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Addressing the Sustainability Issue in Smart Cities: A Comprehensive Model for Evaluating the Impacts of Electric Vehicle Diffusion

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Abstract: The present paper proposes a model for evaluating environmental, social, and economic impacts exerted by the diffusion of electric vehicles (EVs), which is a phenomenon that can significantly affect the achievement of some of the objectives set by the Sustainable Development Agenda. The impact evaluation is carried out through the System Dynamics methodology, combined with scenario analysis. Considering the Piedmont region (Italy) as a case study, the model forecasts the impacts of EV diffusion using a simulation timeframe of 12 years and leveraging eight EV diffusion scenarios. According to the model, an increase in the number of EVs results in less air pollution and, therefore, minor public health expenditure. These cost savings can be turned into incentives for purchasing new EVs, which make the fleet increasingly greener as part of a self-reinforcing loop. Despite the fact that the model could be improved through additional research on some variables' definitions, this ex ante evaluation tool represents a valuable instrument for policy-makers. In fact, it provides a comprehensive picture of EV diffusion in view of the triple sustainability principles: System Dynamics, in particular, allows singling out causal relationships among variables, thus anticipating possible effects of planned policy actions.

Keywords: sustainability; system dynamics; electric vehicles; 2030 Agenda; sustainable development goals

1. Introduction

In the last decade, policy-makers had to deal with global challenges posed by unprecedented demographic and social issues, climate change, and the consequences of the recent economic crisis [1]. In this context, the sustainability paradigm has become a leitmotiv for shaping a wide range of policies that regard, among others, mobility and transportation, production and consumption systems, and the environment at large. Acknowledging the importance of this topic, the United Nations promoted the 2030 Agenda for Sustainable Development [2], adopted by world leaders in September 2015. The agenda aims to provide guidelines and set concrete objectives in order to end all forms of poverty, fight inequalities, and tackle climate change. More specifically, themes covered by the agenda meet relevant needs in terms of social (e.g., hungry, health and well-being, education), economic (e.g., work and economic growth, industry, responsible production), and environmental (e.g., water, energy, land use, climate change) issues, in line with the triple sustainability approach [3]. According to the agenda, these elements are deeply intertwined and are fundamental for promoting the well-being of individuals and societies.

Drawing on these considerations, the present paper casts a light on a phenomenon that can significantly affect the achievement of some of the Sustainable Development Goals [4] defined by the Agenda, namely the diffusion of electric vehicles (EVs) in modern cities. As a matter of fact, sustainable mobility is crucial for achieving the 2030 Agenda for Sustainable Development and its Sustainable Development Goals. In this regard, the report published by the Sustainable Mobility for All initiative [5] proposes an assessment of the transport sector and its contribution to a sustainable future. It identifies green mobility as one of the four key attributes that will characterize the future mobility system.

In more detail, by adopting a comprehensive and systemic approach, this article aims at evaluating the impacts exerted by the partial substitution of the conventional vehicle fleet with electric vehicles. Impacts under the lens have to do with the environment and climate change (Sustainable Development Goal 13), population health and well-being (Sustainable Development Goal 3), and the development of smart cities (Sustainable Development Goal 11). This last topic is of utmost importance and has been examined by many authors in recent years. Even if there is not a unique and universally accepted definition for the term "smart city" [6,7] there is a large consensus on the need to consider not only the technological dimension of the phenomenon, but also other social, cultural, economic, environmental, and governance factors [8,9]. In this regard, themes related to mobility are certainly relevant.

Since traffic emissions significantly contribute to air quality [10], policy-makers are aware of the need to encourage actions that boost alternative mobility solutions [11,12]. Initiatives in this vein are, for instance, the promotion of the public transport system, the diffusion of car/ride sharing, and the allocation of incentives to stimulate the adoption of green vehicles. The latter is certainly one of the most impactful types of initiatives, as demonstrated by countries in which it is already a well-established practice (e.g., Norway [13]). Moreover, policy-makers need to understand the extent to which their planned actions could be effective and capable of unleashing benefits for the entire community.

Grounding on these considerations, this study makes reference to the two typologies of electric vehicles currently available: (a) battery electric vehicles (BEVs), which run exclusively on electricity via on-board batteries that are charged by plugging them into a charging station, and (b) plug-in hybrid electric vehicles (PHEVs), which have both an electric motor and an internal combustion engine (ICE) but the primary energy source is the electric motor, whose batteries can be charged by plugging in. The remainder of the vehicle fleet analyzed consists of conventional vehicles, including gasoline-fueled, diesel-fueled, and conventional hybrid vehicles.

The main objective of the present study is to show the social, economic, and environmental benefits that can be achieved by (partially) replacing the conventional urban vehicle fleet with electric cars and to understand what the variables that significantly influence the achievement of such benefits are. Moreover, the study points out the relevance of using a scenario-based, ex ante evaluation tool for improving decision-making processes.

In order to accomplish these objectives, in this paper EVs impacts are evaluated by focusing on the environmental, social, and economic dimensions, thus following the triple sustainability approach and in line with priorities set by the Sustainable Development Agenda.

The present article considers the Italian region Piedmont as case study. Piedmont is a region in the North of Italy that has to tackle with relevant issues related to air pollution. According to the last report of the environmental association Legambiente [14] some of Piedmont's provincial capitals (Torino, Alessandria, and Cuneo) fall within the main polluted cities in Italy. On its side, the regional government is evaluating and putting in place several actions aimed at reducing air pollutants' emissions, focused on sustainable mobility options [15].

Considering this regional background EVs impacts are evaluated through a scenario-based, ex ante approach that leverages System Dynamics (SD) simulation [16]. Such an approach has been selected as it allows the analysis of a complex system by considering the causal and dynamic relationships existing among the defined variables. The reference time horizon chosen for the simulation is 12 years: it starts in 2018 and ends in 2030, in line with the timeline of the Sustainable Development Agenda.

Concluding these introductory comments, the paper is structured as follows: Section 2 focuses on materials and methods with the aim to justify the choice of SD methodology for analyzing EVs' impacts. Furthermore, it describes the model and the portfolio of chosen scenarios. Section 3 illustrates the main outputs of the simulation and, finally, Section 4 critically discusses the work carried out, highlights concluding remarks, and provides suggestions for future research.

