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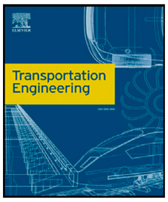

Full length article

A user-tailored tool for comparative cradle-to-grave environmental assessment of car retention versus replacement

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ABSTRACT

This work presents the development of a novel tool to support environmentally informed decision-making in the automotive sector by comparing two competing scenarios: maintaining an existing vehicle versus replacing it with a new one. While economic decision-support tools exist for such choices, there remains a critical gap in evaluating the environmental consequences. The proposed tool addresses this by implementing a cradle-to-grave Life Cycle Assessment (LCA) framework, which includes greenhouse gas emissions from vehicle production, maintenance and repair, well-to-wheel fuel or electricity consumption, and end-of-life processes. Unlike existing approaches, the tool accounts for non-average cases and real-world usage patterns. It allows detailed customization based on vehicle segment, powertrain type, energy source, geographic context, and annual mileage. It also explicitly incorporates existing vehicles, for which production emissions are no longer attributable, and introduces a novel attribution method for sharing production and disposal impacts in cases of second-hand ownership or short lifespans. These features enable more accurate assessments of vehicle sustainability across diverse user profiles. The result is a flexible yet robust assessment platform that enables users and policymakers to quantify the environmental consequences of vehicle replacement strategies, providing critical insights into the role of vehicle longevity and individual usage patterns in sustainable mobility transitions.

1. Introduction

The transport sector remains a major contributor to global greenhouse gas (GHG) emissions, accounting for a substantial share of the European Union's carbon footprint [1,2]. In response, the EU has set increasingly stringent CO_2 emission performance standards for passenger cars, aiming to achieve climate neutrality by 2050. While the regulatory focus has largely been on improving the environmental performance of new vehicles, decisions about replacing existing ones versus prolonging their use can have equally significant sustainability implications.

Life Cycle Assessment (LCA) has emerged as the most robust framework for quantifying the environmental impacts of products across their entire life cycle [3,4]. In the automotive sector, a vast body of literature has applied LCA to compare internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Early studies focused on specific powertrain comparisons and policy implications, particularly for hybrid and plug-in hybrid configurations [5,6]. Subsequent works extended the analysis to include the influence of electricity mix and use patterns [7], as well as scenario-based assessments of current and future vehicle technologies [8]. More recent contributions have provided comprehensive comparative analyses across multiple powertrains and geographical contexts [9–11]. These studies typically adopt cradle-to-grave system boundaries, including vehicle production, use-phase fuel or electricity consumption, and end-of-life (EoL) processes. However, most focus on *new* vehicles and rely on average use patterns and energy mixes, which limits their applicability to specific, real world cases.

Recent research has also explored the integration of data-driven and machine learning approaches within LCA and eco-design frameworks. These methods aim to support lifecycle-based design decisions, improve computational efficiency, and enable the exploration of large design spaces [12]. Similarly, simplified eco-design tools for electric mobility systems have been proposed to facilitate early-stage environmental assessments under limited data availability, with machine learning identified as a promising extension for parametric modeling and scenario analysis [13]. While these approaches highlight the potential of combining LCA with advanced data-driven techniques, they primarily focus on design-stage optimization rather than on supporting user-level decisions related to vehicle replacement or continued use.

Another underexplored dimension is the environmental impact of vehicle maintenance and repairs. While LCAs of lubricants [14] and

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Nomenclature

Acronyms

BEP	Break Even Point
BEV	Battery Electric Vehicle
GHG	Green House Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
PHEV	Plug-in Hybrid Electric Vehicle
TTW	Tank To Wheel
WTT	Well To Tank
WTW	Well To Wheel

Subscripts

EoL	Referred to the End of Life phase
i	Referred to generic vehicle category i among those listed in Table 2
P	Referred to the Production phase
U	Referred to the Use phase

Variables

C	Specific consumption expressed in $(\mathrm{l/km})$ or $(\mathrm{kWh/km})$
c	Correction factor applied to S_U^* taking into account age-induced engine degradation
d	Correction factor applied to S_U^* in the case of ICEV taking into account indirect effects from pollutants such as NO_X
EDS	Electric Driving Share
EF	Emission Factor expressed in $(\mathrm{kgCO_{2,eq}/l})$ or $(\mathrm{kgCO_{2,eq}/kWh})$
I	Impact expressed in $(\mathrm{kgCO_{2,eq}})$
m	Vehicle mileage expressed in (km)
S_U^*	Nominal specific use phase impact expressed in $(\mathrm{kgCO_{2,eq}/km})$
S_P	Specific Production impact expressed in$(\mathrm{kgCO_{2,eq}/kg})$
S_U	Corrected specific use phase impact expressed in $(\mathrm{kgCO_{2,eq}/km})$
W	Average vehicle mass expressed in (kg)
y	Vehicle age expressed in years

tyres [15] exist, the literature on the aggregated maintenance footprint of passenger cars remains sparse [10,11,16,17]. In some cases [11], aggregated impact categories are used rather than $\mathrm{kgCO_{2,eq}}$, while in other studies the focus is limited to ordinary maintenance [16]. Some studies have shown that maintenance can affect not only direct material and energy use but also in-use efficiency. For example, timely oil changes can help prevent increased fuel consumption [18,19], while improper tyre inflation, worn spark plugs, or degraded injectors can also increase energy demand [20,21]. Despite these insights, few LCA models systematically integrate maintenance into vehicle sustainability assessments.

A further research strand relevant to this work addresses the question of *when* to replace a vehicle versus keeping it in service. The concept of an environmental break-even point (BEP) is commonly used to identify the moment when the cumulative emissions of a new, more efficient vehicle become lower than those of continuing to use an existing one [16,22,23]. Some studies extend this approach by modeling optimal replacement timing using consequential LCA frameworks and real world usage patterns [9,11,24]. Earlier research indicates that, under standard conditions, prolonged use of an existing vehicle may result in lower environmental impact than replacement [25]. While instructive, BEP-based studies frequently rely on average driving profiles, idealized conditions, or new-vehicle scenarios, and rarely consider second-hand ownership, partial allocation of production and EoL burdens, or very low-mileage users.

A concise overview of the main research strands relevant to this work, together with the corresponding gaps that this study aims to address, is provided in Table 1.

These limitations highlight the need for a more flexible and context aware assessment framework capable of supporting real world, user level decisions. This work addresses this gap by presenting a novel decision-support tool that compares the environmental performance of keeping an existing vehicle versus replacing it with a new one. The tool implements a cradle-to-grave LCA framework that explicitly includes maintenance and repair, well-to-wheel (WTW) energy use, and EoL processes, and introduces a method for attributing production and EoL burdens in cases of used vehicles or partial ownership periods. Crucially, it enables non-average, user specific scenarios by incorporating variables such as vehicle segment, powertrain type, regional energy mix, annual mileage, and intended period of ownership.

The remainder of this paper is structured as follows: Section 2 presents the LCA methodology underpinning the tool. Section 3 demonstrates its application through a selection of representative scenarios, highlighting cases where vehicle replacement is or is not environmentally justified. Section 4 summarizes the key findings and outlines directions for future work.

2. Methodology

This study adopts a LCA approach, following the ISO 14040 and ISO 14044 standards, to quantify the Global Warming Potential (GWP) associated with the full life cycle of a range of road vehicles. The assessment includes production, use, maintenance, and end-of-life phases. While a substantial body of literature focuses on selected aspects—most notably the use phase—other stages such as maintenance and repair are often neglected or insufficiently detailed. This study aims to address that gap by adopting a more comprehensive and realistic approach.

A key element of novelty lies in the representativeness of the analysis: rather than evaluating a single, average vehicle, the study employs a statistical framework built upon a population of vehicles representative of different segments, fuel types, and powertrains. This enables the modeling of diverse user behaviors and driving patterns, yielding results that are more applicable to real-world conditions.

In line with LCA best practices, the study explicitly defines:

- the goal and scope, including the functional unit, the impact category and the system boundaries (Section 2.1)
- the life cycle inventory (Section 2.2)
- the life cycle impact assessment and interpretation (Section 2.3).

Particular attention is devoted to the robustness of the data sets used, which are drawn from transparent sources. All data inputs—ranging from fuel consumption and maintenance profiles to production and end-of-life processes—are clearly documented to ensure both the reproducibility of the results and comparability with other studies in the field.

Table 1
State of the art on vehicle sustainability assessment and gaps addressed by this work.

