


Article

Traffic Simulation-Based Approach for A Cradle-to-Grave Greenhouse Gases Emission Model

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Abstract: This paper presents a model to evaluate the life cycle greenhouse gases (GHG) emissions, expressed in terms of carbon dioxide equivalent (CO₂eq), of a generic fleet composition as a function of the traffic simulation results. First we evaluated the complete life cycle of each category of the vehicles currently circulating; next, by defining a general linear equation, the traffic environmental performances of a real road network (city of Rome) were evaluated using a traffic simulation approach. Finally, the proposed methodology was applied to evaluate the GHG emission of a 100% penetration of battery electric vehicles (BEVs) and various electric and conventional vehicles composition scenarios. In terms of life cycle impacts, BEVs are the vehicles with the highest GHG emissions at the vehicle level (construction + maintenance + end-of-life processes) that are, on average, 20% higher than internal combustion engine vehicles, and 6.5% higher than hybrid electric vehicles (HEVs). Nevertheless, a 100% BEVs penetration scenario generates a reduction of the environmental impact at the mobility system level of about 65%.

Keywords: traffic emissions; traffic simulation; electric vehicles; greenhouse gases emissions; life cycle assessment

1. Introduction

Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), collectively called Plug-in Electric Vehicles (PEVs), and hybrid electric vehicles (HEVs), have recently been offered as a mass-market alternative to conventional cars with petrol and diesel engines (i.e., Internal Combustion Engine Vehicles (ICEVs) [1]. They have been introduced as a solution to the problem of dependency on fossil fuels, increasing carbon dioxide (CO₂) emissions, and other environmental issues [2]. Literature regarding the life cycle assessment (LCA) of PEVs, HEVs, and ICEVs is quite extended. Studies are mainly focused on the “vehicle” system and on the comparison of different technologies (BEVs, PHEVs, HEVs, and ICEVs). Studies concerning cars for individual transportation are dominant with respect to other vehicle types (e.g., heavy or light-duty trucks, buses, etc.) that are investigated in very few works [3]. The different technologies perform differently in terms of environmental impact, and there is not a single technology with good performance in all the environmental impact categories. Hawkins et al. (2012) [4] carried out a comparison of an electric vehicle (EV) and an ICEV over their entire life cycle and found that the greenhouse gases (GHG) emissions decrease of EVs powered by the current European electricity mix is 10% and 24% compared to conventional diesel and gasoline vehicles, respectively. Ellingsen et al. (2016) [5] found that when comparing equal vehicle sizes, the EVs have 20–27% lower lifecycle impact than the ICEVs using the average European electricity mix. Using a Monte Carlo method to simulate EVs use-phase under a wide range of driving conditions, Canals Casals et al. (2016) [6] calculated the GHG emission associated with EVs and ICEVs for the EVs’ top-selling European countries. They found that only France (76% nuclear power

energy ratio) and Norway (94% hydropower) ensures global warming potential (GWP) reductions for the whole EVs energy consumption range. Woo et al. (2017) [7] compared the GHG emissions associated with EVs with those from the ICEVs for 70 countries. Their findings indicated that countries with high nuclear power and renewable energy ratios in their generation mix have lower GHG emissions for BEVs. Kamiya et al. (2019) [8] confirmed this and found that British Columbia (mainly hydro-based) has the greatest emission reduction potential for PEVs (78–98%) compared to ICEVs. Furthermore, EVs showed the potential for significant increases in some impact categories (human toxicity, freshwater eutrophication, and metal depletion). According to De Souza et al. (2018) [9], among the technologies, BEVs emerge as the vehicles with the lower environmental charges. The manufacturing phase of BEVs has high relative importance in terms of life cycle impact, and it has a significantly higher impact than ICEVs, mainly due to the production and disposal processes of batteries [10–13]. Due to energy production and consumption, the use of vehicles is identified as the most relevant life cycle phase regarding the majority of environmental impact indicators considered, both for ICEVs—for which also the effects of lightweighting strategies are analyzed—and the different types of EVs [14–17]. Moreover, the impact reduction potential of EVs is estimated as gradually increasing with the optimization of the electricity mix (renewable energies penetration) and the wide application of advanced electricity technologies [18–21]. The disposal phase was found to have a minor influence on the total environmental burdens [22], even if different recycling technologies for the end-of-life of the vehicle could significantly differ in terms of impact [23].

