NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY POLITEHNICA BUCHAREST

Doctoral School of Biotechnical Systems Engineering

Domain: Environmental Engineering

DOCTORAL THESIS SUMMARY
ASSESSING THE SUSTAINABILITY OF PUBLIC TRANSPORT THROUGH THE ANALYSIS OF EMISSIONS AND CARBON FOOTPRINTS

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Foreword

As we have reached the end of a long, arduous, but rewarding journey, culminating in the revelation of self-knowledge, I can say that I will miss the challenge, I will miss the people with whom I sought answers to so many questions and, last but not least, the state of yearning to always assimilate the work well done, and I would like to express my sincere gratitude to all those who were involved in the emotional journey I have been a part of.

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I would like to end by thanking my family and friends for their encouragement, support, patience, and understanding, which were essential in helping me reach this remarkable achievement. I am grateful to everyone who believed in me and accompanied me on this unique journey toward excellence.

"The aim of education is not to fill a pot, but to light a fire."

— William Butler Yeats

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Lista abrevieri

OMS – World Health Organization
CE – European Comission
NO_x – Nitrogen oxides
O_3 – Ozone
PM – Particulate matter
SO_2 – Sulfur dioxide
CO – Carbon monoxide
CO_2 – Carbon dioxide
CH_4 - Methane
COV – volatile organic compounds
SLCP - Short-Lived Climate Pollutants
BC – Black Carbon
HFC – Hydrofluorocarbons
GHG – Greenhouse gases
$PM_{2,5}$ – Fine particles in suspension with a diameter of ≤2,5 μm
PM_{10} - Fine particles in suspension with a diameter of ≤10 μm
NH_3 – Ammonia
BaP – Benzo(a)pyrene
GWP – Global warming potential
CCAC - Climate and Clean Air Coalition
AT – Active transportation
MT – Motor vehicles
CWC – Closed Window condition
CWO – Car with open windows
UFP – Ultrafine particles
BPOC - Chronic obstructive pulmonary disease
UV - Ultraviolet radiation
CTM – Chemical transport models
EPA – Environmental Protection Agency
GATOR - Global Atmospheric Transport and Chemistry Model
CMAQ - Community Multiscale Air Quality Model
LUR - Land Use Regression
V2I - Vehicle-to-Infrastructure
UE – European Union
AEM – The European Environment Agency
BEV – Battery-powered electric vehicles
COVID-19 – The COVID-19 pandemic
CO_{2e} – Carbon dioxid equivalent
PNRR - National Recovery and Resilience Plan
IPPC - Integrated Pollution Prevention and Control
SF_6 - Sulfur hexafluoride
SCR – Selective catalytic reduction systems
SEE – European Economic Space
TEN-T - Trans-European Transport Network
CAGR - Compound annual growth rate
U.R.A.C. Repair Plant and Central Workshop

ROCAR - Romanian manufacturer of buses, trolleybuses, and light commercial vehicles**I.C.P.E.-S.A.E.R.P.-S.A**. - Institutul de Cercetare și Proiectare pentru Electrotehnică – Societatea de Acționări Electrice și Relee de Protecție
P.M.U.D. – Sustainable Urban Mobility Plan
STL – Long-term strategy
PNIESC - National Integrated Plan on Energy and Climate Change
SRE - Share of renewable energy sources
IPPU - Industrial processes and use of products
REF – The reference scenario
HGV – Heavy vehicles
LCV – Light-duty vehicles
SRE-T - Renewable energy in transport
EwbTAG - Web-based transportation analysis guide
BEI - European Investment Bank
BERD - European Bank for Reconstruction and Development
LEAP_ RO – Low Emission Analysis Platform in Romania
INS - National Statistical Institute
JRS TIMES EU – Transport model for decarbonization scenarios
ELIPTIC – Electrification of Public Transport In Cities
PAED - Sustainable energy action plans
PACED - Action plans for climate and sustainable energy
IRR - Internal rate of profitability
NPV - Net present value of the project
ACE - Cost-effectiveness analysis

CHAPTER 1 CURRENT STATUS OF ATMOSPHERIC POLLUTION

1.1. General considerations on atmospheric pollution

The effects of atmospheric pollution and climate change are global phenomena that are mutually reinforcing. The relationship between the two is complex and interactive, as the main sources of air pollution, namely industrial activities, transport emissions, and fossil fuel-based energy production, also contribute to climate change [1].

In 2016, air pollution was considered by the World Health Organization (WHO) to be the most significant risk to environmental deterioration and was attributed to 7 million premature deaths annually [2,3]. In Romania, emissions causing air quality deterioration are mainly located in large urban agglomerations and derive from both stationary sources, such as combustion plant and industrial activities, and from mobile sources, in particular road transport.

According to WHO estimates, over 99% of the global population is overexposed to air pollution levels that are higher than the recommended limits in air quality standards [2,3].

The combustion processes of biofuels, biomass, and biogas can generate emissions of volatile organic compounds (VOCs) and particulate matter, contributing to air quality damage [4] and the incomplete combustion of those types of fuels in closed environments is estimated to be responsible for approximately 3.5 million deaths annually globally [5].

Consideration should also be given to shorter-lived atmospheric pollutants, known as short-lived climate pollutants (SLCPs), including methane (CH_4), black carbon, and selected hydrofluorocarbons (HFCs), which significantly contribute to short-term global warming [6]; which, although they have a significantly shorter lifetime than carbon dioxide (CO_2), still have a significant global warming potential and are a major source of the short-term climate change [7-11].

Over the last 10 years, concerns about identifying solutions and reducing the impact of air pollution on quality of life has been a major focus of scientific research, driven by the rapid increase in greenhouse gas emissions and the growing incidence of respiratory diseases among urban populations. In this area, two search engines that included transport and carbon footprints were particularly noteworthy, as shown in Figure 1.1.

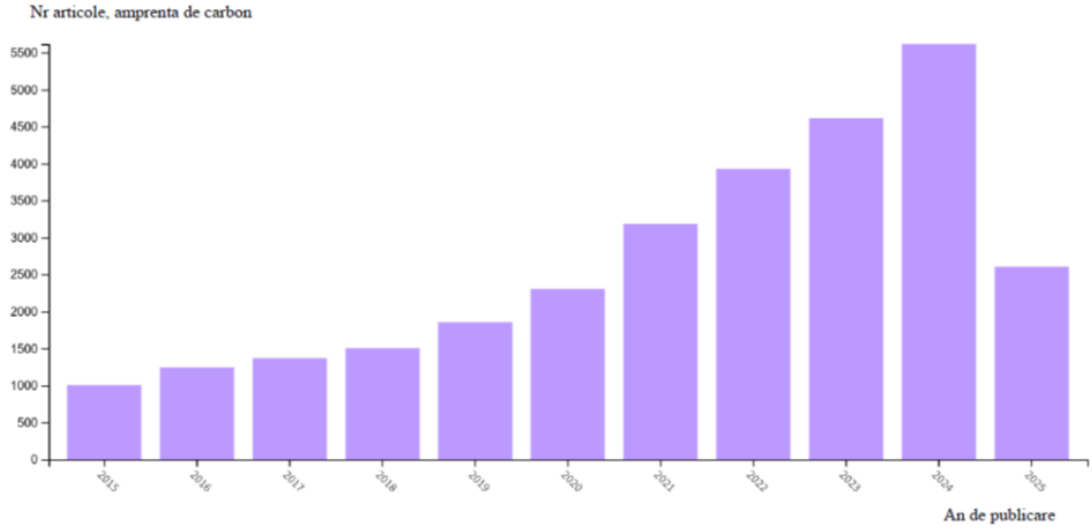


Figure 1. 1 1. Publications according to Web of Science using the keywords "Public Transport Pollution" and "Carbon Footprint" for the period 2015-2025

Types of pollutants and sources of air pollution

Air pollution, and CO_2 emissions in particular, cause serious environmental challenges, which are mainly caused by human activities. The main activities that generate primary and

secondary pollutant emissions include industrial processes, transportation, and energy production [12]. All these pollutants, that affect human health, represent up to 8.2% of global greenhouse gas emissions [13] and cause an increase in global CO_2 emissions, further contributing to the worsening of climate change.

Road transport represents a significant source of air pollutants, indicating an urgent need to implement effective measures to reduce emissions associated with road transportto ensure optimal public health [14]. In in addition to technological solutions, air pollution reduction strategies also include restricting the use of private vehicles and promoting sustainable public transport.

The impact of air pollution and the effects on the planet and people

The World Health Organization (WHO) considers that the survival of humanity is currently the most vulnerable dimension in the face of climate change, overtaking all other identified sources of threat [15]. The process of burning fossil fuelsrepresents the main source of global greenhouse gas emissions, substantially contributing to climate change and simultaneously generating emissions of air pollutants with detrimental effects on air quality and public health [16].

Based on the latest Global Burden of Disease study, the age-standardized mortality rates associated with the main causes of air pollution have dropped by 23% between 2006 and 2016, which shows significant progress in reducing the impact of air pollution on people's health [17].

