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Air Pollutant Emissions of Passenger Cars in Poland in Terms of Their Environmental Impact and Type of Energy Consumption

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Abstract: The increasing number of vehicles operating in Poland, especially passenger vehicles, justifies the need to conduct air pollution emission tests in the context of the impact of vehicles on the natural environment. Firstly, this article reviews the publications related to air pollutant emissions and passenger vehicles traveling on Polish roads. However, it presents a special method using advanced research equipment to determine air pollutant emissions. The above research methods are justified in implementing clean transport zones. Real Driving Emissions represent an essential procedure in the implementation of clean transport zones in Poland, verifying the actual emissions of air pollutants and modeling this phenomenon using the results of real air pollutant emissions. The results of this research state that establishing a link between a vehicle's air pollutant emissions and its age can support making transport or delivery planning more sustainable and choosing less carbon-intensive means of transport to reduce the negative impact of transport on the environment. The scientific novelty of the proposed solutions is the verification of the actual emissions of Euro 6 vehicles and the modeling of air pollutant emissions as a function of speed and acceleration. The research results are included in this article and will become input data for further analysis in examining the impact of vehicle operating age on air pollution emissions. Consequently, the novelty of the present research also lies in its focus on the verification of the impact of operating age, particularly in the context of vehicles exceeding 15 years of age, on air pollutant emissions. By establishing a correlation between a vehicle's air pollutant emissions and its operating age, it becomes possible to make transport or delivery planning more sustainable. Furthermore, the selection of less carbon-intensive means of transport can contribute to reducing the negative impact of transport on the environment.

Keywords: transport emissivity; air pollution; road transport; emissions modeling; vehicle aging; exhaust gas emissions; air pollutant emissions; Real Driving Emissions

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1. Introduction

More than 39.470 million cars were registered in Poland in 2022, which means that the number of registered cars was greater than the population of Poland [1]. On the other hand, the Act on Electromobility and Alternative Fuels is the legal basis for implementing clean transport zones in Poland [2]. This act regulates issues related to introducing clean transport zones in cities. Poland also ranks second in the European Union in terms of car saturation, with as many as 747 cars per 1000 inhabitants [3]. Luxembourg is ranked first (781 cars), followed by Italy in third place with 742 cars per 1000 inhabitants. This index will continue to increase in the coming years as the number of cars in operation in

Poland continues to grow. In recent decades, Poland has witnessed rapid changes in vehicle ownership, primarily passenger cars, which are unheard of in developed countries [4]. Regarding statistical data showing the number of vehicles registered in Poland, the situation will change significantly due to the verification of the Central Register of Vehicles and Drivers scheduled for 2024. Vehicles not subjected to technical inspections in the last ten years will be removed from the repository of vehicles registered in Poland. The number of registered vehicles is estimated to decrease by nearly 7 million [5]. Then, the saturation indicators for the vehicles mentioned above will approach the average value in Europe, which is currently approximately 560 vehicles per 1000 inhabitants, which seems consistent with vehicle saturation forecasts [6] from the perspective of 2025. These statistics have implications for car fueling issues, the selection of environmentally friendly fuels, and assessing the means of transport environmental impact. In 2020, passenger cars were the most common means of transport in Poland (76%). Considering their power sources, 45% of passenger cars are models with petrol engines. Passenger cars powered by diesel engines accounted for 40%, while 14% were LPG (liquefied petroleum gas)-fueled cars. Hybrid cars accounted for only 1% of the total fleet. The share of electric and CNG (compressed natural gas) cars was negligibly small. In 2020, there were only 9300 registered electric cars in Poland. It should, however, be noted that the number of electric cars used on Polish roads is increasing every year. The increasing number of electric and low-emission cars used in Poland will not, however, fully replace conventional cars [7]. Thus, the search for methods to improve the verification of actual air pollutant emissions in connection with, among others, the implementation of clean transport zones in urban areas and reducing the negative environmental impact of transport, seems to be an ongoing topic. The timeliness of the issue of measuring air pollutant emissions is also affected by the age structure of cars used on public roads in Poland. The research objective of this paper is to compare the air pollutant emission results for different passenger car types, obtained in Real Driving Emissions (RDE) tests and procedures, and the application of air pollutant emission modeling [8]. The aim of this research is to map the characteristics of air pollutant emissions as a function of car speed and acceleration and to determine the extent of the means of transport environmental impact in terms of air pollutant emissions. The research question is whether it is possible to determine the emissivity of passenger cars with the assurance of results based on real-world testing, using modeling-based methods.

Significant changes were undertaken in the Polish energetic product mix in 2023. For the first time in history, the share of hard coal and lignite in energy production in Poland fell to 60.5%, almost 10% less than in 2022 [9]. The renewable energy sources that generate energy are responsible for 27% of electricity generation. It is worth noting that Poland's energy transformation has an uneven pace of updates. Energy transformation is output in the power sector, not input, including transport. State decarbonization policy needs to be revised to the scale of the challenges characteristic of climate neutrality while maintaining energy security and operational competitiveness. One of the key challenges currently facing Poland is the issue of greenhouse gas emissions from the use of different means of transport. This challenge is especially significant in the case of vehicles imported into Poland. The number of shared cars, which constitute the share of electric vehicles or LPG vehicles in public transport in the total vehicles traveling along Polish roads, is marginal.

In this paper, the authors draw attention to important ecological conditions influencing transport's impact on Poland's natural environment. The key factor influencing the growing emissions of air pollutants in transport in Poland is the increase in the import of used vehicles, which are disposed of for recycling in exporting countries. Furthermore, the prevalence of aging vehicles in Poland raises concerns about road safety given the potential shortcomings in the technical specifications of imported vehicles. There is a threat to human health due to increased exhaust emissions coming from imported vehicles, and the environment is burdened with waste and toxic gases.

The import of used vehicles may affect car manufacturers in Poland, including purchasing used vehicles instead of investing in new models. If customers are more likely to choose cheaper vehicles, new car manufacturers will experience reduced sales. Introducing new regulations on the import of used cars, such as emission standards or clean transport zones, may discourage customers from purchasing used vehicles. However, manufacturers are increasing their investment in innovation and technology development to attract customers and increase the sales of new vehicles. In summary, importing used cars can be a challenge for manufacturers, but the target group of customers in Poland must be considered: approximately 1 million used vehicles are imported annually, and only about 30% are sold as new.

2. Environmental Impact of Passenger Cars and Their Structure in Poland—State of the Art and Literature Review

Passenger cars account for the largest share of air pollutant emissions in Poland, with their fuel structure shown in Figure 1. Despite ambitious plans to achieve zero-emission transport in the European Union, compliance with this condition in Poland can be challenging as conventional fuels are still the dominant fuels in the domestic orientation. In 2020, more than 85% of passenger cars used in Poland were powered by petrol or diesel. Their environmental impact was directly related to their year of manufacture, technical condition, and the manner in which they were used.

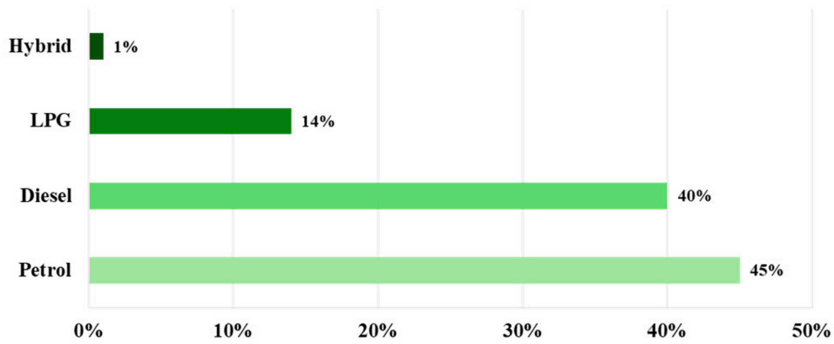

Figure 1. Structure of passenger cars by fuel type, Poland 2020 [3].