The research presented in this paper aimed at evaluating the environmental effects of individual transport by cars by combining the full life cycle implication at the vehicle level and the traffic simulation results. In fact, we evaluated the complete life cycle (per unit of kilometer) of each category of currently circulating vehicles, and defined a general equation to calculate the impact of the fleet composition on a real road network (city of Rome). The core of this study was to define a linear equation to evaluate the life cycle GHG emissions, expressed in terms of carbon dioxide equivalent (CO_2eq), of a generic fleet composition as a function of the traffic simulation results. The proposed approach was used to evaluate both the environmental performances, in terms of GHG emissions, of the current scenario of the city of Rome and the environmental performance of a 100% BEVs penetration scenario. Finally, the GHG emissions of various mixed fleet composition scenarios were also evaluated to show how the linear equation proposed in this paper can be applied in any context characterized by a given fleet composition and by a specific output of the traffic simulation.

The remainder of the paper is organized as follows. Section 2 outlines the materials and methods used both for the LCA and for the traffic simulation analysis. Section 3 presents and discusses the results of the study. Section 4 concludes and summarizes the paper, including a discussion on the assumptions of this study and future research needs.

2. Materials and Methods

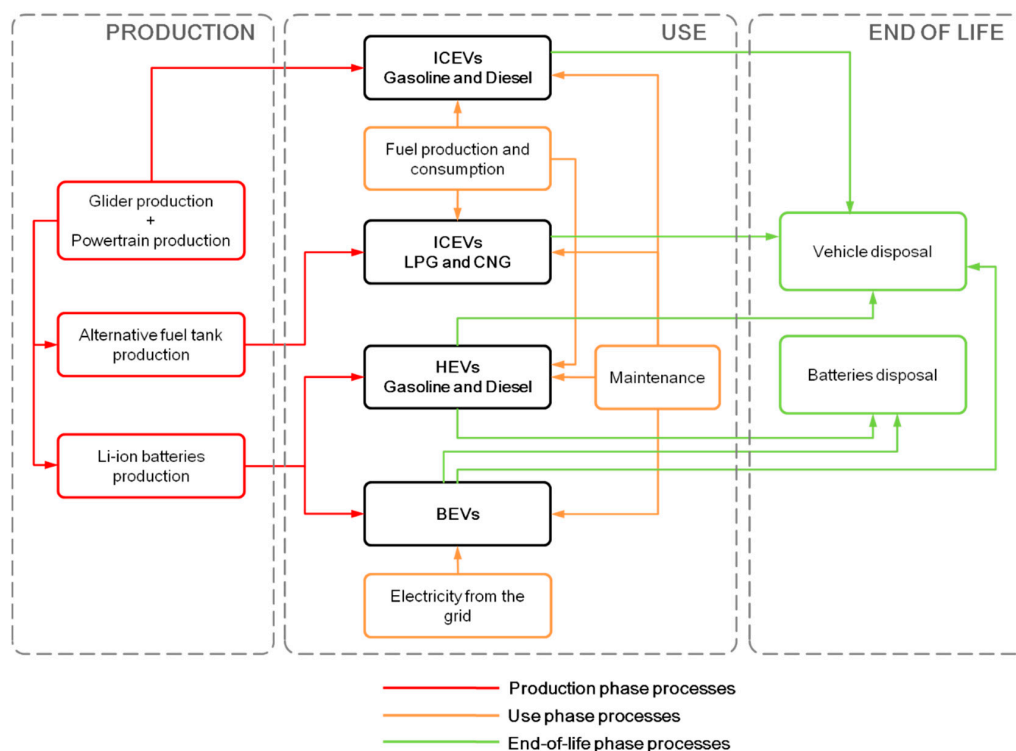
The LCA study considered a medium-sized passenger car as reference vehicle, and it was performed with a cradle to grave approach, i.e., considering all the life cycle stages from raw materials acquisition to vehicle end-of-life. The life cycle inventory (LCI) of the vehicle construction phase was modeled on the basis of existing literature [9,24–26] and data included in available databases [27], while the end-of-life was modeled by a disposal scenario specific to the considered area. Regarding the use phase, the modeling was based on the traffic simulation results, in terms of vehicle kilometer traveled (VKT). GHG emissions related to the use phase of BEVs strongly depend on the electricity generation mix of the country; emissions decrease when the contribution of renewable energies increases in the grid. In this work, we referred to the current electricity generation mix of Italy (Table 1), without considering different future scenarios, in order to evaluate the worst case in terms of environmental impact.

Table 1. Italian generation mix, reference year 2016 [28].