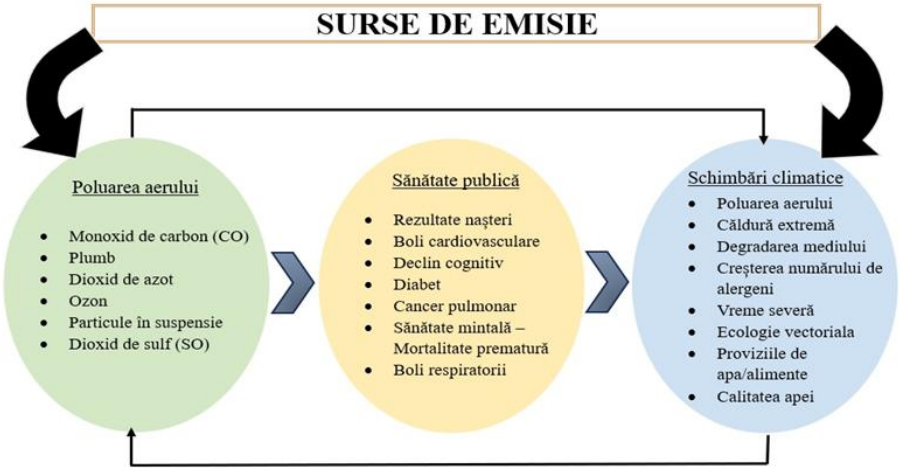


Figure 1.3.1. The connection between air pollution, climate change, and human health [18].

1.4. Measures to reduce air pollution through the implementation of sustainable solutions.

At the global level, only about 12% of the urban population is living in areas that are in compliance with the air quality standards established by the World Health Organization (WHO) [19].

1.4.1. Sustainable energy and transport systems

The integration of renewable energy sources makes a significant contribution to environmental protection, thereby also having a positive impact on the economy by reducing dependence on capital imports and stimulating job creation in sustainable sectors [20]. Renewable energy sources are a fundamental pillar of the transition to a sustainable development model, ensuring environmental sustainability by reducing greenhouse gas emissions and conserving natural resources [21]. The share of energy from renewable sources in total electricity consumption increased significantly, from 10% in 2008 to 18.1% in 2017, reflecting the progress of energy transition from fossil fuels to renewable sources [22].

1.4.2. Green infrastructure and energy-efficient construction

In the final energy consumption mix of many countries, the residential and non-residential sectors have a significant share, collectively representing around 40% of total energy demand. Urban green infrastructure is gaining acceptance as a strategic policy tool for climate change mitigation [23].

Figure 1.4.2.1 presents comparative flow patterns of air and atmospheric pollutant dispersion in street canyons, based on the presence or absence of different urban vegetation patterns.

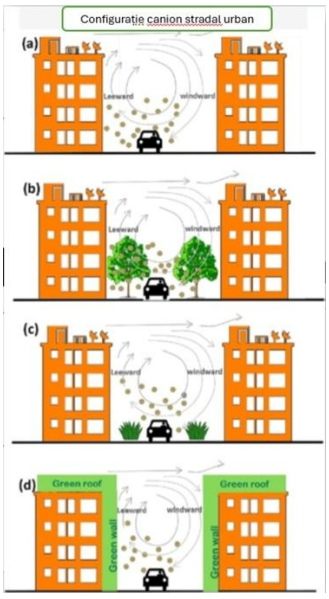


Figure 1.4.2.1. Flow dynamics and pollutant dispersion analysis in a street canyon [24].

1.4.3. Air pollution simulation models

Simulations are increasingly used to understand and predict how pollution propagates [25].

Several Chemical Transport Model (CTM) models are now available, such as the Urban Airshed Model (developed by the EPA), the Caltech model, the Global Atmospheric Transport and Chemistry Model (GATOR) and the Community Multiscale Air Quality Model (CMAQ). These computational tools are essential components in air quality assessment and planning, through their ability to simulate atmospheric transport, chemical processes, and pollutant dispersion at multiple temporal and spatial scales, from local to global. Land use regression (LUR) models represent an accurate method for improving estimates of air pollutant concentrations at the ground level.

1.4.4. Control measures

The recommended actions can be applied in a variety of situations, depending on the specific source of air pollution. Figure 1.4.4.1. shows the basics of how the actions work.

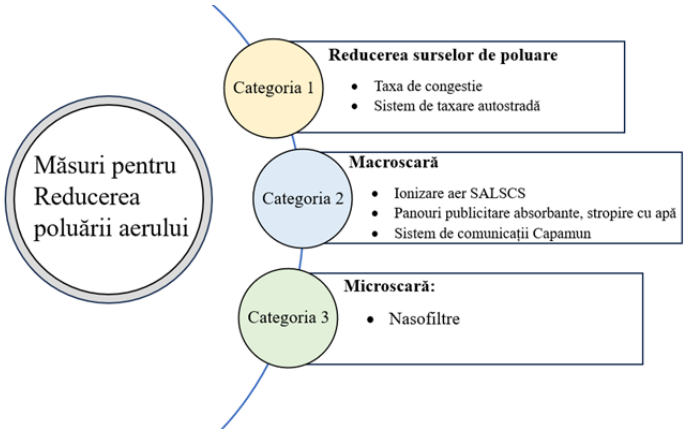


Figure 1.4.4.1. Rentable strategies for air pollution control [26]

CHAPTER 2. THE INFLUENCE OF THE TRANSPORT SECTOR ON AIR QUALITY

2.1. Current situation in the European Union regarding transport activity and environmental quality

Transport is an sector that is essential for the operation of modern economies, for the mobility of the population, and the transition to a more sustainable transport sector requires consistent public policies and strategic investments, focused on solutions to reduce the impact on the environment, climate, and human health [27].

In 2022, Romania ranks among the European Union member states with the highest levels of carbon dioxide emissions, mainly due to a poor tax policy regarding the imposition of charges on polluting emissions, as shown in Figure 2.1.

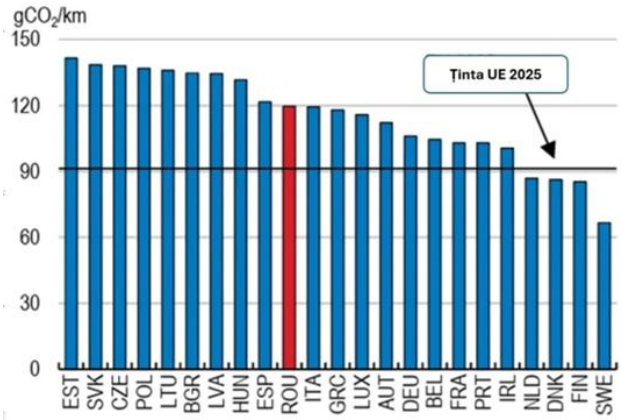


Figure 2. 1. CO_2 emissions from cars in 2022 [28].

With an estimated population of 2,133,306 inhabitants in 2024 [29], Bucharest Municipality, Romania, in recent years has seen increased investment in transport infrastructure to respond to increasingly complex urban mobility challenges. Even so, the expansion of infrastructure hasn't been followed by a real decrease in the pressure on the road network. Bucharest is ranked 8th globally in terms of the Road Traffic Congestion Index, according to data for 2023, with average congestion estimated at around 55%.

2.2. Key performance indicators for emissions to air from the transport sector

Emissions of most air pollutants from the transport sector in the EU-27 were significantly declining [30] as can be seen in Figure 2.2.

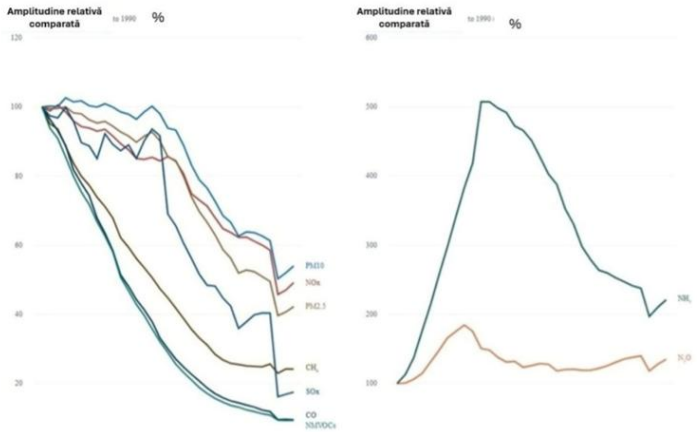


Figure 2. 2 Emissions of pollutants from transport in the EU-27 [30].

Roads are the primary source of emissions in the transport sector, responsible for 73.2% [30] of total greenhouse gas emissions produced by this sector in the European Union in 2022, encompassing both domestic and international freight transport.

2.3. Health impacts from air pollution caused by transport

Long-term exposure to transport noise has been shown to have negative effects on human health, including stress, sleeplessness, cardiovascular disease, and ear damage. Based on data reported in 2017 in accordance with the Environmental Noise Directive, it is estimated that, at EU level [31], around 18 million people are seriously affected and another 5 million experience

significant sleep disturbance from long-term exposure to traffic noise. This is why the EU's "Zero Pollution" Action Plan sets a goal to reduce the number of people exposed to transport noise by 30% by 2030 compared to 2017 levels.

2.4. The impact of different transport modes on air pollution

The main objectives of the European Environment Action Plan for Sustainable Development of Transport include halving the volume of rail freight transport by 2050 and increasing inland waterway transport and short sea shipping by 25% by 2030. The European Commission launched a series of strategic initiatives addressing the supply aspect of the transport system, which include the revised Regulation on the trans-European transport network (TEN-T) [32], entered into the national legislation of all Member States in July 2024.

