Data-Driven GHG Estimation for Local Public Transport Fleets: Pescara City Case Study

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Abstract

The transport sector is among the highest contributors to greenhouse gas (GHG) emissions. Consequently, the European Union has established ambitious targets to accelerate the transition to zero-emission mobility, with a specific focus on public transit fleets. Under current directives, urban bus fleets must reduce GHG emissions by 90% by 2030 and achieve full conversion to zero-emission vehicles by 2035. In this context, continuous monitoring of emission trends by public transport operators is crucial to ensure alignment with decarbonization goals. This study presents a pragmatic, data-driven methodology for estimating GHG emissions from local public transport (LPT) fleets. Designed to be both cost-effective and easily replicable, the approach leverages real-world operational data to generate context-specific emission estimates across various vehicle categories. The methodology integrates traffic volume data with detailed fleet characteristics, such as dimensional vehicle class, passenger capacity, energy carrier type, and engine emission standard, sourced from transport operators and national statistical databases. GHG emissions are quantified for CO_2, CH_4, and N_2O, and aggregated into CO_2-equivalent (CO_2e) metrics. Particulate matter emissions ($PM_{2.5}$ and PM_{10}) are also assessed independently. Beyond quantifying energy consumption and GHG emissions, the study introduces a set of unitary performance indices. These incorporate passenger loads and operational parameters, enabling more precise and detailed per-capita assessments of environmental impact. The methodology is applied to a case study in Pescara, a medium-sized city in central Italy, using high-resolution data from the local transit operator TUA S.p.A. A sensitivity analysis on vehicle occupancy rates has assessed the impact on per-capita energy use and emissions, highlighting key environmental performance drivers. Additionally, a strategic scenario analysis has been carried out to evaluate fleet decarbonization pathways toward a zero-emission target by 2035. Owing to its low implementation cost and reliance on readily available data, the proposed method serves as a valuable decision-support tool for public transport operators. It supports both environmental impact assessments and the strategic planning of emission reduction policies, with strong potential for adaptation across diverse urban contexts.

Keywords: *Local Public Transport, Energy Consumption, GHG Emissions, Unitary Performance Indices.*

1. Introduction

The transition to low-carbon transportation has become a central pillar of the European Union's climate agenda. As of recent estimates, road transport is responsible for nearly 20% of the EU's total greenhouse gas (GHG) emissions, with urban mobility making up a significant portion due to dense traffic volumes and intensive travel patterns [1]. To address the pressing challenge of climate change, the EU has adopted progressively stricter targets aimed at decarbonizing public transport systems. Directive (EU) 2019/1161, which amends the Clean Vehicles Directive, mandates that by 2030, a minimum of 65% of newly procured urban buses must meet clean vehicle criteria, of which at least 50% must be zero-emission. By 2035, a full transition to zero-emission technologies is expected for city bus fleets [2].

Urban areas with high population densities and significant traffic volumes face acute environmental and health challenges due to the concentration of transport-related emissions. Within this context, local public transport (LPT) systems - particularly bus fleets - represent a strategic focus for emission reduction efforts. Their central role in daily urban mobility, combined with their relatively high energy consumption and frequency of operation, makes them a key target for decarbonization strategies.

Replacing or upgrading conventional internal combustion engine (ICE) buses with low- or zero-emission alternatives, such as electric or hydrogen vehicles, has been shown to significantly lower GHG emissions [3]. These improvements have direct implications for urban air quality and public health. Exposure to traffic-related air pollution remains a major risk factor for respiratory and cardiovascular diseases, particularly in densely populated cities where vulnerable groups are disproportionately affected [4].

This transition not only demands technical [5 - 8] and operational adaptations but also entails significant economic implications for public transport operators, who must invest in new vehicles, infrastructure upgrades, and ongoing maintenance. In this context, assessing the total cost of ownership (TCO) becomes essential for strategic planning. As highlighted by Di Pasquale et al. [9 -10], TCO analysis provides a comprehensive framework to evaluate both direct and indirect costs over the vehicle lifecycle, including

purchase, operation, energy consumption, and environmental externalities, enabling more informed investment decisions in sustainable mobility.

Consequently, interventions in the LPT sector offer dual benefits: they contribute to climate change mitigation goals and yield measurable health benefits for urban populations [11]. Strategic investment in cleaner public transport technologies is therefore essential for cities aiming to meet sustainability targets while improving quality of life.

Traditional emission inventory models such as COPERT 5 [12], HERMESv3 [13], and the US EPA's MOVES model [14] require detailed, high-resolution traffic and fleet data that smaller municipalities often lack. Recent advances leveraging mobile phone and remote sensing data offer promise but face challenges due to data complexity and proprietary restrictions [15].

In response to these challenges, this study introduces a cost-efficient and scalable methodology for estimating GHG emissions and particulate pollutants (PM_{10}, $PM_{2.5}$) from LPT systems. The method integrates fleet characteristics and activity data with emission factors from established guidelines SORT cycle data [16] to quantify emissions of CO_2, CH_4, and N_2O, aggregated into CO_2-equivalents (CO_2e). Notably, we introduce a set of performance indices that normalize emissions per kilometre and per passenger, enabling a more nuanced understanding of environmental efficiency across different operational conditions.