Energy Source	Share (%)
Gas	43.6
Hydropower	15.3
Coal	13.3
Photovoltaics	7.6
Wind power	6.1
Petroleum Oil	4.2
Biomasses Biofuels	5.9
Geothermal power	2.2

2.1. Life Cycle Assessment Analysis

LCA is a methodology that allows the evaluation of the environmental impact of products and services across all their life cycle stages, i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair, maintenance, and final disposal or recycling. As far as this study is concerned, an attributional LCA according to ISO 14040 and 14044 [29,30] was performed with the aim of evaluating the life cycle GHG emissions associated with a 100% EVs scenario at the urban mobility level, compared with the current scenario of the case study city, which is Rome. The LCA study was carried out with a “cradle-to-grave” approach; therefore, all the life cycle stages from raw materials acquisition to vehicle end-of-life were considered (Figure 1). The selected functional unit was 1 km driven by a medium-sized passenger car characterized by a lifespan of 150,000 km. Life lengths of vehicles can vary largely according to the specific characteristics of different models, but the assumed lifespan value is widely used as a reference for LCA studies of small- to medium-sized passenger cars [4,14,18,19,22]. A detailed description of the modeling assumptions for each life cycle stage is given in the following sections.

**Figure 1.** System boundaries adopted for the life cycle assessment (LCA) of the considered vehicles.

2.1.1. Production Phase Modeling

A vehicle is an assembly of many systems that can be divided into sub-systems up to single components/materials. For the modeling of the vehicles, two common main larger systems were considered: the glider, which consists of the vehicle body and chassis, and the powertrain. The powertrain of ICEVs includes the internal combustion engine and its accessories, while for BEVs it consists of the electric motor, charger, inverter, power distribution unit, cables, and converter. The alternative fuel tanks — Liquified Petroleum Gas (LPG) and Compressed Natural Gas (CNG) — for bi-fuel ICEVs, as well as the batteries pack (Li-ion typology considered) for EVs, were considered as separate systems. The main source of data for the modeling of the production stage of the vehicles was the database Ecoinvent v3 [27]. Regarding specific components for which datasets are not available in the Ecoinvent database, data on the subcomponents/materials used were gathered from available manufacturer datasheets and from literature.

Table 2 summarizes the weight data for each vehicle and each included system, while the inventory data for the construction of each considered system are reported in the supplementary material.

Table 2. Weight of the systems included in the considered vehicles.

Component		ICEVs				HEVs		BEVs
		Gasoline	Diesel	LPG	CNG	Gasoline	Diesel	
Powertrain	kg	338	397	338	338	338	397	240
Glider (body + chassis)	kg	961	903	961	961	961	903	900
Secondary fuel tank and accessories	kg			21	51			
Battery and accessories	kg					120	120	300

2.1.2. Use Phase Modeling

Vehicles energy consumption and emissions are affected by many variables that are related to different factors. Zhou et al. (2016) [31] classified these variables into six broad categories, i.e., those related to travel characteristics (travel distance and times), to the vehicle (engine, vehicle loading, speed, and acceleration), to ambience (temperature, humidity, and wind), to the road network (roadway grade, surface roughness, and horizontal curvature), to traffic (traffic flow and signaling), and to the driver (driver behaviour and aggressiveness). In general, energy consumption is shown as increasing with speed and acceleration, both for ICEVs [32,33] and EVs [34], even if EVs seem to be more efficient in urban driving conditions, both considering laboratory driving tests and real-world vehicle activity patterns [35–37]. Moreover, the use of a global average value of energy consumption in [Wh/km]—as most of the LCA literature model the use phase of EVs—is considered an approximation that does not allow one to capture the real consumption of EVs among different driving cycles [38].

In this study, therefore, for a more detailed modeling of the use phase, we considered specific energy consumption/emission factors related to different driving conditions, i.e., intra-urban roads and highways, for each considered type of vehicle currently circulating in Rome. Table 3 shows the current fleet composition of Rome [39]. As shown in this table, the EVs diffusion amongst Roman households is quite limited. However, recent initiatives to promote sustainable mobility in the city of Rome have been reported by [40–42]. Most relevant factors and barriers affecting Italian consumer EV adoption intentions have been examined by Asdrubali et al. (2018) [43], and a general overview of consumer EV adoption behavior can be found in [2].

Table 3. Fleet composition of Rome, reference year 2017 [39].

Propulsion	Number of Vehicles	%
Gasoline	1,424,986	49.45
Diesel	1,148,833	39.86
LPG	266,739	9.26
Natural gas	21,235	0.74
Hybrid electric vehicles (HEVs)	19,460	0.68
Battery electric vehicles (BEVs)	703	0.02

Regarding ICEVs, emission factors were gathered from the database of emission factors for road transport in Italy [44], which applies a methodology based on EMEP/EEA air pollutant emission inventory guidebook [45] and is coherent with IPCC guidelines on GHG [46]. Specific fuel consumption factors in g/km were then estimated starting from the available emission factors for the different gases in g/km and in g/g of fuel. Data are summarized in Table 4. Regarding EVs, instead, electricity consumption factors were assumed as specified in Table 5 for intra-urban roads and highways. Even if the assumed values represent estimates, they are in line with values resulting from standard driving cycles NEDC [47,48] and WLTC [49] that simulate both urban driving and highway conditions, obtained from [38,50]. The traffic simulation procedure, described in the next section, provided the vehicle kilometer traveled (VKT) for each link (intra-urban or highway) of the road network. Regarding the current scenario, VKT values were split according to the percentages of the fleet composition shown in Table 3. Next, the emissions were estimated using the factors reported in Tables 4 and 5. Regarding HEVs, it was assumed an electric operation for traveling speeds under 50 km/h and a conventional fuel operation for speeds higher than 50 km/h.

