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MODELING THE QUANTIFICATION OF THE VEHICLES' EMISSION LOAD: RESEARCH STUDY IN THE CONTEXT OF CROSS-BORDER COMMUTERS' MOBILITY

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Abstract

The manuscript focuses on the quantification of exhaust emission load generated by commuters' road vehicles along a selected cross-border section between the Czech Republic (South Bohemian region) and Bavaria, which is heavily used by Czech residents for daily work-related commuters' mobility. An examined model route – Volary–Passau – was defined for the investigation, characterized by its length (i.e., travel distance), traffic load, and operational circumstances. In regard to a territorial perspective, approximately 25–30% of emissions produced along the route are attributable to the Czech route section and 70–75% to German section, which corresponds to the distance ratio of the given route. The quantification was conducted based on emission factors according to the EEA/COPERT 5.5 methodology, when taking into account the actual vehicle numbers and emission categories recorded during traffic surveys on 26 May 2025 and 30 May 2025. Emission indicators were expressed as "on-road" values in units of $g \cdot km^{-1}$ and subsequently converted to the total travel distance and both travel directions ("round-trip"). Specifically, along the examined model route (Volary–Passau), the following values of emission indicators were recorded for the total daily balance: 9.2 t CO_2, 18.9 kg NO_x, and 1.4 kg PM. The quantified attributes of the model route confirm that gasoline vehicles dominate the production of carbon monoxide (CO) and hydrocarbons (HC), diesel vehicles are the primary source of nitrogen oxides (NO_x) and particulate matter (PM), and carbon dioxide (CO_2) accounts for more than 99% of the total mass of all calculated emissions.

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1. Introduction

Urban transportation systems belong among the most significant contributors to anthropogenic air pollution and greenhouse gas (GHG) emissions worldwide [1]. The rapid growth in vehicle ownership, coupled with increasing urbanization, has intensified concerns regarding environmental degradation, energy consumption, and public health impacts. Road traffic emissions – particularly from passenger vehicles – are a dominant source of pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM), which collectively exacerbate climate change and deteriorate air quality [2]. Although substantial efforts have been devoted to the development of alternative propulsion systems for vehicles, machinery, and various technical devices, the internal combustion engine remains the predominant source of motive power and, consequently, a major contributor to atmospheric pollutant emissions. The operation of an internal combustion engine begins with the starting process, typically initiated by a starting device such as an electric starter. During this phase, pollutant emissions are particularly elevated, often reaching their highest levels due to incomplete combustion and the suboptimal operating conditions characteristic of engine start-up [2, 3].

Recent research has increasingly focused on quantifying vehicular emissions and understanding their spatial and temporal distribution within urban environments. For instance, Alqubaysi [4] highlights the importance of estimating emissions along arterial roads to inform sustainable urban mobility strategies. Similarly, Cheng et al. [5] develop a multi-agent simulation approach for analyzing traffic conditions near urban scenic destinations in tourist cities, with tourist behavior represented through a dedicated agent. These methodological advancements enable more accurate assessments of emission patterns and their environmental consequences.

In parallel, the environmental performance of vehicle fleets has become a key area of investigation. The aging structure of passenger car fleets significantly influences emission levels, as older vehicles typically exhibit lower fuel efficiency and higher pollutant output [6]. Moreover, commuting patterns and cross-border mobility have been shown to contribute substantially to CO_2 emissions, reflecting the socio-economic dimensions of transportation systems [7]. Beyond road transport, comparative analyses of alternative transport modes – such as maritime shipping – provide insights into potential pathways for reducing emissions and improving sustainability [8]. At the same time, emission inventory studies and integrated modeling frameworks have been developed to support policymaking and urban planning, offering comprehensive tools for evaluating mitigation strategies [9, 10].

According to data compiled from the ACEA and Eurostat databases, approximately 8.15 million road vehicles (i.e., total Czech vehicle fleet) were registered in the Czech Republic in 2023. Passenger cars (category M1) constituted the dominant proportion, accounting for around 6.51 million vehicles, which represents more than 80% of the total vehicle fleet. Motorcycles (L-category) formed another significant segment, with 812,925 units, followed by light commercial vehicles (N1 category, commonly referred to as vans), totaling 618,073 units. Heavy goods vehicles (categories N2 and N3) accounted for 188,370 registered units, while buses (categories M2 and M3) represented approximately 22,144 vehicles (see Figure 1) [11].