The environmental impact of passenger cars depends on their technical condition and the emission standards met by the car. Air pollutant emission studies are widely known [10]. Still, large-scale studies of air pollutant emissions have yet to be conducted in the context of the changing operating age of vehicles. Less common studies examining the impact of vehicle age and technical conditions on air pollution emissions include research such as [11–15]. The age distribution of vehicles is an essential factor that should be considered when assessing the impact of air pollution emissions on the environment. This type of research is described in [15] regarding the effects of vehicle aging on air pollutant emissions in a sample of 600 vehicles. A strong impact of the vehicle's operating age on the emission level was observed. Research [15] confirmed that air pollution emission standards were exceeded by as much as 50% for vehicles in the age group over 12 years. The above observation indicates the validity of verifying vehicle authorizations for vehicles of a specific operating age in selected urban zones. The changing emissions of air pollutants generated by vehicles are also influenced by external factors such as the quality of propellants [16] and standards describing their production.

Research regarding air pollutant emissions is widely published, yet no large-scale research on air pollutant emissions in terms of the changing operational age of means of transport has been noted so far. The emission standards for passenger cars are directly correlated with a car's year of manufacture. The implementation of the various emission standards has taken place in stages: Euro 1 (1994–1996) [17], Euro 2 (1997–1999) [18,19], Euro 3 (2000–2004) [20], Euro 4 (2005–2009) [21], Euro 5a and Euro 5b (2010–2015) [22], Euro 6 (from 2016) [23]. Carbon monoxide emissions for petrol and diesel cars were reduced from 2.72 g/km to 0.1–0.3 g/km between 1993 and 2025 through the implementation of the Euro standards system. It is noteworthy that despite the implementation of successive air pollution emission standards, the average age of passenger cars in Poland is 15.5 years. Given the large number of imported cars, their average age is 12.7 years [3] (Figure 2). The youngest group of passenger cars in Poland, i.e., up to 4 years old (13%), includes a large share of diesel cars (62%). Diesel cars in this age group account for only 27%, while LPG cars account for 4%. Hybrid cars, on the other hand, account for nearly 7%. The share of electric cars in this age group is negligibly small. The next and most numerous group of cars in Poland are cars aged between 5 to 10 years (17%).

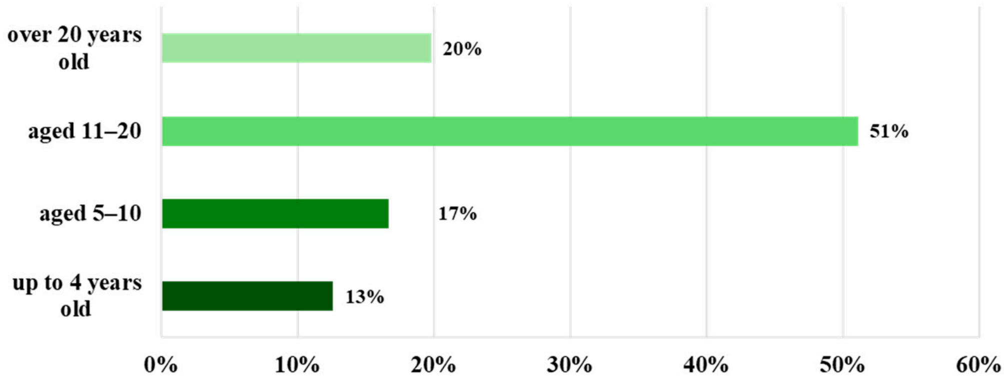

Figure 2. Age structure of passenger cars, Poland 2020 [3].

Among these, diesel cars represent the largest group with a share of 47%. There are 2% fewer petrol models in this segment and 7% fewer LPG passenger cars. In contrast, in the case of the two largest groups, i.e., 11- to 20-year-old (51%) and over 20-year-old cars (20%), more change is observed. These include 15% and 24% LPG cars, respectively. There are 46% of diesel cars in the 11–20-year range and 27% of cars aged above 20 years. The share of petrol-fueled engines is 39% for cars in the 11–20-year range and 49% for cars aged above 20 years. Poland features mass import of cars from abroad, which negatively affects the indices for the average age of passenger cars in use. Almost one million second-hand passenger cars imported from abroad, mainly from Germany, Switzerland, Belgium, and France, are registered in Poland every year. More than half of the passenger cars imported into Poland are older than 10 years [3]. Around 38% of the cars are between 4 and 10 years old. Newer cars, i.e., no more than four years old, account for only 6%. Unfortunately, post-accident cars with so-called total damage are often imported to Poland. This has a negative impact on the technical condition of the cars used in Poland and their environmental impact, not to mention road safety aspects and the influence on the linear infrastructure quality. In most Western countries, cars classified as total damage, despite being repaired, cannot enter public roads. However, Polish law still allows such cars to be placed on the market and used legally. Considering the average age of passenger cars in Poland, a car representing this age group was manufactured around 2007 and meets the Euro 3 or older emission standards. In the case of imported cars, despite the slight difference in average age, cars meet the Euro 4 standard in 37.4% of cases and the Euro 5 standard in 29% of cases. In addition, more than 15% of imported passenger cars meet the latest Euro 6 standard. Only 14.6% of imported cars meet the Euro 3 or older standard. Only 8% of cars in Poland's passenger car fleet met the latest emission standards in 2020. No more than half of the cars meet Euro 3 and 4 standards. The share of the least environmentally friendly and oldest cars meeting Euro 3 and older standards is only 21%. This result may still be satisfactory considering that only 0.5% of passenger cars met the Euro 6 standard as recently as 2012. Furthermore, 20% of the cars did not even meet the Euro 1 standard [3]. The projected structure of cars meeting specific air pollutant emission standards is shown in Figure 3.

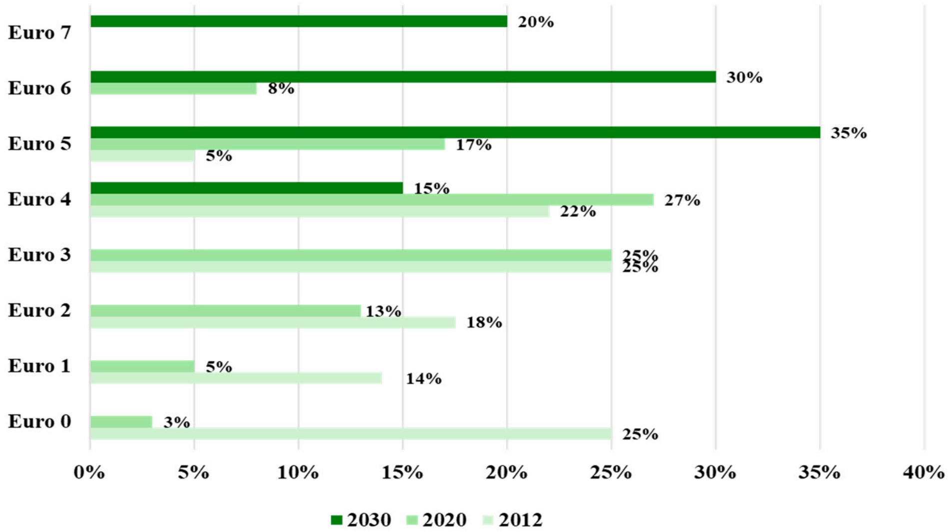

Figure 3. Projected structure of cars by Euro standards met, Poland 2012–2030 [24].

