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Progressive Methods of the Harmfulness Evaluation of Transport in Terms of Emission Production

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Abstract: Today, the key challenge is to ensure environmentally acceptable and sustainable transport. This paper analyzes the current state of emissions and greenhouse gases and their impact on the environment. In more detail, it is focused on relevant transport emissions data and their development in the Slovak Republic. It describes and analyzes proposals to improve the current state of rail transport and reduce greenhouse gas (GHG) emissions. Furthermore, it examines current transport trends and their impact on the environment and then analyzes and evaluates these relevant data concerning specific types of emissions. The differences between road, rail, and pipeline transport modes are analyzed and quantified through graphical analysis and analysis of variance (ANOVA) at 5% significance using IBM SPSS statistics software. A subsequent Scheffé post-hoc test is utilized. The usage of ANOVA enables the determination of whether the differences between the transport modes are statistically significant and generalizable or if they arise due to random variation. Based on the knowledge gained, specific measures and strategies are proposed that could contribute to a more efficient use of rail transport to reduce greenhouse gas emissions. The originality and novelty of the contribution lie in the connection between environmental science and applied statistics as well as in finding new progressive synergistic effects between them. The results provide important information for decision-making in the field of investment and planning of rail infrastructure and transport to promote environmental sustainability and reduce the negative environmental impact of rail transport. The research results contribute to the development of a sustainable transport system and will be used in other scientific research activities of the authors in more detailed research on individual proposed measures.

Keywords: emissions from transport; sustainable transport; greenhouse gas emissions; CO_2 emissions; measures

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1. Introduction

As global concerns surrounding climate change, urbanization, and resource depletion intensify, the need to establish an environmentally acceptable and sustainable transportation system has become paramount. Sustainable transport is defined as modes of transport that meet the needs of the present without compromising the ability of future generations to meet their own needs. This encompasses not just the reduction in greenhouse gas emissions but also the overarching goal of minimizing environmental degradation, enhancing social equity, and promoting economic viability. The challenge lies not only in reducing the current levels of harmful emissions but also in transitioning to innovative technologies and practices that will foster sustainable urban development and mobility.

This article deals with the prevalent emissions produced by various transport modes, including road vehicles, rail systems, maritime transport, and aviation. By assessing the current data on emissions and greenhouse gases, key trends, sources, and the relative contributions of each transport sector to overall environmental degradation are identified.

The analysis will extend to the implications of these emissions, including their roles in climate change, air pollution, and public health concerns. This examination will emphasize the urgent need to communicate the environmental impact of transport emissions to policymakers, industries, and the public, as well as highlight strategies for mitigation and the adoption of cleaner technologies.

Specifically, this study focuses on the Slovak Republic, providing a comprehensive overview of transport emissions within the country. By analyzing statistical data from local and national transport authorities, historical trends in emissions are tracked, current policies are evaluated, and projections for future emissions scenarios are explored. This includes a breakdown of emissions by transportation mode and the effectiveness of existing measures to curb them. Additionally, this study examines the socio-economic factors driving transport emissions in Slovakia and the potential barriers to implementing more sustainable practices. The objective of this research is to offer practical insights that may guide future efforts to reduce emissions and advance environmentally friendly transportation options that are suited to Slovakia's requirements and circumstances by clearly establishing the study within the framework of Slovak industrial practices and transportation policy.

Almost every human activity impacts the environment. Economic development also brings negative impacts, such as carbon dioxide emissions and the greenhouse effect. The greenhouse effect is a natural phenomenon that allows Earth to maintain a higher temperature suitable for human life. Without the greenhouse effect, the average temperature on Earth would be −18 °C instead of the current 15 °C. The increase in CO_2 emissions from human activity significantly strengthens the greenhouse effect due to the increased amount of greenhouse gases in the atmosphere, leading to global warming. Energy, industry, and transport are significant sources of greenhouse gases, especially carbon dioxide, which makes up 99.16% of all greenhouse gases [1].

The statistics of CO_2 emissions in several European countries currently do not consider the environmental impact of railway transport with electric traction, despite the fact that the production of electrical energy in most of them has negative impacts. Some gases in the atmosphere act as greenhouse gases, i.e., emissions arise during natural processes and human activities. The main sources of greenhouse gases from human activity include the burning of fossil fuels for electricity production, transport, industry, agriculture, households, and changes in land use, such as deforestation, landfills, and the use of industrial gases containing fluorine [1].

As part of the research addressed in this study, it is essential to reference several key publications, studies, and publications related to greenhouse gas emissions in railway transport and the ecological sustainability of the transportation sector. The research presented in these publications is very important in terms of a detailed examination of the current state of research. The benefit is evident in the comparison of individual aspects of research in the fields of environmental sustainability and ecological transport. For example, previous contributions [2–4] have provided broader insights into this topic, emphasizing the importance and advancement of environmentally sustainable transport modes, including the operation, planning, and effective management of water and rail transport systems.

The subsequent contributions are more closely aligned with this topic. For example, a previous paper [5] constructed new estimates of the air pollution, greenhouse gas, and spill and accident costs from the long-distance movement of petroleum products by rail and pipelines. The main result of another article [6] was the proposal of the frameworks for greenhouse gas (carbon and sulfur dioxide) emission calculations in the context of road freight transport of material and finished manufactured passenger cars for the automotive industry. The proposed frameworks were applied and verified. The use of the proposed frameworks can be expected in logistic planning and decision making. The authors of another paper [7] within the model example dealt with the calculation of energy consumption in transport and the calculation of greenhouse gas emissions generated by transport. The model example showed passenger transport between point A and point B via bus transport and alternatively using air transport combined with bus transport.

Another study [8] investigated greenhouse gas emissions and their distribution during waste collection and transport activities in the Dammam region of Saudi Arabia. Greenhouse gas emissions and associated global warming factors were estimated based on diesel fuel consumption during waste collection and transport activities. Another paper [9] selected six transport sectors and constructed a hybrid input–output model to study the impact of transportation restructuring on the intensity of CO_2 and non-CO_2 greenhouse gas emissions in each sector during different periods. There was another strategy presented in another contribution [10]. Based on our cost assumptions, grid-connected electric vehicles play no major role in the analyzed scenarios until 2030 but reach high market shares (over 90%) under stringent greenhouse gas mitigation targets by 2050.

Another article [11] aimed to present a mathematical modeling study to quantify greenhouse gas emissions in the scope of urban mobility and propose actions for more sustainable cities. Other contributions [12–14] also dealt with environmental management and the setting up of a suitable transport system in terms of emissions, greenhouse gases, and other negative effects on the environment. A lot of relevant and useful information can be found in the current paper [15], where the latest valuable research is connected to energy saving and emission reductions. Since the mentioned contribution places significant emphasis on ecologically sustainable and environmentally acceptable modes of transport, it is possible to find significant scientific and professional breakthroughs with the contributions [16,17] that focus on maritime transport. All these research studies are also relevant and follow on from the research activities of the authors of this paper, as well as science in the field of environmental management of transport processes. Based on them, it is possible to enrich our knowledge in the fields of transport ecology and environmental management. They also present the current state of the issue of ecological transport systems and energy efficiency organization and strategy, a methodology for calculating greenhouse gas emissions, new estimates of water and air pollution, and the expression of these outputs through mathematical models.

Nevertheless, the main focus of this contribution will be on the diverse emissions associated with transport; hence, it will examine and quantify the effects of various modes of transportation with respect to specific gases and substances that contribute to the greenhouse effect. Subsequently, specific measures will be proposed to increase the environmental friendliness of rail transport and the overall saving of fossil fuels since the electrification of railway lines is not the only solution. In general, it can be stated that the more electrified lines there are, the more environmentally friendly train transportation is. This also relies on how electricity is produced and obtained, though. This contribution's originality mostly resides in the way in which the progressive statistical methods declared are implemented, as they have not yet been used in environmental science or transportation process studies. These methods enhance this study.

As part of this contribution, this issue will be addressed in the Slovak Republic, as we have specific and up-to-date relevant data regarding greenhouse gases available for this country. These data will be scientifically evaluated in the following chapters, and specific solutions will be proposed based on them, which could be generally applied in other countries as well.

2. Materials and Methods

In order to point out the new research presented in this article, it is necessary to present and analyze the current existing materials with the relevant information and data and, subsequently, present the methods used in this research.

2.1. Current Materials

The important materials for this contribution are statistical data on greenhouse gas emissions and other sources of air pollution, their development, and their impact on the environment, divided by year and type of transport. These data are available on the website of the Ministry of Transport of the Slovak Republic, the Statistical yearbook of Eurostat, and in other studies and publications published online. These sources are mentioned in Sections 3.1–3.3.