2. Materials and Methods

2.1. Methodology

In the recent past, many scholars ventured into research on road traffic implications and studied the effects of pollutant emissions on the environment and on human health. This topic is of utmost importance for policy-makers that need to define effective strategies to prevent further damage to the whole society. Along this strand of research, the examination of alternative mobility strategies has become a crucial topic for the scientific community.

EVs' impacts have been investigated through two main methodologies: Life Cycle Assessment (LCA) and Scenario Analysis.

The first methodology (LCA) [17] has been adopted primarily for studying environmental impacts in terms of greenhouse gas emissions and energy consumption [18]. These kinds of LCA models, however, rarely account for socioeconomic effects and, due to this reason, may not be sufficient to fully assess the long-term sustainability of alternative vehicles' diffusion.

On the other hand, scenario analysis [19] can be combined with diffusion modelling and/or simulation techniques (e.g., System Dynamics, Agent-based modelling) in order to shed light on the causal relationships existing among the several variables that are part of a complex system.

The System Dynamic approach [16] has been considered the most suitable technique to accomplish the objectives of the present study. In fact, it allows to analyze in a systemic way all the variables determining EVs diffusion as well as their interdependences and causal relationships [20]. Worth of note is that SD has already been used in other studies on EV impacts, even if many of them are centered on very specific aspects as they consider case-by-case one of the triple sustainability principles as predominant over the others [21–24]. The present study, instead, aims to leverage the SD method to further elaborate EVs impacts analysis by putting together the social, environmental and economic dimensions. An approach in this vein intends to provide a contribution to limited research available in this regard [25,26] while reflecting the systemic approach envisaged by the 2030 Agenda for Sustainable Development.

Figure 1 shows how the SD approach, coupled with scenario analysis, has been applied in this article. Firstly, the SD Causal Loop and Stock and Flows diagrams have been created: drawing on an extensive review of pertinent research literature, variables involved in the model and their relationships have been identified and, afterwards, they have been quantitatively defined using available data collected on transportation/mobility websites and specialized reports. Moreover, the review of existing studies on EVs future trends inspired the characterization of eight EV diffusion scenarios. Finally, the SD simulation outputs have been used as basis for estimating EVs' impacts adopting the counterfactual approach (i.e., comparison of each scenario's results with a reference scenario).

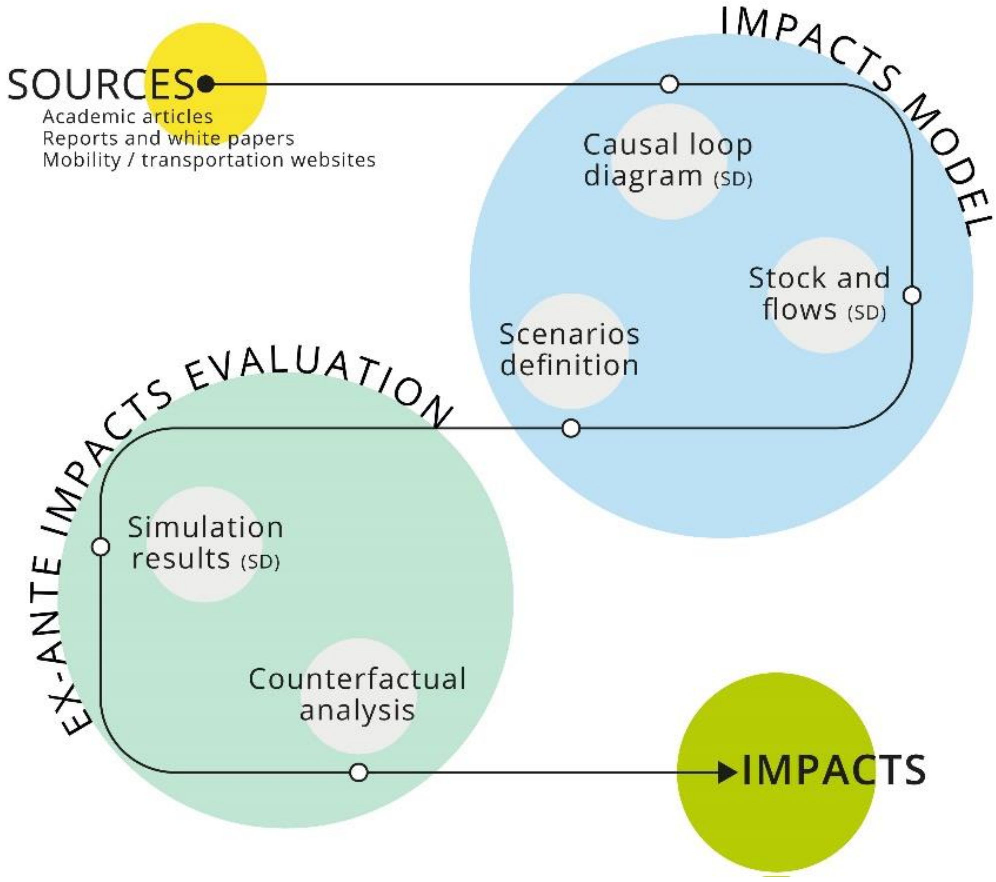

Figure 1. Research methodology.

2.2. The Model

The present paper is framed around the System Dynamics model built to evaluate the impacts exerted by the introduction of electric vehicles in the current vehicle fleet. The model has been conceived in order to improve the achievements of a previous research work discussed by the authors in [26]. In more detail, following the triple sustainability approach [3], the model factors in:

- the environmental sphere in terms of reduction of greenhouse gases (GHG) and pollutant emissions;
- the social dimension in terms of impacts on the health of people residing in the area (minor health costs). Authors assume that improved environmental and health conditions can be associated to a better quality of life, in accordance with the OECG Better Life Index [27]; and
- the economic sphere in terms of reduction of public health costs and distribution of these public cost savings as incentives for the purchase of new BEVs.

Figure 2 visualizes a simplified version of the model, emphasizing the triple sustainability dimensions and the main feedback loop that involves:

- The number of operating vehicles;
- The total amount of pollutants with negative effects on health (i.e., $PM_{2.5}$, NMVOC, NO_x, and SO_2);
- The total public health costs associated to such pollutants; and
- The related savings for public health that can be turned into incentives for the purchase of new BEVs (i.e., 'BEV extra').