Compared to the European average, the Czech Republic exhibits a higher proportion of passenger cars within its total fleet and a relatively lower proportion of heavy commercial vehicles. This structural composition indicates that transport-related emissions in the Czech Republic are predominantly generated by passenger car operations, making this segment a key focus when assessing the environmental impacts of road transport, particularly in relation to air quality [12].

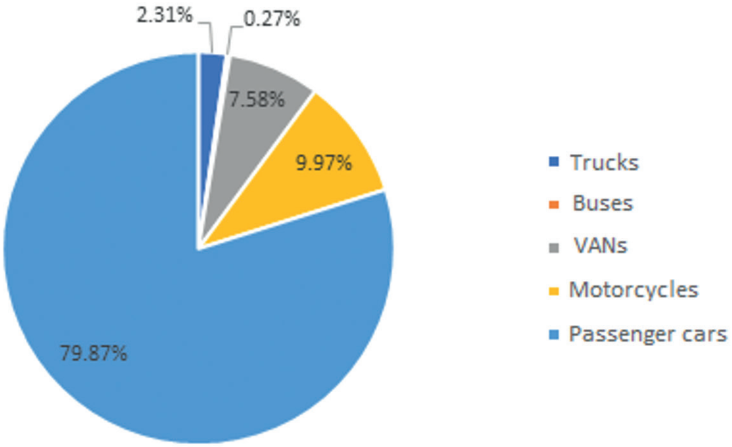

Fig. 1. Structure of the vehicle fleet in the Czech Republic in 2023 [11]

Between 2019 and 2024, the passenger car fleet in the Czech Republic exhibited steady growth, increasing from 5.92 million to 6.64 million vehicles (approximately +12%). In terms of fuel composition, gasoline-powered vehicles (i.e., with spark ignition engine) continue to dominate, rising from 3.48 million in 2019 to 3.82 million in 2024, with their proportion stabilizing at around 57% of the total fleet. Diesel vehicles (i.e., with compression ignition engine) represent the second largest category, showing a moderate increase from 2.31 million to 2.52 million units (+9%). However, their relative proportion has gradually declined over time, from 39% in 2019 to approximately 38% in 2024. Vehicles powered by alternative fuels (such as LPG and natural gas) maintain only a marginal presence, collectively accounting for less than 2.5% of the fleet, with only slow growth observed in absolute terms. The most dynamic development has occurred in the segment of battery electric vehicles (BEVs), whose numbers increased from 4,950 in 2019 to 36,341 in 2024–representing more than a seventeen-fold rise. Despite this rapid growth, electric vehicles still accounted for only 0.55% of the total fleet in 2024, which remains significantly below the European Union average of approximately 2.5% (see Table 1) [11, 13].

Overall, the trend indicates a gradual yet slow transition toward low-emission technologies, with fleet renewal still predominantly reliant on internal combustion engine vehicles. From an environmental perspective, this development suggests that reductions in CO_2 and NO_x emissions in the Czech Republic will remain constrained in the coming years due to the limited penetration of electromobility and the relatively high average age of the existing combustion-engine vehicle fleet [14, 15].

Number of vehicles registered in the Czech Republic over the years 2018–2024 are summarized in Table 1.

Tab. 1. Number of vehicles registered in the Czech Republic over the years 2018–2024 [11, 15]

	2018	2019	2020	2021	2022	2023	2024
Gasoline	3,390,776	3,475,194	3,515 604	3,523,023	3,633,447	3,747,918	3,816,058
LPG	103,838	106,613	106,573	108,611	114,392	117,901	120,873
Diesel	2,205,495	2,313,009	2,388,353	2,415,250	2,508,001	2,473,580	2,524,164
NG	16,552	18,611	19,933	20,717	22,694	22,990	23,066
Electro	3,405	4,950	8,109	9,051	14,195	22,441	36,341
Total	5,747,913	5,924,995	6,049,255	6,088,730	6,305,934	6 512,774	6,638,172

Given the above-described developments, the present research area lies at the intersection of transportation engineering, environmental science, and urban planning. It seeks to integrate empirical data, modeling techniques, and policy considerations to address the challenges posed by vehicular emissions in modern cities.