The methodology is applied to a real-world case in Pescara, a medium-sized Italian city, using detailed data provided by the local transit operator TUA S.p.A. (Regional Public Transport Company) [17]. The analysis includes sensitivity testing on vehicle occupancy levels, highlighting the influence of passenger load variability on per-capita emission intensity. The proposed framework offers an accessible decision-support tool for transit agencies seeking to align fleet operations with decarbonization targets, with potential for replication in diverse urban settings.

Section 2 describes the methodological framework for the calculation of consumption and emissions. Section 3 presents the application of the methodology to a case study, including the related results, their discussion and sensitivity and transition analyses. Section 4 provides the conclusions and outlines future developments.

2. Methodology

The proposed methodology aims to quantify the energy consumptions and GHG emissions resulting from the operation of LPT vehicle fleets deployed in local public transport services. The overall methodological framework is illustrated in the block diagram provided in Fig. 1.

The methodology integrates traffic volume data with detailed fleet characteristics, such as dimensional vehicle class, passenger capacity, energy carrier type, and engine emission standard, sourced from transport operators and national statistical databases. GHG emissions are quantified for CO_2, CH_4, and N_2O, and aggregated into CO_2e metrics. Particulate matter emissions ($PM_{2.5}$ and PM_{10}) are also assessed independently.

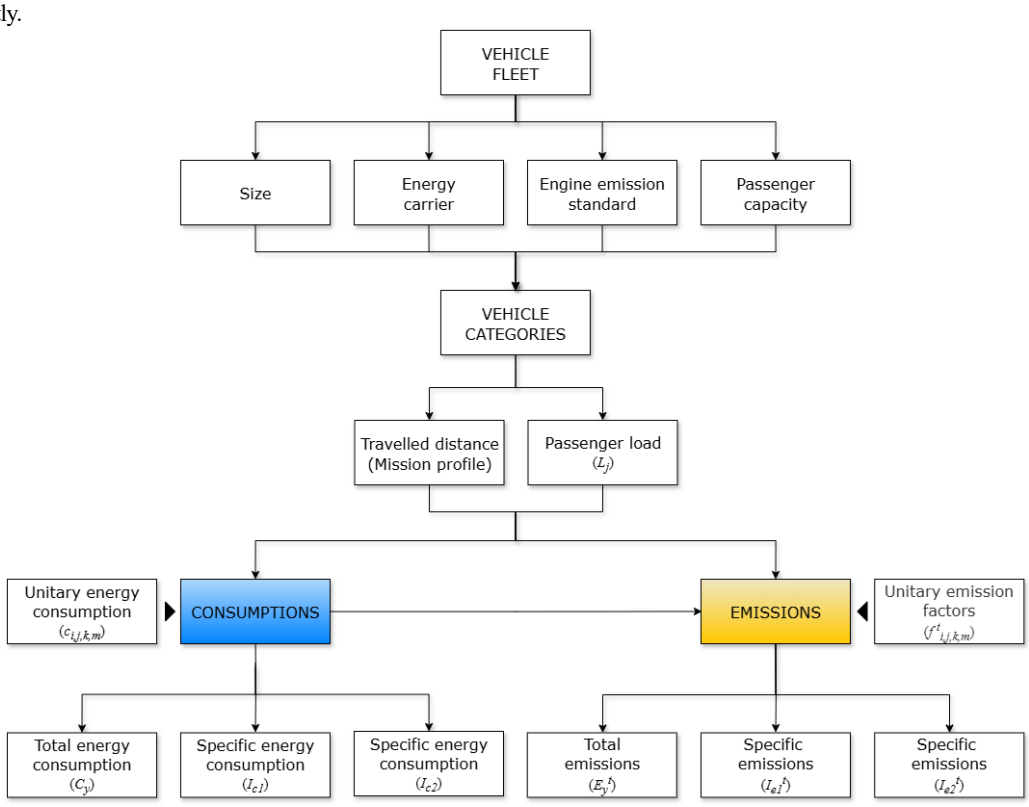

Fig. 1. Methodological sequence diagram

Given a fleet of n vehicles (n = 1, ..., N, where N denotes the total number of vehicles), the methodology entails the qualitative and quantitative characterization of the fleet vehicles, which are grouped into homogeneous categories based on dimensional, passenger capacity, energy and environmental attributes. Vehicles, belonging to the set N, are grouped into the following classes based on their technical and operational characteristics:

- Size *i-th* (i = 1, …, I, where I represents the number of size classes), accounting for the physical size, mass of vehicle, etc.;
- Passenger capacity *j-th* (j = *1, …, J,* where J indicates the number of passenger capacity classes), referring to the vehicle configuration in terms of the maximum number of passengers ($P_{max,j}$) that can be accommodated on each vehicle class;
- Energy carrier *k-th* (k = *1, …, K,* where K denotes the number of fuel classes), referring to the energy source used for traction (e.g. diesel, compressed natural gas - CNG -, electric, etc.);

- Engine emission standard *m-th* (*m = 1, …, M,* with *M* denotes the total number of emission standard category), indicating the regulatory level defined by European emission standards (e.g. Euro 3, Euro 4, Euro 5, Euro 6, etc.) [18 - 20].