The aging population of passenger cars in Poland causes negative consequences for road safety but also has a negative environmental impact on inhabitants. The operation of cars for a period exceeding 15 years is associated with a lack of systems to support exhaust gas treatment. Car manufacturers are introducing technological solutions to meet new, increasingly stringent emissions standards. The solutions in the engine area directly concern the combustion of the fuel–air mixture. In addition to the engine solutions, a number of new exhaust gas treatment devices and systems are being introduced to exhaust systems (exhaust gas recirculation—EGR, three-way catalyst—TWC, diesel oxidation catalyst—DOC, diesel particulate filters—DPF or gasoline particulate filters—GPF, and the selective catalytic reduction system—SCR). These solutions are based on chemical processes such as oxidation, reduction, or filtration. Air pollutant emissions from using passenger cars are affected by many factors, i.e., technical condition, operating age, manner of operation, and place of operation. Despite Poland's aging fleet and the implementation of new solutions to minimize the effects of air pollutants, the projected structure of cars in use by 2023 [24] is optimistic and assumes that cars meeting the Euro 3 standard will constitute a marginal share in 2030. The vast majority will be Euro 5 and Euro 6 cars. Moreover, up to 20% of the fleet will comply with the Euro 7 standard, which is planned for introduction in the future (Figure 3). The above projections are important because air pollutant emissions stemming from road transport particularly affect the Earth's atmosphere [25]. Defining the relationship between the atmospheric carbon dioxide (CO_2) concentration and temperature is essential to understanding environmental changes and modeling future climate trends [26]. Observing CO_2 concentrations and average annual temperatures allows us to provide information relevant to possible climate changes. Compared to today's global yearly temperatures of 14.5 °C, the average annual temperature in the Middle Miocene (approximately 15 million years ago) was 18.4 °C, corresponding to the predicted average temperature of 2100. Monitoring shows that it is therefore possible to accelerate the rate of melting of glaciers and inevitable further ecological consequences [27]. It is estimated that to stabilize the balance of the Earth's atmosphere composition, greenhouse gas emissions must be reduced by as much as 60% by 2025 [28]. The greenhouse effect is recognized in the literature as the most dangerous as its effects will persist over a long period of time and will have a global impact. Atmospheric exhaust gas emissions also contribute to the ongoing deterioration of air quality. In local circumstances, it contributes to the formation and persistence of smog over a long period of time. This is due to the fog binding with exhaust gas compounds such as particulates, sulfur oxides, or carbon monoxide. Large urban areas often have a smog problem, especially in city centers. Car transport is often mistakenly blamed as the culprit of this phenomenon, yet according to research, it is only responsible for 16% of air pollution defined as smog [3]. Similar statistics indicate a 16% share in the transport of air pollutants, including road transport at 11.9%, which are available in a previous report [29]. The reoccurrence of this phenomenon many times a year has a very negative impact on the environment, including, to a large extent, humans. Exhaust gas emissions have an equally negative impact on other areas of the environment, namely flora and fauna. The aim of the measures planned over the next few years will be primarily to change the way passengers and goods are transported, combine different means of transport in a single journey, and promote green solutions for entrepreneurs. Funding for investment, rolling stock, and infrastructure modernization will be increased and solutions to increase resilience to future economic turmoil will be promoted, while clean road transport zones will be introduced in urbanized areas.

3. Problem and Research Method

Globally, passenger cars account for more than 61% of atmospheric air pollutant emissions [30] generated by means of transport. Transport alone accounts for 13% of all emissions in economic sectors [30]. In Poland, a passenger car travels an average of 8607 km per year (2019). Using the average emission indices for means of transport [31], a petrol passenger car, combusting an average of 7 dm^3 of fuel per 100 km, emits more than 137 kg of carbon monoxide, 34 kg of nitrogen oxides, and 18 kg of hydrocarbons into the atmosphere per annum. Furthermore, an average passenger car consumes around 6 kg of fuel and around 120 m^3 of air per hour at 50 km/h. For comparison, humans consume only 0.7 m^3 of air per hour. Considering all the above effects of exhaust gases on different areas of the environment, passenger car traffic has a very negative impact on the environment and humans. In addition to all the emission-reducing solutions cited above, corporations are focusing their attention on expanding their electric car portfolios. These cars are powered by electricity, 70% of which is obtained in Poland by combusting fossil fuels. The electricity consumption when using such a car is approximately 15 kWh per 100 km. In Poland, according to [32], the emission of 840 g of CO_2 is required to generate 1 kWh of energy. This means that the carbon dioxide emission equivalent of producing enough energy for an electric car to travel 100 km is 12.6 kg. Carbon dioxide emission equivalent is a metric that the European Union [33] suggested to compare the emissions of various greenhouse gases based on their global warming potential by converting quantities of other gases into the equivalent amount of carbon dioxide (IPCC Third Assessment Report 2001 [34]). Using the average emission indices for transport means again, an SI passenger car will emit approximately 10 kg of carbon dioxide into the atmosphere after traveling 100 km (with a fuel consumption of approximately 5 dm^3 per 100 km). The energy costs of coal mining and oil production are estimated to be similar enough to be ignored in the discussion. This means that an electric car in Poland emits as much, if not more, carbon dioxide than an internal combustion car. Therefore, the paper is focused on the issue of measuring air pollutant emissions of passenger cars, because passenger cars constitute the most numerous among populations of motor vehicles in Poland. Furthermore, this paper features a comparison of the results of measurements of actual air pollutant emissions for different types of passenger cars and the development of a model of air pollutant emissions as a function of the test car speed and acceleration. The test method used in this study consisted of measuring actual emissions using test equipment, i.e., a SEMTECH DS exhaust gas analyzer and the EEPS 3090 mass spectrometer to measure the number of particles. Characteristics of the SEMTECH DS analyzer (SEMTECH DS, Sensors Inc., Saline, MI, USA) are presented in Table 1.

The SEMTECH DS analyzer consists of several autonomous measurement modules:

- A flame ionization detector (FID) used to determine the total concentration of hydrocarbons known as THCs (total hydrocarbons) in exhaust gases.
- A non-dispersive ultraviolet analyzer (NDUV—non-dispersive ultraviolet), intended for the measurement of concentrations of nitric oxide and nitrogen dioxide.

- A non-dispersive infrared analyzer (NDIR), designed to measure the concentrations of carbon monoxide and carbon dioxide.
- A paramagnetic analyzer (PMD—paramagnetic detector) to determine the oxygen concentration in exhaust gases.

Table 1. Characteristics of the Semtech DS analyzer with reading of the vehicle's data transmission system.

Parameter	Measurement Method	Accuracy
CO	NDIR, 0–10%	±3% range
HC	FID, 0–10,000 ppm	±2.5% range
NO_x ($NO + NO_2$)	NDUV, 0–3000 ppm	±3% range
CO_2	NDIR, 0–20%	±3% range
O_2	paramagnetic, 0–20%	±1% range

The research method also included modeling air pollution emissions based on real tests. All vehicles covered by the test and the measuring equipment were stationed in garage conditions at a temperature of approximately 20 °C before the tests began. The gaseous components of exhaust gases were measured using the SEMTECH DS analyzer, which comprehensively measures the CO, CO_2, and NO_x content in exhaust gases. An exhaust gas collection system is mounted between the exhaust gas analyzer and the vehicle's exhaust system, in which the exhaust gases move at a temperature of 191 °C to prevent water condensation. After introducing the exhaust gases into the analyzer through a special filter, solid particles are separated and the exhaust gases go to FID, where the hydrocarbon concentration is measured. Then, the exhaust gases were cooled to a temperature of 4 °C and moved to a non-dispersive analyzer using ultraviolet radiation (NDUV), where the concentration of nitrogen oxides was determined. The exhaust gas mixture was then directed to the NDIR analyzer, which also uses the non-dispersive method. However, the carbon monoxide and carbon dioxide concentrations were measured using infrared radiation. Finally, using an electrochemical analyzer, the SEMTECH DS device measured the oxygen concentration. The separated solid particles were also sent to the second TSI analyzer—the solid particle counter. The exhaust gas flow rate was measured using a 2″ measurement probe. Due to road conditions, it is necessary to attach a probe to ensure tightness with the vehicle's exhaust system. The TSI Incorporated—EEPS 3090 (Engine Exhaust Particle Sizer™ Spectrometer, EEPS 3090, TSI Incorporated, Aachen, Germany) analyzer was used to measure particle diameters. It allowed for the measurement of solid particles in the range of solid particle diameters from 5.6 nm to 560 nm. The technical data of the TSI 3090 EEPS analyzer are presented in Table 2.

Table 2. Technical data of the EEPS particulate matter analyzer.