2.5. Bus and train pollution indicators

Promoting sustainable modes of transport, in particular public transport, has been identified as an essential instrument for achieving the decarbonization of transport, and the European Union's Strategy [33] on sustainable and smart mobility underlines the key role of public passenger transport as part of the transition to a more sustainable transport system.

2.6. Statistics on the sustainability of mobility systems in Europe

The total volume of passenger transport registered in the EU-27 in 2019amounted to 6 billion passenger-kilometers, not including international air transport (non-EU), which reflects a 33.5% increase in passenger mobility compared to 1995 [34]. Global transport activity is expected to keep growing from 5,618 billion passenger-kilometers in 2015 to 6,088 billion passenger-kilometers in 2025 (98.4% compared to 2015), and to 6,487 billion passenger-km in 2030 (15.5% compared to 20215), according to the European Commission's recent MIX-FF55 scenario [35].

2.6.1. Transportation by car

In 2022, approximately 4,100 billion passenger kilometers traveled by car, and between 1995 and 2022, this increase was 24.8%. The COVID-19 pandemic has significantly impacted car connectivity, with approximately 4.299 billion passenger-km in 2019, representing a 30.9%

increase compared to 1995. In 2022, cars accounted for about 73% of passengers per km, falling by only 1.4% between 1995 and 2019.

2.6.2. Public transport

In 2022, compared to 1995, transport activity measured in passenger-kilometers declined by 13.2% for buses, 28.7% for trains, and 8.4% for trams and subways.

2.6.3. Mitigating greenhouse gas emissions from heavy-duty vehicles across Europe.

The data on passenger rail transport indicates a significant expansion of activity in the high-speed rail segment, from 32.5 billion passenger-kilometers in 1995 to a peak of 134.0 billion passenger-kilometers in 2019, when this mode of transport accounted for 31.8% of total rail passenger traffic in the EU-27 [33]. According to predictions, passenger transport by buses and coaches is estimated to hit 542 billion passenger-kilometers by 2030.

2.6.4. Air transport (domestic and international intra-EU)

Domestic and international air transport in the European Union (EU-27) recorded a maximum of approximately 575 billion passenger-kilometers in 2019, accounting for a modal share of 9.6% of total passenger transport activity, and during the COVID-19 pandemic, it declined by more than 50% (in 2020) to approximately 176 billion passenger-kilometers [36]. Projections estimate that intra-EU-27 domestic and international air transport activity will reach 612 billion passenger-kilometers by 2030.

2.6.5. Maritime transport (domestic and international intra-EU)

In 2019, maritime passenger transport, on both domestic and international intra-EU routes, registered a total volume of approximately 21 billion passenger-kilometers, representing a modal share of 0.4% of total passenger transport activity. This mode of transport was one of the most severely affected by the impact of the COVID-19 pandemic, with a significant decline to 11 billion passenger-kilometers in 2020 and by 2022 [36].

2.6.6. Other transportation systems

Two-wheeled motor vehicles represented approximately 2.0% of total passenger kilometers in 2022, remaining relatively constant over the years at 2% of the transport activity, which corresponds to an estimated total of approximately 110 billion passenger kilometers[36].

2.7. Public transport in Romania

2.7.1. The public transport system

Romania is a country with a solid industrial tradition in urban transport, as highlighted by the activity of vehicle manufacturers such as URAC Bucharest, Electroputere Craiova, and Electro Timiș. One of the strategic directions of the PMUD is to restructure modal transport distribution in favor of electric vehicles for public transport, with the objective of these vehicles representing 77.1% of the total fleet by 2030 [37].

In spring 2015, with the support of the Bucharest City Hall, two types of electric buses [38,39] were tested at STB-S.A.: the SOR EBN 10.5 bus and the BYD EBUS -12 model K9 bus. These were later removed from service due to a lack of charging infrastructure

2.7.2. Transport decarbonization strategy in Romania

In Romania, the Long-Term Strategy (LTS) for reducing greenhouse gas emissions – "Neutral Romania" – was adopted by Government Decision No. 1215/2023 [40].

The long-term strategy (LTS) is based on a benchmark analysis of three development scenarios: the reference scenario (REF), the intermediate scenario (Medium) and the "Neutral Romania" scenario (Neutral RO). Under the RO Neutral scenario, GHG emissions in the transport sector will be cut by 82% by 2050. By comparison, the RO Neutral scenario is 88% ambitiously than the REF scenario.

In the RO Neutral scenario, a big drop in the share of diesel-powered freight vehicles (HGVs and LCVs) is predicted, from about 90% in 2019 to around 55% in 2030, and these vehicles are expected to be phase out completely by 2050.

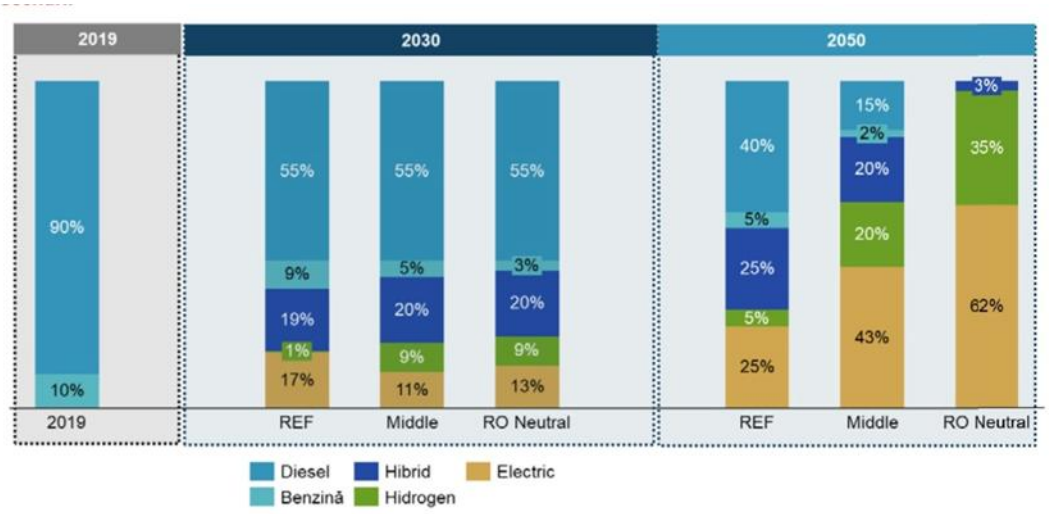


Figure 2.7. The evolution of the types of freight vehicles based on the fuel used according to the three scenarios [41].

CHAPTER 3. OBJECTIVES AND WORKING METHODOLOGY

3.1. Purposes and objectives of the doctoral thesis

In the doctoral thesis, the following scientific and technical objectives were considered:

1. Greenhouse gas (GHG) emissions estimation for conventional, hybrid, and electric buses, using the JASPERS method for quantifying and comparison of specific emissions for all bus types.
2. Identifying the determination factors of the carbon footprint
3. Comparison of ecological and economic efficiency, evaluating the environmental and economic benefits of public transport electrification compared to conventional solutions
4. Modelling optimization scenarios to estimate GHG emissions and carbon footprintby using the JASPERS method, in accordance with national and regional environmental protection policies.
5. Drafting recommendations for decision-makers, suggesting ways to improve public transport to cut carbon footprints and align with urban sustainability targets.
6. Making public transport systems better by calculating CO_{2e}, particularly for bus line 368.

3.2. Research methodology

The research methodology developed for estimating emissions and carbon footprintshas been applied for the first time in Bucharest, for conventional, hybrid, and electric buses. Electric buses were introduced in 2024.

The research method for figuring out GHG emissions and the carbon footprint is shown in Figure 3.2.1.

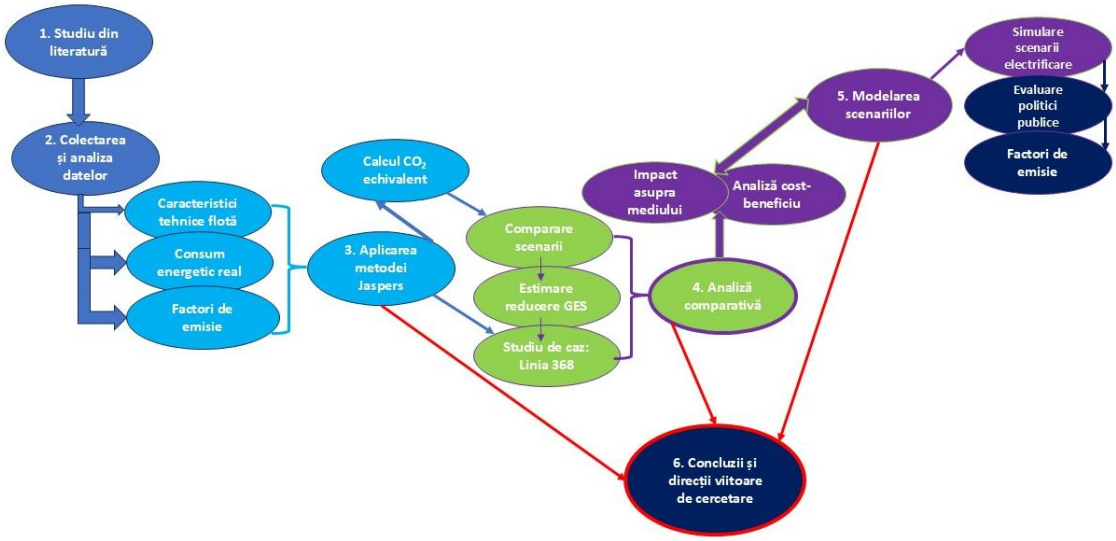


Figure 3. 1. 1. Schematic representation of the worksheet

3.1.Metode de analiză

For the quantitative assessment of GHG emissions and carbon footprint, the transport sector-specific aggregate method, Jaspers (Joint Assistance to Support Projects in European Regions) [42], was used. The info used comes from the transport model, including: the assessment year (as a reference for projections), the annual vehicle mileage, detailed by technology category (EURO III, EURO IV, EURO VI, hybrid, and electric buses). For electric vehicles, the specific energy consumption (kWh/km) was taken from the WebTAG database (Transport Analysis Guidance, United Kingdom). The emission rate associated with electricity consumption reflects the amount of greenhouse gases (GHG) emitted per unit of energy (kWh) consumed from the national electricity grid.