Moreover, for the needs of advanced research within the contribution, it is necessary to take inspiration from publications that deal with the processing and analyzing of statistical data, data evaluation, statistical methods, and similar issues. The mentioned outputs will be useful in the processing and evaluation of individual environmental statistics, which will be used subsequently in specific proposals and their practical applications. These are very important and high-quality scientific publications in the mentioned field. For example, Nagaraja and a collective of authors in their article [18] investigated the optimization of heat transmission in Casson–Carreau nanofluid flow over a curved surface using ANOVA and the Taguchi method. They examined the effects of various factors, such as thermal radiation and Joule heating, employing the Cattaneo–Christov model and Runge–Kutta–Fehlberg scheme for analysis. Their results showed that thermophoresis significantly impacted heat transport, with the optimal heat transfer rate achieved at specific parameter values. Masarotto and their collective of authors addressed the problem of comparing several samples of stochastic processes based on their second-order structure and identifying the main modes of variation within this structure.

This involved performing an analysis of variance (ANOVA) and Principal Component Analysis (PCA) on covariance operators in functional data analysis. They introduced a novel approach using optimal (multi)transport, where each covariance was represented by a centered Gaussian process [19]. A group of writers led by Gradov explored the evolution of drying methods in process engineering, focusing on continuous veneer drying to achieve optimal product moisture content efficiently. ANOVA-based sensitivity analysis identified the radiator temperature, initial moisture content of veneer sheets, and conveyor speed as critical parameters influencing the drying rate, highlighting the effectiveness of automatic damper lid control in maintaining optimal drying conditions at reduced energy costs [20].

Hobbs and colleagues explored how Earth-observing satellites contribute to estimating atmospheric greenhouse gas concentrations and understanding the global carbon cycle. Their study [21] integrated complex inversion systems to assess carbon sources and sinks globally, considering factors like atmospheric transport models and satellite data aggregation methods that influence flux estimates. Using analysis of variance (ANOVA) and Functional ANOVA, they identified significant spatiotemporal patterns in carbon flux increments across large scales, while also highlighting the impact of different satellite retrieval methods on uncertainty at smaller scales. Their findings underscored the Functional ANOVA's ability to distinguish between spatiotemporal coherence in carbon cycle processes and algorithmic influences in flux inversion experiments.

Saha and Sinha investigated sedimentary environments in Chandipur, India, using grain size variations across a 100 m-long cross-shore transect. They employed bivariate data plots and discrimination functions to analyze grain size data, distinguishing tidal flat, beach, and dune environments based on granulometric parameters. Surface morphologies of quartz grains provided insights into recent mechanical and chemical processes along the transect, with the one-way analysis of variance (ANOVA) highlighting significant differences in microtextural features among different geomorphic units. Their findings indicated that aeolian transport influenced surface textures, offering a modern analog for interpreting ancient siliciclastic coastal deposits [22].

Habibillah and colleagues investigated in-flight seating comfort as a critical factor in air transport passenger satisfaction and loyalty. They conducted a seating experiment in an aircraft cabin mock-up involving 30 volunteers with varying anthropometric dimensions, adjusting seat pitch across six settings from 26 inches to 41 inches. ANOVA highlighted seat pitch as the primary factor influencing seating comfort, contributing 94.02% to comfort ratings [23]. Pandey and Mishra conducted a study [24] on heat transfer and nanoparticle migration in a stagnation point flow of nanofluid over a continuously deforming riga plate using passive flow control techniques. They employed Buongiorno's two-phase convective heat transport model, transforming the resulting partial differential equations into dimensionless ordinary differential equations via similarity variables. Taguchi optimization, ANOVA, and multivariate regression analyses were utilized to optimize heat transfer, with results indicating that thermophoresis significantly affects the Nusselt number compared to Brownian motion.

All the scientific outputs mentioned are very useful and relevant for our further research. As part of previous research, a large number of scientific research activities were carried out, which addressed the issue of the impact of harmful substances on the air and the environment. However, no research has yet addressed the issue of the detailed development of emissions from transport for other years, including detailed calculations for transport units of individual modes of transport and especially the issue of scientific analysis of the detailed impact of greenhouse gases on these modes of transport.

The originality and novelty of the research will therefore lie in specific statistical indicators, on the basis of which measures will be proposed to reduce greenhouse gases in transport. A unique connection between statistical analysis science and environmental processes science will be achieved. No authors have yet addressed this connection and this type of research.

2.2. Research Methods

For the originality and uniqueness of the research and creation of proposals for individual measures, it is necessary to use universal and specific scientific methods that ensure a higher scientific level of the proposed outputs.

Several significant scientific methods in the proposal part of this research are used. The most advantageous is to use expert methods that are based on expert estimates in this case. The mentioned methods are general (universal) and specifically related to the mentioned research. Within the solved research problem, which is the subject of the mentioned contribution, the most advantageous is to use the following general scientific methods:

- The panel expert method—a forecasting method that, based on the input data, provides a vision or recommendations for future options and needs related to the analyzed transport topic; the method involves about 15–20 experts who work on a certain problem for a certain period of time (3–18 months). The basis is the elaboration of final outputs on the basis of joint compromises and joint scientific and professional research.
- The system approach method—a method that emphasizes the overall picture and the interrelationships and connections between the individual components of the whole; it can be called the science of management, decision making, or the science of systems thinking.
- The heuristic method—this method offers and discovers new ways of solving problems and inventing certain new contexts; it is a scientific activity based on a "discovery" procedure, which usually starts with a general proposal or some rough estimate, which is gradually refined; this method represents an intersection between empirical and exact methods [25].

In this research, an analysis of variance (ANOVA) was employed at 5% significance to compare emissions across different modes of transport—road, rail, and pipeline. ANOVA is a powerful statistical method used to determine whether there are statistically significant differences between the means of three or more independent groups. Unlike simple *t*-tests, which are limited to comparing only two groups, ANOVA allows for the simultaneous comparison of multiple groups, reducing the risk of Type I error that arises when performing multiple pairwise comparisons. The key advantage of ANOVA is its ability to identify differences across several groups without inflating the error rate, as would occur with multiple *t*-tests [26]. This makes it particularly suited for our study, where three distinct transport modes are compared. ANOVA also assumes homogeneity of variance, which allows for a robust assessment of whether the observed differences are meaningful or due to random variability. Following the ANOVA, the Scheffé post-hoc test was applied, which is particularly advantageous for controlling Type I errors in complex, unequal group comparisons, providing conservative and reliable pairwise comparisons. The combination of the ANOVA and the Scheffe post-hoc test not only reveals statistically significant differences between transport modes but also provides detailed insights into which specific groups differ, ensuring a more comprehensive understanding of the emission patterns across road, rail, and pipeline transport.

The proposal part is largely based on heuristics, which includes methods offering and discovering new ways of solving problems and inventing certain new contexts. It is a scientific activity based on a "discovery" procedure, which usually starts with a general proposal or some rough estimate, which is gradually refined. Heuristic methods represent an intersection between empirical and exact methods. The proposed procedure is also based on this intersection, with some steps using exact methods or exact problem-solving procedures. The mentioned heuristic method is applied to the heuristic procedure in Figure 1, including particular steps. In this case, the application of these methods is new, and the methods serve to identify individual partial steps of this heuristic procedure.

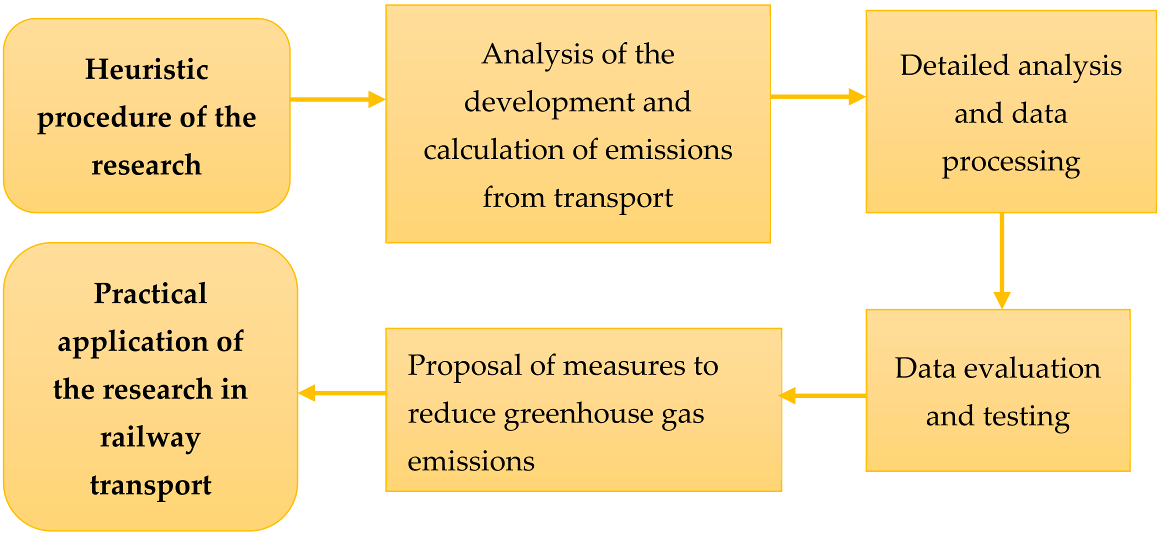

Figure 1. Heuristic procedure of the research.

As for the relevant materials used in the proposal part of the contribution, in addition to the publications mentioned in the second chapter, it mainly contains the relevant statistical data obtained from the Eurostat Statistical Office, the Statistical Office of the Slovak Republic, the Ministry of Transport of the Slovak Republic statistical data, and, last but not least, other studies and contributions.