Operating Features	Value
Particle size range	5.6 nm to 560 nm
Particle size resolution	16 channels per decade (32 total)
Electrometer channels	22
Time resolution	10 size distributions/s
Sample flow	10 dm^3/min
Sheath air	40 dm^3/min
Operating temperature	0 °C to 40 °C

The task of the mass spectrometer was to perform a dimensional and mass distribution of the total number of emitted particles. In the first phase of measurement, the solid particles in the spectrometer were positively charged using the charging electrode and then fell along the ring electrodes. Depending on the size of the solid particle, it fell higher or lower onto the electrode, which collected its positive charge, classified it, and assigned it the appropriate diameter. The more measurement channels a given analyzer has, the more accurate it is. The EEPS 3090 device has 32 measurement channels, and the measurement range of solid particle diameters is 5.6 nm to 560 nm. Geographical coordinates were recorded in a spreadsheet to create a journey map.

Each time before the measurement, the SEMTECH DS analyzer was calibrated with standard gases and zeroed with ambient air. The need to measure the concentration of harmful compounds in the surrounding air was compensated by using ambient air for zeroing. At the same time, the zero drift for each measurement track (harmful compound) was recorded each time, and the obtained concentration results were corrected. In the case of the particulate counter, the contamination was determined each time at each electrode, and the measured value was corrected. Figure 4 shows a diagram of the research method.

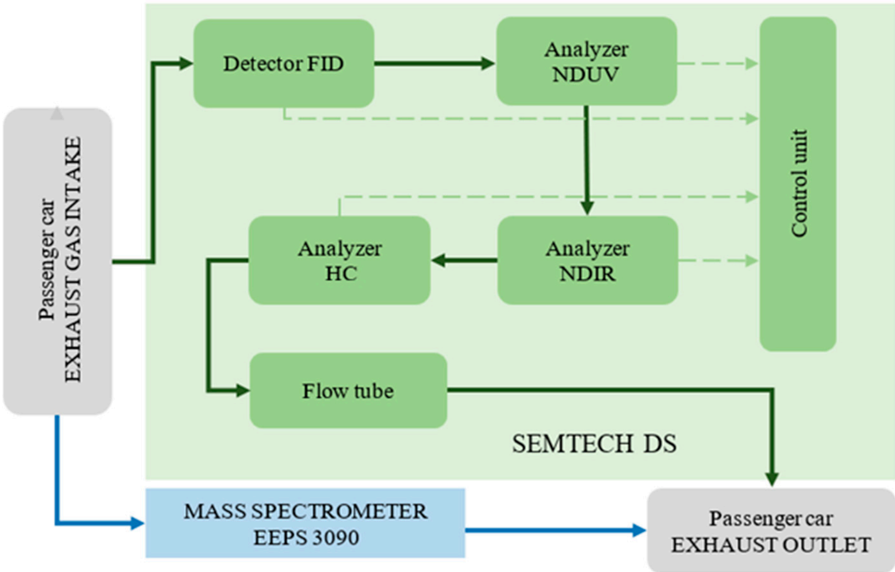

Figure 4. Diagram of the research method, own work.

A control unit was connected to the SEMTECH DS device to complete the measurement, which acquires measurements of the concentration of individual harmful compounds, exhaust gas flow, and external environmental parameters (temperature, humidity, and ambient pressure) in real time. Additionally, using the OBD system, we determined the basic parameters of the vehicle's journey and the values. The present research system has also been previously used for vehicle types other than passenger vehicles. Previous research included vehicles such as agricultural vehicles [35], specialized vehicles for wood mining [36], hybrid and electric vehicles [37], and delivery vehicles [38]. Then, after the real tests, air pollution emissions were modeled (numerical modeling).

Modeling is widely used in the area of transport [39,40]. Road air pollutant emission tests carried out as RDE tests can then be imaged to map the air pollutant intensity using an emission model [41] along any route. It is possible to use approximate methods to determine air pollutant emissions [42]. In order to determine the total emissions of any compound along any route, it is necessary to record the test car's traveled longitude and latitude using any recording system with GPS technology at a measurement frequency of 1 Hz. Once the travel distance has been recorded using GPS, the resulting data should be opened in a spreadsheet to create a model [43]. The first step is to determine the characteristics of speed versus test time and car acceleration versus test duration. The next step is to create a two-dimensional designation of the one-second work time intervals ($t_{m\times n}$) for the given car's speed and acceleration (half-open) intervals. The designation of the one-second work time intervals is described by Equation (1).

$$t = f(V, a) \quad (1)$$

The two-dimensional designation allows the characteristic values of the car's performance to be determined, which enables us to determine the overall on-road emissions of harmful compounds. The previously carried out RDE tests are the source of the actual emissions data. Each work field is assigned a range of speed and acceleration with a span described by Equations (2) and (3).

$$\Delta V = \frac{V_{max} - V_{min}}{N} \quad (2)$$

$$\Delta a = \frac{a_{max} - a_{min}}{M} \quad (3)$$

The characteristic values of the ends of the intervals are determined for each field of work and are the arithmetic mean of the beginning and end of the interval for a given car's speed and acceleration. Typically, the acceleration ranges are taken in 0.5 m/s^2 increments to simplify and increase the readability of the graph. The number N is chosen to ensure integer numbers of speed intervals, while the number M—to ensure no less than 10 acceleration intervals. Once the matrix has been created in the spreadsheet, the formulae are used to assign a value in seconds to the dynamic state of the car located in the corresponding work field. The final step is the product of the previously obtained two-dimensional emission intensity matrices ($E_{x,m \times n}$) for individual compounds as a function of car acceleration and speed and the previously created matrix of the car's work time designation ($t_{m \times n}$) under the given dynamic conditions as a function of speed and acceleration. This allows for obtaining three-dimensional mass designations of any pre-measured compound in the exhaust gas (in the car's various work intervals). When the values from all the work fields are added, the total mass of a given compound emitted during the recorded route is obtained. The disadvantage of the proposed method is the time-consuming nature of RDE measurements and the need to use expensive research equipment. A single air pollutant emissions test takes approximately 120 min. The advantage of the proposed method is the measurement accuracy, which meets the technical conditions for air pollution emission tests in conditions of real use of means of transport. Carrying out a series of air pollution emission tests using the RDE test may contribute to developing methods for modeling the air pollution phenomenon. It is possible to create a library of RDE test results and model air pollutant emissions for various types of vehicles. The research methodology developed this way will transpose the proposed model to vehicles with lower emission classes than those considered in this article. It is advisable that air pollution emission tests using the RDE test be performed for vehicles with equal mileage to determine and examine the impact of operating age on the emissions of means of transport and to determine possible correction factors for the emissions of means of transport given in the purchase of new means of transport.