The phases of using the working tool are presented in Figure 3.2.2.

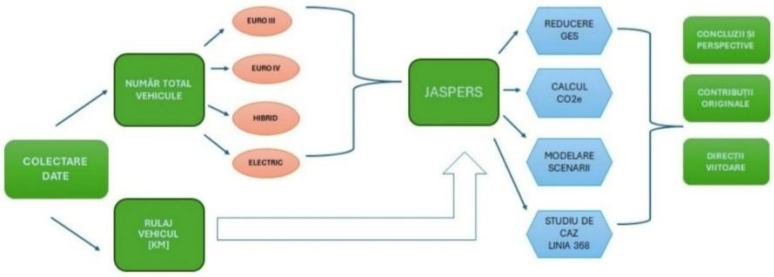


Figure 3.2.2. Stage of use of the working tool

3.1.1. GHG emissions estimation and carbon footprint calculation for the bus fleet

The GHG emissions were estimated based on annual fuel and electricity consumption data for each type of vehicle in the fleet. The analyse included thre main types of buses: conventional diesel buses, hybrid buses and electric buses powered by the national grid.

The following parameters were taken into account for each vehicle category: specific annual fuel consumption (liters) or electricity consumption (kWh); emission factors (kg CO_2e/unit of fuel); number of kilometers traveled annually; and specific energy efficiency of vehicles.
For electricity, emissions were estimated based on Romania's national energy mix, considering an average factor of 0.29 kg CO_2e/kWh. For diesel buses, non-CO_2 emissions (CH_4 and N_2O) were also considered, converted to CO_2 equivalents based on global warming potential (GWP) as follows:

- 1 kg CH_4 = 23 kg CO_2e
- 1 kg N_2O = 298 kg CO_2e.

CAPITOLUL 4. RESEARCH ON ESTIMATING EMISSIONS FROM THE BUCHAREST TRANSPORT OPERATOR'S BUS FLEET

4.1. Analysis of the Bucharest public transport fleet between 2021 and 2024 in relation to environmental targets.

In order to estimate the GHG emissions generated by the STB fleet, the first stage of the doctoral research involved analyzing the current situation and correlating it with environmental targets. The study period for the data collection and processing was between 2021 and 2024, considering that this is the period of modernization of the STB.

The public transport operator in Bucharest covers a total area of 1,335 km², of which 240 km² is in the urban area. The Bucharest Transport Company (STB S.A.) provides mobility for approximately 1.071 million passengers daily, operating a network of 1,640 buses, 265 trolleybuses, and 527 trams [38]. Over the last four years, the STB-S.A. fleet has been modernized by 43% following the procurement of 130 hybrid buses and 100 electric buses.

4.2. Multi-purpose use of the electricity supply infrastructure of transport operators in Bucharest.

Since 2006, Romania has been one of the main beneficiaries of JASPERS technical assistance for project development, with a focus on addressing cross-sectoral challenges and strengthening the institutional capacity of beneficiaries.

As part of the European Eliptic project, it has been found that, following the modernization of the drive systems installed on electric vehicles, energy consumption has decreased, and it has been calculated that the average hourly consumption and maximum hourly consumption for the 38 existing electrical substations.

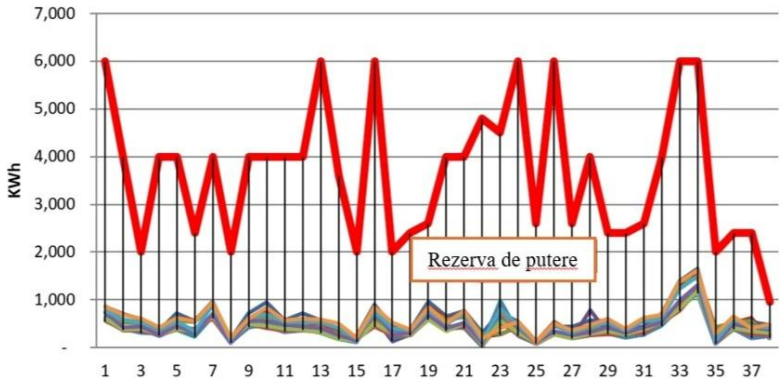


Figure 4. 1.1. Maximum hourly consumption and installed power (KWh) / (KVA).

Using this energy resourcefor charging electric vehicle batteries is associated with additional energy losses, which can reach approximately 40% of the total energy used. That's why an energy balance should be done to see if this solution is feasible given the transport infrastructure that's about to be upgraded.

For this purpose, in 2023, feasibility studies were carried out for the construction of three tram depots in Bujoreni, Berceni, and București Noi for electric bus charging stations, in order to provide the necessary infrastructure for environmentally friendly transport, in accordance with European standards in vigor - European Directive 2009/33/EC [43] promoting clean and sustainable transport, which were actually started in 2024.

CAPITOLUL 5 . ESTIMATION OF GHG EMISSIONS FROM THE BUS FLEET OF THE BUCHAREST TRANSPORT OPERATOR AND CARBON FOOTPRINT ASSESSMENT

5.1. Bus fleet available at the time of the estimate and emission factors taking into account

In order to calculate emissions, several specific emission factors were taken into account, in accordance with the JASPERS methodology and the guidelines of the IPCC (Intergovernmental Panel on Climate Change) Guide.

When calculating GHG estimates using the Jaspers method, it was assumed that the existing bus fleet in December 2024, after the modernisation of the fleet, would take into account the existing fleet of buses. This is presented in Table 5.1.

Table 5. 1 STB – S.A. bus fleet at December 2024 [38].

Category	Bus type	Total fleet	Active fleet
Euro III	MERCEDES E3	498	319
Euro IV	MERCEDES E4	500	407
Euro VI	OTOKAR	400	375
Hybrid	MERCEDES HYBRID	130	124
Electric	ZTE GRANTON	100	59
Uncategorized	DAF, ROCAR, VOLVO	10	-
TOTAL		1638	1284

The GHG emissions rate for electricity in Romania is 0.517 kgCO2/kWh. The equivalent GHG factors used to convert each greenhouse gas into CO2e are presented in Table 5.3. For electric buses, the mileage (km) and energy consumption (kWh) were taken into account, using conversion factors from Table 5.3. [44].

Table 5. 2 Equivalent GHG factors for converting each greenhouse gas into CO2e [44].

Gas	Conversion factor
CO_2	1
N_2O	298
CH_4	23

5.1. Estimated GHG calculations for the bus fleet of the transport operator in Bucharest for the period 2021-2024.

In order to estimate CO2, CH4, N2O, and CO2e emissions for 2021-2024, the Jaspers methodology was used, including the conversion factors corresponding to the associated GHG gases. The GHG emissions of the bus fleet and the mileage of the buses owned by the transport operator in Bucharest in 2021, 2022, 2023, and 2024 are presented in Tables 5.2.1–5.2.4.

Table 5.2.1. GHG emissions and mileage in 2021 for the STB S.A. bus fleet [38].

Bus type	Mileage in 2021 [km]	Fuel consumption 2021 [l]	Average fuel consumption in 2021 [l/100 km]	CO_2 [kg]	N_2O [kg]	CH_4 [kg]	CO_{2e} [kg]
Mercedes E3	18,226,110	7,774,928.57	42.66	20,681,310.00	1,088.49	1,088.49	21,030,715.29
Mercedes E4	20,135,777	9,234,892.85	45.86	24,564,814.98	1,292.88	1,292.88	24,979,831.07
Mercedes E6	26,090,771	11,702,904.76	44.85	31,129,726.66	1,638.41	1,638.41	31,655,655.20
Mercedes Hibrid	8,438,313	3,662,690.47	43.41	9,742,756.65	512.78	512.78	9,907,357.96
Total 2021	**72,890,971.00**	**32,375,416.65**		**86,118,608.29**	**4,532.56**	**4,532.56**	**87,573,559.51**

GHG emissions for the bus fleet owned by the transport operator in Bucharest in 2022 are estimated in Table 5.2.2.