3. Results

In this chapter, we present individual parts of the heuristic procedure. We gradually describe the analysis, calculation, evaluation, and testing of data and proposals for specific solutions. We also describe specific parts of the heuristic procedure in the following subchapters.

3.1. Greenhouse Gases and Their Impact on the Environment

Greenhouse gases are gaseous substances that contribute to the greenhouse effect. These include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). These gases are emitted during natural processes and human activities. The most significant natural greenhouse gas in the atmosphere is water vapor. Greenhouse gases are quantified in terms of CO_2 equivalents, which measures their global warming potential (GWP) relative to carbon dioxide. This metric helps in comparing the impact of different gases based on their ability to trap heat in the atmosphere. Greenhouse gas emissions are often aggregated into a single value representing the total emissions of all gases converted to CO_2 equivalents [27].

As indicated in Figure 2, emissions of all greenhouse gases in the Slovak Republic have significantly decreased since 1990 by more than 49%. Since 2005, the emissions of all greenhouse gases have decreased by 26.9%, indicating positive progress. This reduction can be attributed to stricter national legislation, changes in industrial structure, and shifts in consumer behavior. It is noteworthy that 2020 and 2022 saw the lowest emissions values since 1990. However, in 2021, there was a 10.8% year-on-year increase in greenhouse gas emissions. Nevertheless, a relatively stable trend is observed in the short term. Greenhouse gas emissions arise from both natural processes and human activities. During human activities, significant quantities of other greenhouse gases are released into the atmosphere, leading to higher atmospheric concentrations of these gases, thereby reinforcing the greenhouse effect and contributing to climate warming. The primary sources of greenhouse gases from human activities include [27]:

- The burning of fossil fuels (coal, oil, and gas) for electricity generation, transportation, industry, and residential use (CO_2).
- Agriculture (CH4) and changes in land use such as deforestation (CO_2).
- Landfills (CH4).
- The use of industrial gases containing fluorine.

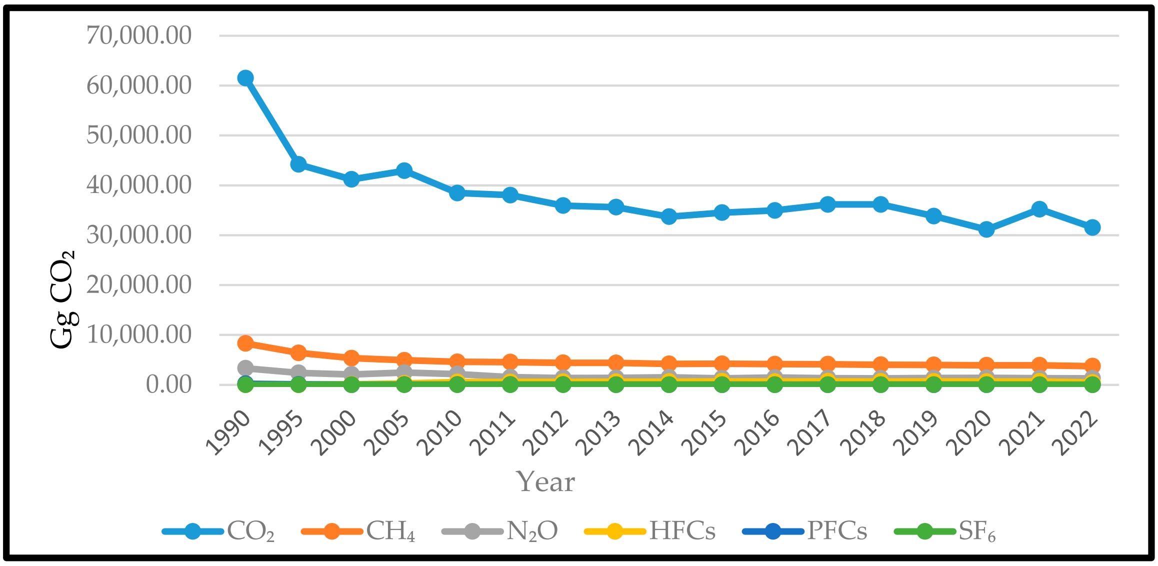

Figure 2. Greenhouse gas emissions expressed in Gg CO_2 eq. in SR [27].

3.2. Emissions from Transport in the Slovak Republic

Transportation is one of the primary sources of greenhouse gas emissions in Slovakia. Greenhouse gas emissions from transportation are considered within Slovakia's national and international policies and climate agreements. In 2020, the Slovak government adopted the National Plan for Energy and Climate Stability, which includes measures to reduce greenhouse gas emissions from transportation, such as promoting eco-friendly vehicles and improving public transportation. Slovakia has also ratified the Paris Agreement, committing to reducing greenhouse gas emissions and protecting the climate. The most significant emissions in transportation are carbon dioxide (CO_2). As indicated in Figure 3, this study focuses on personal transportation. Vehicle exhaust gases contain substances that contribute to the greenhouse effect and other pollutants harmful to human health. The volume of these emissions is directly proportional to fuel consumption. The most effective way to reduce emissions is by decreasing fuel consumption. Exhaust gases not only impact human health negatively but also contribute to global climate change.

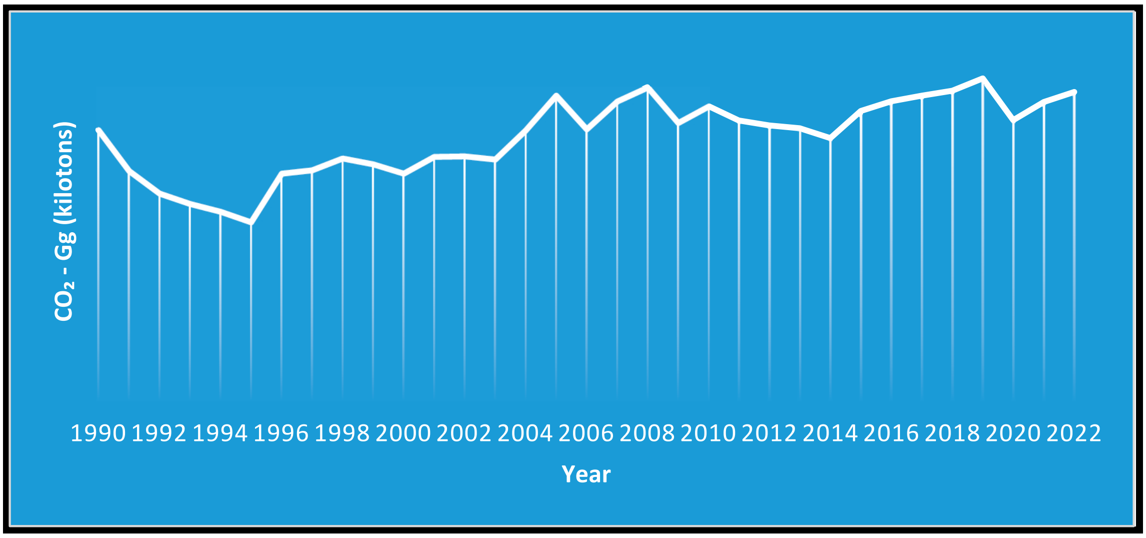

Figure 3. Total emissions from transport CO_2 in Slovak Republic [27].

Figure 3 shows the total CO_2 emissions from transportation. The figure shows that the historical drop in CO_2 was in 1994, which may be due to the fact that a few years after the end of the communist regime in 1989, unemployment was relatively high, and thus fewer people owned private vehicles. However, in the second half of the 1990s, the standard of living in Slovakia began to rise, which had a significant impact on the population's purchasing power and a significant increase in individual motoring. This subsequently caused a continuous increase in CO_2 in the following years. Subsequently, in the later years of the 21st century, measures were taken to revitalize public passenger transport, and the rise in individual car transport stabilized. Transport represents a substantial source of greenhouse gas emissions and pollutants. Despite improvements in vehicle engine efficiency in recent decades, road transport, in particular, remains a significant emitter of CO_2, NOx, CO, PM, and copper emissions. Emissions are measured in CO_2 equivalents (CO_2 eq.), which are calculated based on the Global Warming Potential (GWP) index.

The data indicate that 18.2% of emissions originate from transportation, with the majority coming from road transport, accounting for 98.73% according to the source [28]. Figure 4 further illustrates that within road transport, passenger cars contribute the most to CO_2 emissions at 72.14%, while motorcycles contribute the least at 0.28%. Railway transport accounts for 1.17% of the total emissions. CO_2 emissions in railway transport primarily stem from liquid fuels and biomass, with biomass representing the largest share of emissions. Electricity and diesel are the predominant sources in railway operations. As the number of electrified rail lines increases and renewable energy sources become more prevalent in electricity production, alternative fuels struggle to compete. Electric locomotives are undeniably more advantageous both in terms of cost and environmental impact from emissions [29].