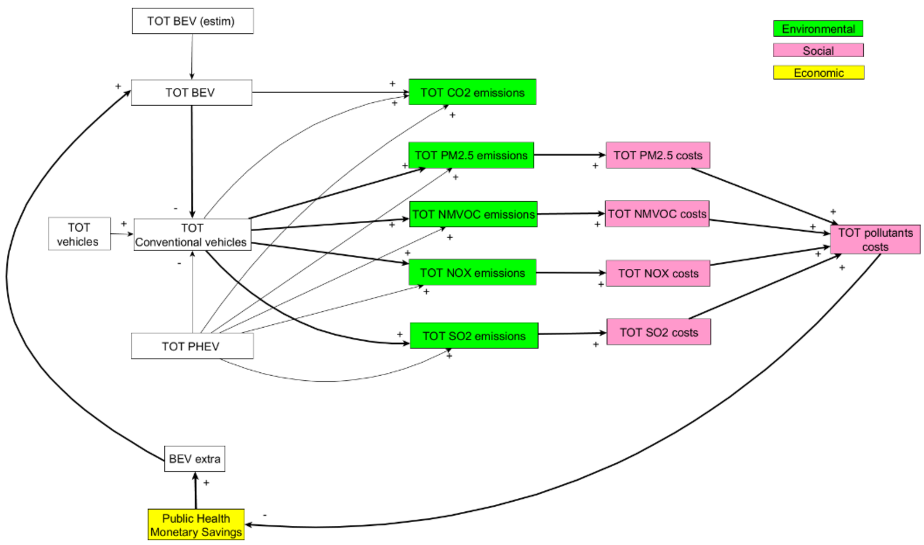

Figure 2. Simplified view of the model: causal relationships involving electric vehicles (EVs) uptake.

The complete version of the model—which comprises about seventy variables (Figure A1)—and the related table of variables (Table A1) is shown in Appendix A.

The model refers to a generic BEV and a generic PHEV considering average data of the five best-selling electric vehicles in Italy in 2018 according to European Alternative Fuels Observatory [28]. Selected models are reported in Table 1.

Table 1. Five best-selling EVs in Italy in 2018.

BEV	PHEV
Nissan Leaf	BMW 225xe Active Tourer
Renault Zoe	Mini Countryman PHEV
Smart For two ED	Mercedes GLC350e
Tesla Model S	BMW i3 Rex
Citroen C0	Volkswagen Golf GTE

Selection from EAFO [28].

Hereafter a brief description of the model is provided.

Firstly, the model allows to determine the total number of operating EVs in the region ('TOT EV') as the sum of circulating BEVs and PHEVs:

$$\text{TOT EV} = \text{TOT PHEV} + \text{TOT BEV}. \quad (1)$$

'TOT EV' depends on a fixed component ('TOT EV (estim)') defined on the basis of existing trends in literature [29] and on a model-dependent component ('BEV extra'), that represents the supplementary set of BEVs that can be introduced in the vehicle fleet as consequence of the distribution of the Public Health Monetary Savings:

$$\text{TOT EV} = \text{TOT EV (estim)} + \text{BEV extra} \quad (2)$$

$$\text{TOT EV (estim)} = \text{TOT PHEV} + \text{TOT BEV (estim)} \quad (3)$$

Secondly, for each typology of vehicle (BEV, PHEV, and Conventional) it is possible to calculate the total emissions generated by the main air pollutants. The authors selected CO_2, $PM_{2.5}$, NO_X, NMVOC, and SO_2 as the main elements that significantly contribute to the traffic road pollution. This choice has its roots in scientific evidence and model-specific constraints in terms of data availability and variable definitions.

In this regard, it is worth reminding that, unlike PHEVs and conventional vehicles, BEVs don't emit pollutants while travelling, thus being responsible only for the emission of CO_2 in the energy production process:

$$CO_2 \text{ emissions BEV} = \text{Amount energy required to travel} \times \text{Factor emission } CO_2 \text{ production} \quad (4)$$

where 'Factor emission CO_2 production' depends on the national energy production mix. Note that the use of renewable sources for the national energy production would significantly improve this value.

CO_2 emissions significantly contribute to global warming and climate change [11,30] while their impact on human health is not taken into account by the model as epidemiological studies usually do not consider this GHG. Other pollutants, for their part, are considered for both their environmental impact and their indirect social and economic impacts in view of the existing research in this field [31–35].

Health costs of air pollution are evaluated in several studies by connecting pollutant concentration to hospital admissions and, consequently, to their costs [32,33]. Along these lines, the proposed SD model estimates the total amount of pollutant emissions. It is worth noting that there is no evidence in the existing literature of a linear relationship between the total emissions and their concentration [34]. Due to this reason, the model refers to the outputs of the HEATCO project [35], which defines a unit cost (€/t) for each pollutant generated by road transport ($PM_{2.5}$, NO_X, NMVOC, and SO_2). The study links the total emissions of circulating vehicles to healthcare costs in terms of reduction of life expectancy (YOLL: years of life lost), and to a number of other health costs in addition to damage to buildings and crops. The total cost of emissions is calculated by multiplying, for each pollutant, its related cost factor.

Finally, after having computed the sanitary costs for pollutant emissions, it became possible to estimate for each year the related cost savings. This was done by comparing the cost per annum with the value obtained for the previous year. As per the logic underlying the SD model, these savings are converted into incentives for facilitating the purchase of new BEVs (i.e., 'BEV extra'). Specifically, the number of 'BEV extra' is defined as the minimum between 'BEV extra potential' and 'BEV extra theoretical', where:

- 'BEV extra potential' is the ratio between 'Public Health Monetary Savings' and the incentive ('incentives' = 'incentives rate' × 'average price BEV'). It represents the potential number of BEVs that could benefit from the distribution of the public health monetary savings, according to the model.
- 'BEV extra theoretical' is the theoretical number of new BEVs that could be introduced in the market corresponding to a specific 'incentives rate'. This value has been modelled on the basis of the ICCT white paper [36] and is obtained considering the relationship between the BEV market share and the incentives rate in some European countries. This represents the number of BEVs that customers are willing to buy, given a specific incentive.