The categorization of the vehicle fleet allows its technical and performance heterogeneity to be reduced to a discrete set of representative configurations, to which the technical and operational parameters required for modelling are assigned. Each vehicular class combination (*i, j, k, m*) is associated with the following parameters:

- Average energy consumption $c_{i,j,k,m}$ (kWh/km), based on SORT driving cycle data;
- Average emission factors $f^t_{i,j,k,m}$ (g/km), referring to the considered pollutants *t* (*t = 1, …, T*, with *T* representing the total number of pollutants);
- Travelled distance $d_{i,j,k,m}$ (km), accounting for the mission profile;
- Passenger load L_j, defined as the number of passengers on board, is calculated as the product of $P_{max,j}$ and the vehicle occupancy rate α_j, where $\alpha_j \in [0,1]$.

The proposed approach supports the estimation of annual energy consumption and emissions, as well as unit-based performance index, as discussed in the following sections.

2.1 Consumptions

This sub-section is focused to the quantification of energy consumption related to fleet operation.

The average energy consumption $c_{i,j,k,m}$, fuel-dependent, is expressed in kilowatt-hours per kilometer (kWh/km) based on the corresponding lower heating value (LHV) of each energy carrier.

The proposed approach, applicable to any distance input, aims to estimate the total energy consumption associated with the fleet's operation. When annual mileage is considered, the variable $D_{\mathrm{i,j,k,m}}$ is defined as the total distance travelled by each vehicle category over one year period (km/y). The annual energy consumption C_y (GWh/y) is computed according to the following relation.

$$C_y = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} c_{i,j,k,m} \cdot D_{i,j,k,m}}{10^6} \tag{1}$$

In addition, two unitary consumption performance indices are introduced, as follows:

a) I_{c_1} (kWh/km), representing the specific energy consumption per kilometer travelled, defined by relation (2).

$$I_{c_1} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} c_{i,j,k,m} \cdot d_{i,j,k,m}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} d_{i,j,k,m}} \tag{2}$$

b) I_{c_2} (kWh/(km·pass)), denoting the specific energy consumption per kilometer-passenger, defined by relation (3).

$$I_{c_2} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} c_{i,j,k,m} \cdot d_{i,j,k,m} \cdot L_j^{-1}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} d_{i,j,k,m}} \tag{3}$$

2.2 Emissions

This part of the section outlines the methodology used to estimate direct atmospheric emissions attributable to LPT fleet operations. The analysis covers GHG emissions that are quantified for three main greenhouse gases: carbon dioxide - CO_2, methane - CH_4, and nitrous oxide - N_2O, and aggregated into CO_2-equivalent (CO_2e) metrics. Other regulated GHG are not relevant to the transport sector [21]. Particulate matter emissions ($PM_{2.5}$, and PM_{10}) are also assessed independently.

Total atmospheric emissions associated with annual fleet operation, denoted as E_y^t (tons/y), are calculated, for each pollutants *t*, using the following equation.

$$E_y^t = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} f^t_{i,j,k,m} \cdot D_{i,j,k,m}}{10^6} \tag{4}$$

GHG emissions can also be expressed in CO_2e terms, leading to the following equation.

$$E_y^{CO_2e} = \sum_{t=1}^{T} E_y^t \cdot GWP^t \tag{5}$$

where:

- $E_y^{CO_2e}$ indicates the total annual CO_2e emissions (tons CO_2e/y)
- GWP^t represents the Global Warming Potential associated with each individual GHG, defined as follows: $CO_2 = 1$; $CH_4 = 27$ and $N_2O = 273$ [22].

In addition, two unitary emission performance indices are introduced:

a) $I^t_{e_1}$ (g/km), representing the unitary emissions of the pollutant *t* per kilometer travelled, as defined in the relation (6).

$$I^t_{e_1} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} f^t_{i,j,k,m} \cdot d_{i,j,k,m}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} d_{i,j,k,m}} \tag{6}$$

b) $I^t_{e_2}$ (g/(km·pass)), representing the unitary emissions of the pollutant *t* per kilometer-passenger, as defined in the relation (7).

$$I^t_{e_2} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} f^t_{i,j,k,m} \cdot d_{i,j,k,m} \cdot L_j^{-1}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M} d_{i,j,k,m}} \tag{7}$$

Indices $I_{e_1}^t$ and $I_{e_2}^t$, from relations (6) and (7) respectively, can be formulated in terms of CO_2e emissions (g CO_2e/km and g CO_2e/(km·pass)) as follows:

$$I_{e_{1,2}}^{CO_2e} = \sum_{t=1}^{T} I_{e_{1,2}}^t \cdot GWP^t \quad (8)$$

3. Case Study

This section applies the proposed methodology framework illustrated in the previous section, within the context of the city of Pescara, a coastal city in central Italy with about 120,000 residents and an area of 34 km². Located in the Abruzzo region, it features flat coastal terrain that transitions into gentle inland hills.