2. Materials and Methods

2.1. Analysis of passenger cars based on emission standards

According to the latest statistics, approx..6.83 million passenger cars were registered in the Czech Republic as of July 2025. Of this total, vehicles complying with the Euro 6 emission standard constitute the largest proportion, amounting to 2.25 million units, or roughly 33% of the entire fleet. Other significant groups include vehicles meeting the Euro 4 standard

(1.31 million, ~19%) and Euro 3 (1.08 million, ~16%). Vehicles classified under Euro 5 account for approximately 13%, while Euro 1–2 categories represent about 10% of the fleet. The oldest vehicles, which do not comply with any Euro emission standard, still make up nearly 9% of registered vehicles, indicating a relatively slow rate of fleet renewal [15].

Compared to the European Union average, where Euro 6 vehicles already account for approximately 47% of the fleet, the Czech Republic exhibits a relatively older emission structure. From an air quality perspective, this implies that nearly half of the vehicles in operation comply only with Euro 3–4 standards, which are associated with higher emissions of nitrogen oxides (NO_x) and particulate matter (PM) [16].

Table 2 presents the number of vehicles in the Czech Republic by Euro emission standards, while Figure 2 provides a clear overview of the current breakdown of these standards within the national vehicle fleet [15].

Tab. 2. Number of vehicles in the Czech Republic by Euro emission standards (July 2025) [15]

	Number	Proportion (%)
EURO 6	2,251,443	32.94
EURO 5	883,230	12.92
EURO 4	1,305,844	19.11
EURO 3	1,084,237	15.86
EURO 1 and 2	681,623	9.97
Older	628,250	9.19
Total	**6,834,627**	**100.00**

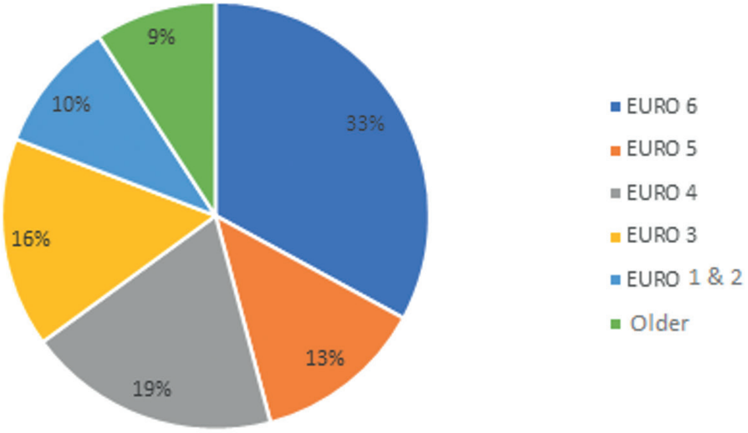

Fig. 2. Breakdown of individual Euro standards in the Czech Republic (July 2025)

2.2. Features of the model route Volary – Passau

The analyzed section was selected as a representative (model) corridor characterized by a high intensity of daily cross-border commuting between the South Bohemian Region and Bavaria. The objective of the analysis is to quantify the emissions generated by passenger cars operated by Czech commuters traveling to workplaces in Germany (Bavaria) and back.

The calculation is carried out separately for the outbound ("towards Germany") and inbound ("towards the Czech Republic") traffic flows. The input data are based on actual traffic counts conducted on two selected days, providing the number of passenger vehicle movements in both directions.

For each vehicle, the emission load is modeled based on [17]:

- the Euro emission standard breakdown of the vehicle fleet in the Czech Republic (as of June 2025),
- emission factors (g/km),
- travel distance of the model road section,
- the number of vehicle passages (in both directions, i.e., outbound and inbound/return trips).

The quantification of the total amount of emissions (CO, HC, NO_x, PM, and CO_2) produced by passenger cars in both directions, including their temporal breakdown over the course of travel represents the desired outcome. The resulting data enable an estimation of the daily emission balance at the border crossing and allow for a quantitative assessment of the environmental impact of cross-border commuting.

The Strážný–Philippsreut border crossing is located in the southwestern part of the Czech Republic, within the Prachatice district (South Bohemian Region), and connects the Czech road I/4 with the German B12 towards Passau. It represents one of the principal road crossings between the Czech Republic and Bavaria, playing an important role not only in transit transport but also in the daily cross-border mobility of commuters. The I/4 road constitutes a key transport axis linking Prague, Strakonice, and Vimperk with the Bavarian region around Freyung and Passau, and forms part of the European transport corridor E49 [18].