4. Testing Air Pollutant Emissions Under Real Traffic Conditions

The measurement procedure for on-road passenger car emissions has been changing with the introduction of successive emission standards. The issue of laboratory measurements based on the NEDC (New European Driving Cycle) or WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure) procedures was the poor correlation between the car's dynamic conditions on the dynamometer and under real traffic conditions. Laboratory measurements did not accurately reflect reality, and manufacturers adapted combustion engines to meet all requirements only during testing. Hence, the measurement of exhaust gas emissions under real traffic conditions based on the RDE on-road exhaust gas emission test [44] has been implemented. Every car approved from 2017 onwards must meet the requirements of the RDE test in addition to the WLTC test requirements. As part of the research work, the subjects of the tests were passenger cars equipped with different types of (combustion) engines. During the test carried out using the PEMS (portable emission measurement system), the on-road emissions of harmful compounds in exhaust gases are measured during car use in urban, rural, and motorway conditions. During the test, the route must be adjusted to prevent the interruption of the test's continuity. Data should also be recorded without any interruption. The RDE test should be carried out on paved carriageways during working days. The regulations prohibit the use of the neutral gear for too long in the initial stage after starting the engine during the test. The route should run for a minimum of 16 km in urban, rural, and motorway conditions. The speed obtained in urban areas should not exceed 60 km/h and the average speed should be between 15 and 45 km/h. The share of each road section should be approximately one-third of the total travel distance. Deviations of 10 percentage points are allowed, but the urban section should not represent less than 29% of the total test travel distance. Moreover, stops, i.e., when the car is not moving faster than 1 km/h, should not account for more than 30% of the total travel distance in the test's urban section. In the rural section, the car should travel at least 16 km at speeds between 60 and 90 km/h. In the motorway section, speeds greater than 90 km/h should be adhered to and the maximum speed should not exceed 145 km/h. However, if the maximum speed is exceeded, the result will be accepted for validation if it does not account for more than 3% of the test's total travel distance. An important aspect of the RDE test is also the need not to exceed an altitude difference of 100 m above sea level between the start and end points. This eliminates the issue of the results' reproducibility in different parts of the world due to increased emissions when climbing hills. Petrol cars with an automatic transmission emit twice as much exhaust gas when climbing a road with a 10% gradient [44]. Commission Regulation (EU) 2016/427 [43] introduced requirements for test equipment intended for measuring road emissions during the RDE test. According to the regulation, on-road exhaust gas emissions should be measured by means of a mobile apparatus mounted in the tested car. The apparatus should not interfere with the car's normal operation and should not disrupt its aerodynamics. An independent power source, preferably an external generator, should be used to power the apparatus. It is advisable to minimize the weight of the measuring equipment as far as possible. Measurements of particulate matter do not follow a specific method, but their frequency should not be less than 1 Hz. The measurement of speed, together with position and altitude above sea level, should be recorded by a GPS system or by means of the car's on-board diagnostic (OBD) system. The coolant temperature should be recorded using the same system. Furthermore, the outdoor temperature, ambient pressure, and relative humidity are recorded during the test. The RDE measurement methods reported in the literature [45] take into account analyses of factors affecting air pollutant emissions. Factors influencing the emission of air pollutants include vehicle charging, topography, degree of congestion [46,47], and other factors such as the propellant, driving conditions, vehicle type, and location of operation [48–53]. As mentioned above, transport has a negative impact on the environment and human health. It is a source of significant amounts of greenhouse gases and chemical compounds that are toxic to humans [54,55]. The compounds generated by diesel vehicles are hazardous: benzene, benzo(a)pyrene, and acetaldehyde. Analyses of hydrocarbons' qualitative and quantitative composition [54] clearly indicate the presence of strongly carcinogenic compounds in exhaust gases emitted, mainly from vehicles with compression-ignition engines. It can be assumed that the emissions of harmful chemical compounds other than greenhouse gases also increase with the operating age of means of transport, including imported vehicles. Electric vehicles are an alternative to conventional transport, but renewable energy sources must power them [56]. On the other hand, the ecological means of transport can be used in taxi services or public services with eco-friendly buses in city traffic conditions [57], which may be additionally underlined in the areas of transport poverty of high ecological relevance (mountain, forest, wilderness, areas of outstanding ecological values, etc.).

5. Research Experiment and Results Discussion

The emissivity of three means of transport was tested with the application of RDE as part of the calculation example. The characteristics of the cars used for the analysis are shown below in Table 3. The RDE tests were carried out in Poznan city and the eastern and western parts of its metropolitan area, following guidelines appropriate to the conditions of the RDE test. Air pollutant emissions were also determined using an air pollutant emission modeling methodology for one selected car traveling on any route.

Table 3. Features of cars tested by RDE (passenger car, sedan, front-wheel drive).

Car Feature	Car V1	Car V2	Car V3
Engine type	petrol	diesel	hybrid (petrol & electric)
Capacity [cm^3]	1984	1968	1798
Max. power [kW]	196	140	90
Max. torque [Nm]	350	400	163
Car weight [kg]	1349	1651	1536
Year of manufacture	2015	2018	2019
Vehicle mileage [km]	152,000	109,000	62,000
Emission standard	Euro 6	Euro 6	Euro 6d Temp
Declared CO_2 emissions [g/km]	139	119	80

The study examined three categories of vehicles, equipped with either petrol, diesel, or hybrid engines. The objective of the research was to develop models for vehicles with varying fuel supplies, while simultaneously ensuring compliance with a single exhaust toxicity standard and evaluating the impact on mileage. A common feature was the similar empty weight and operational parameters of the vehicles (including power and maximum torque), which made it easy to compare them in terms of the speed and acceleration values achieved.

The route traveled by the three test cars in the RDE test is shown in Figure 5. The urban section ran through Poznan's main thoroughfares and ended in the north-eastern part of Poznan at the junction with domestic Road No. 92. The rural section of the RDE test, which consisted of a section of domestic Road 92 and the S5 expressway, began at this point. The S5 expressway turns around at the Wierzyce interchange and the test transitioned to the motorway section, where the car traveled at the highest possible speed on the S5 section and at around 125 km/h on entering the A2 motorway. The measurement route had to be arranged to meet all the criteria of the European Commission regulations [43]. The selection criteria for RDE testing routes are shown in Table 4.

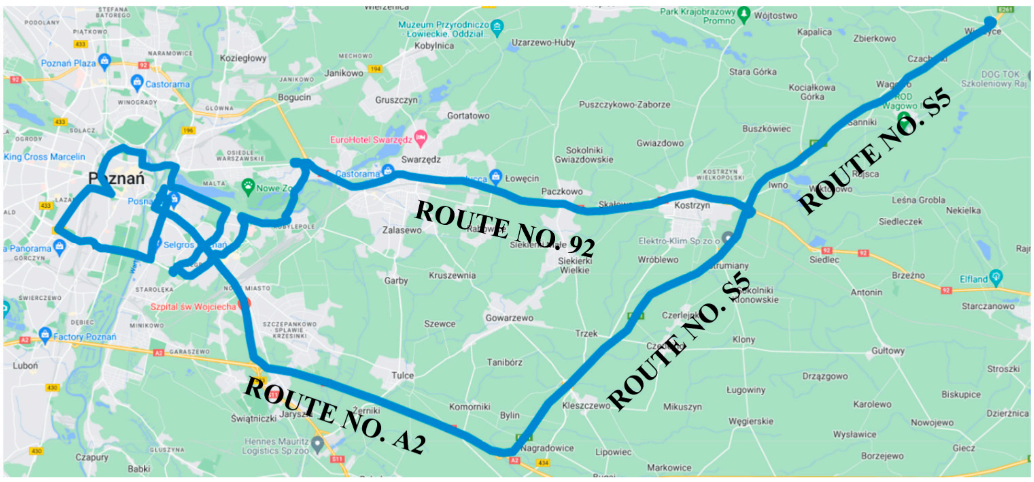

Figure 5. Routing of cars V1, V2, and V3 in the RDE test.

Table 4. The selection criteria of RDE testing routes.

Parameter	V1	V2	V3	Norm	Is the Norm Fulfilled?
Urban route length [km]	33.72	31.70	35.29	>16	YES
Suburban route length [km]	37.71	31.23	31.52	>16	YES
Highway route length [km]	29.67	33.15	31.13	>16	YES
Total route length [km]	101.10	96.08	97.93	>48	YES
Urban route share [%]	33.35	32.99	36.03	29–44	YES
Suburban route share [%]	37.30	32.50	32.18	23–43	YES
Highway route share [%]	29.35	34.50	31.79	23–43	YES
Average speed on an urban route [km/h]	27.77	30.11	29.36	15–40	YES
Share of stops on an urban route [%]	19.45	15.01	16.04	6–30	YES
Driving time above 100 km/h [min]	17.32	15.87	15.55	>5	YES
Maximum driving speed [km/h]	125.5	125.5	116.97	<160	YES
Share of driving time above 145 km/h [%]	0.00	0.00	0.00	<3	YES
RDE test duration [min]	116.48	105.87	114.72	90–120	YES

The origin and destination spots of the test route were the building of the Faculty of Civil Engineering and Transport of the Poznan University of Technology at 3 Piotrowo Street. The urban part ran through the main communication arteries of Poznan and ended in the north-eastern part of Poznan at the intersection with domestic road No. 92. This was where the non-urban road began, which consisted of a section of domestic road No. 92 and the S5 expressway. At the Wierzyce junction of the S5 expressway, the route turned around and the test moved to the motorway part, where on the S5 section, the vehicle was traveling at the highest possible permissible speed, and afterward, entered the A2 motorway at a speed of approximately 125 km/h. Ultimately, all three vehicles should cover the same route; however, due to unplanned construction works, road congestion, or detours, the total distance traveled by the three vehicles differs slightly. However, all runs still meet the requirements for the RDE test and do not affect the differences in exhaust emission measurements. All journeys took place during the holiday season in 2022 within a period of two weeks. The research was conducted in the morning hours of weekdays, from 10 a.m. to 12 p.m., therefore it can be stated that the road conditions and vehicle traffic flow were comparable. The temperature on individual days of the study ranged from 20 °C to 25 °C, and the atmospheric pressure was 1003 hPa each day.