Note that the model relies on the choice of an optimal value for the 'incentives rate' that will be discussed at the beginning of Section 3.

The main assumptions underlying the modelling of the complex system herein illustrated are listed below:

- the trend of the total vehicle fleet operating ('TOT vehicles') follows the estimates by PWC [37], which forecasts that in Europe the car inventory will decrease by 25% by 2030. Moreover, the same report predicts that, despite this decrease in the total circulating fleet, new vehicle sales ('TOT new vehicles') will visibly increase (in Europe by 34%). The report forecasts a renewal of the vehicle fleet in the next 10 years characterized by an increasing presence of low emission vehicles, coupled with the diffusion of autonomous and shared autonomous vehicles (a similar vision is pointed out also by McKinsey and Company [38]);
- The number of electric vehicles operating over time ('TOT EV') depends on well-established trends defined in the literature [29] already reflecting some significant factors (e.g., the total

cost of ownership, complementary assets, range anxiety) that, consequently, are not taken into consideration within the model;

- the incentive mechanism depends on the theoretical relationship between incentives and new BEV market share [36] and it is assumed to be constant over time. It has to be said that this is a pessimistic assumption, as projections show an increasing trend of electric vehicle sales [37] over time;
- the average purchase price of BEVs decreases over time according to the hypotheses formulated by Bloomberg New Energy Finance [39] and Deloitte [40];
- the average purchase price of PHEVs is not considered in the model because incentives introduced for the purchase, converted from monetary savings in public health, stimulate only the adoption of new BEVs that don't contribute to pollutants with negative effects on health;
- healthcare savings ('Public Health Monetary Savings') are entirely converted into incentives for BEV purchase ('BEV extra') with the idea of fostering the adoption of green vehicles that don't produce pollutants with negative effect on human health and, hence, don't determine additional healthcare costs; and
- NO_x, NMVOC, SO_2, and $PM_{2.5}$ are assumed to be the main pollutants causing detrimental effects on human health [31,35]. CO_2 is one of the main components of GHGs and is considered for its environmental impact [11,30] but its effects on human health are not taken into account due to the paucity of relevant studies in this regard.

2.3. Scenarios

As previously explained the total number of operating EVs in the model ('TOT EV') depends on a fixed component ('TOT EV (estim)') defined on the basis of existing trends in the literature and on a model-dependent component ('BEV extra').

Specifically, grounding on the analysis of previous studies and data on EVs in Europe [29,41], eight simulation scenarios have been defined. They can be used for evaluating the impacts of EV uptake using a counterfactual approach: simulation results obtained through the simulation of each scenario until 2030 can be compared with a reference scenario in order to quantify the impacts of a specific policy action.

In the model, the eight EVs diffusion scenarios are used as input data for 'TOT BEV (estim)' and 'TOT PHEV' variables and have been shaped by combining the following two dimensions:

1. EV Trend: The number of circulating electric cars ('TOT EV (estim)') is deduced from the pertinent literature [29]. In more detail, four trends were selected: they follow the study published by the Italian Sustainable Development Foundation [29], which identifies four possible trends for electric vehicle diffusion, ranging from a pessimistic trend (i.e., 10% of new car sales in 2030 are EVs) to an extreme optimistic diffusion (i.e., EV market share equal to 80% in 2030). Figure 3 briefly summarizes the trends considered by the SD model: their operationalization was performed by adapting Italian data used by the Italian Sustainable Development research to the Piedmont case [41].
2. Market split of BEVs and PHEVs: Two levels of distribution of EV fleet have been hypothesized:

   (a) the total presence of BEVs in 2030 vehicle fleet (i.e., 100% BEVs and 0% PHEVs):

$$\text{TOT EV (estim)} = \text{TOT BEV (estim)} \tag{5}$$

This split is coherent with the current distribution of BEVs and PHEVs in the car fleet (i.e., 239 BEVs and seven PHEVs operating in Piedmont in 2017, according to ACI data [41]) and in line with some estimates provided by electric mobility experts [42].

(b) an equal split of BEVs and PHEVs in the vehicle fleet (i.e., 50% of electric vehicles operating in Piedmont in 2030 are BEVs and 50% are PHEVs):

$$\text{TOT BEV (estim)} = \text{TOT PHEV} = 50\% \times \text{TOT EV (estim)} \quad (6)$$

This assumption is a pessimistic hypothesis, since data and estimates [42,43] show the prevalence of BEVs in the market.

Table 2 proposes a summary of the resulting scenarios (S1–S8).

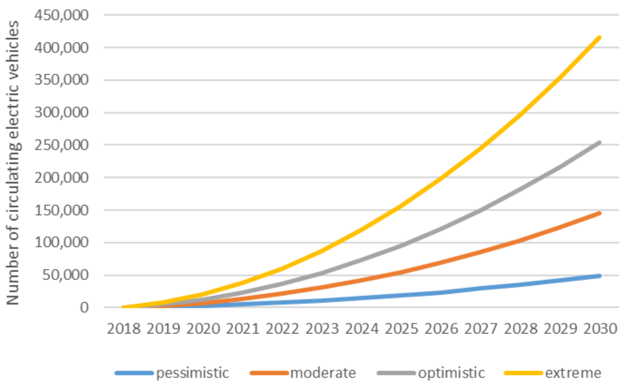

Figure 3. The four EV trends ('TOT EV (estim)') in Piedmont. Authors' elaboration from [29,41].

Table 2. Scenarios at a glance.

Scenario	EV Trend	'TOT EV (Estim)' [1]		Market Split (%)	
		In 2018	In 2030	'TOT BEV (Estim)'	TOT PHEV
S1 (reference)	Pessimistic	446	49,112 (2.8% of tot vehicles)	100	0
S2				50	50
S3 S4	Moderate	446	145.077 (8.3% of tot vehicles)	100 50	0 50
S5 S6	Optimistic	446	254.267 (14.6% of tot vehicles)	100 50	0 50
S7 S8	Extreme	446	415,323 (23.8% of tot vehicles)	100 50	0 50

[1] Authors elaboration from [29,41].

For carrying out the counterfactual analysis, the authors chose S1 as the reference scenario, which is based on a 'pessimistic' trend and a market split of BEVs/PHEVs that reflects, as much as possible, the current one in the target area.