Strand	Representative references	Typical focus/findings and identified gaps
LCA of passenger vehicles	[5–10,12,13,23,26–28]	Cradle-to-grave comparisons across ICE/HEV/PHEV/BEV; BEVs show higher production but lower use-phase, sensitive to grid mix and usage. Gaps: emphasis on *new* vehicles and average profiles; limited support for user-specific contexts (mileage, geography) and treatment of existing vehicles whose production/EoL burdens are no longer attributable; recent data-driven approaches remain largely focused on design-stage optimization rather than user-level decision support.
Environmental implications of maintenance	[10,11,14,15,18–21]	Component-focused LCAs (lubricants, tyres) and studies linking routine upkeep (oil, tyre pressure, etc.) to efficiency. Gaps: scarce integration of *aggregate* maintenance (ordinary & extraordinary) into whole-vehicle LCA; limited modeling of maintenance-driven efficiency degradation/mitigation over time.
Vehicle replacement vs. retention (BEP and beyond)	[9,11,16,22–25]	Use of environmental breakeven point or optimization techniques to time replacement decisions. Gaps: BEP often based on idealized or average conditions; limited handling of second-hand ownership, partial ownership allocation, short leases, or low-mileage users.

2.1. Goal and scope

The goal of the proposed tool is to compare the GHG associated with two competing mobility scenarios: (i) keeping and maintaining an existing vehicle on the road, and (ii) replacing it with a new vehicle. To this end, a comparative LCA is carried out, encompassing the full cradle-to-grave spectrum of the vehicle life cycle—including production, use, maintenance, and EoL phases. The analysis is not static, but rather designed to be dynamically configured based on specific user contexts. For this reason, different vehicle categories, as listed in Table 2, are considered. These include a range of vehicle types and powertrains to reflect the diversity of current and future user scenarios.

For each vehicle category listed in Table 2, a set of representative car models has been identified to provide realistic and segment-specific reference values throughout the analysis. Table 2 reports a selection of representative models for each category; these are not intended to be exhaustive, but rather illustrative examples, as the underlying data are derived from a broader set of vehicles. For example, in the Segment C Diesel VI category, the selected models include: Audi A3 8Y, BMW F40, Citroën C4 III, Fiat Tipo, Ford Focus IV, Honda Civic XI, Lancia Delta, Opel Astra J, Peugeot 308 III, Renault Megane IV, Seat Leon IV, Volkswagen Golf VIII, Toyota Corolla E210, and Volvo V40.

The functional unit is defined as the total distance traveled (or, equivalently, the duration of use) corresponding to the residual window of usage of the current vehicle. The definition of the end-of-usage of the current vehicle is a key aspect of the analysis and may be determined by different conditions, such as reaching the end-of-life (EoL), the termination of a leasing contract, or the attainment of a predefined vehicle age. This aspect is discussed in detail in Section 2.3. Within this framework, two alternative scenarios are compared: (i) continued use of the current vehicle over its remaining lifetime, and (ii) replacement with a new vehicle operated over the same distance (or time horizon). In both cases, maintenance and repair activities are included. This definition ensures that the comparison is performed over a consistent usage period, allowing the total environmental impact, expressed in $\mathrm{kgCO_{2,eq}}$, to be directly compared between the two options. A schematic overview of the compared scenarios is provided in Fig. 1. The “current” and “new” vehicles considered in the analysis may belong to any of the categories in Table 2, allowing for a broad range of substitutions, including cross-segment and cross-powertrain comparisons.

The selected impact category is GWP, expressed in $\mathrm{kgCO_{2,eq}}$. While it is recognized that GWP, as a mid-point indicator, may not fully capture other relevant environmental burdens (e.g., the impacts of landfill at EoL are minimal in terms of GWP but significant in terms of human and ecosystem toxicity) see e.g., [3,4], the focus on GWP aligns with current European Union policy frameworks and the Net Zero agenda [1,2]. Thus, this focus ensures consistency with regulatory benchmarks and climate neutrality targets in the automotive sector.

2.2. Life cycle inventory

The life cycle inventory (LCI) data used in this study is compiled from a variety of high-quality and complementary sources to ensure robustness and relevance across all life cycle phases. Primary sources include peer-reviewed scientific articles, official European Union resources and reports, established LCA databases and gray literature. The latter is particularly important for modeling the use phase, where realistic $\mathrm{kgCO_{2,eq}/km}$ emissions are derived from empirical data on actual fuel and energy consumption, rather than idealized test conditions. This approach allows for a more accurate representation of real-world vehicle performance.

2.2.1. Production and EoL

Production. A literature review based on scientific papers and institutional reports has been conducted to derive the specific production impact $S_{P,i}$ ($\mathrm{kgCO_{2,eq}/kg}$) for each vehicle category i. The selected references were grouped by powertrain type to ensure consistency and representativeness.

The collected values showed good agreement across sources, with variations generally within a 15% band for all vehicle categories and below 10% for conventional internal combustion engine vehicles. This consistency supports the adoption of a single representative value for each category, which is in line with the objective of defining robust average parameters for comparative scenario analysis.

The final values, together with the corresponding literature sources, are reported in Table 3. In addition, an average vehicle mass W_i for

Table 2

Representative vehicle models for each segment and powertrain category. Two illustrative models are reported for each category for clarity; the underlying dataset includes a broader range of vehicles.

Engine/Segment	Segment B	Segment C	SUV
Gasoline IV	Citroën C3 I Opel Corsa D	Honda Civic VIII Volkswagen Golf V	Toyota RAV4 XA20 Suzuki Grand Vitara
Gasoline V	Ford Fiesta VI Volkswagen Polo V	Ford Focus III Volkswagen Golf VI	Nissan Qashqai (Mk1, J10) Volkswagen Tiguan (Mk1)
Gasoline VI	Peugeot 208 Hyundai i20	Peugeot 308 III Toyota Corolla E210	Hyundai Tucson (Mk3) Peugeot 3008 (Mk2)
Diesel IV	Peugeot 206 HDi Volkswagen Polo IV TDI	Ford Focus I TDCi Opel Astra H CDTI	Volvo XC90 D5 Toyota RAV4 D-4D
Diesel V	Ford Fiesta VI TDCi Volkswagen Polo V TDI	Volkswagen Golf VI TDI Ford Focus III TDCi	Volkswagen Tiguan (Mk1) TDI BMW X5 (F15) xDrive30d
Diesel VI	Peugeot 208 BlueHDi Renault Clio V dCi	Peugeot 308 III BlueHDi Toyota Corolla E210 D-4D	Peugeot 3008 (Mk2) BlueHDi Volvo XC60 (II) D4
Full/Mild Hybrid	Toyota Yaris IV Hybrid Suzuki Swift VI Mild Hybrid	Toyota Corolla E210 Hybrid Seat Leon IV eTSI	Toyota RAV4 Hybrid Kia Sportage Mild Hybrid
Plug-in Hybrid	– –	Volkswagen Golf GTE Peugeot 308 PHEV	Ford Kuga PHEV BMW X3 xDrive30e
Battery Electric	Renault Zoe Peugeot e-208	Nissan Leaf Volkswagen ID.3	Volkswagen ID.4 Škoda Enyaq

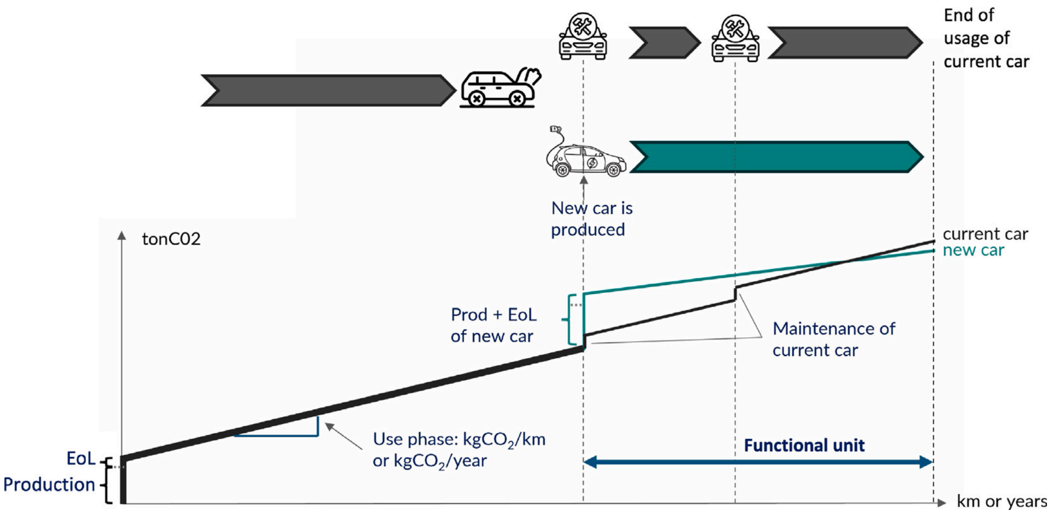


Fig. 1. Visual representation of the two alternative scenarios in terms of cumulative $\mathrm{kgCO_{2,eq}}$ emissions over distance (or time). The functional unit adopted for the comparative LCA, defined over a consistent usage window, is also illustrated for clarity.

each segment and engine type was established based on the representative models per category described in Section 2. Table 4 reports the average curb weight for each category. The values show good consistency across models, with standard deviations below 10% for Segment B and C vehicles and slightly higher variability (around 12%) for SUV categories.