For the sake of the research study, a model commuting scenario was defined along the route Volary–Passau (72.4 km), representing one of the most frequently used transport connections in the area of the Strážný–Philippsreut border crossing. The route was determined using a GPS logger and subsequently processed in Google Earth Pro and GPS Visualizer. For this scenario, both the total route length and its severance into Czech (CZ) and German (DE) sections were established, enabling a separate evaluation of emissions generated on each side of the border [18].

Based on the travel distance, exhaust gas emissions (CO, HC, NO_x, PM a CO_2) are quantified and categorized by vehicle emission standards and direction of travel (CZ→DE and DE→CZ). The total length (i.e., travel distance) of the section is 72.4 km, with approximately 20.7 km situated in the Czech Republic and 51.7 km in the Federal Republic of Germany. The route follows roads I/39 and I/4 on the Czech side and, after crossing the national border at the municipality of Strážný, continues along the federal highway B12 to the city of Passau, a prominent economic and transport hub in the Lower Bavaria region. The route traverses the terrain of the Bohemian Forest foothills. The initial elevation in Volary is approx. 755 masl, while the highest point of the route is located at kilometer 24 (near the national border) at an altitude of 974 masl. From this point, there is a sustained descent to the Inn River in Passau (301 masl), corresponding to a total elevation change of approximately 670 m. The average longitudinal gradient of the entire route in the outbound direction is −2.8%, which significantly affects energy consumption and emission production across individual segments of the journey.

On the Czech side, drivers operate primarily in an extra-urban mode with speed limits of 80–90 km/h, passing through several urban areas (Volary, Lenora) with a 50 km/h limit. After crossing the border, the character of the route transitions on the German B12 to a higher-quality roadway with a maximum speed limit of 100 km/h, occasionally restricted to 70 km/h upon entering built-up areas and within the Passau section. From a modeling perspective, the route is suitable for representing long-distance commuting to employment centers, incorporating a combination of urban, rural, and intercity driving modes. The elevation profile and speed variations allow for the precise application of speed- and gradient-dependent emission factors.

Relevant parameters of the model route are summarized in Table 3, and the vertical alignment of the route is graphically illustrated in Figure 3.

Tab. 3. Volary – Passau – pertinent parameters

	Volary – Passau	
	Section length (km)	**Cumulative section length (km)**
Route no. 39 (Czech Republic)	10.8	10.8
Route no. 4 (Czech Republic)	9.9	20.7
Route no. 12 (Germany)	51.7	72.4
Total	72.4	72.4

Fig. 3. Elevation profile of the Volary – Passau model route

3. Results

3.1. Emission factors

The emission factors used for quantifying emission values from passenger cars with a spark ignition engine are based on the EEA/COPERT 5.5 (2024) methodology and internal emission measurements at the Department of Road and Urban Transport, University of Žilina (Slovakia) [19]. The values represent real-world emissions determined for the purposes of this research. These factors reflect the average emissions of vehicles in real-world traffic, including the effects of engine ageing and exhaust gas treatment systems [20].

Tables 4 and 5 show the emission factors (EF) for the major pollutants of both spark ignition as well as compression ignition engines – carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), PM particles and carbon dioxide (CO_2) [19, 20].

Tab. 4. Emission factors – spark ignition engines

EF	CO [g/km]	HC [g/km]	NO_x [g/km]	PM [g/km]	CO_2 [g/km]
EURO 6	0.550	0.070	0.060	0.002	170.000
EURO 5	0.850	0.100	0.080	0.005	175.000
EURO 4	1.400	0.150	0.100	0.010	185.000
EURO 3	2.100	0.200	0.120	0.020	195.000
EURO 2 and 1	3.100	0.250	0.150	0.020	205.000
EURO 0	6.500	1.200	0.600	0.050	225.000

Tab. 5. Emission factors – compression ignition engines

EF	CO [g/km]	HC [g/km]	NO_x [g/km]	PM [g/km]	CO_2 [g/km]
EURO 6	0.100	0.020	0.350	0.002	155.000
EURO 5	0.200	0.030	0.450	0.004	165.000
EURO 4	0.300	0.060	0.600	0.025	175.000
EURO 3	0.500	0.100	0.800	0.050	185.000
EURO 2 and 1	1.000	0.200	1.200	0.140	210.000
EURO 0	1.200	0.400	1.800	0.250	230.000