The analysis specifically refers to the energy consumption and pollutant emissions of the LPT bus service operated by TUA S.p.A., the local public transport company. Data and fleet characteristics refer to the 2024 service year [17].

Table 1 provides a detailed overview of the bus fleet operating on a representative day within the annual period.

Tab. 1. Characteristics of the bus fleet [17]

Bus model	Number	Length (m)	Weight (ton)	Passenger capacity	Energy carrier	Engine emission standard	Consumption (kWh/km)	Km/ day	Km/ year
Symbol	**-**	**-**	***i***	***j***	***k***	***m***	***c***	***d***	***D***
Irisbus Citelis 18	1	18	30	138	Diesel	EEV	5.616	60	19,102
Irisbus Europolis	2	9.5	16.2	73		4	4.295	287	91,519
Heuliez GX127	1	9.5	14.6	66		4	4.295	263	83,853
BredaMenarinibus NU	2	12	19	108		4	4.853	545	174,126
BredaMenarinibus LU	3	12	18.2	107		3	4.853	472	150,871
BredaMenarinibus MS	2	9	13.65	70		3	4.295	581	185,466
Solaris Urbino U12	25	12	19	99	CNG	EEV	5.223	4,784	1,528,289
Solaris Urbino U18	2	18	30	167		EEV	6.613	300	95,895
Menarinibus Citymood 12	7	12	19	100		6	5.223	1,849	590,546
Menarinibus Citymood 10	3	10.5	19	94		6	4.945	775	247,437
Man Lion's City	1	15	23	106		5	5.223	235	74,908
BredaMenarinibus	8	10.8	19	91		5	4.945	1,301	415,653
Iveco E-way 12	3	12	19.5	75	Electric	-	1.500	806	257,404
Rampini Alè E80	2	8	12	42		-	1.100	512	163,680

Given that the composition of the vehicle fleet varies according to both the day of the week (e.g., weekdays, holidays) and the time of year (e.g., school term, summer period), the simplified assumptions adopted for the analysis involve maintaining a constant fleet configuration, corresponding to that reported in table 1, throughout the entire year. Under this assumption, the total annual commercial service mileage (4,078,750 km/year) carried out by the company TUA [17] is proportionally allocated to each vehicle type, differentiated by classes *i*, *j*, *k*, and *m*, based on their respective daily mileage contributions.

Fig. 2 provides a detailed breakdown of the fleet, showing the number of buses by size category and corresponding energy source.

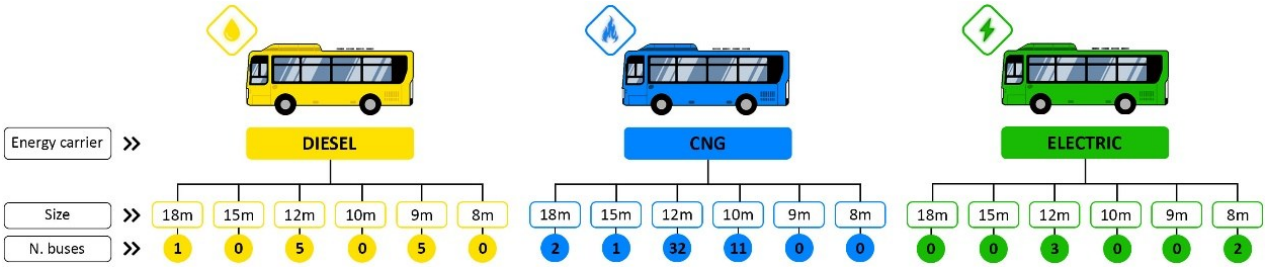

Fig. 2. Fleet distribution by size category and energy source.

In Fig. 3, (a) the number and the percentage of buses operated on the reference day and (b) the total annual mileage are presented, both categorized by energy carriers. It shows that 72.4% of the annual mileage is covered by CNG-powered buses, 17.3% by diesel buses, and the remaining minor share by electric buses.

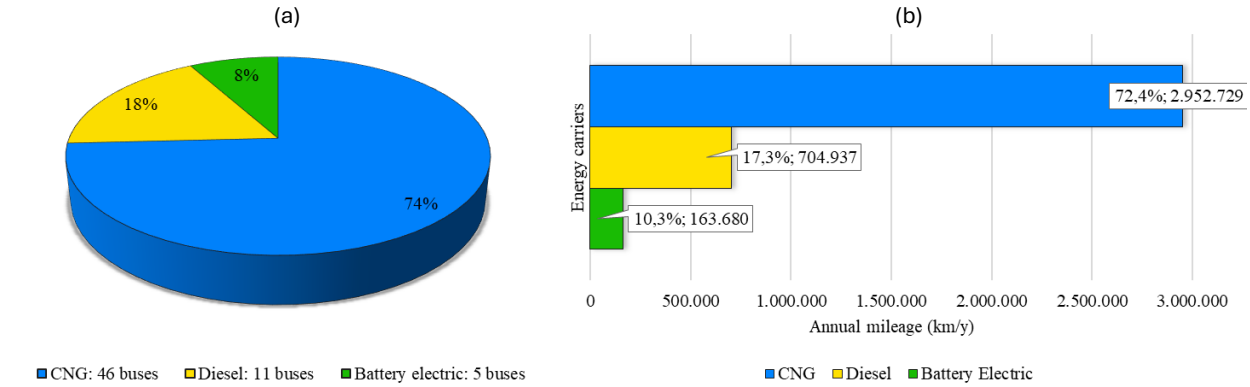

Fig. 3. Categorization of the vehicle fleet (a) and total annual mileage (b), disaggregated by energy carriers