This approach enables the computation of the overall production impact either by relying on the average weight of the relevant category, i.e.

$$I_{P,i} = S_{P,i} \cdot W_i \tag{1}$$

or, when available, by using a more precise mass value specific to the user's vehicle.

End of life. In this study, a cut-off modeling approach is adopted for the EoL phase: no credits are assigned for recycling or other virtuous end-of-life strategies, ensuring a conservative estimation of environmental impacts, in line with ISO 14044 and EN 15804 standards [30]. According to recent life cycle assessments on automotive systems, the GWP impact of the EoL stage is typically limited to less than 5%–10% of production-phase emissions [31]. As illustrated in Fig. 1, the EoL impact is assigned at the beginning of the ownership period, together with the production impact, since disposal is considered a necessary and unavoidable consequence of manufacturing a new vehicle. While this approach may slightly overestimate GWP by omitting possible

Table 3

Specific production impact per unit mass for different vehicle categories. The reported values are derived from a synthesis of multiple literature sources, which show good agreement (typically within a 15% range). Several references address multiple powertrain types and may therefore appear in more than one category.

Engine	$S_{P,i}$ ($\mathrm{kgCO_{2,eq}}$/kg)	Representative references
Gasoline IV	4.2	[5,6,26]
Gasoline V	4.6	[7,8,23,29]
Gasoline VI	4.6	[9–11,28,29]
Diesel IV	4.5	[5,6,26]
Diesel V	4.6	[7,8,23,27,29]
Diesel VI	4.6	[9–11,29]
Mild/Full Hybrid	5.2	[5,6,8–10,27]
Plug-in Hybrid	6.5	[5–7,10,28]
Battery Electric	7.9	[6–10,17,23,26–29]

Table 4
Table reporting the average mass of each vehicle category.

Engine/Segment	W_i(kg)		
	Segment B	Segment C	SUV
Gasoline IV	998	1242	1457
Gasoline V	1060	1310	1545
Gasoline VI	1140	1315	1510
Diesel IV	1023	1267	1490
Diesel V	1080	1327	1560
Diesel VI	1129	1382	1550
Mild/Full Hybrid	1223	1515	1728
Plug In Hybrid	NA	1669	2029
Battery Electric	1429	1809	2358

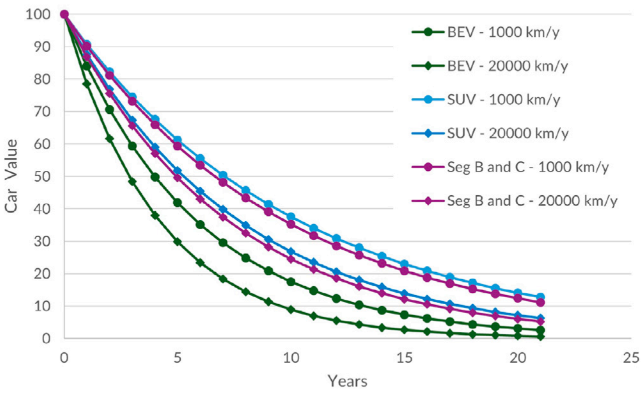


Fig. 2. (a) Depreciation model based on mileage and age for different vehicle categories (b) Example of partial ownership accounting for a car sold/bought three years after its production.

recovery benefits, it strengthens comparability across scenarios. It is also worth noting that other impact categories—such as acidification or toxicity—may show a more significant contribution from EoL, but fall outside the scope of this GWP-focused study.

Partial ownership and emission allocation. A key consideration in the allocation of production and EoL impacts is the scenario of partial vehicle ownership. In the reference case illustrated in Fig. 1 the user purchases a new car and retains it until the end of its useful life, thus bearing full responsibility for both production and EoL emissions. However, this situation does not capture the variety of real-world ownership patterns, such as second-hand vehicle purchases or short-term ownership agreements typical of leasing contracts. To account for these more common cases, the model incorporates a depreciation-based attribution approach. Specifically, a depreciation function—dependent on both time and mileage—is used to distribute the environmental burden of production and EoL phases among successive owners. This approach is inspired by vehicle economic depreciation models, under the assumption that the first owner should bear a larger share of the impact, as they effectively trigger vehicle production and benefit from the car during its highest value period. The depreciation curve employed is of the form

$$I_{P+EoL}(y,m) = I_{P+EoL}(0,0) \cdot e^{-(a\cdot y+b\cdot m\cdot y)} \tag{2}$$

where y and m reflect car age and mileage respectively, and with coefficients a and b tailored to each vehicle category. The resulting attribution profiles are shown in Fig. 2, where BEVs exhibit steeper depreciation, reflecting current market trends and user concerns related to long-term battery performance and resale value. Fig. 3a illustrates an example of application for two distinct cases, both applied to the same car (Gasoline VI segment C). In the first case, the user purchases a new car and keeps it for three years; in the second case, the user buys a three-year-old used car and keeps it until the end of its life. The resulting impacts over time are depicted in the impact-versus-years graph shown in Fig. 3b.

The depreciation models adopted in this study have been cross-verified using academic sources [32,33], and online calculators [34,35] that apply averaged depreciation rates for European and North American scenarios. These rates are typically derived from industry data and are widely used by banks and financial institutions when determining car values for loans, leases, and other financing products. Findings from different sources prove remarkable coherence between empirical research findings and the practical models adopted in the automotive and finance sectors.

2.2.2. Maintenance

The environmental impact of maintenance is estimated starting from a maintenance log, i.e., a list of replaced components, fluids, and other consumables, along with the mileage/age at which these services should be performed. Ordinary maintenance (e.g., tyre replacement, oil and filter changes) is applied at the blackbed manufacturer intervals, while extraordinary maintenance is scheduled according to the expected lifetime of specific components. The impacts of individual components are obtained from relevant literature [14,15], extracted from LCA databases [29], or—when no other data are available—estimated from the average component weight using the same $\mathrm{kgCO_{2,eq}/kg}$ factor adopted for vehicle production. A list of the 200 most frequently replaced components has been used as the basis for the maintenance impact calculation. It is assumed that all components are replaced at least once over the course of a 200,000 km vehicle lifespan. This assumption is intentionally unrealistic, as no car undergoes such extensive replacements. For instance, around 70 major components are considered for substitution at the 150,000–160,000 km mark, yet it is highly unlikely that all of these parts would need replacement in the same vehicle. Nevertheless, even under this conservative scenario, the impact of maintenance—excluding EV batteries—amounts to at most 1.4 t $\mathrm{CO_{2,eq}}$, corresponding to approximately 10% of the production footprint. Such values are in line with those found in [10], while other studies [16], which focus more on planned maintenance, found lower values. A visual representation of the procedure followed to obtain the maintenance footprint $S_{M,i}(y,m)$ can be found in Fig. 4, which illustrates the sequence from maintenance log definition, to component impact estimation, and final aggregation over the vehicle lifetime.

Boundaries of the maintenance analysis. Consistent with the assumptions made for car manufacturing, logistics are not included.

The contribution of workshop energy consumption is estimated as follows: (i) the annual electricity consumption of a car workshop is derived from industry data; (ii) workshop size and productivity are estimated at 2.2 cars per bay per day; (iii) assuming 250 working days/year and 20 total visits over a 200000 km vehicle lifetime, the resulting workshop emissions amount to approximately 60 $\mathrm{kgCO_{2,eq}}$—less than the impact of producing a new alternator—and are thus negligible.