3.2. Identifying the number of vehicles

In the subsequent calculations, the number of passenger cars (i.e., commuters) was determined following a traffic survey conducted at the Strážný–Philippsreut border crossing. Data collection was carried out on two working days – Monday, 26 May 2025, and Friday, 30 May 2025 – which were defined as representative of typical commuter departure and return patterns. During the survey, vehicles travelling towards Germany (during morning hours) and returning to the Czech Republic (during afternoon hours) were identified through video/camera recordings and license plate registration analysis. Vehicles were classified as commuter vehicles only if they were demonstrably recorded in both directions on the same day, meaning that their outbound and return trips were both captured within a single daily cycle.

Based on the collected data, the average proportion of Euro emission standards for these vehicles was subsequently established. The proportions of individual emission categories were then further classified according to propulsion type (spark ignition gasoline engines and compression ignition engines).

The resulting vehicle counts, which serve as the basis for calculating the total emission load in the subsequent stages, are presented in Tables 6 and 7.

Tab. 6. Number of commuters on the outbound journey 26 May 2025

26 May 2025	Number	EURO 6	EURO 5	EURO 4	EURO 3	EURO 2 and 1	EURO 0
Total	349	115	45	67	55	35	32
Gasoline	202	67	26	39	32	20	19
Diesel	147	48	19	28	23	15	13

Tab. 7. Number of commuters on the outbound journey 30 May 2025

30 May 2025	Number	EURO 6	EURO 5	EURO 4	EURO 3	EURO 2 and 1	EURO 0
Total	132	43	17	25	21	13	12
Gasoline	77	25	10	15	12	8	7
Diesel	55	18	7	11	9	6	5

3.3. Quantifying the pollutant emissions

The following sections of the manuscript present the quantified mass values of pollutant emissions, namely, CO, HC, NO_x, PM and CO_2 generated by passenger cars equipped with spark ignition and compression ignition engines during a one-way journey along the defined model route. The calculations were based on the numerical representation of individual Euro emission classes within the sample of 349 and 132 recorded vehicles, respectively, as well as on the established emission factors (g/km) according to fuel type and emission standard [21, 22].

The quantity of emissions generated was determined according to the equation (1) [21]:

$$E_{i,j} = EF_{i,j} \cdot L \cdot N_{i,j} \tag{1}$$

$E_{i,j}$ – total quantity of pollutant emissions i emitted by vehicle category j [g],
$EF_{i,j}$ – emission factor of pollutant i by vehicle category j [g/km],
L – travel distance along the model route [km],
$N_{i,j}$ – number of vehicles by relevant category.

The resulting emissions for each vehicle group represent the aggregate of individual contributions according to the respective Euro emission classes.

The findings clearly indicate that gasoline cars (i.e., with spark ignition engines) produce substantially higher absolute emissions of carbon monoxide (CO) and hydrocarbons (HC). The total calculated mass of CO emissions reached approximately 26.5 kg, while HC emissions amounted to 3.4 kg. These pollutants originate predominantly from vehicles classified under Euro 3 to Euro 0 emission standards, which are characterized by lower combustion efficiency and the absence of advanced catalytic after-treatment systems.

By contrast, diesel-powered vehicles (i.e., with compression ignition engines) constitute the dominant source of nitrogen oxides (NO_x) and particulate matter (PM). Total NOx emissions reached 7.4 kg, which is more than three times the quantity generated by gasoline-powered vehicles. The highest contribution was recorded for Euro 3 and Euro 4 diesel vehicles, i.e., vehicle generations not yet equipped with selective catalytic reduction (SCR) technology [23]. PM emissions from diesel vehicles amounted to 0.5 kg, approximately 2.5 times higher than those produced by gasoline vehicles.

Regarding carbon dioxide (CO_2), the largest overall contribution was associated with gasoline-powered vehicles, which generated 2.73 tonnes of CO_2, compared to 1.87 tonnes produced by diesel-powered vehicles. This difference is primarily attributable to the higher number of gasoline vehicles within the monitored sample and their generally higher specific fuel consumption [24].

The resulting pollutant emissions for a model route (gasoline and diesel vehicles) for the dates 26 May 2025 and 30 May 2025 are summarized in Tables 8–11.