Table 4. Emission and fuel consumption specific factors considered for internal combustion engine vehicles (ICEVs).

Passenger Car	g CO ₂ eq/km		g CO ₂ eq/g Fuel		g Fuel/km	
	Urban	Highway	Urban	Highway	Urban	Highway
Gasoline	267.91	159.38	3.14	3.14	85.32	50.81
Diesel	216.96	159.03	3.11	3.11	69.76	51.14
LPG	231.38	196.49	3.03	3.03	76.36	64.85
Natural Gas	201.99	152.02	2.76	2.76	73.06	55.04

Table 5. Electricity consumption specific factors considered for electric vehicles (EVs).

Authors	Average of Driving Cycles Phases (Wh/km)		Driving Cycles Results (Wh/km)	
	Low Speed	High Speed	NEDC	WLTC
Fiori et al. (2016)	138.17	173.83	148.50	169.80
Paffumi et al. (2015)	157.10	177.06	156.90	178.40
Assumed electricity consumption values				
Intra-urban	150		Wh/km	
Highway	200		Wh/km	

The ordinary maintenance activities that occur during the vehicles' life were modeled using the datasets included in the Ecoinvent database, which includes materials used for alteration parts and the energy consumption of garages, and also accounts for materials transportation (see the electronic supplementary material). A maintenance intervention, consisting in the replacement of the whole

batteries package, was considered for the EVs. Even if some EV manufacturers consider the replacement at about 160,000 km with a 75% remaining charge capacity, the intervention is assumed to be realized after 130,000 km (about 80–85% remaining charge capacity), as a precautionary assumption (worst condition) in terms of life cycle GHG emissions. The impact of the new battery pack has not been fully associated with the life cycle of the vehicles; only the impact related to the 20,000 km remaining to reach the considered lifespan (150,000 km) has been allocated to them.

2.1.3. End-of-Life Phase Modeling

The treatment of vehicles at end-of-life consists of removing vehicle components such as engine, transmission, doors, tires, batteries, etc., in order to reuse components themselves and recycle materials. Even if higher recycling rates are to be expected, also in the light of end-of-life vehicles regulation, it should be expected that approximately 75% of a vehicle, mainly composed of ferrous metal, will be recycled or reused, while the remaining body of the car will be shredded into small pieces that will be landfilled or incinerated [51]. For the purposes of the present study, according to the “polluter pays” approach [52], the end-of-life of the considered vehicles was modeled neglecting the environmental impact reduction related to materials recycling and reuse but taking into account the impact associated with the shredding process and its output waste flows.

The assumption of neglecting the recycling and/or reuse of EVs batteries has to be considered as precautionary, since big recycling companies are nowadays industrializing battery recycling processes, and this will represent a key change in the environmental impact of the batteries of tomorrow. All the considered treatments were modeled using the datasets included in the Ecoinvent database. Inventory data regarding the end-of-life phase are reported in the supplementary material.

2.2. Traffic Simulation

A traffic simulation-based analysis was chosen to evaluate the network performances in terms of travel times and total distance traveled. As to the volume-delay functions, this study used the BPR function (Bureau of Public Roads) [53]:

$$t_a = t_a^0 \cdot \left(1 + \alpha \cdot \left(\frac{q_a}{C_a}\right)^\beta\right),$$

where t_a^0 is the free-flow travel time of the road link a ; α , and β are road-type specific parameters; q_a is the load on the link a ; and C_a is the link's capacity.

The simulation was performed through a static traffic assignment model (using EMME by INRO). The morning peak origin-destination (O-D) trip matrix was loaded onto the traffic network of Rome, and the total amount of vehicle-trips assigned was 404,055. The O-D matrix was previously updated from recent traffic counts following the procedure described by Cascetta and Nguyen (1988) [54].

The traffic assignment procedure provided the traffic volume as well as the speed for every link of the road network. The network of Rome was modeled with 565 centroids (zones) and 6873 road links; of these, 5532 were intra-urban links.