Estimates of energy consumption and emissions, both referring to the vehicle fleet, are presented in the sub-Sections 3.1 and 3.2, respectively, in accordance with the methodology described in Section 2.

3.1 Consumption calculation

Energy consumption was calculated using a vehicle-specific approach, whereby each vehicle type, differentiated by classes *i*, *j*, *k*, and *m*, is assigned an average fuel consumption rate per kilometer.

By applying Relation (1), the total annual energy consumption (C_y) is estimated at 19.17 GWh/year and is presented in Fig. 4, disaggregated by vehicle energy carrier type.

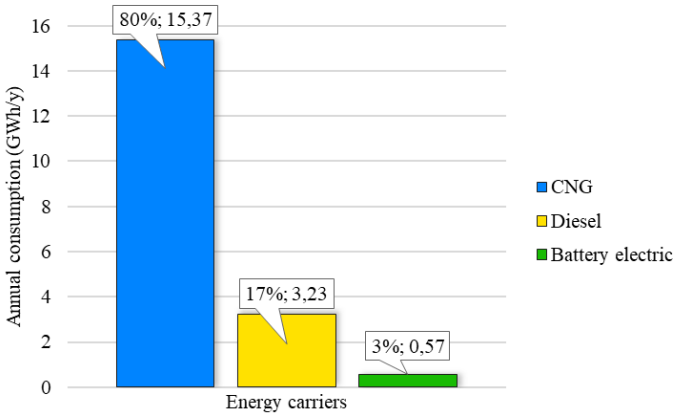

Fig. 4. Annual energy consumption for each type of vehicle energy carrier.

The specific energy consumption per kilometer travelled (I_{c_1}) and per passenger-kilometer (I_{c_2}) are calculated using Relations (2) and (3), respectively, assuming a constant average vehicle occupancy rate α_j of 0.3 for each vehicle type, differentiated by classes i, j, k, and m. The results are presented in table 2.

Tab. 2. Value of indices I_{c_1} and I_{c_2}.

Index	Value	Unit
$\mathbf{I_{c_1}}$	4.70	kWh/km
$\mathbf{I_{c_2}}$	0.16	kWh/(km·pass)

3.2 Emissions calculation

Pollutant emissions are estimated through a bottom-up approach that links fuel consumption and operational data to emission factors specific to each vehicle category. The analysis includes the following key pollutants: CO_2, CH_4, N_2O, $PM_{2.5}$, and PM_{10}. GHG (CO_2, CH_4, and N_2O) emissions are also expressed in terms of CO_2-equivalent (CO_2e) using their respective GWP.

Emission factors $\left(f^t_{i,j,k,m}\right)$, expressed in grams of pollutant per kilometer (g/km), are sourced from the ISPRA (Italian Institute for Environmental Protection and Research) database [23]. These factors are not uniform; rather, they are a function of dimensional class (weight category – i), passenger capacity (j), energy carrier (k), and engine emissions standard (m). This allows for a differentiated and technology-sensitive estimation of emissions, reflecting the specific characteristics of each vehicle model operating in the fleet (table 3).

Tab. 3. Emission factors (g/km) for each vehicle model.

Bus model	Weight (ton)	Passenger capacity	Energy carrier	Engine emission standard	CO_2	CH_4 (g/km)	N_2O	$PM_{2.5}$	PM_{10}
Symbol	*i*	*j*	*k*	*m*	f^{CO_2}	f^{CH_4}	f^{N_2O}	$f^{PM_{2.5}}$	$f^{PM_{10}}$
Irisbus Citelis 18	30	138	Diesel	EEV	1,284.95	0.01	0.04	0.12	0.18
Irisbus Europolis	16.2	73		4	1,014.94	0.01	0.01	0.11	0.16
Heuliez GX127	14.6	66		4	757.75	0.01	0.04	0.09	0.15
BredaMenarinibus NU	19	108		4	1,290.09	0.01	0.01	0.13	0.19
BredaMenarinibus LU	18.2	107		3	1,375.98	0.1	0.01	0.33	0.39
BredaMenarinibus MS	13.65	70		3	822.72	0.1	0.01	0.22	0.27
Solaris Urbino U12	19	99	CNG	EEV	1,132.74	0.95	0.10	0.10	0.07
Solaris Urbino U18	30	167		EEV	1,359.29	1.14	0.12	0.12	0.08
Menarinibus Citymood 12	19	100		6	958	0.82	0.09	0.11	0.22
Menarinibus Citymood 10	19	94		6	958	0.82	0.09	0.11	0.22
Man Lion's City	23	106		5	1042	0.91	0.10	0.10	0.25
BredaMenarinibus	19	91		5	1042	0.91	0.10	0.10	0.25
Iveco E-way 12	19.5	75	Electric	-	-	-	-	0.01	0.02
Rampini Alè E80	12	42		-	-	-	-	0.01	0.02

Based on the data reported in tables 1 and 3, and by applying relations (4) and (5), table 4 shows the total atmospheric emissions (E_y and $E_y^{CO_2e}$) associated with annual fleet operation.