Tab. 8. Resulting emissions (gasoline; 26 May 2025)

Gasoline-powered cars	CO (g)	HC (g)	NO_x (g)	PM (g)	CO_2 (g)
EURO 6	2 668	340	291	10	824,636
EURO 5	1 600	188	151	9	329,420
EURO 4	3 953	424	282	28	522,366
EURO 3	4 865	463	278	35	451,776
EURO 2 and 1	4 489	362	217	29	296,840
EURO 0 EF	8 941	1 651	825	69	309,510
Total (g)	26,517	3 427	2 045	180	2,734,548
Total (kg)	26.5	3.4	2.0	0.2	2 734.5

Tab. 9. Resulting emissions (diesel; 26 May 2025)

Diesel-powered cars	CO (g)	HC (g)	NO_x (g)	PM (g)	CO_2 (g)
EURO 6	348	70	1 216	7	538,656
EURO 5	275	41	619	6	226,974
EURO 4	608	122	1 216	51	354,760
EURO 3	833	167	1 332	83	308,062
EURO 2 and 1	1 086	217	1 303	152	228,060
EURO 0 EF	1 129	376	1 694	235	216,476
Total (g)	4 279	993	7 381	534	1,872,988
Total (kg)	4.3	1.0	7.4	0.5	1 873.0

Tab. 10. Resulting emissions (gasoline; 30 May 2025)

Model route – gasoline	CO (g)	HC (g)	NO_x (g)	PM (g)	CO_2 (g)
EURO 6	996	127	109	4	307,700
EURO 5	615	72	58	4	126,700
EURO 4	1 520	163	109	11	200,910
EURO 3	1 824	174	104	13	169,416
EURO 2 and 1	1 796	145	87	12	118,736
EURO 0 EF	3 294	608	304	25	114,030
Total (g)	10,046	1 289	770	68	1,037,492
Total (kg)	10.0	1.3	0.8	0.1	1 037.5

For gasoline-powered cars operating along the investigated model route, the total quantified pollutant emission load amounted to 10.0 kg of CO, 1.3 kg of HC, 0.8 kg of NO_x, 0.07 kg of PM, and 1.04 tonnes of CO_2. The highest proportion of CO and HC emissions originated from vehicles classified within Euro 3 to Euro 0 emission categories, representing older vehicle generations lacking modern combustion-control systems and efficient catalytic converters. These cars exhibit significantly higher specific emissions, particularly under low-load operating conditions and fluctuating speed profiles. In contrast, modern Euro 6 vehicles demonstrated a reduction in CO and HC emissions exceeding 80% compared to earlier emission standards, reflecting the substantial effectiveness of advanced three-way catalytic converter technologies [25].

Tab. 11. Resulting emissions (diesel; 30 May 2025)

Model route – gasoline	CO (g)	HC (g)	NO_x (g)	PM (g)	CO_2 (g)
EURO 6	130	26	456	3	201,996
EURO 5	101	15	228	2	83,622
EURO 4	239	48	478	20	139,370
EURO 3	326	65	521	33	120,546
EURO 2 and 1	434	87	521	61	91,224
EURO 0 EF	434	145	652	91	83,260
Total (g)	1 665	386	2 856	208	720,018
Total (kg)	1.7	0.4	2.9	0.2	720.0

Diesel-powered cars generated a total of 1.7 kg of CO, 0.4 kg of HC, 2.9 kg of NO_x, 0.21 kg of PM, and 0.72 tonnes of CO_2. Nitrogen oxide emissions represent the dominant pollutant category, with Euro 3 and Euro 4 vehicles constituting the principal source of these substances. In these vehicle categories, engines still largely operate without selective catalytic reduction (SCR) systems, resulting in substantially higher NO_x outputs. Particulate matter emissions primarily originated from vehicles belonging to older emission classes (Euro 2 and below), which are not equipped with diesel particulate filters (DPF). Despite the lower numerical representation of diesel vehicles within the analyzed sample, they accounted for more than 75% of total NO_x emissions and nearly 80% of total PM emissions [26].

4. Discussion

Tables 12 and 13 present the quantified masses of generated pollutant emissions over two monitored days – 26 May 2025 (Monday) and 30 May 2025 (Friday) – which represent a typical working day at the beginning and end of the week.