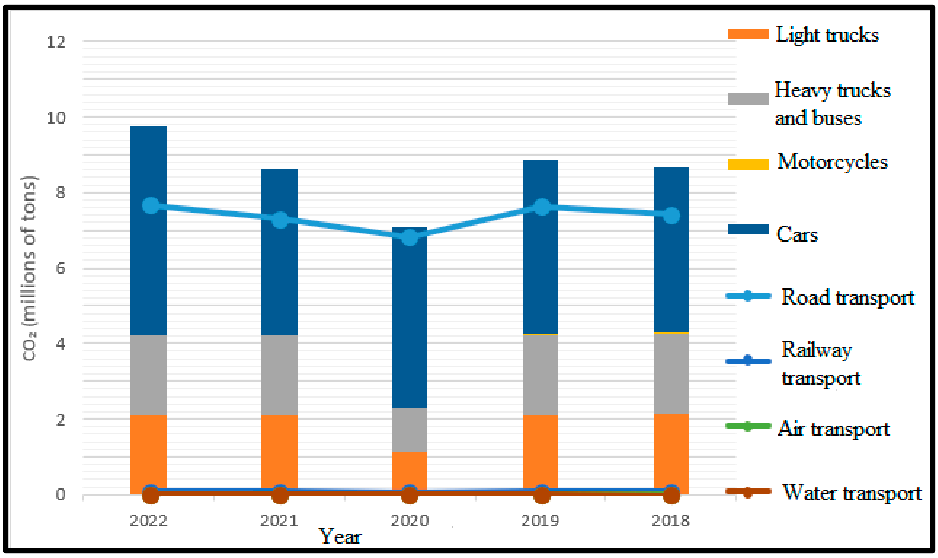

Figure 4. Development of CO_2 greenhouse gas emissions by mode of transport in the Slovak Republic for the years 2017–2021 [28].

3.3. Emissions Development from Transportation in the Slovak Republic

The development of emissions from transport is influenced by several main components, including carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SOx), nitrogen oxides (NOx), volatile organic compounds (VOCs), and others. Factors influencing emission trends include increased traffic volume, such as rising vehicle numbers and mileage, shifts in fuels and technologies, environmental regulations, demographic changes, and unforeseen events.

According to Figure 5, the trend in greenhouse gas emissions from transport shows a slow rise in comparison to the decreasing total produced emissions. A small noticeable decline in transport emissions is observed between 2019 and 2020 due to the implementation of COVID-19 anti-pandemic measures. Based on earlier findings, it is evident that individual car transport has a significant impact on greenhouse gas emissions. In 2022, emissions from transport accounted for 20.96%. Using data on transport and its performance, emissions per transport unit in Slovakia can be calculated using the following formula:

$$emissions\ per\ transport\ unit = \frac{amount\ of\ CO_2\ emissions}{transport\ performance} \quad (1)$$

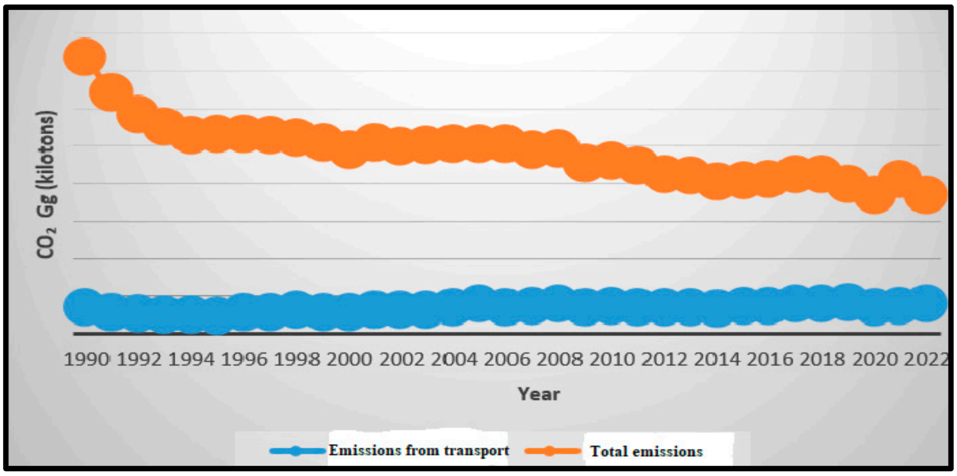

Figure 5. Development of CO_2 greenhouse gas emissions from transport compared to total CO_2 greenhouse gas emissions [30].

This forecast is satisfactory for comparing total transport quantities across different modes of transport. However, in reality, the actual emissions will vary due to factors such as transport distance, vehicle type, emission standards, and other variables. In practical applications of the model, the calculation can be implemented separately for each mode of transport to provide more accurate assessments.

3.3.1. Calculation for Road Transport

$$emissions\ per\ transport\ unit = \frac{758.391}{4854} = 0.156\ \text{kg/pass.km}$$

When calculating emissions per transport unit in road transport, we employed a method that utilized the ratio of CO_2 emissions to transport volume or transport performance. This calculation encompassed public road transport, urban public transport, and non-public road transport. CO_2 emissions were converted from kilotons to megatons. Specifically, CO_2 emissions in road transport amount to 0.156 kg per passenger-kilometer.

3.3.2. Calculation for Railway Transport

$$emissions\ per\ transport\ unit = \frac{8.2294}{3226.97} = 0.002\ \text{kg/pass.km}$$

When calculating emissions per transport unit in rail transport, we proceeded as with formula 1 in road transport. The amount of CO_2 emissions in railway transport is 0.002 kg/pass.km.

3.3.3. Calculation for Air Transport

$$emissions\ per\ transport\ unit = \frac{0.1481}{832} = 1.780\ \text{kg/pass.km}$$

Emissions per transport unit in air transport amount to 1.780 kg/pass.km.

3.3.4. Calculation for Water Transport

$$emissions\ per\ transport\ unit = \frac{0.5293}{3} = 0.1764\ \text{kg/pass.km}$$

Emissions per transport unit in water transport amount to 0.1764 kg/pass.km.

3.4. Comprehensive Evaluation

Based on the calculations, air transport exhibits the highest CO_2 emissions per transport unit with regard to the assessed distance and transport performance, respectively. Following air transport is water transport, which averages 0.1764 kg per passenger-kilometer. Road transport emits 0.156 kg per passenger-kilometer, while rail transport produces the lowest CO_2 emissions at 0.004 kg per passenger-kilometer. Air transport surpasses road transport in CO_2 emissions primarily due to higher fuel consumption, resulting in widespread dispersion of emissions. In contrast, rail transport emits less CO_2 compared to road transport. The electrification of railways contributes to reduced energy consumption and lower emissions during passenger transport.

CO_2 emissions from passenger transport are calculated in grams of CO_2 per passenger based on seating capacity. According to Figure 6, it is evident that ships are the least environmentally friendly, emitting nearly 28,000 g of CO_2 per kilometer per passenger. In contrast, rail transport emerges as the most environmentally friendly option for passenger transportation [31].

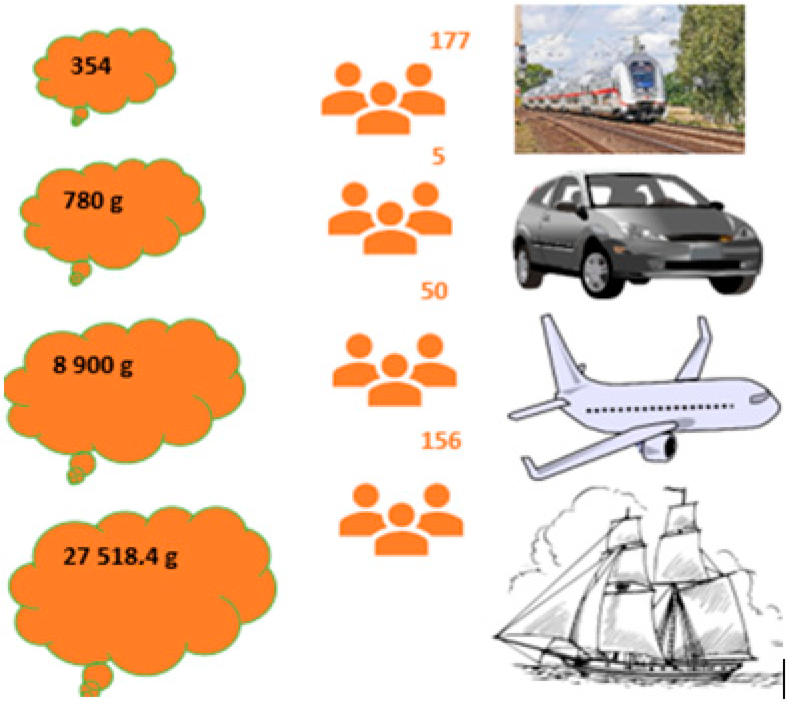

Figure 6. CO_2 emissions from passenger transport in kg/pass.km.

3.5. Graphical Analysis Using the ANOVA Method

In this study, the effects of several means of transportation on the environment in Slovakia were analyzed using two primary methods: graphical analysis and analysis of variance (ANOVA) performed via software IBM SPSS Statistics v 28.0. The impacts of road, rail, and other transport including pipeline, air, and other transport in Slovakia were evaluated. The results were compared both in terms of freight and passenger transport for all types of transport.