3. Results

The model has been built and verified by means of Vensim software (Harvard, MA, USA) [44]. Whilst the chosen time horizon is 12 years (until 2030), the simulation time step equals one year.

Before delving into the details with the analysis of the simulation results, it is fundamental to illustrate the criteria that has been followed for the choice of the value for the 'incentives rate' in the model. The choice was made for improving the results obtained in the first version of the model (discussed by the authors in [26]), which was based on the assumption that all the healthcare savings were converted in new BEVs (full 'incentives rate' = 100% 'Average price BEV'). Following the assumption of the previous model, in fact, the number of 'BEV extra' stemming from a full 'incentives rate' constitutes a lower bound for the variable. In order to overcome this issue, in this paper the optimal 'incentives rate' is proposed.

The optimal value of the 'incentives rate' can be identified by monitoring how the 'BEV extra' variable changes considering decreasing 'incentives rate' (from 100%). The variable reaches a peak in correspondence of an optimal 'incentives rate' value, and then it drops. Figure 4 exemplifies this trend for the S1 scenario as an example of sensitivity analysis conducted on this key parameter. Similar trends have been identified for all the scenarios.

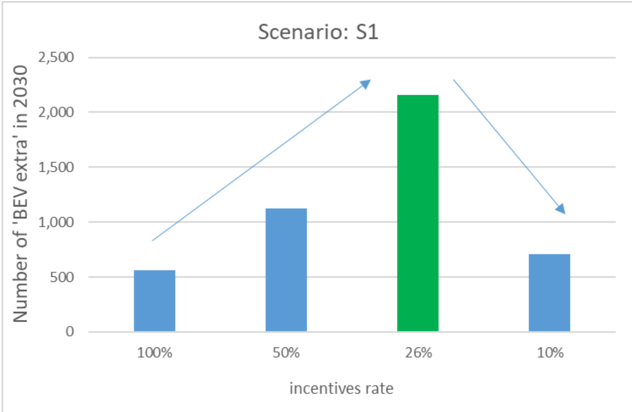

Figure 4. Number of 'BEV extra' in S1 scenario according to different incentive rates.

The optimal value of the 'incentives rate' represents the trade-off value of the 'incentives rate' that maximizes the cumulative 'BEV extra potential' at 2030. In other words, it is the highest value of the 'incentives rate' for which 'BEV extra' = 'BEV extra potential' in 2030. Table 3 summarizes the optimal 'incentives rates' considered for the eight scenarios.

Table 3. Optimal 'incentives rate' considered for the eight scenarios.

Scenario	Optimal 'Incentives Rate'
S1	26%
S2	25.9%
S3	27.9%
S4	27.3%
S5	29.9%
S6	28.9%
S7	32.7%
S8	31.4%

In synthesis, the selection of the optimal 'incentives rate' allows to obtain better results in terms of additional BEVs introduced in the vehicles fleet, public health monetary savings, and a higher reduction of pollutants. Grounding on the choice of the optimal value of the 'incentives rate', in the following part of the chapter the main simulation results are illustrated by taking into consideration the three dimensions of the triple sustainability approach, namely environmental, social, and economic.

Table 4 explains how electric vehicles are going to (partially) replace the conventional fleet in the hypothesized scenarios. The percentage of circulating EVs in Piedmont ('TOT EV')—currently close to 0—is ripe to reach significantly higher values in 2030: the pessimistic scenarios (S1–S2) forecast the achievement of the target of 3.06% EVs in 2030, while, for the extreme ones (S7–S8), EVs can represent almost a quarter of the total vehicle fleet in 2030.

When it comes to environmental impacts, simulation results show decreasing trends for the emissions of all the pollutants considered. In this regard, Figure 5 proposes, as example, the trend of CO_2 emissions ('CO_2 Emission Total') in the eight scenarios. In the best case (S7) the difference between CO_2 emissions at the beginning of the simulation (2018) and at the end of the simulation (2030) is 1 Mt, while in the worst case (S2) it is 0.85 Mt.

Table 4. Percentage of EVs operating in the total vehicle fleet ('TOT EV').

Scenario		2018	2020	2025	2030
S1–S2	Pessimistic	0.02%	0.15%	1.00%	3.06%
S3–S4	Moderate	0.02%	0.35%	2.71%	8.57%
S5–S6	Optimistic	0.02%	0.58%	4.65%	14.84%
S7–S8	Extreme	0.02%	0.91%	7.53%	24.08%

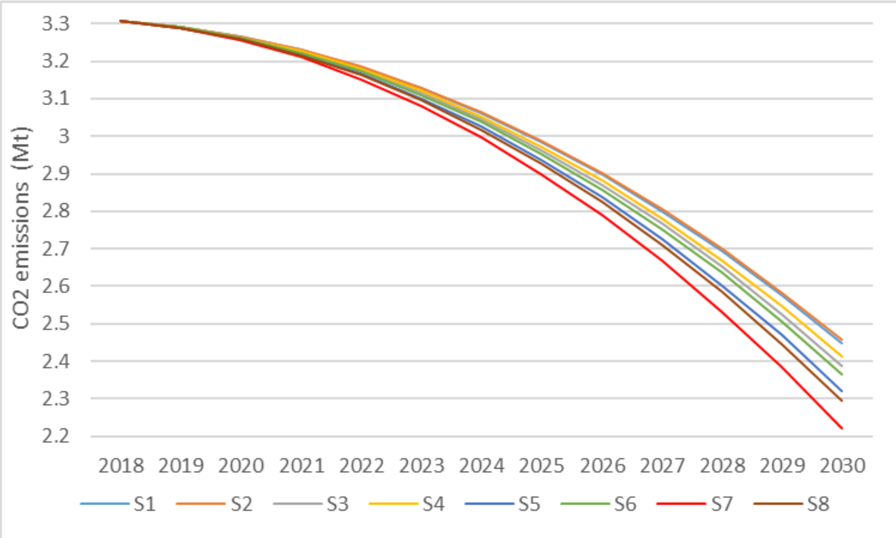

Figure 5. CO_2 emissions in each year of the simulation for the eight scenarios.