A focus on batteries. Maintenance requirements differ according to powertrain type: for instance, BEVs do not require oil changes but may involve battery replacement, a controversial aspect given that current BEVs often make battery substitution impractical. Batteries are highly impactful components; for instance, life-cycle emissions of production range from 56 to 494 $\mathrm{kgCO_{2,eq}/kWh}$ [36], with a meta-analysis [37] indicating a median global warming potential of 17.63 $\mathrm{kgCO_{2,eq}/kg}$ of battery, i.e., approximately 130 $\mathrm{kgCO_{2,eq}/kWh}$ (standard deviation of 7.34 $\mathrm{kgCO_{2,eq}/kg}$), emphasizing sensitivity to electricity mix and production scale. Future developments may either align battery lifespan with that of the vehicle or facilitate replacement. To account for this uncertainty, the tool includes both scenarios (with and without battery replacement), with differentiated lifetime assumptions and $\mathrm{kgCO_{2,eq}/kWh}$ values depending on the source.

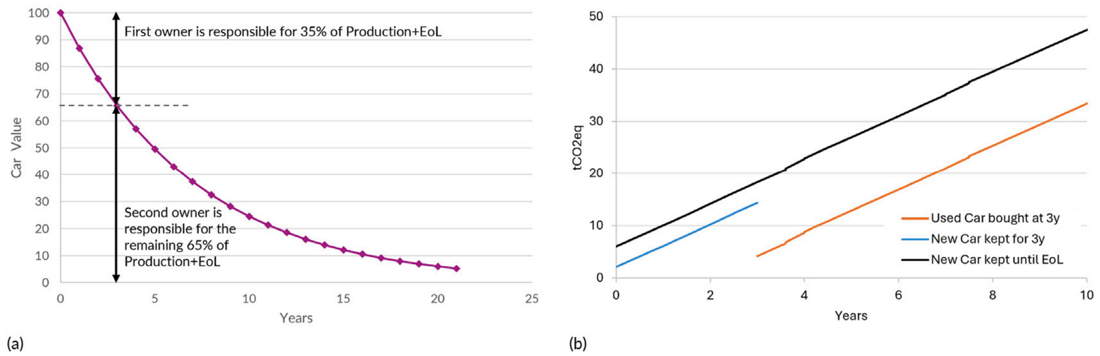
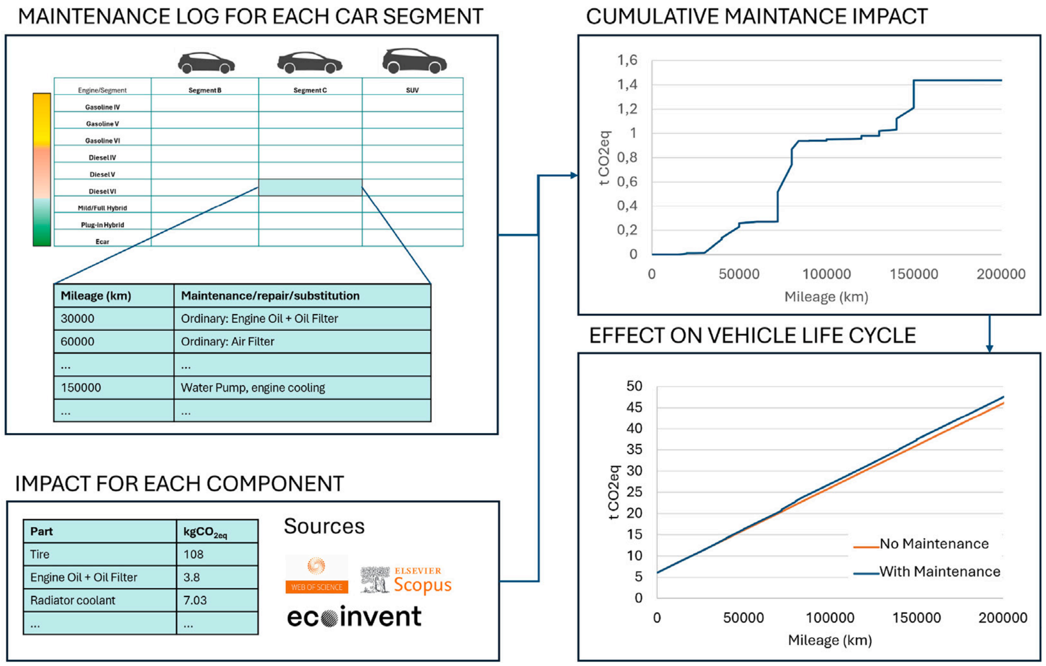


Fig. 3. Example of partial ownership accounting for a car sold/bought three years after its production for a segment C Gasoline VI vehicle, driven 20000 km/year. (a) Depreciation model used to estimate the portion of production to allocate to each case (b) Example of impact computation.



Engine/Segment	Segment B	Segment C	SUV
Gasoline IV			
Gasoline V			
Gasoline VI			
Diesel IV			
Diesel V			
Diesel VI			
Mild/Full Hybrid			
Plug-in Hybrid			
Ecar			

Mileage (km)	Maintenance/repair/substitution
30000	Ordinary: Engine Oil + Oil Filter
60000	Ordinary: Air Filter
...	...
150000	Water Pump, engine cooling
...	...

Part	$kgCO_{2eq}$
Tire	108
Engine Oil + Oil Filter	3.8
Radiator coolant	7.03
...	...

Fig. 4. Visual representation of the procedure followed to estimate the effect of maintenance during the vehicle life cycle.

Main take-aways. Two main considerations emerge:

- although the total maintenance impact typically accounts for no more than 10% of production emissions over the lifetime of an ICE vehicle, it must be considered for a robust analysis;
- maintenance is not an optional contribution, but an essential requirement to keep a vehicle operational—i.e., a 200000 km service life cannot be realistically modeled without it.

2.2.3. Use

The use phase represents one of the most impactful stages in the vehicle life cycle, particularly for Internal Combustion Engine (ICE) vehicles and hybrids. In this study, the aim is to determine, for each vehicle category listed in Table 2, the slope of the cumulative emissions curve shown in Fig. 1. This slope corresponds to the specific climate change impact per kilometer of use $S_{U,i}$, expressed in $(\mathrm{kgCO}_{2,\mathrm{eq}}/\mathrm{km})$, and forms the core metric to estimate emissions on an annual basis when combined with the user's average annual mileage. To ensure consistency and comparability across vehicle types and energy carriers, a Well-to-Wheel (WTW) approach is adopted, in line with EU recommendations and established LCA guidelines [38]. The WTW approach accounts for both:

- Well-to-Tank (WTT): upstream emissions related to fuel or electricity production and distribution;
- Tank-to-Wheel (TTW): direct emissions produced during vehicle operation.

All vehicle categories—except BEVs—include both WTT and TTW components. BEVs, by definition, have no tailpipe emissions (TTW = 0), but the upstream emissions from electricity generation (WTT) remain significant and must be accounted for. For electric-based powertrains (BEVs and PHEVs), WTT emissions are computed based on the country-specific electricity mix, using EU-wide data [39]. However, users have the option to override this value with a customized emission factor $(\mathrm{kgCO}_{2,\mathrm{eq}}/\mathrm{kWh})$, for instance, if the car is regularly charged at home using a known energy source (e.g., certified renewable electricity or local grid factor).

The resulting average values of the specific climate change impact per kilometer of use $S_{U,i}$ for all vehicle categories are reported in Table 5. The following paragraphs recount the methodology followed to obtain all the values.

Internal combustion engine and mild hybrid vehicles. The specific climate change impact per kilometer of use $S_{U,i}$, expressed in $(\mathrm{kgCO}_{2,\mathrm{eq}}/\mathrm{km})$, is here found by multiplying the Emission Factor $EF_{WTW,g}$ or $EF_{WTW,d}$,

Table 5

Table reporting the average specific climate change impact per kilometer of use of each vehicle category - values emission factor.

Engine/Segment	$S_{U,i}$ $(\mathrm{gCO_{2,eq}/km})$		
	Segment B	Segment C	SUV
Gasoline IV	210	226	293
Gasoline V	181	222	279
Gasoline VI	147	200	233
Diesel IV	181	208	322
Diesel V	179	203	254
Diesel VI	179	186	218
Mild/Full Hybrid	149	168	176
Plug In Hybrid	NA	74	96
Battery Electric	41	44	51

Table 6

Table reporting the emission factors EF_{WTT} and EF_{TTW} for diesel and gasoline.

