, maintenance, fuel quality, pilot operation, and so on. It is also necessary to assess the sensitivity of the ranking to changes in the weights of the criteria. These directions will make it possible to adapt the proposed approach to specific railway networks and operational scenarios.

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Conflict of Interest

There is no conflict of interest. The authors of the article did not take part in the peer-review process or in editorial decisions regarding their own manuscript.

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Визначення пріоритетних напрямків зменшення вуглецевих викидів в залізничних перевезеннях за допомогою багатокритеріального аналізу

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Анотація. У короткостроковій та середньостроковій перспективі декарбонізація дизельної тяги не може ґрунтуватися виключно на повній електрифікації та швидкій заміні рухомого складу, що зумовлює потребу у використанні відновлюваних дизельних палив. Метою дослідження було розроблення багатокритеріальної процедури ранжування відновлюваних дизельних палив для залізничної дизельної тяги та визначення пріоритетного варіанта для скорочення викидів вуглецю. У статті було розглянуто чотири альтернативні види відновлюваного дизельного палива: повністю гідроочищене рослинне паливо (HVO), чисте біодизельне паливо, суміш, що містить 20 % біодизеля та 80 % викопного дизельного палива, а також синтетичне парафінове дизельне паливо. Запропоновано формалізовану процедуру вибору на основі поєднання методу аналізу ієрархій (AHP) та методу наближення до ідеального рішення (TOPSIS). Сформовано матрицю з семи критеріїв: екологічна ефективність, технічна сумісність, експлуатаційна придатність, економічна доцільність, доступність сировини, сумісність з інфраструктурою та відповідність нормативним вимогам. Вагові коефіцієнти критеріїв були визначені за допомогою методу аналізу ієрархій, перевірено узгодженість оцінок, а ранжування альтернатив здійснено методом TOPSIS. Результати дослідження засвідчили перевагу парафінових палив – повністю гідроочищеного рослинного палива та синтетичного парафінового дизельного палива, які можуть використовуватися без модернізації наявного рухомого складу. Ці види палива продемонстрували найкраще поєднання низьких сукупних викидів парникових газів протягом життєвого циклу палива та високої технічної сумісності. Чисте біодизельне паливо та суміш із вмістом 20 % біодизеля посіли нижчі позиції через меншу технічну та експлуатаційну придатність, вищу чутливість до умов зберігання й поводження з паливом, а також менш виражений ефект скорочення викидів у випадку суміші з 20 % біодизеля. Запропонований підхід може бути використаний залізничними операторами, менеджерами інфраструктури, транспортними органами та науковцями як інструмент підтримки прийняття рішень щодо поетапного переходу від викопного дизельного палива до відновлюваних рідких палив у залізничному секторі

Ключові слова: декарбонізація; транспортні технології; відновлювані дизельні палива; дизельна тяга; біодизельне паливо; сумісність з паливом; експлуатаційна придатність