Once these outputs are obtained, the life cycle GHG emissions, regarding both the current and different EVs market penetration rates scenarios, can finally be estimated and compared.

3. Results

3.1. Traffic Simulation

The Rome AM peak origin-destination (O-D) trip matrix was loaded onto the traffic network using EMME to estimate the link speeds, vehicle-kilometer, travel times, and average network speed. The simulation results are shown in Table 6 in terms of vehicle kilometer traveled (VKT), total time spent (TTS), and network speed.

Table 6. Simulation results: (a) intra-urban and highways and (b) entire road network. (VKT: vehicle kilometer traveled; TTS: total time Spent.)

	VKT (veh*km)	TTS (veh*h)	Network Speed (km/h)
INTRA-URBAN ROADS	2,204,596	179,033	12.3
HIGHWAYS	2,029,259	40,267	50.4
ENTIRE ROAD NETWORK	4,233,855	219,300	19.3

Figure 2 shows the volumes on links resulting from the assignment procedure. A red bar represents high volumes on the link (>3000 vehicles), volumes from 1000 to 3000 vehicles are represented with green bars, and a thin blue represents small volumes (<1000 vehicles). Higher volumes can be observed in the ‘Grande Raccordo Anulare’ (GRA, i.e., a ring-shaped, 68.2 kilometers long freeway that encircles Rome) and in the high-capacity roads connecting the GRA to the city center.



Figure 2. Simulation results: traffic volume on road links.

3.2. GHG at the Vehicle Level

At the vehicle level (Figure 3), i.e., focusing on the sum of construction, maintenance, and end-of-life processes, BEVs are characterized by the highest life cycle GHG emissions, which are 23.2% higher than that of gasoline-fueled ICEVs, 22.6% higher than that of diesel-fueled ICEVs, and 17.9% and 17.4% higher than that of LPGs and CNG ICEVs, respectively. This higher impact is mainly due to the construction phase and, in particular, to the production of the Li-ion batteries package, which accounts for the 16.3% of the whole impact at the vehicle level. On the other hand, BEVs showed an impact

that is 6.9% higher compared to gasoline-fueled HEVs, and 6.2% higher compared to diesel-fueled HEVs. For all the vehicles, the construction is the major impacting phase: 68.0–70.5% for ICEVs, 72% for HEVs, and 87.6% for BEVs. Regarding the BEVs, the Li-ion batteries production generates 18.6% of the construction impact, with the cathode (LiMn_2O_4) and anode (graphite) that represent, respectively, 47.4% and 29.1% of the impact related to the batteries production. The end-of-life phase makes a minor contribution to the impact (in the range 4–7% for all the vehicles), while the maintenance activities have a relevant role on the GHG emissions of ICEVs and HEVs (22–28%) and slightly contribute to the ones of BEVs (about 6%). Authors would like to stress that such results do not include the use phase impact, since a single emission factor was not considered for this phase but rather specific emission factors that are coupled with traffic simulation results. In the next section, by including the GHG emissions related to the use phase, our analysis will show that HEVs and BEVs as less impacting compared to conventional ICEVs.

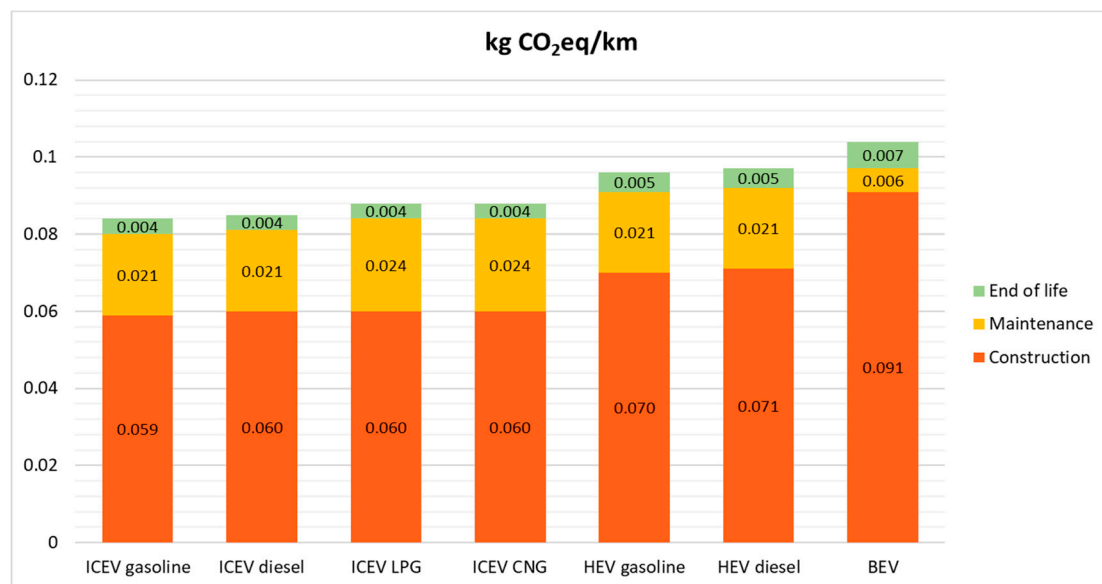


Figure 3. LCA results at the vehicle level.