Figure 6 illustrates that also the costs associated to pollutants with negative effects on human health ('TOT pollutants costs') are going to decrease following a similar trend, thus contributing to a better quality of life (social impacts). The related public costs savings that can be turned in incentives for the purchase of new BEVs are 136 M€ in the best case (S7) and 85 M€ in the worst case (S2) (economic impacts).

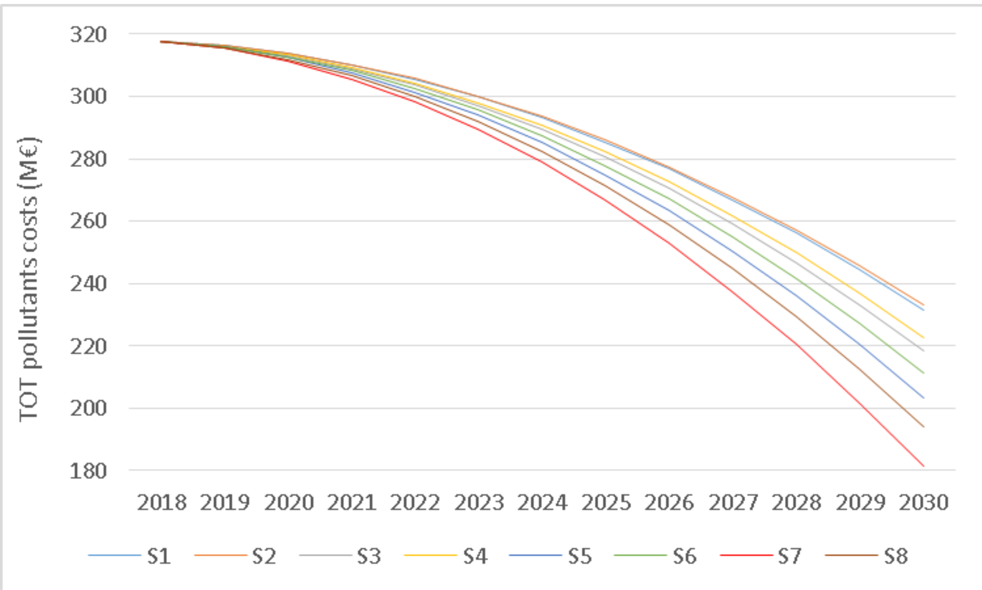

Figure 6. Pollution-related health costs in each year of the simulation for the eight scenarios.

Finally, the next two tables report the main results of the simulation in absolute values (Table 5) and compared to the reference scenario chosen for conducting the counterfactual analysis (S1) (Table 6).

Table 5. Main results cumulated to 2030 (absolute values).

Scenario	# BEV Extra	Public Health Monetary Savings Cumulative (M€)	CO_2 Saved Cumulative (Mt)
S1	2159	73.6	0.858
S2	2129	72.3	0.850
S3	2318	84.77	0.918
S4	2262	80.94	0.893
S5	2487	97.47	0.985
S6	2396	90.77	0.941
S7	2712	116.2	1.084
S8	2583	105.3	1.012

Table 6. Main results cumulated to 2030 (counterfactual analysis with reference to S1).

Scenario	# BEV Extra	Public Health Monetary Savings Cumulative (M€)	CO_2 Saved Cumulative (Mt)
S2 vs. S1	−30	−1.3	−0.008
S3 vs. S1	159	11.17	0.060
S4 vs. S1	103	7.34	0.035
S5 vs. S1	328	23.87	0.127
S6 vs. S1	237	17.17	0.083
S7 vs. S1	553	42.6	0.226
S8 vs. S1	424	31.7	0.154

Taking S1 as reference, results show that the most encouraging scenario is the extreme one having a 100% BEV market split (S7). Conversely, the most unpromising is the pessimistic one with 50% BEVs–50% PHEVs (S2). Moreover, for all the EV trends hypothesized, the scenarios corresponding to a full adoption of BEVs (100% BEVs) yield better results (Table 7). This outcome is ascribed to the different contribution provided by PHEVs and BEVs to pollutant emissions: BEVs, in fact, are only responsible of CO_2 emissions in the energy production process, while they do not emit other pollutants when travelling.

Table 7. Percentage increase of the simulation results in the 100% BEVs scenarios with respect to the fifty-fifty ones (50% BEVs). The table refers to counterfactual results presented in Table 6.

Scenario	# BEV Extra	Public Health Monetary Savings Cumulative (M€)	CO_2 Saved Cumulative (Mt)
Moderate (S3 vs. S4)	+35%	+34%	+42%
Optimistic (S5 vs. S6)	+28%	+28%	+35%
Extreme (S7 vs. S8)	+23%	+26%	+32%

By taking advantage of the proposed approach, policy-makers become able to explore the effects of different mobility strategies through a what-if analysis. By doing this, they have at their fingertips foreseen impacts of the different scenarios in terms of environmental, social, and economic benefits. As an example, if compared to the reference scenario S1, S7 determines a minor amount of air pollutants with negative effects on human health (−2.91 Mt in 2030). This will, in turn, reduce costs incurred for the public health, thus resulting into higher monetary savings (42.6 M€ in total, approximately 3.5 M€ per annum).

4. Discussion

The present study intends to advance and systematize how the impacts of EV uptake are evaluated in a regional context. To this end, an SD model has been designed following the triple sustainability principles. To estimate the total amount of pollutants as well as related costs, authors have established eight different EV diffusion scenarios. The rationale underlying the model is that an increase in the number of electric vehicles ('TOT EVs') determines less air pollutants (CO_2, NO_x, NMVOC, SO_2, $PM_{2.5}$) (environmental impact) and fewer costs incurred for public health ('TOT pollutant costs'), thus contributing to a better quality of life (social impact). Governments, thus, have the opportunity to turn these cost savings ('Public Health Monetary Savings') into incentives for purchasing new BEVs ('BEV extra'), which, in turn, make the fleet increasingly greener as part of a self-reinforcing loop (economic impact). The optimal value of the incentive can be fine-tuned in view of (a) resource constraints (i.e., public health monetary savings), and (b) the theoretical number of BEVs that customers are willing to buy, given a specific incentive, defined according to ICCT white paper [36]. Generalizing the results obtained through the simulation, in the present case this value fluctuates around 30% of BEVs price: not only seems this value reasonable, but also in accordance with existing policies on EVs incentives [36].