	$EF_{WTT}(\mathrm{gCO_{2,eq}/l})$	
Reference	Gasoline	Diesel
[40]	16.9	18.9
[38]	17.0	18.9
[41]	19.0	18.7
	$EF_{TTW}(\mathrm{kgCO_{2,eq}/l})$	
[41]	2.323	2.697
[42]	2.466	2.697
[43]	2.360	2.650
[44]	2.421	2.675

expressed in $(\mathrm{kgCO_{2,eq}/l})$, of each fuel type (gasoline or diesel) by the specific consumption of each vehicle category C_i expressed in $(\mathrm{l/km})$

$$S^*_{U,i} = EF_{WTW,g} \cdot C_i = (EF_{WTT,i} + EF_{TTW,i}) \cdot C_i \tag{3}$$

The emission factors' values have been derived from a comprehensive review of recent literature and technical sources. The selected emission factors are highly consistent across independent studies and have been cross-verified through multiple datasets, ensuring both robustness and transparency of the methodology. The results are shown in Table 6.

The specific fuel consumption C_i, expressed in $(\mathrm{l/km})$, was determined for each vehicle category through the integration of multiple gray literature sources. User-reported consumption data from Spritmonitor.de [45] were first analyzed, offering extensive datasets for individual vehicle models. While the large sample size represents a clear advantage, the data required careful cleaning to address variability and occasional outliers. For each category, more than ten representative models were considered, and the category-average consumption was calculated. These values were subsequently validated against measurements published by alvolante.it [46], where consumption is determined under realistic driving conditions using high-precision flow meters. Although this latter source ensures high measurement accuracy, its coverage is limited to a single data point per model and a reduced number of available models.

According to [47], TTW emissions (i.e., $EF_{TTW,i} \cdot C_i$) can be derived from NEDC or WLTP declared values $(\mathrm{gCO_{2,eq}/km})$ by applying specific correction coefficients. To validate the proposed approach—at least for the TTW component—the WLTP/NEDC-corrected $(\mathrm{gCO_{2,eq}/km})$ values were compared with those obtained using the methodology described above for four representative car models (Ford Fiesta 1.4 16V, Volkswagen Polo 1.0 TGI 5p BMT, Peugeot 207, and Renault Clio 1.5 dCi 90). Good agreement is observed for gasoline vehicles, whereas for diesel vehicles the correction factors still appear to underestimate TTW $(\mathrm{gCO_{2,eq}/km})$ values by approximately 10%.

Incorporating vehicle degradation and indirect GHG emissions into ICE use-phase estimates. Furthermore, the resulting $S^*_{U,i}(\mathrm{kgCO_{2,eq}/km})$ values for each vehicle category are corrected by two additional factors that significantly affect the environmental performance of internal combustion engine (ICE) vehicles over time.

Table 7

Table reporting the correction factor $c(y)$ as a function of vehicle age y.

Reference	$c(y)$ at $y = 1$ year
[18]	1.008
[19]	1.008
[48]	1.02 seg. B and C – 1.01 SUV.
[49]	1.01

$$S_{U,i}(y) = S^*_{U,i} \cdot c(y) \cdot d \tag{4}$$

First, a literature review was conducted to assess whether quantitative models exist that correlate vehicle age or mileage with increased emissions $c(y)$ due to engine degradation and reduced efficiency. The search yielded few relevant studies [18,19,48,49], which are summarized in Table 7. Publications [18,19] address the impact of oil age on emissions and fuel consumption, both base their conclusions on purposely performed tests. Publications [48,49] focus on fuel economy of vehicles in realistic driving conditions, basing the findings on public surveys [48] and odometer data [49]. Although the literature on this topic is relatively limited, the findings consistently suggest a modest but non-negligible increase in emissions over time. On average, a +1% increase in specific emissions is observed after one year, with cumulative effects becoming more pronounced with continued vehicle use. Several sources underscore the influence of routine maintenance on limiting increases in fuel consumption. Notably, [18,19] emphasize the effect of timely oil changes, while others [20,21] link increased fuel consumption to additional factors such as under-inflated tyres, worn spark plugs, and degraded injectors. Consequently, two maintenance scenarios are modeled:

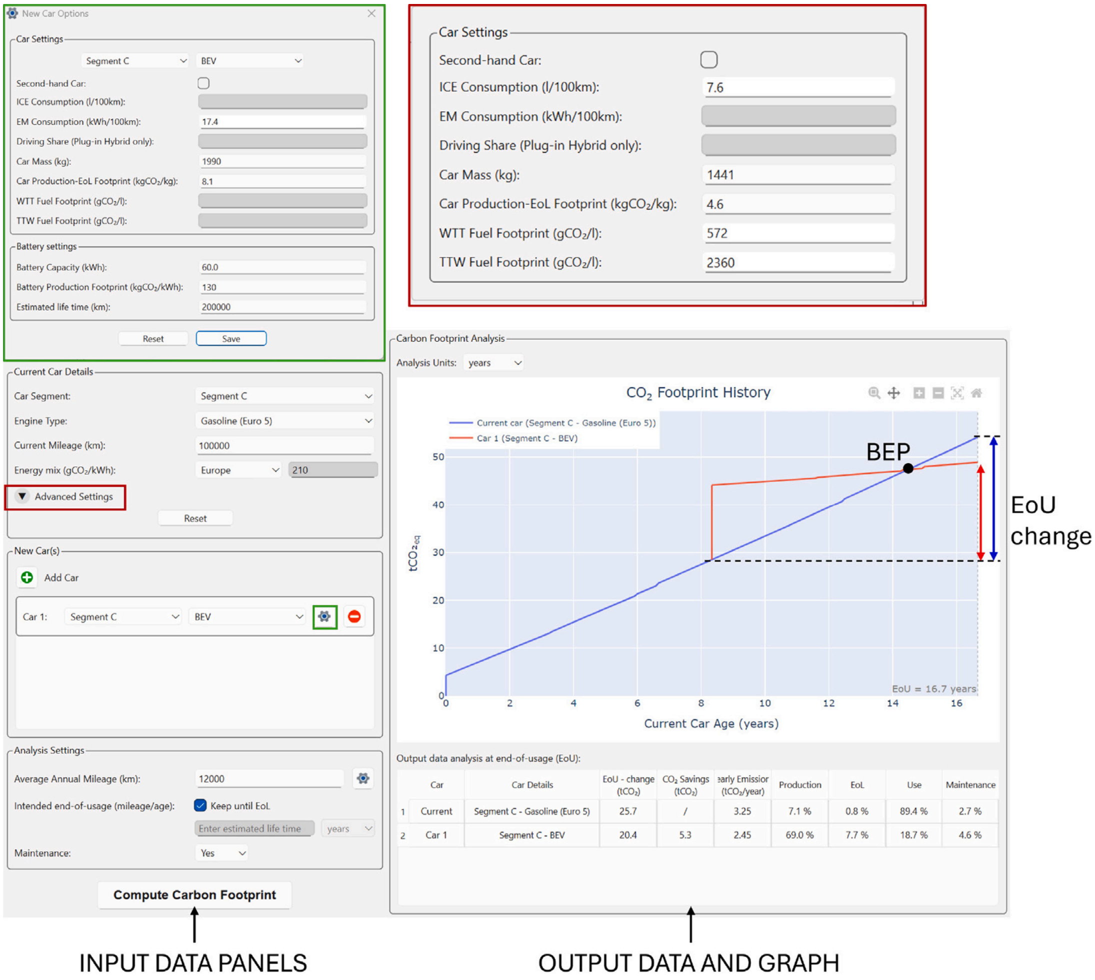
- no maintenance—assuming a 1% annual increase in fuel consumption (and thus $\mathrm{kgCO_{2,eq}/km}$);
- ordinary maintenance—limiting the increase to 0.5% per year.

Second, ICE tailpipe emissions include pollutants other than CO_2, such as nitrogen oxides (NO_X), hydrocarbons (HC), and carbon monoxide (CO), which indirectly contribute to global warming. To include these effects, the following methodology is adopted:

- Conversion factors are sourced from reputable databases and literature [50–52] to express each pollutant in terms of $(\mathrm{gCO_{2,eq}})$.
- Typical emission levels for each pollutant have been compiled, obtaining representative values of their relative percentage contribution, using recent average values from certified testing data and technical reports. [50,53].

The inclusion of these indirect pollutants results in an average +7% increase in the calculated use-phase GWP impact for ICE vehicles, i.e. $d = 1.07$.