Tab. 4. Annual atmospheric emissions.

Index	CO_2	CH_4	N_2O	$PM_{2.5}$	PM_{10}	CO_2e	Unit
E_y	3,940.91	2.73	0.30	0.44	0.60	-	tons/y
$E_y^{CO_2e}$	-	-	-	-	-	4,095.37	tons CO_2e/y

Fig. 5 illustrates the amount of annual emission of CO_2 (a) and CH_4, N_2O, $PM_{2.5}$, and PM_{10} (b), disaggregated by vehicle energy carrier type.

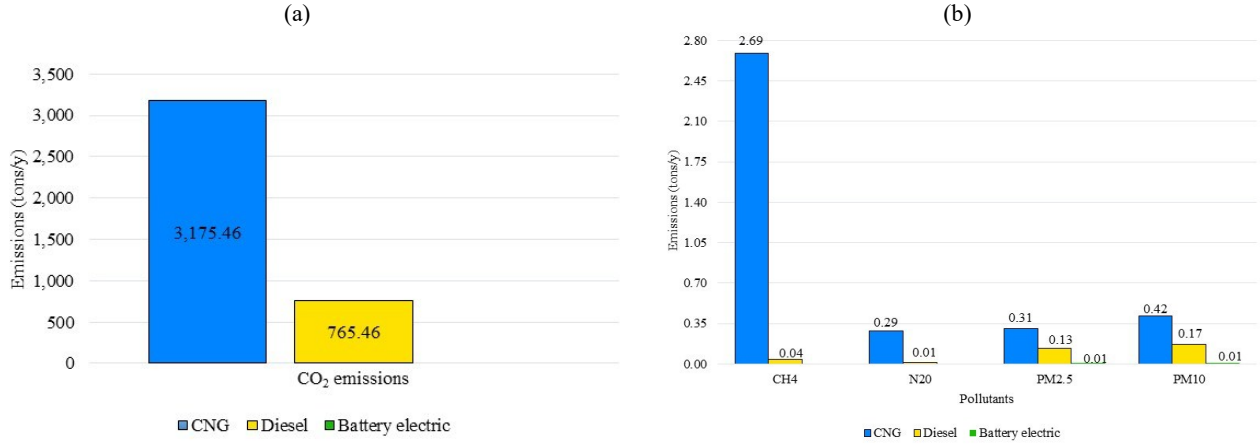

Fig. 5. Amount of CO_2 (a), CH_4, N_2O, $PM_{2.5}$, and PM_{10} (b) annual emission for each vehicle energy carrier.

More in detail, Fig. 6 shows the percentage distribution of total annual emissions for each pollutant across the vehicle energy carriers.

CNG-powered vehicles account for the dominant share of emissions across all pollutant categories, particularly for CO_2 (approximately 81%), CH_4 (over 98%), and N_2O (about 97%). Diesel vehicles contribute to particulate matter emissions, accounting for roughly 30% of $PM_{2.5}$ and PM_{10}, as well as about 19% of total CO_2 emissions.

Battery electric vehicles do not contribute to direct GHG emissions and account for less than 1% and 2% of total emissions for $PM_{2.5}$ and PM_{10}, respectively.

To enable a more detailed assessment, in addition to total annual emissions, specific performance indices have been calculated.

Table 5 presents the unitary emission performance indices ($I_{e_1}^t$, $I_{e_2}^t$, $I_{e_1}^{CO_2e}$, $I_{e_2}^{CO_2e}$) by applying relations (6), (7), and (8), assuming a constant vehicle occupancy rate α_j equal to 0.3 for each energy carrier.