The findings shown in Table 12 indicate that a higher number of commuter cars travelled along the given route on Monday, 26 May 2025, resulting in correspondingly higher total emissions. The overall emission balance for the complete round journey ("outbound and inbound/return") amounted to 61.6 kg of CO, 8.8 kg of HC, 18.9 kg of NO_x, 1.4 kg of PM, and 9.2 tonnes of CO_2. Gasoline-powered vehicles contributed more significantly to CO and HC production, whereas diesel-powered vehicles were the dominant source of NO_x and PM emissions [27]. When geographically divided, approx. 28.6% of total pollutant emissions were generated within the Czech route section (20.7 km), while 71.4% were attributed to the German section (51.7 km), reflecting not only the proportional route length (i.e., distance traveled) but also differences in route profile.

Table 13 presents the findings corresponding to Friday, 30 May 2025, when a lower traffic volume was recorded (77 gasoline-powered cars and 55 diesel-powered cars), which was directly reflected in a proportionally reduced emission load. Total pollutant emissions reached 23.4 kg of CO, 3.3 kg of HC, 7.3 kg of NO_x, 0.6 kg of PM, and 3.5 tonnes of CO_2. Compared with Monday, this represents an approximate 60% decrease across all monitored emission categories, thereby confirming the substantial influence of traffic intensity on the resulting overall emission balance.

Tab. 12. Resulting emissions for the model route (26 May 2025)

Model route – 26 May 2025	CO (g)	HC (g)	NO_x (g)	PM (g)	CO_2 (g)
Gasoline	26,517	3 427	2 045	180	2,734,548
Diesel	4 279	993	7 381	534	1,872,988
Total "outbound"	30,795	4 420	9 426	714	4,607,536
Total "outbound" and "inbound"	61,591	8 840	18,852	1 427	9,215,072
Total "outbound" a "inbound" (kg)	61.59	8.84	18.85	1.43	9 215.07
Czech section (20.7 km) (kg)	17.61	2.53	5.39	0.41	2 634.70
German section (51.7 km) (kg)	43.98	6.31	13.46	1.02	6 580.38

Tab. 13. Resulting emissions for the model route (30 May 2025)

Model route – 30 May 2025	CO (g)	HC (g)	NO_x (g)	PM (g)	CO_2 (g))
Gasoline	10,046	1 289	770	68	1,037,492
Diesel	1 665	386	2 856	208	720,018
Total "outbound"	11,711	1 675	3 627	276	1,757,510
Total "outbound" and "inbound"	23,421	3 349	7 253	553	3,515,020
Total "outbound" a "inbound" (kg)	23.42	3.35	7.25	0.55	3 515.02
Czech section (20.7 km) (kg)	6.70	0.96	2.07	0.16	1 004.99
German section (51.7 km) (kg)	16.72	2.39	5.18	0.39	2 510.04

Figure 4 illustrates a comparison of total pollutant emissions generated along the model route on 26 May 2025 and 30 May 2025. During the second observation period, a clear reduction is evident across all monitored pollutants (namely, CO, CO_2, HC, NO_x, and PM), reflecting the lower number of recorded commuter journeys (travels). CO_2 emissions unequivocally dominate the overall emission balance and substantially exceed all other exhaust gas components in absolute volume. At the same time, CO_2 levels also demonstrate a day-to-day decrease consistent with the reduced traffic intensity, further confirming the direct relationship between transport volume (i.e., distance traveled) and total emission output (load).

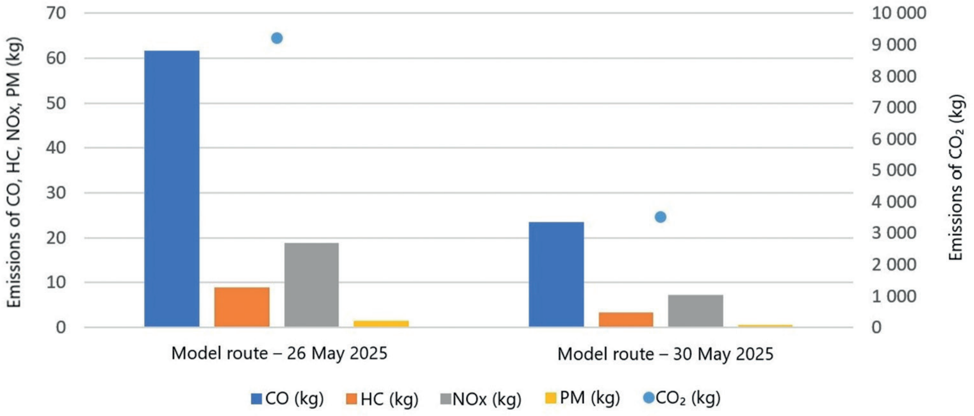

Fig. 4. Total emission load for the model route (26 May 2025 – left part; 30 May 2025 – right part)