Table 5.2.2. GHG emissions and mileage in 2022 for the STB S.A. bus fleet [38].

Bus type	Mileage in 2022 [km]	Fuel consumption 2022 [l]	Average fuel consumption in 2022 [l/100 km]	CO_2 [kg]	N_2O [kg]	CH_4 [kg]	CO_{2e} [kg]
Mercedes E3	12,776,333	5,936,630.00	46.46	15,791,435.80	831.13	831.13	16,058,227.95
Mercedes E4	22,141,716	9,710,440.47	43.86	25,829,771.65	1,359.46	1,359.46	26,266,158.84
Mercedes E6	28,856,728	13,604,726.20	47.15	36,188,571.69	1,904.66	1,904.66	36,799,968.09

Mercedes Hibrid	3,483,087	1,477,369.04	42.42	3,929,801.65	206.83	206.83	3,996,194.61
Total 2022	**67,257,864.00**	**30,729,165.71**		**81,739,580.79**	**4,302.08**	**4,302.08**	**83,120,549.50**

Tabel 5.2.3. GHG emissions and mileage in 2023 for the STB S.A. bus fleet [38].

Bus type	**Mileage in 2023 [km]**	**Fuel consumption 2023 [l]**	**Average fuel consumption in 2023 [l/100 km]**	**CO_2 [kg]**	**N_2O [kg]**	**CH_4 [kg]**	**CO_{2e} [kg]**
Mercedes E3	11,181,123.18	5,404,561.81	48.34	14,376,134.41	756.64	756.64	14,619,015.42
Mercedes E4	22,602,869.62	10,414,273.80	46.08	27,701,968.31	1,458.00	1,458.00	28,169,985.77
Mercedes E6	25,847,518.17	12,252,853.42	47.40	32,592,590.10	1,715.40	1,715.40	33,143,233.33
Mercedes Hibrid	7,690,672.00	3,493,423.34	45.42	9,292,506.08	489.08	489.08	9,449,500.53
Total 2023	**67,322,182.97**	**31,565,112.37**		**83,963,198.90**	**4,419.12**	**4,419.12**	**85,381,735.05**

Tabel 5.2.4. GHG emissions and mileage in 2023 for the STB S.A. bus fleet [38].

Bus type	**Mileage in 2024 [km]**	**Fuel consumption 2024 [l]**	**Average fuel consumption in 2024 [l/100 km]**	**CO_2 [kg]**	**N_2O [kg]**	**CH_4 [kg]**	**CO_{2e} [kg]**
Mercedes E3	7,729,288	3,736,066.05	48.33	9,937,935.70	523.05	523.05	10,105,834.51
Mercedes E4	21,302,756	9,815,246.36	46.08	26,108,555.31	1,374.13	1,374.13	26,549,652.48
Mercedes E6	20,790,982	9,855,834.25	47.40	26,216,519.11	1,379.82	1,379.82	26,659,440.30
Mercedes Hibrid	8,204,755	3,726,941.24	45.42	9,913,663.69	521.77	521.77	10,081,152.43
Total 2024	**58,027,781**	**27,134,087.90**		**72,176,673.81**	**3,798.77**	**3,798.77**	**73,396,079.72**

CO_{2e} emissions for the complete bus fleet in 2024 are estimated in Table 5.2.5.

Table 5.2.4. Estimated CO_{2e} emissions of STB-S.A. in 2024, after modernization of the fleet with electric vehicles

Bus type	Mileage 2024[km]	CO_{2e} [kg]
GRANTON	2,081,429	1.090
Total flotă autobuze STB-S.A.	**60,109,210**	**74,485,933.81**

The total CO2e emissions estimated for 2024 are 74.5 kilotons, which is a substantial reduction of almost 13% compared to 2023; this improvement is due to the reduction in the mileage of the entire bus fleet, but also to the introduction of electric buses. Emissions from buses running exclusively on diesel engines were cut by about 12 million kg CO_{2e} during the period analyzed, pointing to the start of a shift toward a more sustainable urban transport system.

The evolution of the total annual turnover and the turnover specifically attributed to hybrid and electric buses for the STB S.A. bus fleet between 2021 and 2024 is presented in Figure 5.2.1.

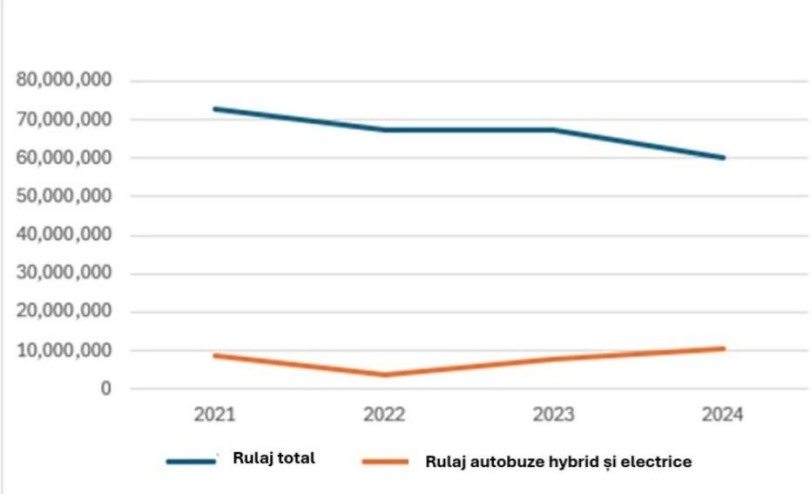


Figure 5. 2. 1 Bus mileage in the STB S.A. fleet between 2021 and 2024. The blue line represents the total mileage of all buses, and the orange line reflects the mileage of hybrid and electric vehicles.

While electric and hybrid vehicles account for a relative share of total kilometers traveled, their upward curve reflects a positive trend toward reducing emissions and improving energy efficiency in urban public passenger transport. Figure 5.2.2. illustrates the share of electric and hybrid buses compared to the total fleet between 2021 and 2024.

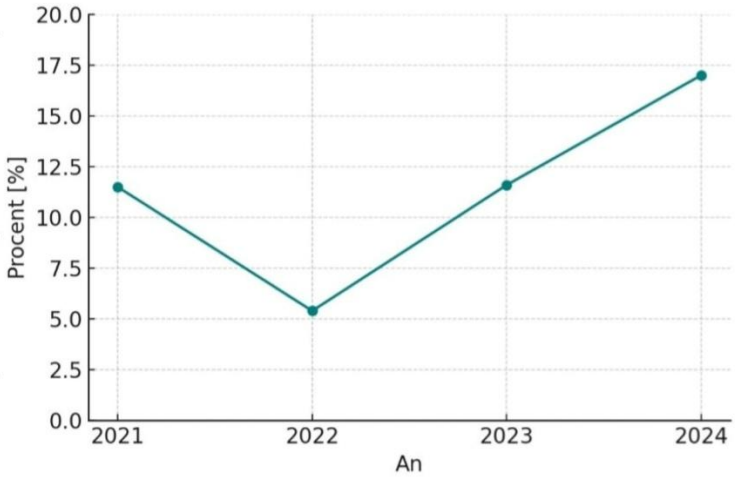


Figure 5.2.2. The share of hybrid and electric buses operating for STB S.A. between 2021 and 2024.

In 2024, electric buses accounted for approximately 3.47% of the total distance traveled by the vehicle fleet.

A relevant comparison can be noted between 2023 and 2024: specific emissions per kilometer are very closer in value between these years, being 1.268 kg/km in 2023 and 1.264 kg/km in 2024, only for diesel vehicles (Figure 5.2.3). The introduction of electric buses in 2024 has led to a 2.68% reduction in specific emissions per kilometer compared to the previous year.

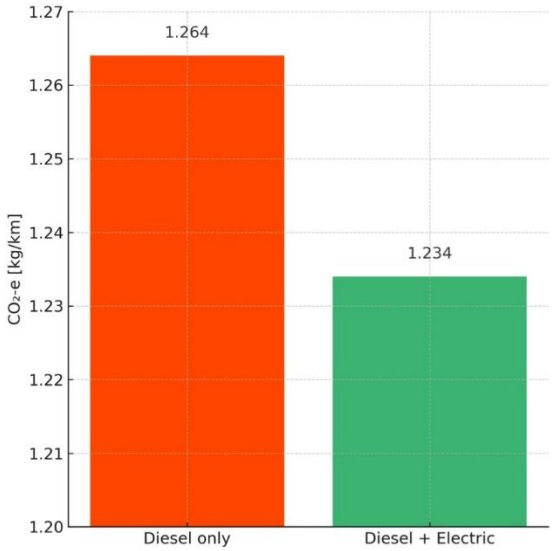


Figure 5.2.3. Specific CO2e emissions per km of the bus fleet operated by STB-S.A. in 2024.

The estimated evolution of greenhouse gas emissions for the STB-S.A. bus fleet in the period 2021-2024 is presented in Figure 5.2.4.