Taken together, the integration of vehicle aging effects (+1% every year) and non-$(\mathrm{CO_{2,eq}})$ tailpipe emissions (+7%) contributes to a more conservative and realistic estimation of internal combustion vehicle emissions. These corrections ultimately strengthen the robustness of predictions in scenarios where the environmental cost of keeping older vehicles on the road is compared to replacing them with new alternatives powered by battery-electric or hybrid systems. Degradation effects have deliberately not been applied to BEVs and hybrids (see following paragraphs), partly to reflect anticipated technological advancements in the near future and, once again, to ensure that any recommendations supporting the retention of older ICE vehicles remain conservative and robust.



Car Settings

Segment C BEV

Second-hand Car: ☐

ICE Consumption (l/100km):

EM Consumption (kWh/100km): 17.4

Driving Share (Plug-in Hybrid only):

Car Mass (kg): 1990

Car Production-EoL Footprint (kgCO₂/kg): 8.1

WTT Fuel Footprint (gCO₂/l):

TTW Fuel Footprint (gCO₂/l):

Battery settings

Battery Capacity (kWh): 60.0

Battery Production Footprint (kgCO₂/kWh): 130

Estimated life time (km): 200000

Car Settings

Second-hand Car: ☐

ICE Consumption (l/100km): 7.6

EM Consumption (kWh/100km):

Driving Share (Plug-in Hybrid only):

Car Mass (kg): 1441

Car Production-EoL Footprint (kgCO₂/kg): 4.6

WTT Fuel Footprint (gCO₂/l): 572

TTW Fuel Footprint (gCO₂/l): 2360

Current Car Details

Car Segment: Segment C

Engine Type: Gasoline (Euro 5)

Current Mileage (km): 100000

Energy mix (gCO₂/kWh): Europe 210

Advanced Settings

New Car(s)

Car 1: Segment C BEV

Analysis Settings

Average Annual Mileage (km): 12000

Intended end-of-usage (mileage/age): ☑ Keep until EoL

Enter estimated life time years

Maintenance: Yes

Carbon Footprint Analysis

Analysis Units: years

Output data analysis at end-of-usage (EoU):

	Car	Car Details	EoU - change (tCO₂)	CO₂ Savings (tCO₂)	ɜarly Emissior (tCO₂/year)	Production	EoL	Use	Maintenance
1	Current	Segment C - Gasoline (Euro 5)	25.7	/	3.25	7.1 %	0.8 %	89.4 %	2.7 %
2	Car 1	Segment C - BEV	20.4	5.3	2.45	69.0 %	7.7 %	18.7 %	4.6 %

Fig. 5. Graphical User Interface (GUI) of the impact assessment tool, showing input panels on the left for vehicle and user parameters, and output panels on the right displaying comparative results for one of the selected scenarios.

Battery electric vehicles. The specific climate change impact per kilometer of use $S^*_{U,i}$, expressed in $(\mathrm{kg\,CO_{2,eq}/km})$, is calculated by multiplying the country-specific Emission Factor $EF_{WTT,i}$, expressed in $(\mathrm{kg\,CO_{2,eq}/kWh})$, by the specific electricity consumption of each vehicle category C_i, expressed in $(\mathrm{kWh/km})$:

$$S^*_{U,i} = EF_{WTT,EV} \cdot C_i \tag{5}$$

Using country-specific $EF_{WTT,EV}$ values is of paramount importance to ensure realistic predictions, as these can vary by up to two orders of magnitude, e.g., Estonia (693 $(\mathrm{g\,CO_{2,eq}/kWh})$) vs. Sweden (8 $(\mathrm{g\,CO_{2,eq}/kWh})$). The specific consumption C_i is derived from gray literature sources [45,54], based on the 10+ identified models for each vehicle segment. The specific impact $S^*_{U,i}$ is further corrected by a 15% factor to account for charging losses, following the Association of Fleet Professionals [55]:

$$S_{U,i} = S^*_{U,i} \cdot 1.15 \tag{6}$$

Finally, measured specific consumption values C_i $(\mathrm{kWh/km})$ have been compared to WLTP-declared values and found to be, on average, 20% higher.

Plug In hybrid vehicles. For PHEVs, two independent power sources exist, and the Electric Driving Share (EDS) must be taken into account to compute the specific climate change impact per kilometer of use $S_{U,i}$:

$$S_{U,i} = EDS \cdot EF_{WTT,EV} \cdot C_{i,EV} + (1 - EDS) \cdot EF_{WTW,ICE} \cdot C_{i,ICE} \tag{7}$$

where the subscript "ICE" refers to either diesel or gasoline, depending on the vehicle model. The required data on EDS and specific consumption values are sourced from [56], which presents a large-scale analysis of the average real-world fuel consumption and electric driving share of approximately 9000 private and company PHEVs in Europe. The dataset combines information from gray literature [45] (42%), company reports (33%), the German Aerospace Center (17%), and various websites or surveys (8%).

2.3. Impact assessment and interpretation

The interpretation of results is of paramount importance, as the main goal of the analysis is to answer the question: *Which option—keeping the current car or switching to a new one—is the most sustainable?* The scope of the analysis is limited to the mobility-related carbon footprint of a single user, whose driving habits (i.e., annual mileage) and location (necessary for estimating EF_{WTT} electricity emissions) are assumed to remain unchanged, regardless of the chosen option. The moment in time when the user considers switching to a new car is treated as an input parameter rather than a variable to be optimized.

Graphical User Interface (GUI) structure and workflow. The overall impact assessment is made accessible to the user through a dedicated graphical user interface (GUI), developed in Python, which allows the insertion of all relevant inputs, including details of the current vehicle and potential new vehicle(s). Multiple replacement options can be explored simultaneously. The GUI layout, shown in Fig. 5, features

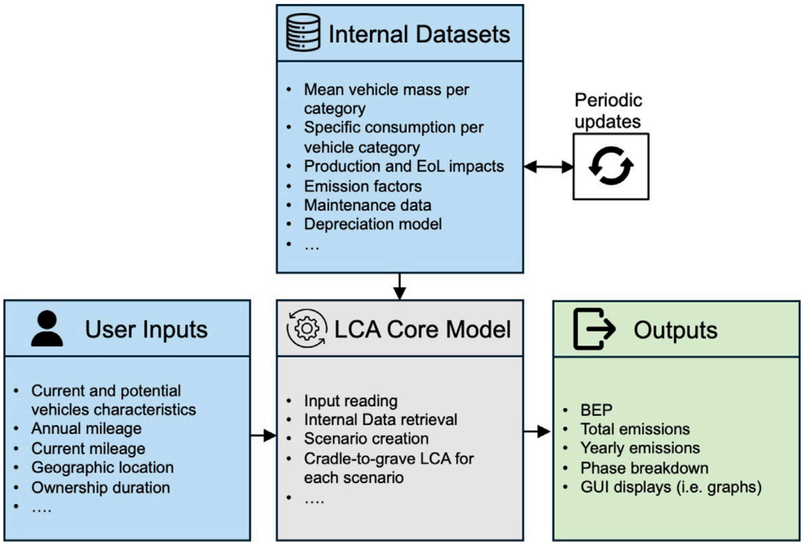


Fig. 6. Schematic representation of the tool architecture and workflow. User defined inputs are combined with internally stored datasets (periodically updated, e.g., electricity mix) and processed by the LCA computational core to generate impact assessment results, which are visualized through the GUI.