Drawing on the results of this study, a number of strategic suggestions for forward-looking policy-makers can be distilled. Firstly, the model recognizes the importance of analyzing, in a comprehensive and harmonized way, the environmental, social, and economic dimensions of electric mobility strategies: this systemic approach allows understanding of all the many side effects of these policies on the society. Secondly, through the SD ex ante evaluation policy-makers can identify relevant variables that influence EV diffusion and single out the causal relationships between them, thus anticipating possible effects of planned policy actions. Moreover, a simulation model similar to the one presented beforehand can be used as a daily working tool by policy-makers responsible for drafting the Sustainable Urban Mobility Plan of a smart city. Their planning could definitely benefit from understanding and quantifying the foreseen impacts, which are heavily dependent on multiple, deeply intertwined factors. Furthermore, this study provides useful suggestions to policy-makers on how to optimally define fiscal incentives on EV purchases in their regions.

Finally, the footprint of urban mobility on our planet is a topical theme, which has a strategic alignment with the 2030 Agenda for Sustainable Development. Along these lines, the paper is centered on some of the core aspects of the 2030 Agenda for Sustainable Development and adopts the same multidimensional approach, acknowledging the importance of zooming in on the interrelation among social, environmental, and economic factors.

In the conclusive remarks, it is crucial to also discuss some of the limitations that characterize the presented work, as they may represent an interesting starting point for future research. For example, the incentive mechanism has been modelled by studying the theoretical relationship between incentives and the new BEV market share [36], and it is assumed to be constant over time. As projections show an upward trend in sales of electric vehicles [37], this assumption might be reviewed in future works. Furthermore, additional research should be undertaken on the relationship between the total amount of pollutant emissions and their related costs in order to build the model on more updated data and, to the extent possible, consider a wider range of pollutants.

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Appendix A

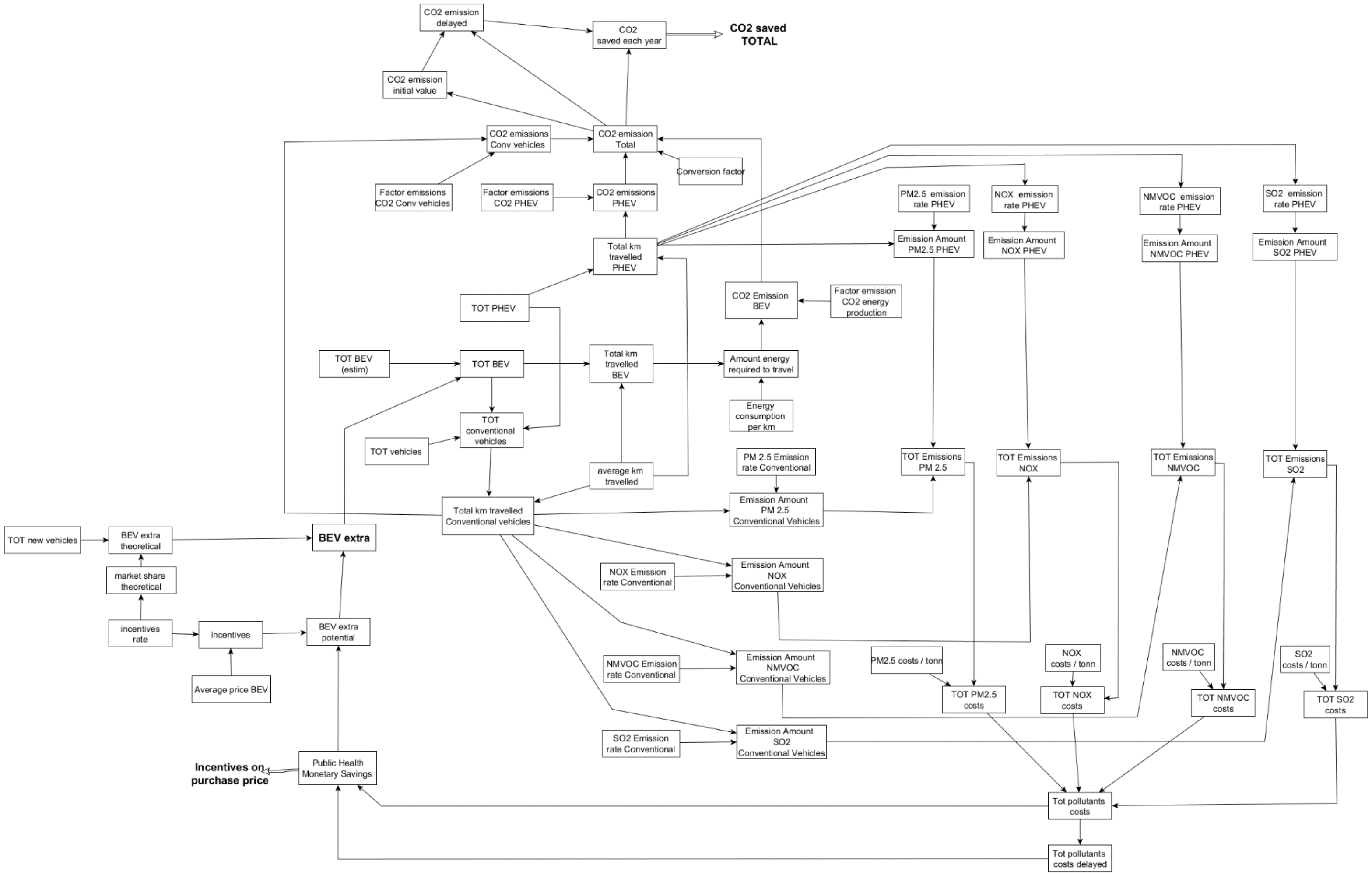

Figure A1. Complete SD model.

Table A1. All variables involved in the SD model.