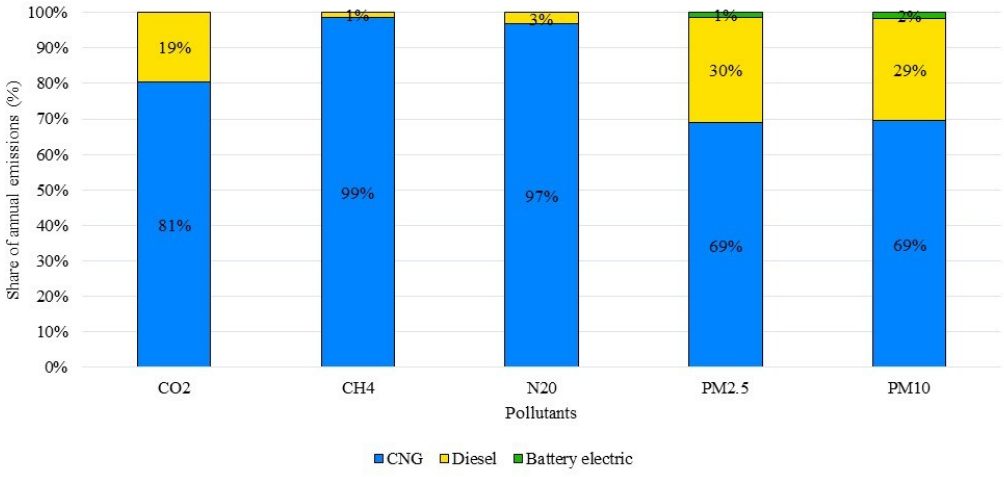

Fig. 6. Share of annual emissions for each pollutant, broken down by energy carrier.

Tab. 5. Unitary emission performance indices.

Index	CO_2	CH_4	N_2O	$PM_{2.5}$	PM_{10}	CO_2e	Unit
I_{e_1}	966.21	0.67	0.08	0.11	0.15	-	g/km
I_{e_2}	32.81	0.022	0.002	0.004	0.005	-	g/(km·pass)
$I_{e_1}^{CO_2e}$	-	-	-	-	-	1,004.93	g CO_2e/km
$I_{e_2}^{CO_2e}$	-	-	-	-	-	34.06	g CO_2e/ (km·pass)

3.3 Sensitivity and transition analyses

To assess the influence of passenger load on the environmental efficiency of public transport, a sensitivity analysis was performed by varying the vehicle occupancy rate (α_j), which significantly affects the unit values of both energy consumption (I_{c_2}) and pollutant emissions (I_{e_2}) per passenger-kilometer (kWh/(km·pass) and g/(km·pass)).

In the baseline scenario, an average occupancy rate of 0.3 (30% of maximum passenger capacity) was assumed for each vehicle type. This section also explores the effects of lower and higher occupancy levels, specifically 20% and 40% of nominal capacity. Pollutant emission calculations were limited to CO_2, given its dominant role in the overall environmental impact.

Table 6 summarizes the values of I_{c_2} and $I_{e_2}(CO_2)$ computed at constant average occupancy rates of 20%, 30%, and 40% across all energy carrier categories.

Tab. 6. Values of the I_{c_2} and $I_{e_2}(CO_2)$ indices.

Index	20%	30%	40%	Unit
I_{c_2}	0.24	0.16	0.12	kWh/(km·pass)
I_{e_2} **(CO₂)**	48.94	32.81	24.65	g CO_2/(km·pass)

Fig. 7. illustrates the variation of consumption (a) and emission (b) indices as a function of the vehicle occupancy rate.

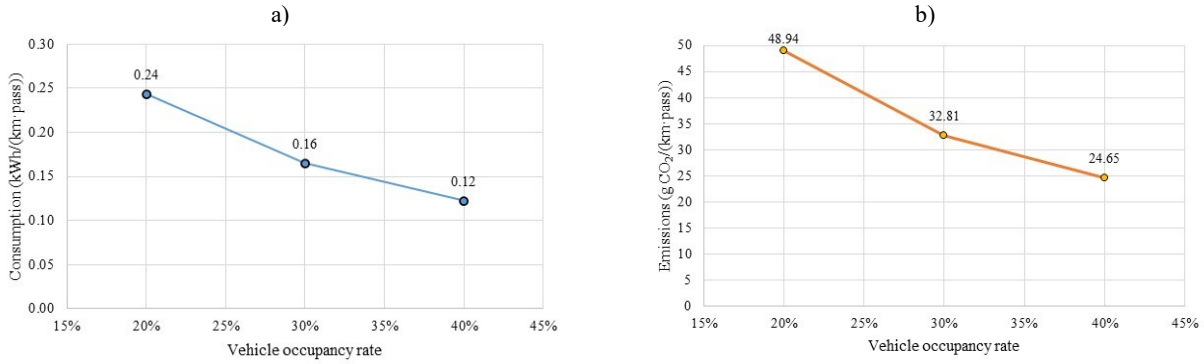

Fig. 7. Variation of consumption (a) and emission (b) indices.

Since the total distance traveled by the fleet remains constant, higher occupancy levels result in lower unit values per passenger-kilometer, highlighting the environmental benefits of improved vehicle utilization.

Increasing the average vehicle occupancy from 20% to 30% and then to 40% reduces I_{c_2} by 32% and 26%, and I_{e_2} by 33% and 25%, respectively.

A further transition analysis is conducted under the preliminary assumption of a linear reduction trend in the annual mileage of both internal combustion energy carriers, diesel and CNG, in favor of electric vehicles, with the aim of achieving the zero-emission targets by 2035.

The scenario assumes a constant total annual mileage, fixed at the 2024 level, and a gradual energy carrier shift occurring within the same vehicle size category. Under these conditions, it has been estimated that an annual mileage reduction of 9.1% for ICE vehicles, progressively replaced by electric ones, would be required to achieve full fleet decarbonization by the target year. The corresponding annual CO_2e emissions throughout the transition period have also been quantified, as illustrated in Fig. 8.