In order to objectify the calculations, it was necessary to include performance in individual transports. In the case of freight transport, performance was included in ton-kilometers, while in the case of passenger transport, it was passenger-kilometers. Data on performance in individual types of transport were available for the years 2017–2023 and were provided by [32]. The development of individual types of transport in the monitored period is shown in Figures 7 and 8.

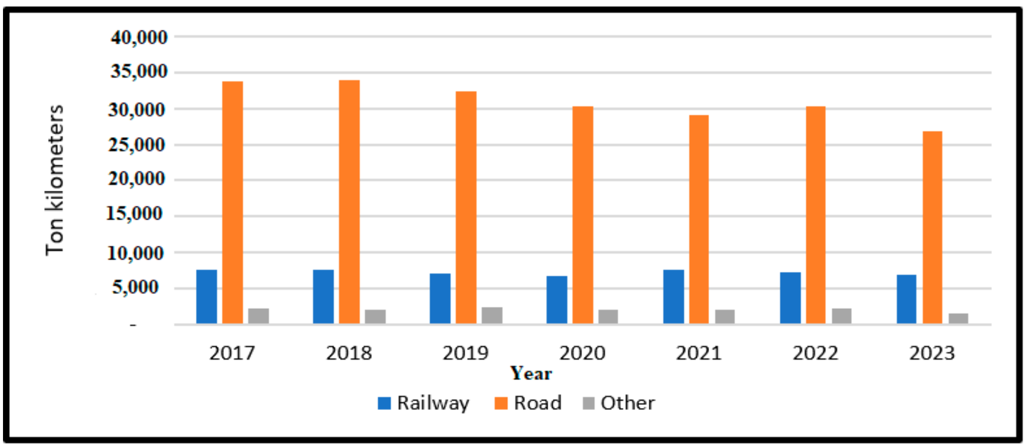

Figure 7. Freight transport performance in the monitored period.

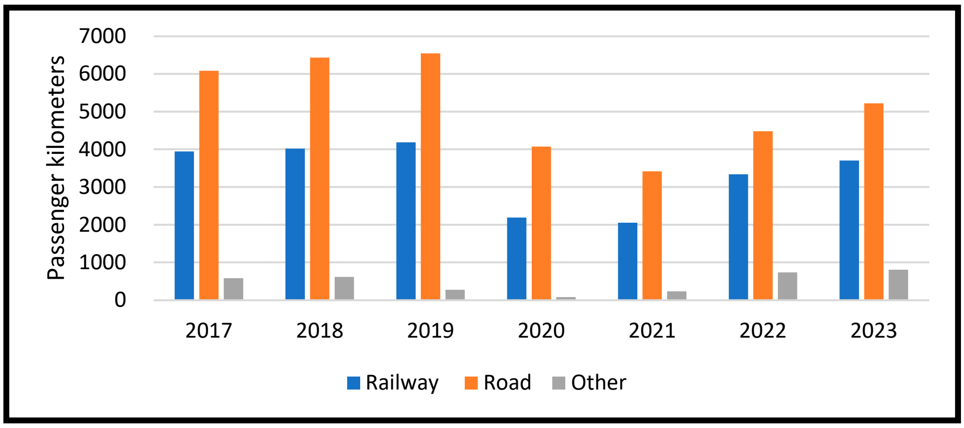

Figure 8. Passenger transport performance in the monitored period.

Both figures indicate the dominant position of road transport performance both in terms of passenger and freight transport. In addition to the performance of individual types of transport, it was also necessary to take into account the impact on the environment. For this purpose, data on emissions of individual types of transport provided by the Department of Emissions and Biofuels were used. Specifically, the emissions of the following gases were evaluated: CO_2, N_2O, and NOx. However, the data were only available for a period of 5 years from 2018–2022 so it was necessary to limit the scope of the analyses to this period only. Aggregated emissions (passenger and freight transport) of individual types of transport are shown in Figures 9–11.

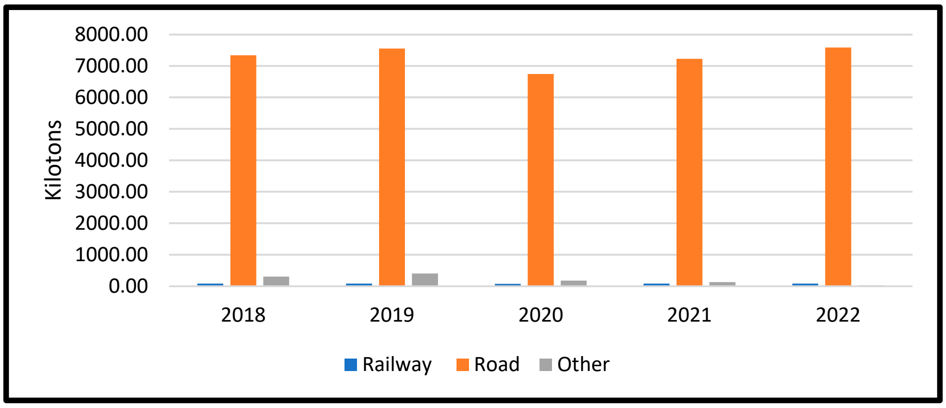

Figure 9. CO_2 emissions.

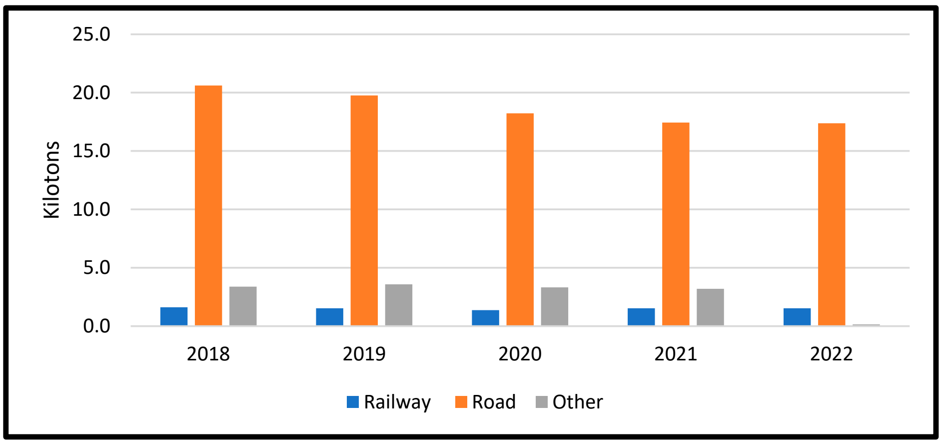

Figure 10. NOx emissions.

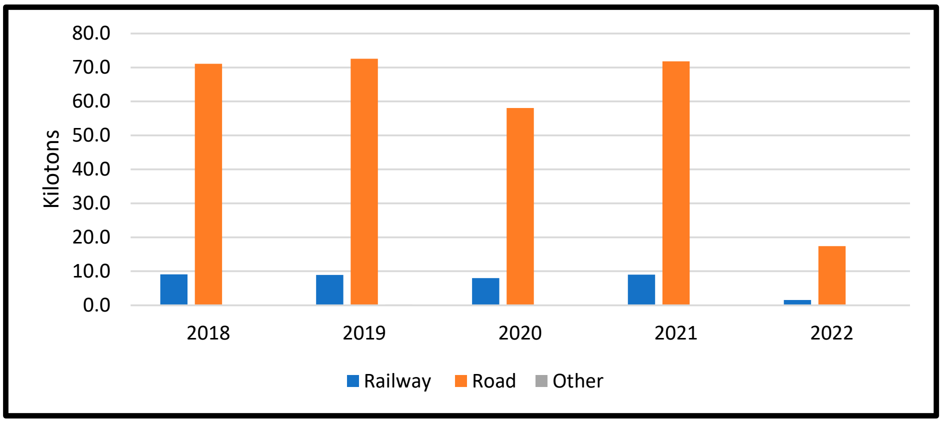

Figure 11. N_2O emissions.

It can be seen from the above figures that road transport dominates not only in terms of performance but also in terms of emissions. Therefore, the answer to the question of which of the mentioned types of transport is the most harmful or, conversely, the least harmful to the environment may not be as simple and obvious at first glance.

In order to be able to objectively compare the effects of individual types of transport on the environment, a new variable was calculated that defined the amount of emitted gas per unit of performance (in the case of passenger transport per passenger-kilometer and in the case of freight per ton-kilometer). The share of emissions per unit of output was calculated using the following formula:

$$H = \frac{E}{P} \quad (2)$$

where:

H—Harmfulness towards the environment.
E—Emissions.
P—Performance, output.

3.6. Data Evaluation and Testing

In this article, the main goal was to compare the harmfulness of individual types of transport to the environment in Slovakia. Since ANOVA, which works with mean values, was used to fulfill this goal, the average values of the harmfulness of individual types of transport were calculated even before the test itself. Harmfulness in individual years was calculated based on Formula (1). As the NOx and N_2O emissions were very low compared to the outputs, the values were multiplied by 1000. The harmfulness of CO_2 is therefore calculated in units of kilotons, but NOx and N_2O were calculated after multiplication in units of tons. The average value for the monitored period was then calculated from individual values for each year. The data are in Table 1 [33].