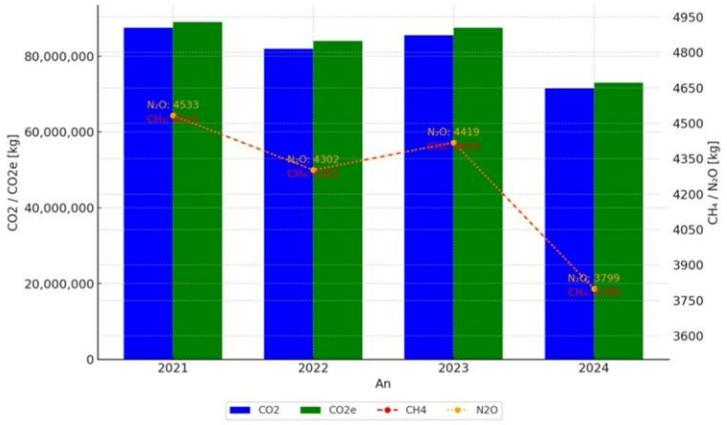


Figure 5.2.3 Estimated GHG emissions for buses in the STB-S.A. fleet between 2021 and 2024.

The estimated carbon footprint reduction for the entire bus fleet is approximately 11 kilotons of CO_2e, confirmed by previous performance. Based on the results of the previous year, we estimated that switching from an all-diesel scenario to one with electric vehicles in 2024 could reduce total emissions by more than 12%. This cut shows how electric vehicles can really make a difference in meeting decarbonization goals. Going electric for transportation also has other benefits, like reducing noise pollution and improving local air quality, which is a win for public health and quality of life in cities.

5.2. Estimated GHG calculations for the bus fleet on STB-S.A. bus line 368.

Line 368 of STB-S.A. is a homogeneous and fluid bus line that serves an important part of Bucharest, as can be seen in Figure 5.3.1.

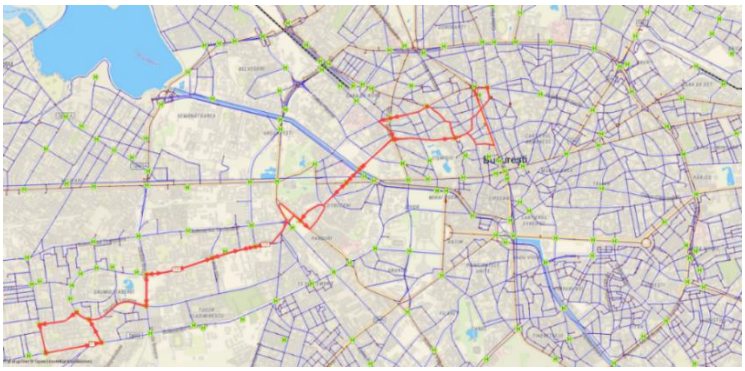


Figura 5.3.1. Map of bus route 368 operated by STB-S.A.

To evaluate the impact of introducing electric buses on the environmental performance of urban transport, the 368 bus line was analyzed, which operates with a total of 15 buses, of which 7 are electric.

Table 5.3.1. presents GHG emissions in both scenarios, diesel-only and diesel + electric.

Tabel 5.3.1. GHG emissions with and without electric buses on line 368 in 2024.

Scenario	**CO_2 [kg]**	**CH_4 [kg]**	**N_2O [kg]**	**CO_{2e} [kg]**	**Specific (kg/km)**	**CO_{2e}**
Diesel only	1,192,481	63	63	1,213,000	1.25	
Diesel+electrice	636,000	33	33	904,000	0.93	

The introduction of the seven electric buses has significantly reduced emissions: the total reduction in carbon footprint is 309 t CO_2e, as shown in Figure 5.3.2.

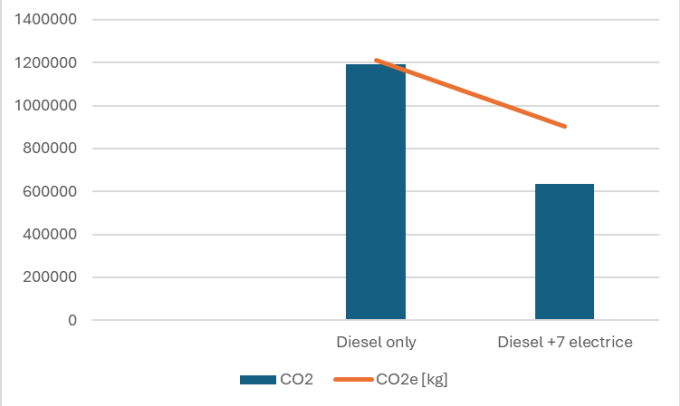


Figura 5.3.2. GHG evolution in the two scenarios for line 368, with and without the seven GRANTON electric buses.

The total emissions reported in reference to the distance traveled gives a specific emission value of 1.25 kg CO_2e/km in the diesel-only scenario and 0.93 kg CO_2e/km in the scenario with seven electric vehicles. This improvement in emissions highlights the positive impact of partial electrification on urban air quality and its contribution to lowering the carbon footprint of public transport, as shown in Figure 5.3.3.

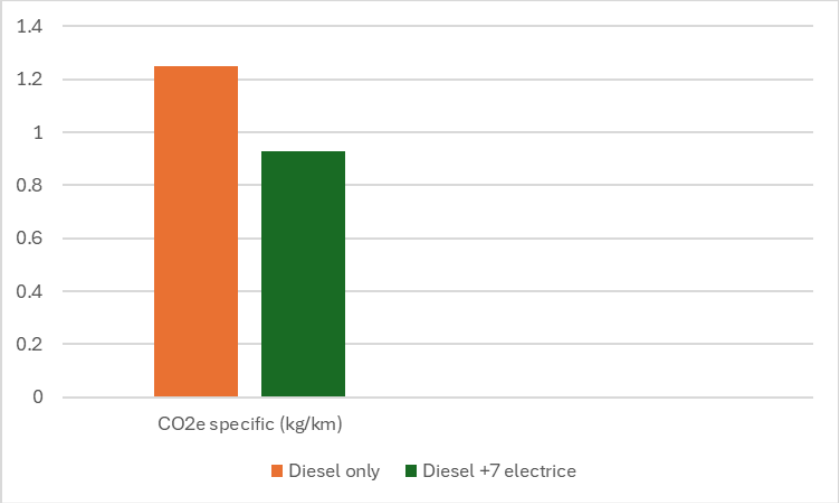


Figura 5.3.3. Specific CO2e for the two scenarios of line 368, with and without electric buses.

Furthermore, a scenario was designed in which, in 2025, five more electric buses will be introduced on line 368. The scenarios include: exclusively diesel operation, the addition of seven electric buses, and expansion to 12 electric buses out of a total of 15. The results are presented in Table 5.3.1, Figures 5.3.4 and 5.3.5, assuming that all 15 buses travel the same mileage in 2025 as in 2024.

Tabel 5.3.2.. GHG emissions for the scenario with and without the introduction of 7 additional electric buses on line 368 compared to 2024.

Scenario	Electric buses	Diesel buses	CO_2 [kg]	CH_4 [kg]	N_2O [kg]	CO_{2e} [kg]	CO_{2e} specific [kg/km]
Diesel only	0	15	1,192,48	63	63	1,213,000	1.25
Diesel+7 electric buses	7	8	636,000	33	33	904,000	0.93
Diesel+ electri	12	3	238,495	13	13	683,000	0.70

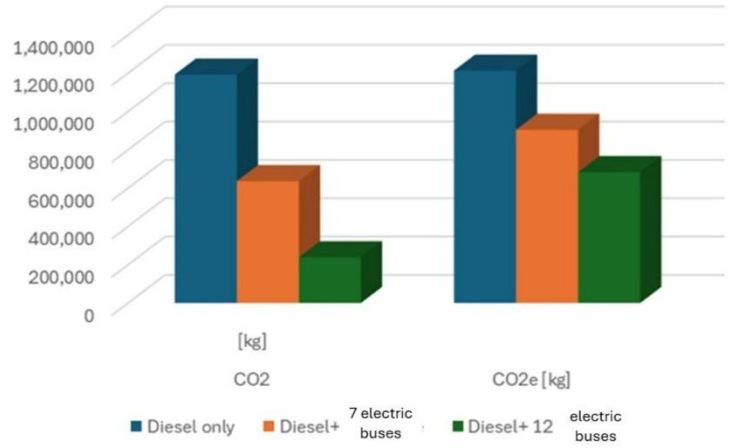


Figura 5.3.4. GHG emissions for the scenario with and without the introduction of 7 additional electric buses on line 368, compared to 2024.

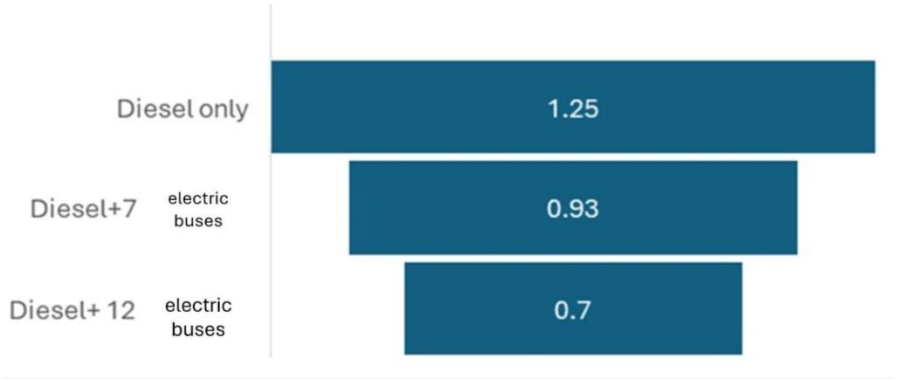


Figura 5.3.5. Specific CO2e for the scenario with and without the introduction of 7 additional electric buses on line 368, compared to 2024.