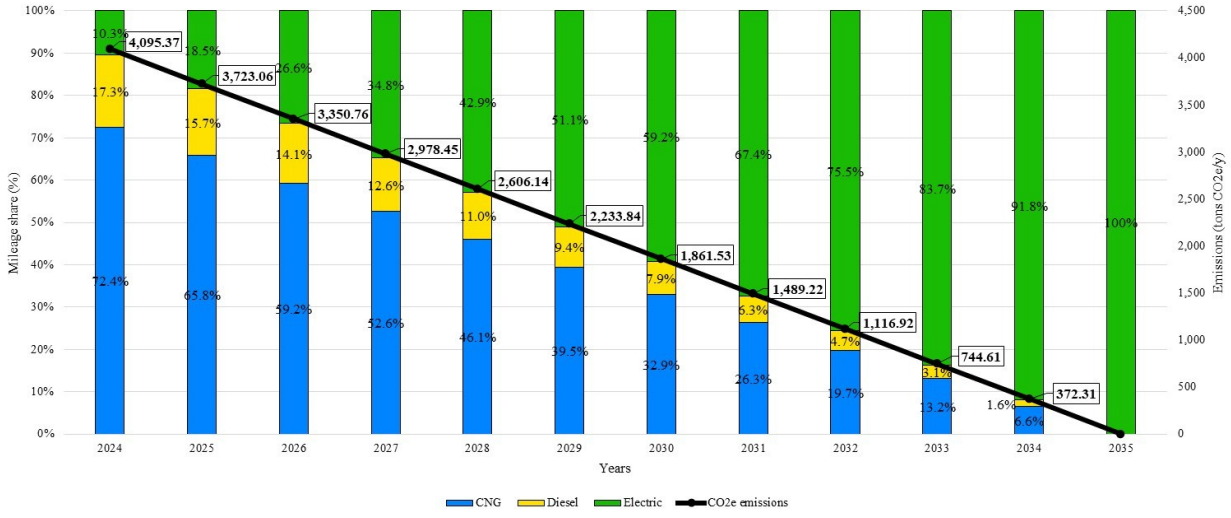

Fig. 8. Annual mileage share (%) by energy carrier required to reach zero emissions by 2035.

This analysis provides a theoretical framework for assessing how a gradual and coordinated reduction in the use of internal combustion technologies, while maintaining constant service levels, can support the transition toward a zero-emission fleet.

4. Conclusion

This study presented a pragmatic, data-driven methodology for estimating energy consumption, greenhouse gases (GHG) and particulate matter (PM) emissions from local public transport vehicular fleet. Designed for cost-effectiveness and replicability, the approach integrates real-world operational data, traffic volumes and detailed fleet attributes (vehicle class, capacity, energy source,

and emission standard), sourced from transport operators and national databases. Emissions of CO_2, CH_4, and N_2O are aggregated into CO_2-equivalents, while $PM_{2.5}$ and PM_{10} are assessed independently.

The proposed framework also introduces unitary performance indicators that account for passenger loads and operational parameters, enabling per-capita environmental assessments.

The methodology was applied to a case study in Pescara, a mid-sized city in central Italy, using data from the local operator, TUA S.p.A. Based on fleet characterization, comprising 74% CNG, 18% diesel and 8% electric vehicles and on annual mileage of 4,078,750 km, assuming an average occupancy of 30% of maximum capacity, the results show:

- Annual energy consumption of 19.17 GWh, with unit performance indices I_{c_1} amounting to 4.70 kWh/km and I_{c_2} amounting to 0.16 kWh/(km·pass);
- Annual GHG emissions of 4,095.37 tons CO_2e, with unit performance indicators $I_{e_1}^{CO2e}$ amounting to 1,004.93 g CO_2e/km and $I_{e_2}^{CO2e}$ amounting to 34.06 g CO_2e/(km·pass).
- Annual particulate matter emissions of 0.31 tons for $PM_{2.5}$ and 0.42 tons for PM_{10}, with unit performance indices I_{e_1} equal to 0.11 g/km, for $PM_{2.5}$ and 0.15 g/km for PM_{10} and I_{e_2} equal to 0.004 g/(km·pass), for $PM_{2.5}$ and 0.005 g/(km·pass) for PM_{10}.

A sensitivity analysis further demonstrated that increasing the average vehicle occupancy rate from 20% to 40% results in a 50% reduction in I_{c_2} and a 49.6% reduction in I_{e_2}, highlighting the strategic relevance of operational measures, such as load optimization and demand stimulation, in complementing the technological transition.

To support decarbonization targets, a strategic scenario analysis has been conducted, proposing a phased vehicle replacement strategy to meet the zero-emission goal by 2035.

The proposed framework offers a transferable tool for environmental assessment, scenario analysis, and long-term fleet monitoring. Future developments will address economic evaluations, such as Total Cost of Ownership, to support strategic planning for sustainable public transport.

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