5. Conclusion

The manuscript focuses on the quantification of exhaust emissions generated by passenger vehicles used for cross-border commuting between the Czech Republic and the German region of Bavaria. This specific cross-border corridor represents an intensively utilized route for daily work-related mobility. For analytical purposes, a representative model route connecting Volary and Passau was defined, taking into account its length (i.e., travel distance), traffic intensity, and operational characteristics.

From a spatial perspective, the distribution of emissions along the route reflects its geographical structure, with approximately 25–30% attributed to the Czech section and 70–75% to the German section. This allocation corresponds closely to the proportional route length (travel distance) within each country.

The emission calculations were conducted using emission factors derived from the EEA/COPERT 5.5 methodology, incorporating real-world traffic data obtained from field surveys carried out on May 26 and May 30, 2025. The dataset included both vehicle counts and their classification according to emission standards. Emissions were initially expressed as "on-road" values (g/km) and subsequently aggregated over the total travel distance, considering bidirectional traffic flow (round trips).

For the analyzed corridor (Volary–Passau), the estimated total daily emissions reached approximately:

- 9.2 tonnes of CO_2,
- 18.9 kg of NO_x,
- 1.4 kg of particulate matter (PM).

The analysis of the model route highlights several key findings:

- gasoline-powered vehicles are the predominant source of carbon monoxide (CO) and hydrocarbons (HC),
- diesel-powered vehicles contribute most significantly to nitrogen oxides (NO_x) and particulate matter (PM),
- carbon dioxide (CO_2) accounts for more than 99% of the total mass of calculated emissions.

The results demonstrate that even a relatively moderate volume of recurring commuter trips can cumulatively represent a considerable source of regional environmental burden, particularly in terms of nitrogen oxides and greenhouse gas emissions. These findings underline the importance of systematically monitoring cross-border mobility flows and support the need for promoting lower-emission transport solutions, such as electromobility, car-sharing schemes, and improved integration of public transport systems across border regions.

Despite its contributions, the study is subject to several limitations that should be acknowledged:

- The analysis is based on a limited number of observation days, which may not fully capture temporal variability in traffic patterns (e.g., seasonal fluctuations, weekday/weekend differences).
- The use of the COPERT-based emission model relies on standardized emission factors, which may not fully reflect real-world driving conditions, vehicle maintenance levels, or driver behavior.
- The study considers a single model route, which restricts the generalizability of the findings to other cross-border regions with likely different infrastructural or traffic characteristics.
- Potential influences such as weather conditions, congestion variability, and road gradient were not explicitly incorporated into the emission modelling.
- The analysis does not account for non-exhaust emissions (e.g., brake and tire wear), which may also contribute significantly to particulate pollution.

Building on the presented findings, further research in an addressed topic could focus on:

- Extending the analysis to long-term monitoring, incorporating seasonal and daily variability in commuting patterns.
- Expanding the study to include multiple cross-border corridors for comparative analysis across different regions.
- Integrating real-world emission measurements (e.g., PEMS – Portable Emission Measurement Systems) to validate and refine model-based results.
- Considering additional emission sources, particularly non-exhaust particulate emissions and cold-start effects.

- Evaluating the impact of alternative transport scenarios, such as increased electrification, modal shift to public transport, or implementation of low-emission zones.
- Analyzing policy measures and incentives aimed at reducing cross-border transport emissions and improving sustainability.
- Incorporating traffic simulation models to better capture dynamic driving conditions and congestion effects.

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7. Nomenclature

BEV	Battery Electric Vehicle
CO	Carbon monoxide
CO_2	Carbon dioxide
DPF	Diesel particulate filter
EF	Emission factor
GHG	Greenhouse gas
GPS	Global Positioning System
HC	Hydrocarbon
LPG	Liquefied Petroleum Gas
masl	meters above seal level
NG	Natural Gas
NO_x	Nitrogen oxides
PM	Particulate matter
SCR	Selective catalytic reduction

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