Specific CO_2e reflects the environmental efficiency of each scenario most reliably: from 1.25 kg/km in the basic scenario to 0.70 kg/km in the advanced scenario.

5.4. Estimates of GHG emissions in situations where the bus fleet of the Bucharest transport operator becomes electricity-powered.

For 2025, a scenario was developed in which 50 EURO III and EURO IV diesel buses were replaced with 50 electric buses, and the total estimated CO_2e emissions of the entire fleet are approximately 71 kt CO_2e, resulting in a reduction of approximately 3 kt CO_2e compared to 2024 (Figure 5.4.1). For this scenario, a constant reference value for diesel-only buses was estimated at 74.5 kilotons of CO_2e, similar to 2024.

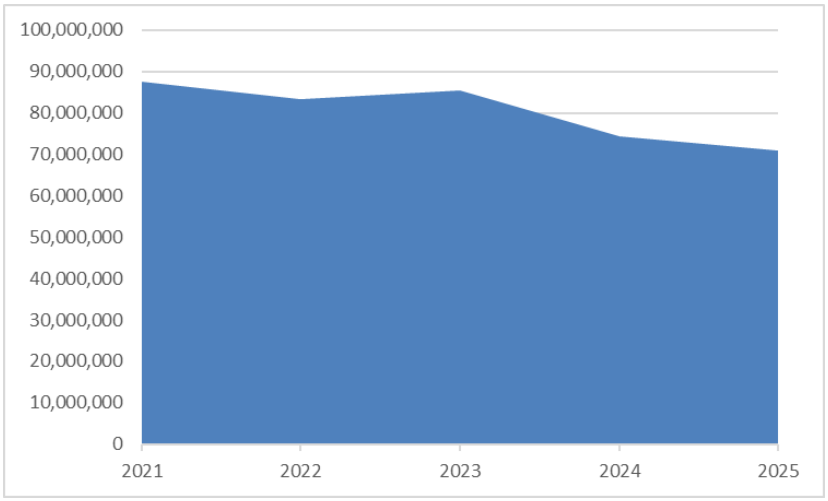


Figura 5.4.1. The carbon footprint in the scenario with the replacement of 50 diesel buses with electric buses in 2025.

Extended the scenario to 2025-2030 and replaced 50 diesel buses with 50 electric buses per year. By 2030, the total estimated CO_2e emissions of the entire fleet will be reduced by more than 11 kt CO_2e compared to 2024. Estimates of CO2 and CO emissions for the period 2025-2030 are presented in Figure 5.4.2.

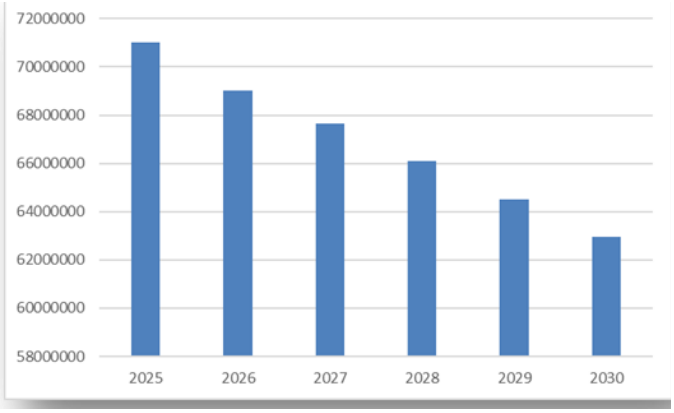


Figura 5.4.2. Estimarea emisiilor de CO_2 și CO_{2e} în scenariul pentru perioada 2025-2030, cu înlocuirea a 50 de autobuze diesel/an cu autobuze electrice.

The progressive and significant annual reduction in CO_2e emissions between 2025 and 2030 highlights the direct impact of the decarbonization of the bus fleet and the integration of clean technologies to achieve climate neutrality by 2050.

5.5. LCA cost comparison for hybrid and electric buses in the STB-S.A. fleet vs. Diesel EURO VI.

A comparative economic analysis was conducted on the life cycle costs of EURO VI diesel, hybrid, and electric buses in the fleet of a transport operator in Bucharest. and electric buses show clear advantages in terms of operating costs and environmental impact, while hybrid buses provide an efficient trade-off between initial investment and partial emission reduction. The transition to electric mobility is economically and strategically justified in the long term, especially when externalities and available funding sources (European funds, green infrastructure support schemes, etc.) are taken into account.

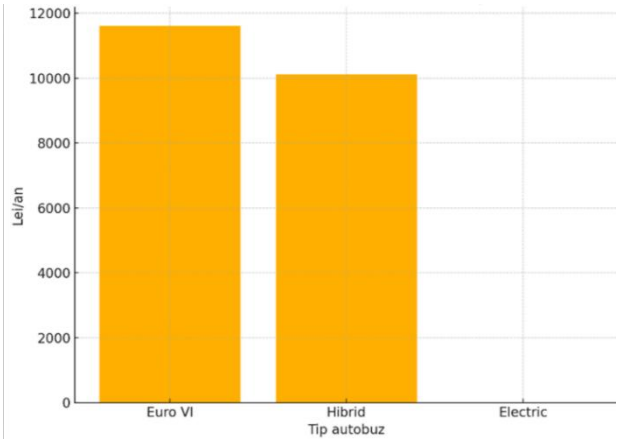


Figura 5.5.1 Total annual operating cost/vehicle for STB-S.A. bus fleet

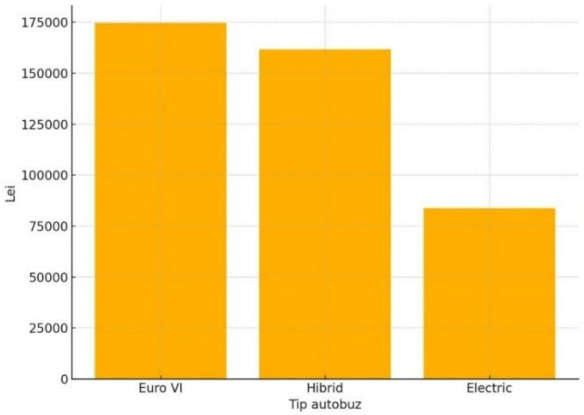


Figura 5.5.2. Annual cost of CO2 emissions per vehicle for the STB-S.A. bus fleet.

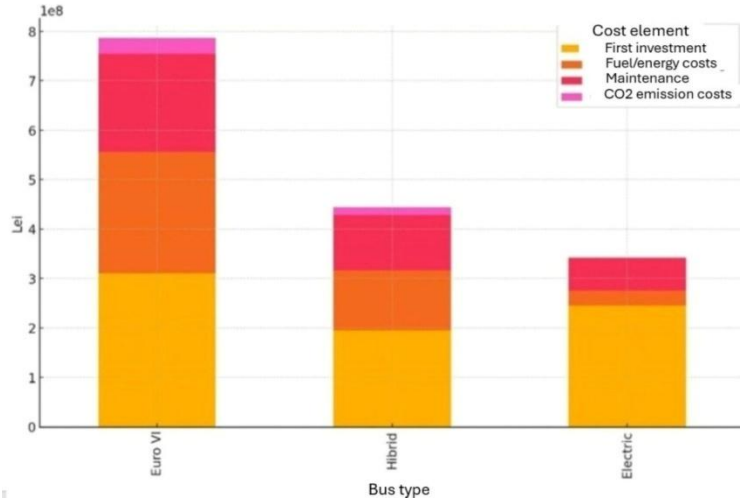


Figura 5.5.3. Life cycle cost distribution by vehicle type.

It can be seen that electric buses have zero CO_2 emissions and the lowest energy costs, but involve a significantly higher initial investment.

In terms of cumulative savings compared to Euro VI, the mixed fleet of 130 hybrid buses and 100 electric buses significantly reduces operating and emission costs as follows:

- The configuration with 130 hybrid buses brings savings of approximately 7 million lei.
- The configuration with 100 electric buses generates savings of over 22 million lei.

5.6.Cost-benefit analysis for electric bus charging stations.

The procurement of electric buses also involves costs for the installation of charging stations. Feasibility studies have been carried out for the modernization of three depots—Berceni, Bujoreni, and București Noi—and work has started, but a lot of time is being lost in obtaining permits, approvals, etc. The performance (number of kilometers per year) increases from 38 million to over 42 million km, and maintenance savings will start in 2025 and increase progressively, signaling the efficiency of the new infrastructure.

Financial indicators:

- FIRR: 24.5% → very good financial profitability.

- NPV: 15,669,535 lei → positive added value.

- Benefit/cost ratio: 1.04 → the project brings more benefits than costs.

In conclusion, the project is economically feasible, with positive cash flow in all operating years and financial indicators confirms the opportunity of the investment.