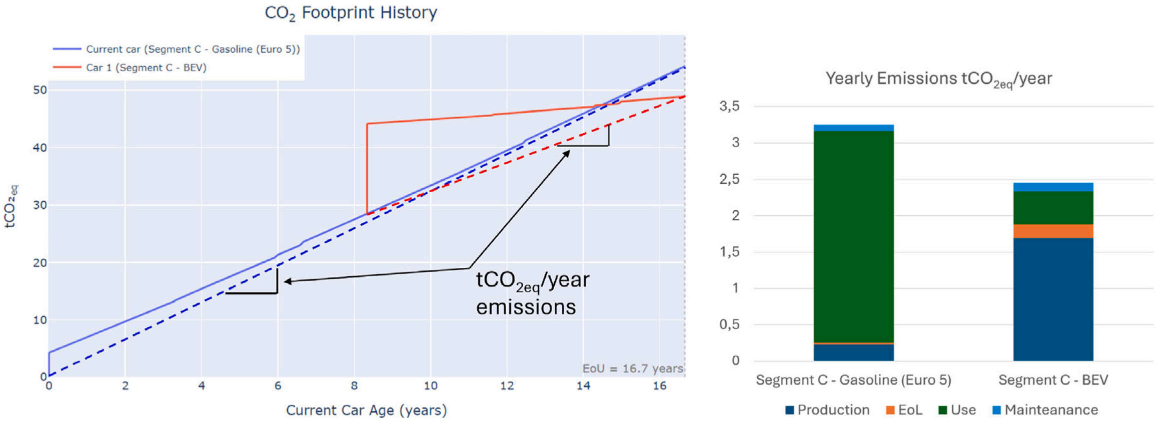


Fig. 7. Visual representation of yearly ($t\,CO_{2,eq}$) emissions and the contribution of each life cycle phase for one selected scenario.

input panels on the left and output data panels on the right, providing an intuitive environment for scenario comparison and decision-making. From a structural perspective, the tool is organized into three main components: (i) user-defined inputs, (ii) an internal database, and (iii) a computational core implementing the LCA model. User inputs include vehicle characteristics, annual mileage, geographical location, and intended ownership duration. These inputs are combined with internally stored datasets, such as emission factors for fuels and electricity mixes, vehicle production footprints, and maintenance parameters. Emission factors are updated on a regular basis, typically annually, with particular attention to the electricity grid mix, which is subject to relatively rapid changes. In contrast, parameters such as average vehicle mass by category, specific energy consumption, production and EoL footprints, which evolve more slowly, are updated less frequently and are planned to be revised in future versions of the tool (e.g., release 2.0), ensuring consistency with technological developments.

The computational core processes both user inputs and database values to generate the life cycle impact results, which are then visualized through the GUI in graphical and numerical formats. The overall workflow of the tool, from data input to result interpretation, is schematically illustrated in Fig. 6. This structure ensures that the tool remains user-friendly while maintaining transparency in the underlying modeling assumptions.

All types of outputs generated by the tool will be discussed in the following paragraph.

Interpretation of graphical outputs and maintenance contributions. The graphical output of the tool, such as the idealized representation shown in Fig. 1 and the example reported in Fig. 7, constitutes the starting point for the interpretation of results. In these graphs, the moment (in terms of time or mileage) at which the user considers switching to a new vehicle—defined as an input to the model—is explicitly visible, as it corresponds to the origin of the curve associated with the new vehicle.

A further aspect that deserves clarification concerns the presence of non-smooth trends (i.e., local spikes) observed in some of the emission profiles. These features are associated with the modeling of the maintenance phase, which is implemented as a set of discrete interventions occurring at predefined mileage or time intervals, according to typical maintenance schedules (cf. Section 2). As a result, maintenance-related impacts appear as stepwise contributions rather than continuous ones. It should be noted, however, that these spikes are of moderate intensity and do not significantly affect the overall trends or the comparative outcomes of the analysis.

Moreover, the magnitude and timing of these contributions depend on the specific scenario under analysis. In particular, the point at which a vehicle replacement is considered influences both the residual maintenance burden of the current vehicle and the initial condition of the new one. For instance, a newly purchased vehicle may not require significant maintenance in the early years, whereas a second-hand vehicle may already be close to scheduled interventions. Consequently, the relative contribution of maintenance may vary across scenarios, contributing to differences in the observed trends.

Results interpretation. Several studies suggest using the *breakeven point* (BEP) when comparing alternative vehicle choices. For example, Del Pero et al. [23] determine the ICE vs. BEV BEP at approximately 45,000 km under certain grid conditions, while Messagie et al. [22] introduce environmental optimization strategies for vehicle replacement that account for total life cycle emissions. While this can indeed be done, it is essential to remain consistent with the boundaries and goals of the present analysis. If the $S_{U,i}$ parameter—the slope of the line representing the use-phase impact per km (or per year)—of the new car is lower than that of the current car, then a BEP can always be found. However, the key question is whether the BEP is reached within a meaningful time frame.

For this reason, as an integral part of the impact assessment, we define an *End of Usage window of observation* as the earliest occurrence among the following:

1. The current car reaches its EoL, here assumed at 200,000 km; at this point, switching to a new car is inevitable.
2. The current car reaches 20 years of age (relevant for very low annual mileage), after which replacement is assumed.
3. The new car reaches the end of its intended period of use (e.g., lease termination), in which case only the portion of the production footprint allocated to the analysis is considered, reflecting the limited ownership responsibility according to the depreciation model shown in Fig. 2.

For example, the end-of-usage window for a car driven 5000 km/year is determined by reaching 20 years, whereas for a car driven 25,000 km/year it is determined by reaching 200,000 km. It should be noted that, while the tool uses standard values of car lifespan in terms of mileage and years (200,000 km and 20 years), these parameters can be customized, ensuring high adaptability to different contexts. If the BEP is reached within the defined observation window, the new car is considered the more sustainable option; otherwise, keeping the current car is preferable.

Beyond the BEP determination, the analysis also yields:

- the user's total footprint in both scenarios, represented by the rightmost point of each line in the graph in Fig. 5,
- the total variation in emitted ($\mathrm{kgCO_{2,eq}}$) after a potential vehicle switch, i.e., the EoU change shown in Fig. 5
- the average yearly emissions ($\mathrm{kgCO_{2,eq}/year}$) for each option, whose numerical values are indicated in Fig. 5 and graphically shown in Fig. 7),
- the relative contributions of each life cycle phase to the total annual emissions (cf. histogram in Fig. 7).

In the chosen example, representing a switch from a Segment C Euro 5 gasoline car to a Segment C BEV, the breakeven point (BEP) is reached within the end-of-use (EoU) window, although close to its limit. This example was purposely selected to illustrate all potential elements of the analysis, including the BEP. As a result, the yearly emissions of the current car are higher than those of the new car.

In this paper, yearly emissions are preferred to the BEP as a comparison metric, as they remain fully consistent with the window of usage, still indicate which option is more sustainable, and additionally provide direct information on the absolute amount of CO_2 emitted, unlike the BEP. A further aspect that deserves clarification concerns the presence of non-smooth trends (i.e., local spikes) observed in some of the cumulative and yearly emission profiles. These features are primarily associated with the modeling of the maintenance phase, which is implemented as a set of discrete interventions occurring at predefined mileage or time intervals, according to typical maintenance schedules (cf. methodology section). As a result, maintenance-related impacts are not distributed continuously but appear as stepwise contributions, leading to localized increases in the emission curves.

Moreover, the magnitude and timing of these contributions depend on the specific scenario under analysis. In particular, the point at which a vehicle replacement is considered (in terms of mileage or age) influences the residual maintenance burden of the current vehicle as well as the initial condition of the new one. For instance, a newly purchased vehicle may not require significant maintenance in the early years, whereas a second-hand vehicle may already be close to scheduled interventions. Consequently, the relative contribution of maintenance can vary significantly across scenarios, contributing to differences in the observed trends.

The selected case studies are therefore intended to illustrate a set of representative conditions rather than exhaustively cover all possible configurations. The variability observed across scenarios reflects the flexibility of the proposed parametric framework, which captures the influence of usage patterns and vehicle history on the overall environmental performance.

The observed differences across scenarios are primarily driven by the interplay between production impacts, use-phase efficiency, and maintenance scheduling, which varies depending on mileage, ownership type, and vehicle condition.

3. Results and discussion

The purpose of this section is to demonstrate the use of the tool presented in this work to analyze a series of specific cases. The aim is to exploit the full potential of the tool to investigate scenarios that, while representative of a large share of the European population, present specific features (in terms of annual mileage, shared ownership, etc.) that make the standard comparisons reported in other studies not fully representative.

The following scenarios are considered:

1. Segment C gasoline Euro 5, switch at 100 000 km; annual mileage: 12 000 km/year (mean EU value). Compares switching to Segment C Euro 6 gasoline, Euro 6 diesel, mild/full HEV, PHEV, and BEV, all possible new options within the same segment.
2. Used Segment B petrol Euro 5 at 100 000 km; annual mileage: 5 000 km/year (very low usage). Compares with used (2 years old and 40 000 km mileage) Segment B Euro 6 and BEV. This represents a user with low annual mileage who prefers used cars.
3. SUV BEV at 100 000 km; annual mileage: 25 000 km/year. Compares with a new SUV BEV.
4. Segment C PHEV to BEV; annual mileage:12 000 km/year (mean EU value), all with a 3-year lease.

These case studies have been selected to cover different vehicle segments, powertrains, and ownership patterns, thereby providing a broad and representative basis for assessing the tool's applicability across a variety of real-world scenarios. A visual representation of the four scenarios described above is provided in Fig. 8.