The test cars traveled approximately 30 km in each section of the RDE test, which was almost double the required value. This also translated into twice the total distance of the required 48 km. The shares of the test's individual sections were around 33%, which was in line with the test's requirement ranges. The lowest average speed in the test's urban section was achieved by car V1 at around 28 km/h, while the highest was achieved by car V2 at around 30 km/h. The lower average speed may have been due to the higher volume of local traffic and was caused by construction works encountered unexpectedly along the test route. The waveforms of car speeds during the RDE tests are presented in Figures 6–8.

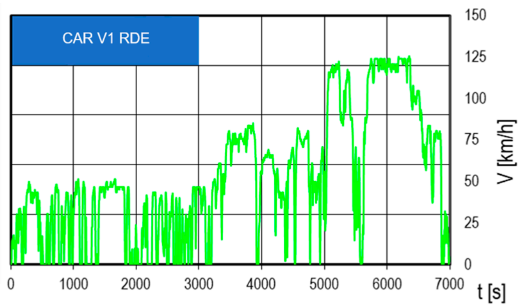

Figure 6. Changes in speed for car V1 during the RDE tests.

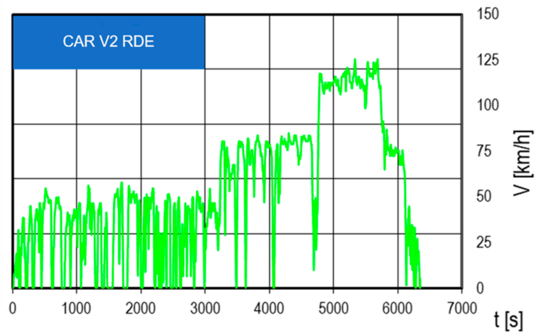

Figure 7. Changes in speed for car V2 during the RDE tests.

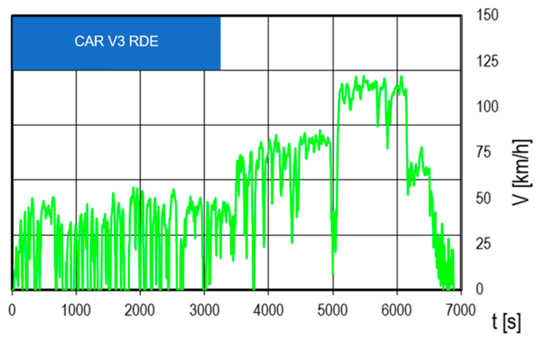

Figure 8. Changes in speed for car V3 during the RDE tests.

The share of stops and driving above 100 km/h in all RDE test cases featured very similar values. The maximum speed for cars V1 and V2 was identical at around 125 km/h, while for car V3, it was around 117 km/h. The duration of the drives fluctuated at around 115 min, while the drive for car V2 was just under 106 min. Ultimately, all three cars tested with the use of RDE should have covered an identical route, but due to unplanned construction works, traffic congestion, or detours, the total distance covered by the three cars varied slightly. However, all of the drives met the requirements for the RDE test and did not result in any differences in the measurement of exhaust gas emissions. The emission results obtained during the RDE tests are presented in Figures 9–12.

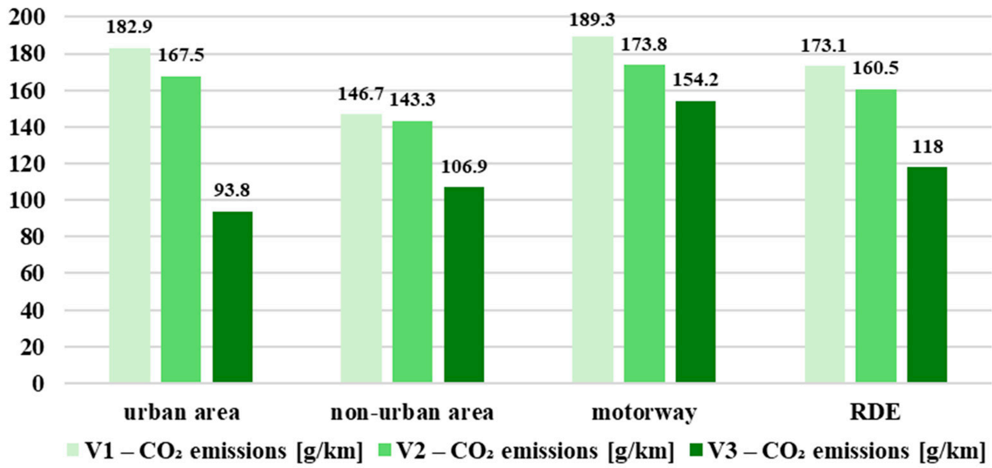

Figure 9. CO_2 emissions.

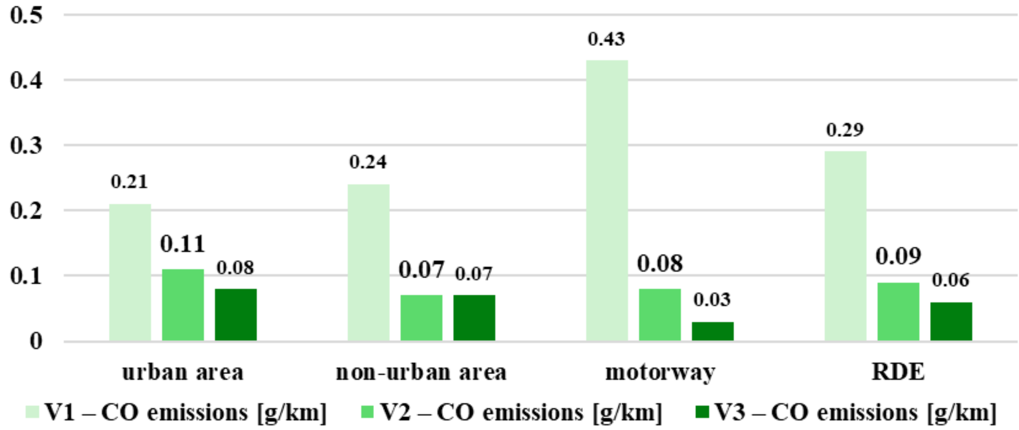

Figure 10. CO emissions.

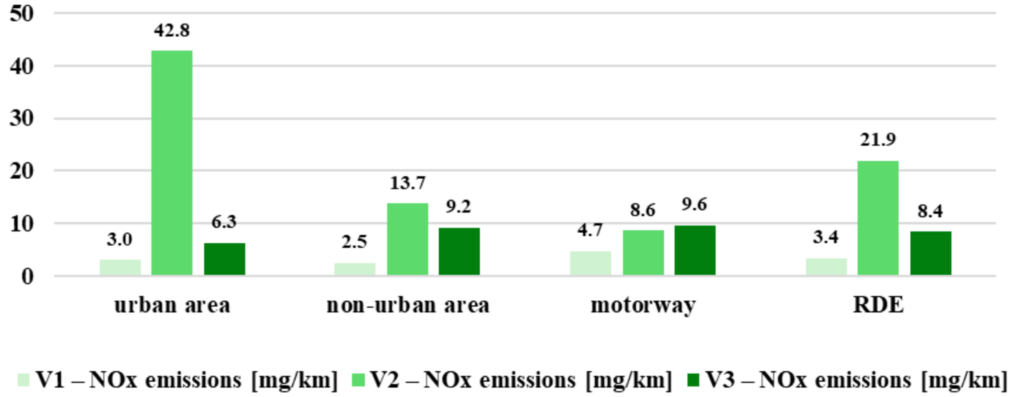

Figure 11. NO_x emissions.