Table 1. Average harmfulness of individual types of transport in the monitored period.

Transport Type	CO_2/Ton km	CO_2/Passenger km	nox/Ton km	NOx/Passenger km	N_2O/Ton km	N_2O/Passenger km
Rail	0.01	0.03	0.21	0.52	1.01	2.57
Road	0.23	1.55	0.60	3.94	1.86	12.26
Other	0.09	0.95	1.26	14.98	0.06	0.53

Based on the above table, it is possible to estimate that the least harmful type of transport seems to be railway, where the average values of harmfulness show the lowest values in most cases. However, it is necessary to answer the question of whether these are random differences or whether they are statistically significant, and it is possible to generalize them to other periods, economically and politically related areas, or countries.

The following tables show the results of the ANOVA, where the Scheffe test was utilized. All tables contain the differences in mean values for all transport combinations and also the statistical significance of these differences in terms of harm to the environment. Table 2 shows the results of the harmfulness of freight transport in terms of the ratio of CO_2 production and performance in individual types of transport.

Table 2. Scheffe Test of CO_2 per ton-kilometer.

(I) TYPE	(J) TYPE	Mean Difference (I − J)	Std. Error	Sig.
Other transport	Rail transport	0.08 *	0.02	0.017
	Road transport	−0.14 *	0.02	<0.001
Rail transport	Other transport	−0.08 *	0.02	0.017
	Road transport	−0.22 *	0.02	<0.001
Road transport	Other transport	0.14 *	0.02	<0.001
	Rail transport	0.22 *	0.02	<0.001

* The mean difference is significant at the 0.05 level.

The results point to the lowest harmfulness of rail transport, which is statistically significantly different from other types of transport and achieves the lowest values of CO_2 emissions in relation to performance.

Table 3 shows the results of the comparison of individual types of passenger transport, also in terms of the ratio of CO_2 production and performance.

Table 3. Scheffe test of CO_2 per passenger-kilometer.

(I) TYPE	(J) TYPE	Mean Difference (I − J)	Std. Error	Sig.
Other transport	Rail transport	0.92	0.36	0.069
	Road transport	−0.60	0.36	0.282
Rail transport	Other transport	−0.93	0.36	0.069
	Road transport	−1.52 *	0.36	0.004
Road transport	Other transport	0.60	0.36	0.282
	Rail transport	1.52 *	0.36	0.004

* The mean difference is significant at the 0.05 level.

As in the case of freight transport, and also in the case of passenger transport, railway transport achieves the lowest environmental damage in terms of CO_2 production compared to performance. The differences are also statistically significant.

The results of the harmfulness analysis in terms of NOx production are captured in Tables 4 and 5, with Table 4 showing freight transport and Table 5 showing passenger transport.

Table 4. Scheffe Test of NOx per ton-kilometer.

(I) TYPE	(J) TYPE	Mean Difference (I − J)	Std. Error	Sig.
Other transport	Rail transport	1.05 *	0.24	0.004
	Road transport	0.66	0.24	0.058
Rail transport	Other transport	−1.05 *	0.24	0.004
	Road transport	−0.39	0.24	0.314
Road transport	Other transport	−0.66	0.24	0.058
	Rail transport	0.39	0.24	0.314

* The mean difference is significant at the 0.05 level.

Table 5. Scheffe Test of NOx per passenger-kilometer.

(I) TYPE	(J) TYPE	Mean Difference (I − J)	Std. Error	Sig.
Other transport	Rail transport	14.46	5.99	0.093
	Road transport	11.04	5.99	0.224
Rail transport	Other transport	−14.46	5.99	0.093
	Road transport	−3.42	5.99	0.852
Road transport	Other transport	−11.04	5.99	0.224
	Rail transport	3.42	5.99	0.852

In terms of harmfulness to the environment due to NOx production, rail transport fared the best again, both in the case of passenger and freight transport. However, the only statistically significant difference was in the comparison of rail freight transport and other freight transport (pipeline and air). It is also interesting that road transport ended up better than the other transport category in terms of environmental damage due to NOx production, but this difference was not statistically significant.

Tables 6 and 7 compare the harmfulness of individual types of passenger and freight transport in terms of N_2O production.

Table 6. Scheffe test of N_2O per ton-kilometer.

(I) TYPE	(J) TYPE	Mean Difference (I − J)	Std. Error	Sig.
Other transport	Rail transport	−0.94 *	0.32	0.037
	Road transport	−1.80 *	0.32	<0.001
Rail transport	Other transport	0.94 *	0.32	0.037
	Road transport	−0.85	0.32	0.059
Road transport	Other transport	1.80 *	0.32	<0.001
	Rail transport	0.85	0.32	0.059

* The mean difference is significant at the 0.05 level.

Table 7. Scheffe test of N_2O per passenger-kilometer.

(I) TYPE	(J) TYPE	Mean Difference (I − J)	Std. Error	Sig.
Other transport	Rail transport	−2.04	2.34	0.691
	Road transport	−11.73 *	2.34	0.001
Rail transport	Other transport	2.04	2.34	0.691
	Road transport	−9.69 *	2.34	0.005
Road transport	Other transport	11.73 *	2.34	0.001
	Rail transport	9.69 *	2.34	0.005

* The mean difference is significant at the 0.05 level.

The results of Tables 6 and 7 show that road transport is the worst in terms of the harmfulness of N_2O production, which in the case of passenger transport was statistically significantly different from both rail and other transport, and in the case of freight transport, it was significantly different from the other transport category. Other transport achieved statistically significantly lower harmfulness than rail only in the case of freight transport, but in this metric, the other transport category fared best.

3.7. Proposal of Measures to Reduce Greenhouse Gas Emissions in Railway Transport

There are numerous solutions available to mitigate the production of greenhouse gases and increase the efficiency of railway transport. Currently, joint efforts involve setting national strategic goals for reducing greenhouse gas emissions.

In terms of overall Slovak transport performance, railway transport is the most environmentally friendly solution, although, from a local perspective, railway transport may have increased greenhouse gas emissions compared to other modes of transport. This is particularly the case if the local performance is inefficient, performed by diesel traction or an older fleet. The study also proposes a framework of measures to reduce emissions from railway transport and transport as a whole. These measures are proposed as a framework based on existing scientific studies and publications. Each measure and its sub-measures should be the subject of separate scientific studies and papers, which the authors will address in the context of further research on the greening and environmental sustainability of transport. Here, we present six measures and their points for reducing emissions in railway transport [34,35].

3.7.1. Railway Electrification

Railway transport in Slovakia is the most efficient and has the lowest emissions when operated by electric traction [36,37]. Supporting the electrification of the network would shift performance from high-emission diesel traction to low-emission electric traction. The graph in Figure 12 compares the % of electrified lines within selected EU countries.

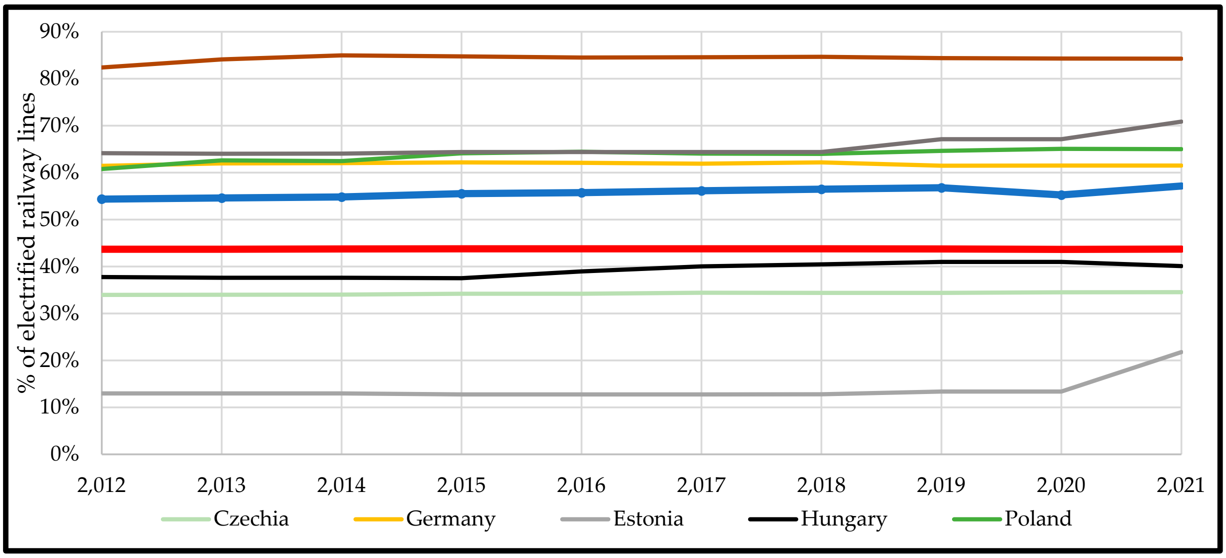

Figure 12. Percentage ratio of railway electrification in EU countries [38].