Variable	Formula	Unit	Source [1]
Amount Energy Required to travel	Energy Consumption per km × Total km travelled BEV	kWh	
Average km travelled	12,487	km	[45]
Average price BEV	From 34,320 (2018) to 22,880 € (2030)	€	Estimated from [39]
BEV extra	min (BEV extra potential, BEV extra theoretical)	vehicles	
BEV extra potential	Public Health Monetary Savings/incentives	vehicles	
BEV extra theoretical	market share theoretical × TOT NEW vehicles	vehicles	
CO_2 Emission Conventional Vehicles	Factor Emission CO_2 Conventional Vehicles × Total km travelled Conventional Vehicle	g	
CO_2 Emission delayed	DELAY FIXED (CO_2 Emission Total, 1 CO_2 Emission Initial Value)	g	
CO_2 Emission BEV	Amount Energy Required to travel × Factor Emission CO_2 Energy Production	g	
CO_2 Emission Initial Value	INITIAL (CO_2 Emission Total)	g	
CO_2 Emission PHEV	Total km travelled PHEV × Factor Emission CO_2 PHEV	g	
CO_2 Emission Total	(CO_2 Emission Conventional Vehicles + CO_2 Emission BEV + CO_2 Emission PHEV) × Conversion Factor	t	
CO_2 saved each year	CO_2 Emission delayed-CO_2 Emission Total	g	
CO_2 Saved Total	INTEG (CO_2 saved each year, 0)	t	
TOT Conventional Vehicles	TOT vehicles—TOT PHEV—TOT BEV	vehicles	
Conversion Factor	$1/(1 \times 10^6)$		
Emission Amount NMVOC Conventional Vehicles	Total km travelled Conventional Vehicles × NMVOC Emission Rate Conventional	g	
Emission Amount NMVOC PHEV	Total km travelled PHEV × NMVOC Emission Rate PHEV	g	
Emission Amount NOX Conventional Vehicles	Total km travelled Conventional Vehicles × NOX Emission Rate Conventional	g	
Emission Amount NOX PHEV	Total km travelled PHEV × NOX Emission Rate PHEV	g	
Emission Amount $PM_{2.5}$ Conventional Vehicles	Total km travelled Conventional Vehicles × PM2.5 Emission Rate Conventional	g	
Emission Amount PM2.5 PHEV	Total km travelled PHEV × PM2.5 Emission Rate PHEV	g	
Emission Amount SO_2 Conventional Vehicles	Total km travelled Conventional Vehicles × SO_2 Emission Rate Conventional	g	
Emission Amount SO_2 PHEV	Total km travelled PHEV × SO_2 Emission Rate PHEV	g	
Energy Consumption per km	0.157	kWh/km	Estimated from [28]
Factor Emission CO_2 Conventional Vehicles	113.7	g/km	[46]
Factor Emission CO_2 Energy Production	397	g/kWh	[47]
Factor Emission CO_2 PHEV	92	g/km	[48]
gram tonn conversion factor	10^{-6}		
incentives	incentives rate × Average price BEV	€	
Incentives on Purchase Price	INTEG (+Public Health Monetary Savings, 0)	€	
incentives rate	See Table 3		
market share theoretical	IF THEN ELSE (incentives rate <0.4, 0.0225 × incentives rate, 0.3769 × incentives rate – 0.1418)		Elaboration from [36]

Table A1. *Cont.*

Variable	Formula	Unit	Source [1]
NMVOC cost/ton	1,600	€/t	[35]
NMVOC Emission Rate Conventional	0.24	g/km	[49]
NMVOC Emission Rate PHEV	0.11	g/km	[49]
NOX cost/ton	3,200	€/t	[35]
NOX Emission Rate Conventional	0.37	g/km	[49]
NOX Emission Rate PHEV	0.029	g/km	[49]
PM2.5 Emission Rate Conventional	0.024	g/km	[49]
PM2.5 Emission Rate PHEV	0.012	g/km	[49]
PM2.5 cost/ton	390,000	€/t	[35]
pollutants costs initial value	INITIAL (TOT pollutants costs)	€	
Public Health Monetary Savings	TOT pollutants costs delayed – TOT pollutants costs	€	
SO_2 cost/ton	3,500	€/t	[35]
SO_2 Emission Rate Conventional	0.00071	g/km	[49]
SO_2 Emission Rate PHEV	0.00044	g/km	[49]
TOT BEV	TOT BEV (estim) + BEV extra	vehicles	
TOT BEV (estim)	Input data (for eight scenarios)	vehicles	Estimated from [29]
Tot Emission NMVOC gram	Emission Amount NMVOC Conventional Vehicles + Emission Amount NMVOC PHEV	g	
TOT Emission NMVOC ton	Tot Emission NMVOC gram × gram tonn conversion factor	t	
Tot Emission NOX gram	Emission Amount NOX Conventional Vehicles + Emission Amount NOX PHEV	g	
TOT Emission NOX ton	Tot Emission NOX gram × gram tonn conversion factor	t	
Tot Emission PM2.5 gram	Emission Amount PM2.5 Conventional Vehicles + Emission Amount PM2.5 PHEV	g	
TOT Emission $PM_{2\ 5}$ ton	Tot Emission PM2 5 gram × gram tonn conversion factor	t	
Tot Emission SO_2 gram	Emission Amount SO_2 Conventional Vehicles + Emission Amount SO_2 PHEV	g	
TOT Emission SO_2 ton	Tot Emission SO_2 gram × gram tonn conversion factor	t	
TOT NEW vehicles	From 276,693 (2018) to 370,369 € (2030)	vehicles	Estimated from [37]
TOT NMVOC costs	TOT Emission NMVOC ton × "NMVOC cost/ton"	€	
TOT NOX costs	TOT Emission NOX ton × "NOX cost/ton"	€	
TOT PHEV	Input data (for eight scenarios)	vehicles	Estimated from [29]
TOT PM2.5 costs	TOT Emission PM2.5 ton × "PM2.5 cost/ton"	€	
TOT pollutants costs	TOT NMVOC costs + TOT NOX costs + TOT PM2.5 costs + TOT SO_2 costs	€	
TOT pollutants costs delayed	DELAY FIXED (TOT pollutants costs,1,pollutants costs initial value)	€	
TOT SO_2 costs	TOT Emission SO_2 ton × "SO_2 cost/ton"	€	
TOT vehicles	From 2,329,173 (2018) to 1,746,880 € (2030)	vehicles	Estimated from [37]
Total km travelled BEV	BEV Operating × Average km travelled	km	
Total km travelled Conventional Vehicles	Conventional Vehicles Operating × Average km travelled	km	
Total km travelled PHEV	PHEV Operating × Average km travelled	km	

[1] Sources are provided for constant/data variables.

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