3.3. GHG Emissions at the Urban Mobility Level

The linear equation model can be expressed as the sum of two components that relate to the driving conditions, i.e., intra-urban roads and highways. Thus, the total energy consumption (E^T), in terms of GHG emission is given by the following equation:

$$E^T = E^H + E^{IU} \quad (1)$$

where E^H represents the emissions in highway condition and E^{IU} relates to intra-urban conditions. If we assume that the total VKT can be divided proportionally to the fleet composition, Equation (1) can be written as follows:

$$E^T = \sum_i \alpha_i^H L_i^H + \sum_i \alpha_i^{IU} L_i^{IU} \quad (2)$$

where the index i represents each vehicle category, the coefficient α represents GHG emission per unit of kilometer traveled, and L is the length traveled in the two different driving conditions (intra-urban roads and highways). Table 7 summarizes the emission coefficients for each vehicle category.

Table 7. α coefficient: greenhouse gases (GHG) lifecycle emission per unit of kilometer traveled. (IU: intra-urban roads; H: highways.)

Vehicle Category (<i>i</i>)	α (kg CO ₂ eq/km)	
	IU	H
Internal combustion engine vehicle (ICEV) gasoline	0.352	0.243
ICEV diesel	0.301	0.243
ICEV Liquefied Petroleum Gas (LPG)	0.319	0.284
ICEV Compressed Natural Gas (CNG)	0.290	0.240
Hybrid electric vehicles (HEV) gasoline	0.166	0.256
HEV diesel	0.167	0.256
Battery electric vehicles (BEV)	0.173	0.196

Using as input to Equation (2) the simulation results shown in Table 6 and the coefficients reported in Table 7, we obtain 1247.46 t CO₂eq, mainly related to “conventional” ICEVs (gasoline and diesel).

3.3.1. Full BEVs Penetration Scenario

By assuming a 100% penetration scenario, in this section we evaluated the environmental effect of the full electrification of private urban transport.

Since this paper represents a first attempt to define an integrated approach to evaluate the life cycle GHG emissions of EVs at the urban mobility level, variations in travel demand (population growth, spatial distribution, mode choice, etc.) were not included. For the scope of this study, we assumed that private vehicles owners are directly converted into BEVs owners, and therefore all the current private car trips are made with BEVs.

Looking at the results at the mobility system level (Figure 4), GHG emissions decrease from 1247.46 t CO₂eq of the current scenario, mainly related to “conventional” ICEVs (gasoline and diesel), to 438.26 t CO₂eq of the 100% BEVs scenario, with a reduction equal to 64.9%. This impact reduction is related to the significant reduction of GHG emissions associated with BEVs operation (electricity consumption). In detail, in the 100% BEVs scenario, the impact of the use phase is 0.33 t CO₂eq, compared to the 889.21 t CO₂eq of the current scenario (due for 89.6% to gasoline and diesel ICEVs).

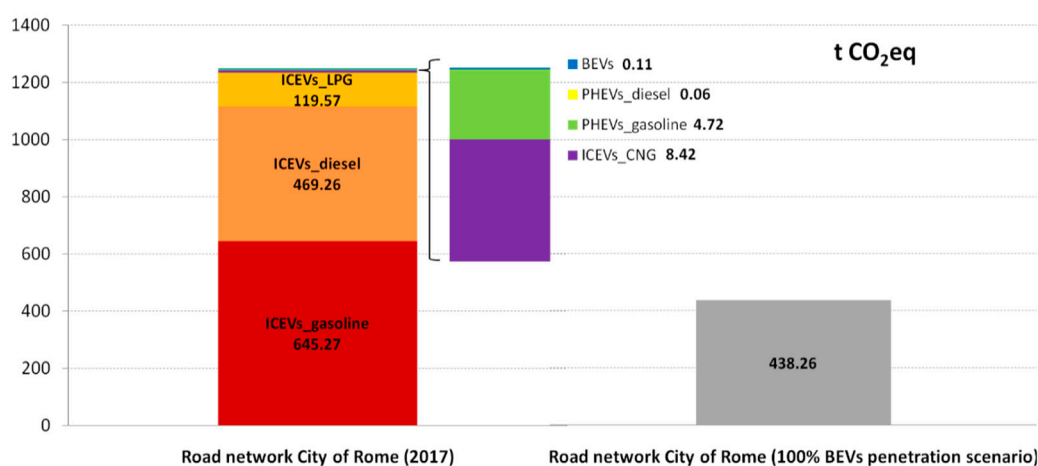


Figure 4. GHG lifecycle emissions at the mobility system level.