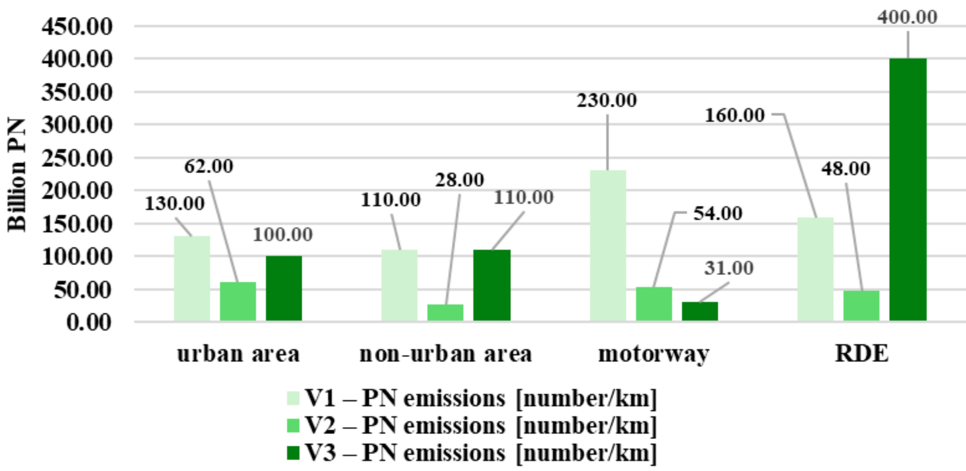

Figure 12. Particle number emissions.

The lowest CO_2 emissions were recorded for the hybrid car. The CO_2 emissions of the hybrid car were 47% lower than those of the petrol car and 36% lower than those of the diesel car. As for carbon monoxide emissions, the hybrid car's emissions were more than four times lower when compared to the petrol car and 50% lower when compared to the diesel car. In terms of NO_x emissions, the diesel car had the highest emissions, followed by the hybrid car, while the lowest emissions were recorded for the petrol car.

It should be emphasized that the emission of combustion products, i.e., their composition, is not the same for petrol and diesel engines. Nitrogen oxides NO_x and PM particles are combustion products in diesel engines.

Following the RDE tests for cars V1–V3, an air pollutant emissions model was developed for cars V1–V3 along the new driving route, based on the recorded actual air pollutant emissions obtained during the RDE test. The speed profile for cars V1–V3 was recorded along the following route: Poznan—Pniewy—Lwowek—Poznan. Cars V1–V3 traveled approximately 70 km on domestic Road No. 92 at a speed of approximately 80 km/h, and then on the A2 motorway toward Poznan, traveling at approximately 125 km/h for 60 km. The urban section was about 15 km, and the traffic volume was standard for the evening hours. It took 7182 s or 1 h 59 min and 48 s to cover the 146.9 km distance. The route of cars V1, V2, and V3 is shown in Figure 13.

Figure 13. Route taken by cars V1–V3 in the V1–V3 MODEL air pollutant emissions model.

The cars' acceleration and speed intervals were measured during the tests. The matrix fields were then supplemented with the number of one-second intervals in which the dynamic parameters of the car's speed and acceleration correspond to the car's work fields, as well as with the emission intensities for the test cars' (V1, V2, V3) individual dynamic driving conditions. The corresponding speed and acceleration fields from the interval number and emission intensity matrices were multiplied by each other to obtain the mass of emitted air pollutants in each work area during the recorded drive in the test's final stage. The model [39] was used to determine a graphic illustration of the air pollutants generated by cars V1, V2, and V3 along the following route: Poznan—Pniewy—Lwowek—Poznan (V1—MODEL, V2—MODEL, V3–MODEL). The air pollutant emission modeling method allows for the determination of the variability of emissions of individual air pollutant types as a function of varying car acceleration and speed. The highest air pollutant emissions were recorded in the model method for car V1's speed in the range of 50–70 km/h. A graphic illustration of air pollutant emissions during car V1's drive along the route (Poznan—Pniewy—Lwowek—Poznan) is presented in Figure 14.

A graphic illustration of air pollutant emissions during car V2's drive along the route (Poznan—Pniewy—Lwowek—Poznan) is presented in Figure 15.

A graphic illustration of air pollutant emissions during car V3's drive along the route (Poznan—Pniewy—Lwowek—Poznan) is presented in Figure 16.

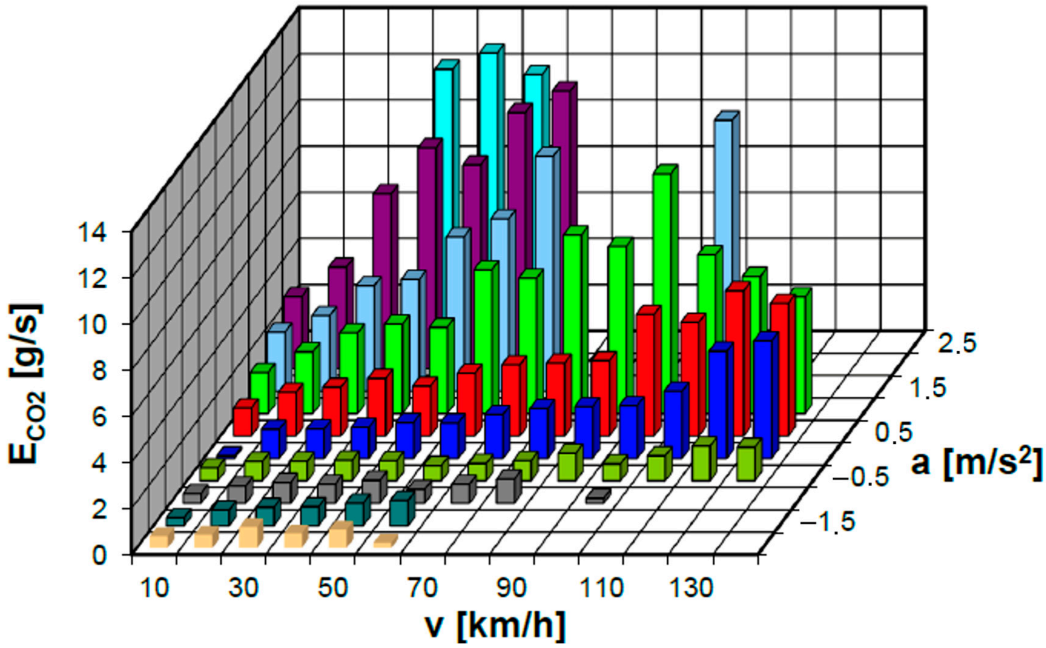

Figure 14. CO_2 emission intensities in speed–acceleration coordinates for car V1—MODEL.