The development of the electrification level in Slovakia is slightly below the EU average and remained unchanged over the period under observation. The graph shows that most post-Soviet countries exhibit a lower percentage of electrification than Western bloc countries. The post-Soviet countries should consider the electrification of railways as a priority. Points of railway electrification development are:

- Extension of electrification: The electrification of railway lines that are currently not electrified. Railway electrification is a way of transferring power from diesel to electric traction, thereby reducing CO_2 emissions [14].
- Determination of priority sections: The selection of the sections to be electrified as a priority based on the demand for transport performances [14]
- Maximizing the utilization of the existing electrification: Utilization of the potential of the existing electrification of the railway network and limiting engine traction on the electrified sections can reduce unnecessary produced emissions [36].

- Alternating traction system: Alternating traction exhibits more efficient transmission of traction energy with lower energy losses without requiring extensive construction of traction inverters [39].
- Partial electrification: The construction of partial electrification as preparation for battery traction in order to reduce the costs associated with total [39].

3.7.2. Renewable Energy Sources

Increasing the electrification of railways may not have the desired effect of reducing emissions and their harmfulness if the source of traction power is high carbon. Emissions production for diesel traction is mentioned in Table 8 and for electric traction in Table 9. Strategies for the utilization of renewable energy sources are:

- Green energy: Transformation of the Slovak energy industry, which supplies traction systems, to renewable sources of energy in the form of wind, hydro, and solar energy with the minimization of nuclear waste. Electricity in Slovakia has one of the lowest CO_2 emission factors in the EU, namely 0.252 tCO_2/MWh, but approximately 60.11% of the energy is from a nuclear power plant producing dangerous nuclear waste [32].
- Green traction energy: The development of electricity supply for traction systems from renewable energy sources only. Eco-friendly power stations are only for railway traction supply [40].
- Energy Recovery: The implementation of energy recovery systems (recuperation) in electric vehicles and the equipping of static energy storages in traction inverters for recovery energy [35].
- Low-Emission Fuels: The purchase of combustion engine railway vehicles using low-emission fuels such as biodiesel, natural gas, hydrogenated oil, and so on, which can reduce emissions of CO_2 or pollutants [41].

Table 8. Emission production in CARGO railway transport in the Slovak Republic—diesel traction at present.

Category of Locomotive	CO [g/1000 net km]	HC [g/1000 net km]	NOx [g/1000 net km]	PM [g/1000 net km]	CO_{2e} [g/1000 net km]
PRE UIC	x	x	2434.624	53.751	139,146.347
UIC I	2.517	0.671	10.063	0.210	738.478
UIC II	87.106	23.228	287.451	7.259	25,555.784
STAGE III A	58.609	8.373	61.959	3.349	14,738.677
STAGE III B	50.291	2.730	53.165	0.359	12,646.835
Weighted average in emissions production	**50.729**	**8.944**	**727.571**	**16.591**	**49,273.584**

Table 9. Emissions production in the Slovak Republic railways—electric traction at present.

Locomotive	CO [g/1000 net tkm]	NOx [g/1000 net tkm]	PM [g/1000 net tkm]	SO_2 [g/1000 net tkm]	CO_{2e} [g/1000 net tkm]
125.8	1.11	3.50	0.18	25.40	3239.64
131	1.11	3.50	0.18	25.40	3239.64
183	1.11	3.50	0.18	25.40	3239.64
240	1.10	3.47	0.17	25.17	3210.81
363	1.11	3.48	0.17	25.28	3225.22
383	1.11	3.48	0.17	25.28	3225.22
Weighted average in emissions production	**1.11**	**3.49**	**0.18**	**25.35**	**3234.19**

3.7.3. Capacity Utilization of the Fleet

Greenness of rail transport is achieved by reducing energy waste. Transporting more cargo or people at similar values to those in Tables 8 and 9 can be achieved by better utilization of vehicle capacity. As a final result, energy consumption will be reduced due to the reduction in redundant train connections. An added value is the reduction in the carbon footprint of the train. Strategies for better vehicle capacity utilization are:

- Modal split: For longer-distance transport, rail transport should be preferred in terms of emissions, and road transport is a feeder [42].
- Traffic distribution over time: Avoiding parallel journeys that compete with each other and decrease vehicles' occupation, which leads to a rise in the carbon footprint [43].
- Promotion of public transport: The aim of promoting public transport is to shift passengers from private car transport to public transport, which can reduce car emissions and the carbon footprint on passengers due to higher occupation of the train [42].
- Reducing empty journeys: Utilizing the available capacity of freight trains in both directions and efficient planning of vehicles' circulations. Loading a freight train in both directions may not reduce emissions, but it does not produce them in vain [43].
- Transformation of under-loaded connections: Change the transport organization on underloaded transport connections in favor of an environmentally friendly mode of transport [42].

3.7.4. Operation Efficiency

Lower emissions of railway transport can be achieved by increasing the operation efficiency. A high percentage of redundant emissions are caused by inefficient fleet operation or if the fleet is outdated. Operation efficiency can be achieved by:

- Maximizing vehicle run-time: Minimizing emissions generated by passive energy consumption during vehicle stays or siding in stations.
- Renewal of Vehicle Fleet: Upgrade railway transport vehicles to more environmentally friendly models that minimize greenhouse gas emissions [14]. Figure 13 shows the emission production per thousand ton-kilometers in relation to the fleet ratio of Stage III B locomotives, which represent the most modern locomotives.

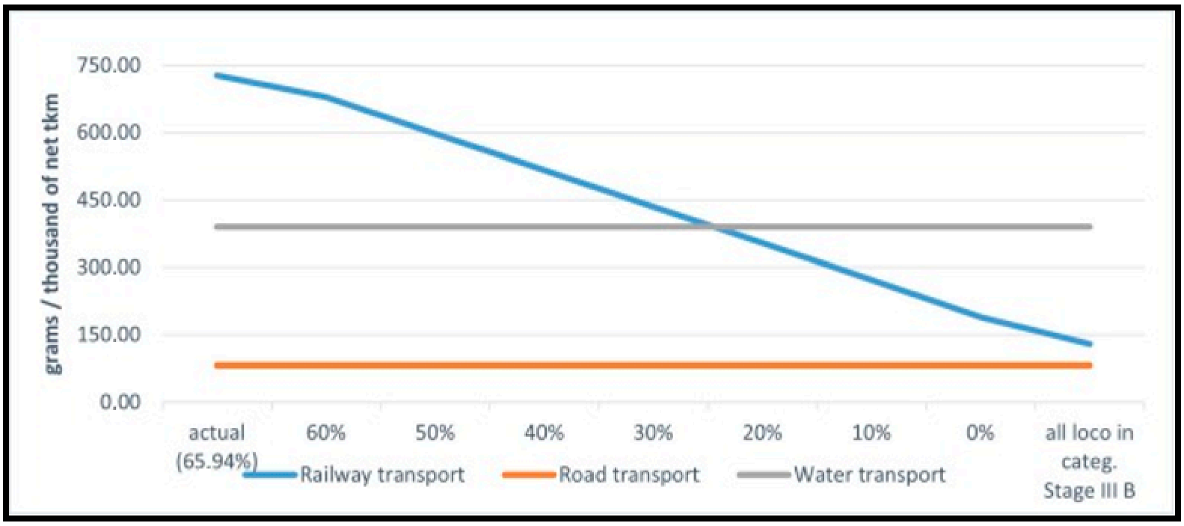

Figure 13. CO_2 emissions production based on Stage III B railway vehicle ratio in transport fleet [14].

- Driving technique optimization: The correct driving technique of the driver can reduce energy consumption and thus produce emissions. When scientists applied the optimized driving technique in their research [44], they achieved a 10% energy saving.
- Infrastructure modernization: Modernized infrastructure enables a smooth and energy-efficient journey [45].

- Sustainable maintenance of railway lines: A previous study [46] showed that using reinforcement learning to optimize track maintenance can reduce carbon emissions from maintenance by 48%.
- Minimum fleet size: Taking travel patterns into account, a driving strategy to minimize fleet size can provide appropriate transport services with lower energy intensity without unnecessary energy consumption during idle periods [47].

3.7.5. Alternative Propulsions

Alternative or hybrid propulsions are another way to reduce emissions on lines where full electrification would not be efficient and profitable [36]. The graph in Figure 13 shows the equivalent CO_2 production per seat-kilometer and the average range when operating multiple units with different propulsion.