3.3.2. Comparison of Future Hypothetical Scenarios

In the previous section, we assumed a 100% penetration scenario to highlight the positive environmental effect of the adoption of BEVs on a real road network. In this section, as an example, we supposed 4 scenarios, shown in Figure 5, characterized by different BEVs and HEVs penetration rate. Table 8 reports the results of the life cycle GHG emissions of the four scenarios. These are

intended only to show how the linear equation proposed in this paper (Equation (2)) can be applied in any context characterized by a given fleet compositions and by the specific output of the traffic simulation. As EV adoption rates vary dramatically by country owing to different levels of the various governments' financial support and the diverse structures of the incentives [55], it is not possible to provide predetermined penetration rates. In Italy, a new incentive named "Ecobonus auto 2019" will start on March 2019. It consists of a monetary incentive ranging from 4000–6000€ to purchase electric cars with a value of up to 54.900€ (VAT included), i.e., non-luxury cars. This is expected to positively influence consumers' intentions toward EVs.

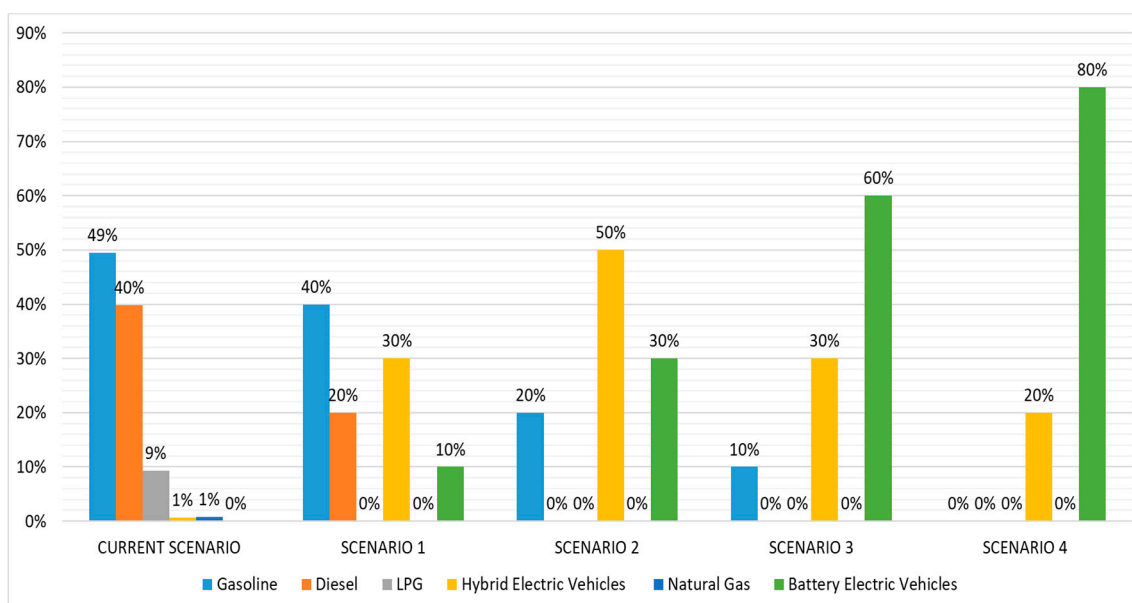


Figure 5. Fleet composition scenarios.

Table 8. Life cycle GHG emissions for different fleet composition scenarios.

Vehicle Category	LCA GHG Emissions (t CO ₂ eq)				
	Current Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
ICEV gasoline	645.27	522.00	261.00	130.50	-
ICEV diesel	469.26	235.45	-	-	-
ICEV LPG	119.57	-	-	-	-
ICEV CNG	8.42	-	-	-	-
HEV gasoline	4.77	204.37	340.61	204.37	136.24
HEV diesel	0.06	-	-	-	-
BEV	0.11	43.83	131.48	262.96	350.61
	1247.46	1005.64	733.09	597.82	486.85

As expected, the more the circulating fleet is composed of EVs, the more the GHG emissions decrease.