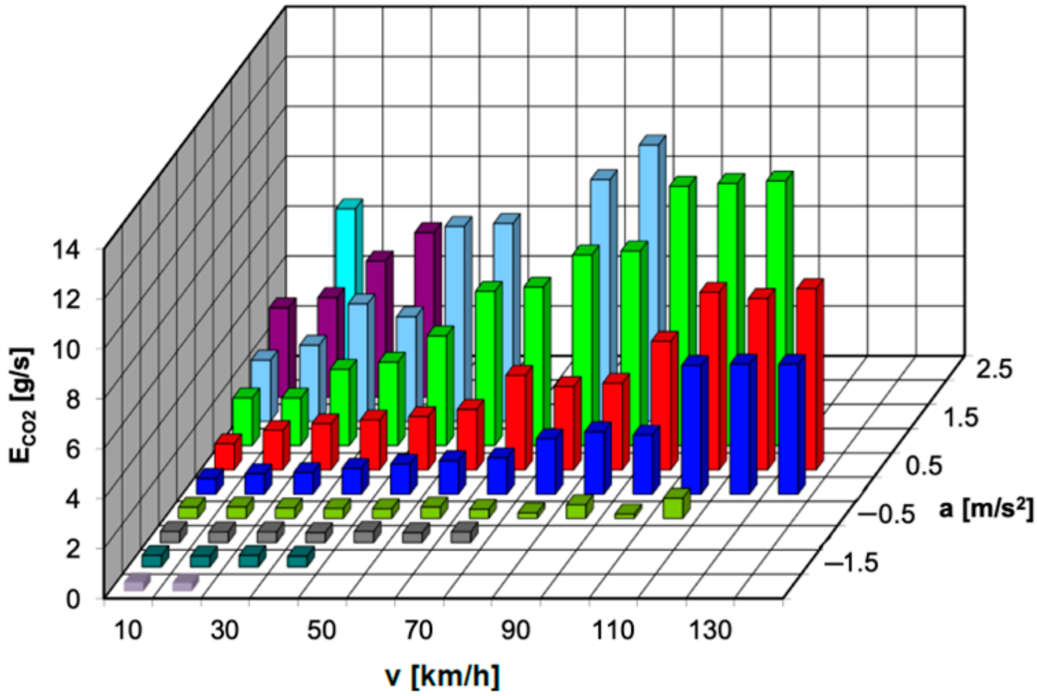

Figure 15. CO_2 emission intensities in speed–acceleration coordinates for car V2—MODEL.

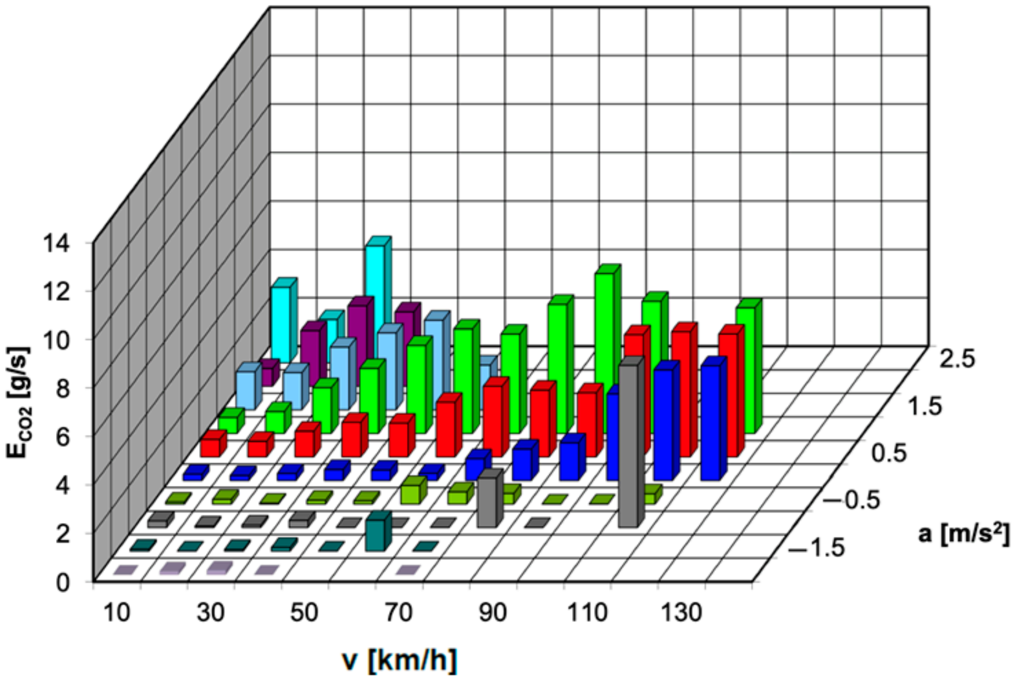

Figure 16. CO_2 emission intensities in speed–acceleration coordinates for car V3—MODEL.

6. Conclusions

After adding up all the work fields according to the exhaust gas emissions model, it was concluded that car V1 emitted a total of 35.3 kg of carbon dioxide along the route traveled. The emissions of other air pollutants were determined in a similar way. After performing the necessary calculations according to the emissions model, car V1 also emitted 60.95 g of carbon monoxide, 929 mg of nitrogen oxides, and 2.73×10^{13} particles. The average on-road emissions of carbon dioxide along the route amounted to 240.3 g/km, carbon monoxide was 0.41 g/km, nitrogen oxides totaled 6.32 mg/km, and particle number equaled 1.8×10^{11} 1/km. The total emissions of air pollutants during the RDE test can be determined in a similar way. Using the test instrumentation, it is possible to determine a given car type's exact air pollutant emissions as part of the RDE tests. Moreover, it is possible to visualize the intensity of air pollutant emissions as a function of car speed and acceleration along any given route for a car with emissions previously designated under real-world conditions. The RDE test is the most accurate method for determining air pollutant emissions. Due to the standardized testing regime and cost-intensive instrumentation, the modeling of car air pollutant emissions allows for the determination of the emissions generated by cars following prior RDE testing. The aging population of passenger cars in Poland causes negative consequences for road safety, yet also has a negative environmental impact on inhabitants. Therefore, the study of air pollutants becomes particularly important as the operation of cars aged over 15 years involves a lack of systems to support exhaust gas treatment. A follow-up study will verify the effect of the operating age on air pollutant emissions. Establishing a correlation between the car's air pollutant emissions and its operating age can make transport or delivery planning more sustainable, and the selection of less carbon-intensive means of transport can reduce the negative impact of transport on the environment. Knowledge of the means of transport emission characteristics as a function of operating age would allow for more detailed modeling of air pollutant emissions in urban areas. It would be possible to formulate new methods allowing for more precise and dynamic determination of car air pollutant emissions based on an analysis of data obtained from publicly available car databases, as well as using image analysis and video recording of cars traveling along a selected road section. Therefore, it seems possible to generate dynamic maps of air pollutant emissions along car routes, provided that the speed limits and road conditions are known.

Carrying out a series of air pollution emission tests using the RDE test may contribute to developing methods for modeling the air pollution phenomenon. It is possible to create a library of RDE test results and model air pollutant emissions for various types of vehicles. The research methodology developed this way will transpose the proposed model to vehicles with lower emission classes than the ones considered in this article. It is recommended that air pollution emission tests using the RDE test be conducted on vehicles with similar mileage to ascertain the influence of operating age on the emission of transport vehicles and to identify potential correction factors for the emission of transport vehicles in accordance with the purchase of new ones. In the context of the impact of transport on the natural environment in Poland, it is advisable to take actions aimed at:

- Limiting the mass import of means of transport that are withdrawn from use in their original operation.
- The introduction of periodic measurement of selected vehicle pollutant emissions using the RDE test.
- The introduction of rigorous assessments of the technical condition of imported vehicles.
- The introduction of age and mileage criteria for imported vehicles.
- The introduction of the obligation to verify the technical and environmental condition of exhaust gas treatment systems.
- The elimination of vehicles that do not meet air pollution emission standards from Polish roads.
- The introduction of a legal restriction on imported vehicles, on the one hand, due to their age, and on the other, due to their technical condition (this especially relates to petrol engine vehicles), as it is necessary to reduce the import of used vehicles in order to increase traffic safety and reduce emissions.
- The elimination of vehicles with removed exhaust gas treatment systems.
- Establishing criteria within clean transport zones that consider the impact of operating age on the emission of air pollutants declared by manufacturers.
- The development of new, non-conventional means of transport that are environmentally and socially beneficial and address transport poverty challenges.

The import of used cars may have an impact on car manufacturers in Poland, potentially leading to a shift in purchasing patterns toward the acquisition of used vehicles rather than new models. The introduction of new regulations governing the import of used cars, such as emission standards or clean transport zones, may act as a deterrent to customers considering the purchase of used vehicles. Nevertheless, manufacturers are increasing investment in innovation and technology development with the objective of attracting customers and increasing sales of new vehicles. In conclusion, the importation of used cars may prove challenging for manufacturers; however, it is essential to consider the target customer group in Poland. Approximately one million used vehicles are imported annually, with only approximately 30% of this number being sold as brand new.

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