Figure 14 demonstrates that the most effective, green, and usable option is an electric vehicle, but it is dependent on electrification. An interesting alternative in terms of emissions is a battery vehicle; nonetheless, it has a short range outside of electrification. A hydrogen vehicle has a relatively long range on one refueling, but the current development state is not a very effective green solution in comparison with diesel vehicles. Emission decreases via alternative propulsion can be achieved by [35,36,40]:

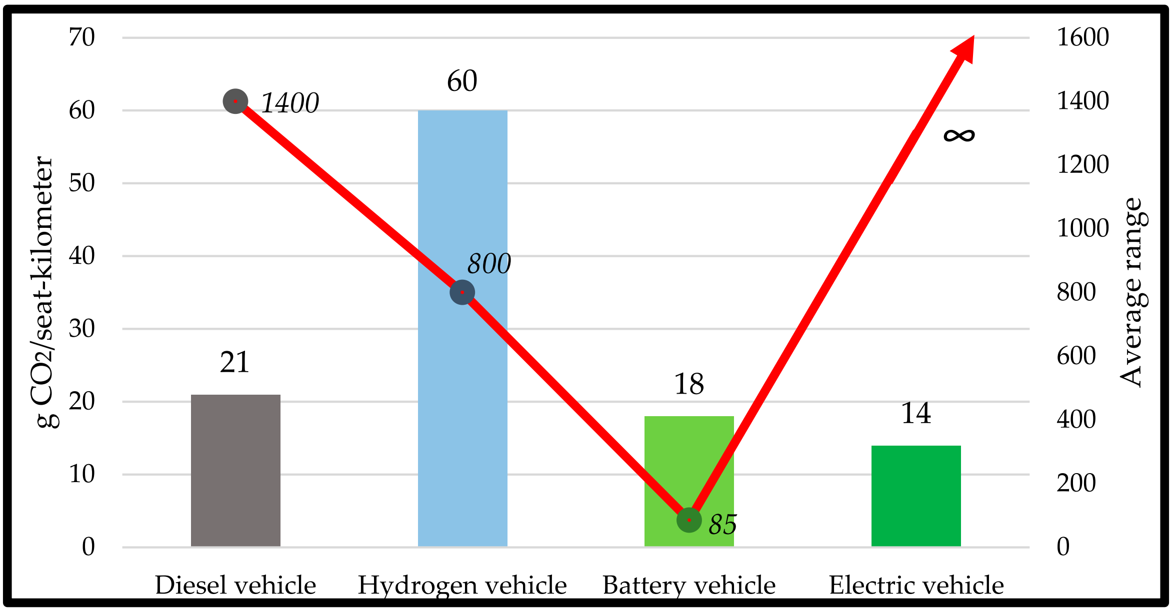

Figure 14. CO_2 production and range of different-powered multiple units according to [35].

- Selection of the best solution: Consider in detail and compare the benefits and disadvantages of each propulsion that can be implemented in the section under consideration.
- Supporting the development of hydrogen traction: Improving the efficiency and reliability of hydrogen traction and logistics of the hydrogen distribution.
- Increasing the range of battery-powered vehicles: Supporting the development of battery-powered vehicles in terms of increasing the range outside the electrified section as a suitable alternative to diesel-powered trains.
- Hybridization of engine traction: Developing diesel-hybrid vehicles with lower emissions and the possibility of recuperation or usage of existing electrification.
- Simply redesigning vehicle: Hybrid vehicle technology enables its seamless conversion to electric or other propulsion.
- Alternative propulsions in freight transport: Development of locomotives powered by alternative energy sources for freight transport.
- Alternative propulsions in shunting: Use of light railway vehicles with alternative propulsion for shunting instead of pure engine vehicles.

3.7.6. Other Measures

Other measures that promote emission reductions and energy savings in industries applicable to railway transport are:

- Tree Planting: Increase tree planting efforts as trees absorb CO_2 and contribute to local emission reductions.
- Employee Education: Provide environmental education to employees to raise awareness and promote sustainable practices.
- Legislation: Legislative measures to support the reduction in transport emissions.
- Remove greenwashing: Greenwashing in the transport field can hinder the achievement of real emission targets due to misleading, inaccurate, or subjective results.
- Incentives for Green vehicles: Offer financial and tax incentives for the purchase and use of environmentally friendly vehicles.

4. Discussion

The contribution follows the EU's transport and environmental policy, the aim of which is to achieve carbon neutrality by 2050 and almost completely ban internal combustion engines. Therefore, it is necessary to look for new, modern, and sustainable solutions. First of all, it is necessary to correctly identify the potential threats, which in this case are the sources of air pollution. In the case of the research mentioned in the contribution, the impact of emissions arising from transport in the Slovak Republic was analyzed in detail. The development of individual harmful substances was gradually monitored over the horizon of several years and subsequently also in the division into individual modes of transport. Subsequent calculations of emissions per transport unit clearly show that rail transport is the most ecological in this case.

The mentioned facts are also confirmed in the case of the influence of CO_2 and NOx on kilotons. In the case of NO_2, it is also a significant advantage compared to road transport, but compared to other transport, where water and air transport can also be included, these emissions are higher, which is, however, influenced by the transport performance of these modes of transport in the Slovak Republic. Subsequently, these claims were statistically confirmed through the ANOVA method and post-hoc test, so that the findings could be generalized to a wider temporal or geographical range. ANOVA efficiently compares means across three or more groups simultaneously, controlling the overall error rate better than multiple *t*-tests. It analyzes both between-group and within-group variations, supports complex designs, and allows for post hoc tests (in this case, Scheffe's post-hoc test was used) to pinpoint specific differences between groups. The test results confirmed, in most cases, statistically significant differences in the harmfulness of individual types of transport, while rail transport was the least harmful.

The contribution of this paper to the literature is considerable and significant, as it offers new ideas in the field of environment and sustainable mobility. It consists mainly of describing a new procedure for analysis of the development and calculation of emissions from transport, data evaluation, and the proposal of relevant measures to reduce greenhouse gas emissions. The novelty and originality of the contribution also lie in the progressive methods of use and practical application of the progressive method and the Scheffe test. The specificity of this research is precisely the connection of two scientific disciplines, namely environmental science and science in the field of statistical analysis. The result is the creation of a sufficient synergistic effect between them and the achievement of relevant and statistical data, which have the potential for use in further progressive scientific research activities.

The contribution is intended mainly for the general professional public. It offers the readers a scientific and professional point of the outputs of relevant indicators in the area of the impact of individual types of transport on the environment. This plan can also contribute to improving the quality of passenger transport globally, not only in the railway transportation process. It is a societal contribution [36,37].

Further research should focus on analyzing and evaluating other types of data, which will also help to relevantly evaluate the impact of harmful substances on the environment and subsequently offer other solutions that will enrich the science in the field of transport processes, and at the same time, find environmentally acceptable and sustainable ways of developing public personal transport with a favorable effect for passengers. It would also be appropriate to carry out all the above-mentioned analyses in other European countries, but we do not yet have the relevant data to base this on. It is possible to add the findings and outputs of related studies and be inspired by data regarding the production of emissions in rail transport in the case of diesel and electric traction (Tables 8 and 9). This issue was addressed in a previous paper [14].

The values in Tables 8 and 9 are the primary input values based on the energy consumption of different trains of electric or diesel traction. These values may affect the results of the entire study. In this paper, we propose several framework measures, which should reduce the unit emission values shown in Tables 8 and 9, thereby increasing the environmental benefits and reducing the harmfulness of rail transport not only locally but also globally. Each measure and its appropriate strategies should be the subject of self-contained scientific studies and papers, which will be addressed by the authors as part of further research on the greening and environmental sustainability of transport. The measures are based on existing studies.

At the same time, it is possible to establish the weighted average emissions from rail transport together for diesel and electric traction. These data can be found in Table 10.

Table 10. Weighted average of emissions from rail transport together for diesel and electric traction.

	NO_x [g/1000 net tkm]	**PM [g/1000 net tkm]**	**CO_{2e} [g/1000 net tkm]**
Weighted average of emissions production combined for both diesel and electric traction	160.215	3.686	11,853.775

However, in the future, it would be appropriate to develop this issue and connect it to the outputs in this paper and then propose new solutions to the mentioned issue.

5. Conclusions

The research presented in this paper analyzes and describes relevant environmental indicators. The second chapter highlights the current significant contributions that address scientific research activities related to the ecological aspects of transport and the impact of harmful substances on the environment, as well as scientific statistical methods used to evaluate and analyze specific types of data. The chapter then describes the specific scientific methods employed in this study. Using the heuristic method, a heuristic procedure is developed that includes all the partial steps of the research. A detailed description can be found in the third chapter. The chapter also presents general and specific measures aimed at reducing greenhouse gas emissions.

Taking measures to reduce greenhouse gases in transport is crucial for several reasons. These emissions contribute to global warming and climate change, which have extensive negative impacts on ecosystems, human health, and the economy. Energy security is another important factor, as reducing the dependence on fossil fuels in transportation can enhance the energy security of countries by lowering their vulnerability to oil price fluctuations and geopolitical conflicts. Furthermore, there are economic benefits, as investments in green technologies and infrastructure can create new jobs and stimulate economic growth.

This research is also linked to the effective management of sustainable processes on Earth, which significantly impacts healthy ecosystems, essential for human health. The quality of air, water, and soil directly affects our health. Research in ecology and environmental science will help maintain quality living conditions for all inhabitants of the planet.

Current and future research will significantly contribute to the sustainability of public passenger transport and cognitive mobility, offering progressive and prosperous solutions for mobility and transport. In this context, optimizing transport systems is of paramount importance. Solutions are being sought to rationalize and optimize transport infrastructure, timetables, and vehicle fleets and subsequently propose more advanced transport systems, such as the implementation of intelligent transport systems, which make transport operations more efficient. The development of this issue will be the focus of further scientific and research activities by the authors.

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