4. Conclusions

This study demonstrated the importance of an integrated approach to evaluate life cycle GHG emissions at the urban mobility level. The results from both LCA and traffic simulation were combined in order to evaluate the full life cycle implications at the mobility system level. The principal objective of this work was to define a general linear equation to evaluate life cycle GHG emissions, expressed in

terms of carbon dioxide equivalent (CO₂eq), of a generic fleet composition as a function of the traffic simulation results. The methodology was tested in the road infrastructure of the city of Rome, but it can be generalized and applied to any urban context characterized by a given fleet compositions and by the specific output of the traffic simulation.

The evaluation of life cycle impacts clearly showed the BEVs have the highest GHG emissions at the vehicle level, which are evaluated as the sum of the construction, maintenance, and end-of-life processes (on average 20% higher than the ones of ICEVs, and 6.5% higher than the ones of HEVs). The Li-ion batteries production process emerged as a relevant contributor, with a share of 16.3% (0.016 kg CO₂eq/km) of the whole impact at the vehicle level. The analysis at the vehicle level also highlighted that the construction phase represents the main contributor to the global impact (68.0–70.5% for ICEVs, 72% for HEVs, 87.6% for BEVs), while the end-of-life gives a minor contribution for all the considered vehicles (4–7%). Maintenance activities assumed a relevant role only for the impact related to ICEVs and HEVs (22–28% of the life cycle GHG emissions), while they slightly contributed to the impact of BEVs (about 6% of the life cycle GHG emissions).

On the other hand, the analysis at the mobility system level (performed considering the vehicles direct impact during the use phase and simulating different scenarios on the real road network of the city of Rome) showed a completely different result trend. In detail, life cycle GHG emissions in the 100% BEVs penetration scenario (438.26 t CO₂eq) resulted in about 65% lower compared to the ones related to the current scenario (1247.46 t CO₂eq). This impact reduction is the consequence of the significant reduction of GHG emissions associated with vehicles operation, which decreased from the 889.21 t CO₂eq of the current scenario to the 0.33 t CO₂eq of the 100% BEVs scenario.

This work incorporated some assumptions, regarding both traffic simulation and LCA analysis. As for the general linear equation, which represents the main contribution of this paper, we assumed that total VKT obtained by the traffic simulation can be divided proportionally to the fleet composition. This assumption was necessary, since it is impossible, for data availability reasons, to associate each trip of the O-D matrix with a specific type of vehicle. However, there are no significant reasons to suppose that the user's choice of vehicle propulsion, in the urban context, depends on the trip distance. In fact, the autonomy of modern BEVs, which are the only kind of vehicles that use energy stored from the grid exclusively, is much higher than the average daily distance traveled in the urban context.

The environmental impact of EVs under different penetration rates was evaluated without including variations in travel demand, population growth, the spatial distribution of trip attractors, mode choice, etc. A complete simulation of the urban evolution is out of the scope of the research presented in this paper. However, the method that we have provided can be replicated in any hypothetical urban mobility structure.

As to the LCA analysis, a medium-sized passenger car with a lifespan of 150,000 km was assumed. Future research could benefit from the proposed approach and attempt to investigate the environmental performances of multiple scenarios characterized by vehicles with different characteristics, especially for EVs. Moreover, the environmental impact reduction related to materials recycling and reuse at the end-of-life was neglected, and the inventory data were taken from datasheets and literature. All the assumptions have been considered reasonable for the final aim of this study, which is to define an integrated approach to evaluate the life cycle GHG emissions at the urban mobility level of any circulating fleet that includes a variable share of EVs. An in-depth analysis of these assumptions is, however, needed for future research developments.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/11/16/4328/s1>, Table S1: Glider, passenger car, 1 kg; Table S2: Internal combustion engine and accessories, 1 kg; Table S3: Electric motor, 1 kg; Table S4: Li-ion battery, 1 kg; Table S5: Charger, electric passenger car, 1 kg; Table S6: Converter, electric passenger car, 1 kg; Table S7: Inverter, electric passenger car, 1 kg; Table S8: Power distribution unit, electric passenger car, 1 kg; Table S9: Secondary fuel tank, ICEV_LPG, 1 piece; Table S10: Secondary fuel tank, ICEV_CNG, 1 piece; Table S11: Maintenance, passenger car 1 piece (ICEVs and HEVs gasoline and diesel); Table S12: Maintenance, passenger car 1 piece (ICEVs LPG and CNG); Table S13: Maintenance, electric passenger car 1 piece; Table S14: Shredding of glider passenger car, 1 kg; Table S15: Li-ion batteries, hydrometallurgical treatment, 1 kg.

Author Contributions: Conceptualization, S.M.P.; Investigation, S.M.P. and F.S.; Methodology, S.M.P. and F.S.; Supervision, F.A. and S.C.; Writing—original draft, S.M.P., F.S. and F.A.; Writing—review & editing, S.M.P., F.S., F.A. and S.C.

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