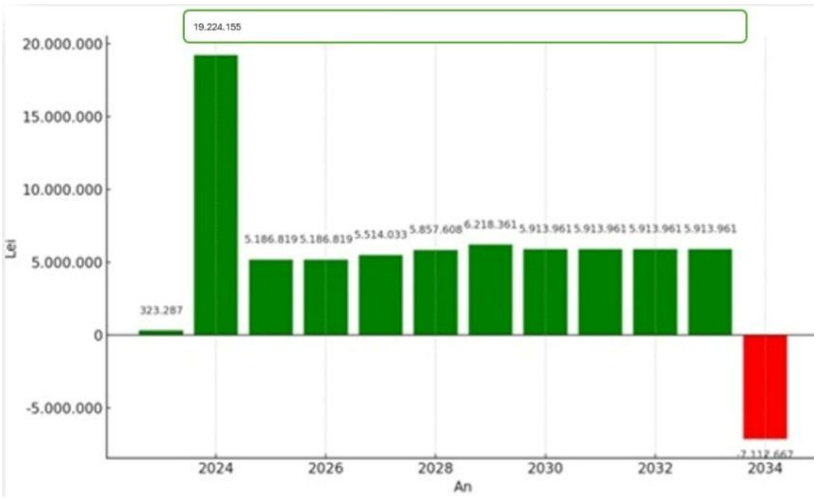


Figura 5.6.1.1 Cost-benefit analysis for the acquisition of non-polluting vehicles by STB-S.A.

5.7.The cost-effectiveness analysis for electric bus charging stations.

Considering the specificity and object of the present investment, it is recommended to perform a cost-effectiveness analysis (CEA) instead of a traditional economic analysis, which involves comparing different project options targeting a unique outcome or effect, which may differ in intensity. This is a specific scenario, focused exclusively on the electric bus charging station infrastructure component.

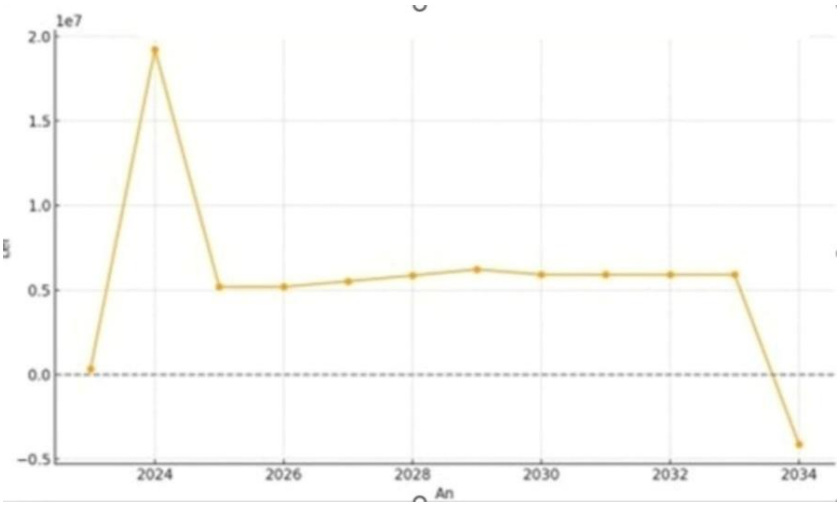


Figura 5.6.1. Cost analysis – Optimal scenario 4x2000kVA

CAPITOLUL 6. CONCLUSIONS, ORIGINAL CONTRIBUTIONS, AND LOOKING AHEAD

6.1. Final conclusions

As part of the doctoral thesis entitled "Assessing the sustainability of public transport through emissions and carbon footprint analysis," it has been researched methods for estimating greenhouse gas (GHG) emissions specific to urban public transport, with a focus on the fleet of classic, hybrid, and electric buses in Bucharest, by comparing existing technologies and identifying appropriate methods for quantifying the emissions associated with each type of bus, in relation to specific energy consumption, the energy mix used, load factors, and operational characteristics.

The introduction of electric buses in Bucharest has been a strategic catalyst for the expansion and reinforcement of the sustainable dimension of urban mobility. At the same time, the investments in charging infrastructure provide certainty for a coherent and sustainable transition towards climate neutrality and compliance with European ambitions.

6.2. Original work.

- The research and modeling activities carried out during this doctoral internship support original contributions to the field of environmental engineering, with an impact on air quality through the assessment of GHG emissions resulting from public transport. My personal contributions are:
- Applying the JASPERS methodology for the first time to estimate greenhouse gas (GHG) emissions generated by the Bucharest city bus fleet, based on actual consumption and mileage data for the period 2021–2024, in particular after the introduction of electric buses in 2024, which accounted for around 3.47% of the total distance traveled by the fleet. The reduction in CO2e compared to 2023 was almost 12 kt CO2e, or 13% of the previous year's emissions.
- Adapting the JASPERS calculation methodology to the national context by using emission factors specific to Romania's energy mix and the characteristics of the local transport fleet. As a result, in the case study for bus line 368, the scenario was adjusted to include five additional electric buses in 2025, and the specific carbon footprint was found to decrease from 1.25 kg/km in the baseline scenario to 0.70 kg/km in the advanced scenario.
- Performing an application study on charging infrastructure for electric buses, focusing on station sizing, technical requirements, and integration with the urban power grid.
- Calculating the average and maximum hourly electricity consumption for electric buses, including the installed power rating and power requirements for the transformer stations at

the charging stations, where a power reserve was identified and, together with the project partners, an energy balance was recommended for the location of the electric bus charging stations.

- Analyse the evolution of electricity consumption at the level of the transport operator STB-S.A., with the aim of correlation of future energy demand with the fleet electrification strategy.
- Elaboration of scenarios for the period 2025–2030, which assess the impact of decarbonizing the bus fleet through the progressive introduction of electric vehicles. For the 2025–2030 scenario, by replacing 50 Euro III, IV, or VI buses with electric buses, we found an estimated reduction in carbon footprint of 11 kt CO2e compared to the initial scenario.
- Calculating and analyzing specific CO_2e emissions (kg/km) for each year studied, highlighting trends and potential reductions achieved in energy transition scenarios. As a result, the carbon footprint decreased from approximately 85 kt CO2e in 2023 to 74.5 kt CO2e in 2024.
- Comparative analysis of the environmental performance of diesel, hybrid, and electric buses based on standardized calculations, providing a basis for evaluating sustainable public procurement policies. Based on this analysis, the introduction of electric buses by 2024 would result in a 2.68% reduction in specific carbon footprint. In addition, the specific climate efficiency is approximately 1.25 kg CO2e avoided per electric bus kilometer.

Estimation of cumulative GHG emission reductions according to the degree of fleet electrification, providing useful quantifiable benchmarks for policy makers and urban mobility strategies.

The results were summarized in the form of comparative indicators (e.g., $kgCO_2/km$, CO_2 equivalent/passenger-km), demonstrating the contribution of each fleet type toward reducing the carbon footprint and achieving local climate goals.

Sustainability becomes an integrating tool for smart public policies focused on resilience and innovation.

Through this multidimensional approach, the thesis has contributed to the strategic decision-making process regarding the modernization of public transport in Bucharest, and to the identification of the most effective options for a transition to low-emission urban mobility, amplifying the process of urban decarbonization with the goal of constructing a sustainable future for next generations.

Future directions

- Extending GHG emissions calculations using the JASPERS method for the entire electrified public transport system in Bucharest.
- Quanification of electricity consumption for electric bus charging stations in order to estimate its carbon footprint.
- Estimation of black carbon (BC) emissions, including PM2.5 and short-lived climate pollutants (SLCPs), such as CH4, using appropriate calculation methods.
- Scenario analysis of the use of alternative fuels such as hydrogen for buses, which is a much-promising solution for conventional electricity supply, especially for long-distance or heavy-duty applications where charging infrastructure is difficult to implement.

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1. Matei E., Râpă M., Mateș I.M., Popescu A.-F., Bădiceanu A., Balint A.I., Covaliu-Mierlă C.I., Heavy Metals in Particulate Matter—Trends and Impacts on Environment, (2025) Molecules, 30 (7), art. no. 1455, DOI: 10.3390/molecules30071455, IF 4.6, CO-AUTHOR
2. Badiceanu, A, Popescu, AF, Balint, AI, Matei, E, Impact of PM_{10} emissions from transport sector on air quality in the Bucharest-Ilfov area, (2025) University Politehnica of Bucharest Scientific Bulletin Series B-Chemistry and Materials Science, VL 87, IS 1, 227-236, WOS:001488435000001, IF 0.3, CO-AUTHOR
3. Popescu, A.F., Matei, E., Bădiceanu A., Balint, A.I., Râpă M., Coman G., Predescu C., An optimistic vision for public transport in Bucharest city after the bus fleet upgrades, (2025),

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- Popescu, A.F., Bădiceanu A., Matei, E., PM_{10} emissions impact on air quality from transport activities (2024), International Conference of Science and Technology Materials ROMAT, 14-15 Noiembrie, 2024, oral presentation.
- Popescu, A.F, Matei, E., Bădiceanu, A., Environmental Impact of Renewable Energy and Electric Propulsion Systems in Public Transport: A Case Study on Bucharest e-Buses (2025) , International Conference on Advanced Automotive Systems ICAAS, November 13-14, 2025 – Participation registration with article MDPI and oral presentation.