3.1. Scenario 1: Mean European user switching from Euro 5 gasoline to various new Segment C options

Scenario 1 represents the typical mean European user: the WTT emission factor is calculated using the average European electricity mix, and the annual mileage (12,000 km/year) corresponds to the mean European value. In this scenario, the user purchases a new vehicle and intends to keep it for a long period (no lease contract), thereby assuming full responsibility for both the production and EoL burdens. The comparison across five alternative options (Euro 6 gasoline, Euro 6 diesel, mild/full HEV, PHEV, and BEV) yields reasonable and realistic results. For a switch to be advantageous, the slope of the use-phase impact curve should differ sufficiently from that of the starting option.

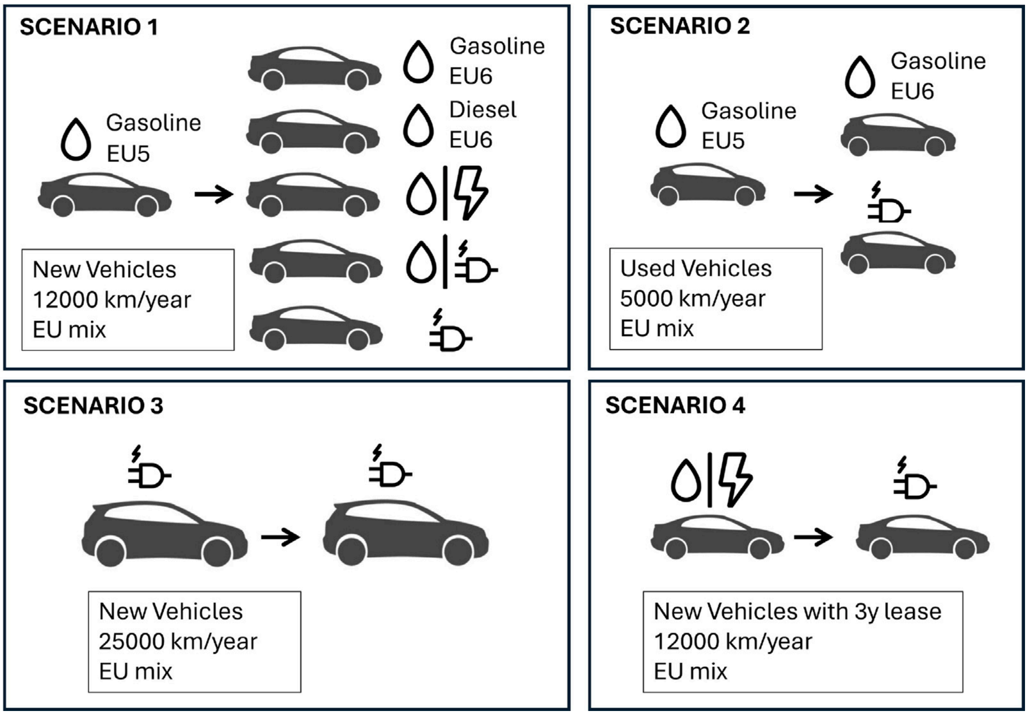


Fig. 8. Schematic representation of the four scenarios analyzed in this study, illustrating vehicle type, used/new/lease condition, and annual mileage for each case.

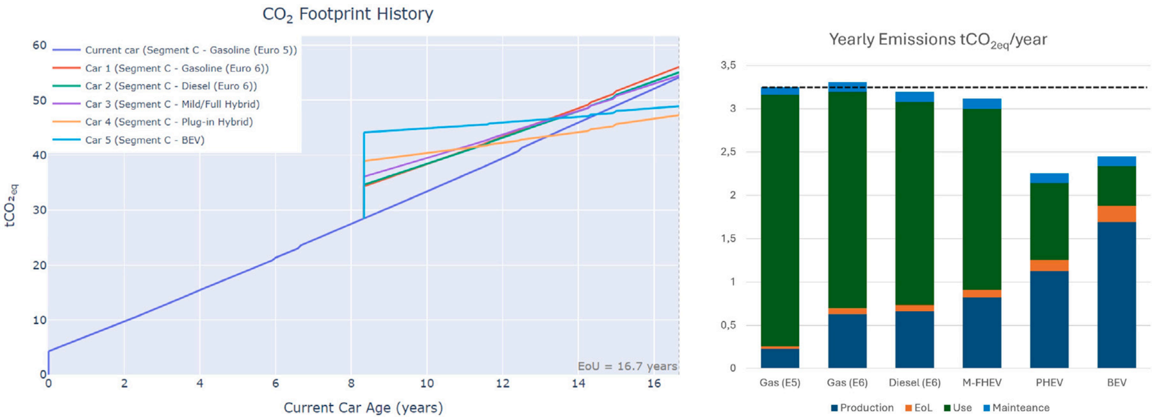


Fig. 9. Scenario 1 results. **Left:** Cumulative $CO_{2,eq}$ footprint over the observation window for the current vehicle and each replacement option. **Right:** Yearly $CO_{2,eq}$ emissions comparison between the current car and potential new vehicles.

In this case, as shown in Fig. 9, PHEV and BEV configurations are particularly advantageous, reducing yearly emissions by approximately 22% and 32%, respectively. In the remaining cases, the switch produces negligible benefits: the total emissions at the end of the usage observation window are essentially identical to those of the original Euro 5 gasoline vehicle. Given the standard settings, this example can also be used as a validation case: the resulting emission values, once converted to ($gCO_{2,eq}/km$) for the different powertrains, match very well with those found by independent recent sources such as the ICCT report [17] and the online calculator provided by Elektromobilität.NRW [57].

3.2. Scenario 2: Low-mileage user preferring used cars

In this scenario, a user with a low annual mileage (5000 km/year) considers switching from a 13-year-old, 100,000 km Euro 5 gasoline Segment B vehicle to either a 2-year-old, 40,000 km BEV or a Euro 6 gasoline vehicle of the same segment. Since the replacement options are used cars, their production and EoL footprints are proportionally reduced according to the allocated ownership share. Nevertheless, despite this reduction in production+EoL impacts and the lower slope of the use-phase line, the results clearly indicate that retaining the current Euro 5 vehicle is still the more sustainable choice.

Specifically, switching to a Euro 6 gasoline car increases the yearly $CO_{2,eq}$ emissions by approximately 20%, while switching to a BEV increases them by around 15%. As shown in Fig. 10, these results hold true even when accounting for the higher maintenance footprint associated with older vehicles. This scenario demonstrates that, for low annual mileages, the environmental cost of production and EoL—despite being lower for second-hand vehicles—still outweighs the potential savings from reduced use-phase emissions, making it more sustainable to keep the current car.

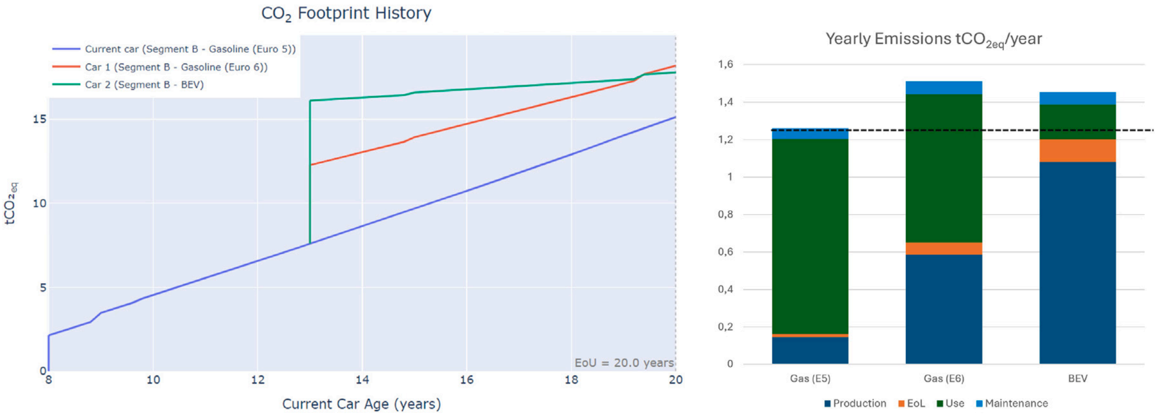


Fig. 10. Scenario 2 results. **Left:** Cumulative $CO_{2,eq}$ footprint over the observation window for the current vehicle and each replacement option. **Right:** Yearly $CO_{2,eq}$ emissions comparison between the current car and potential new vehicles.

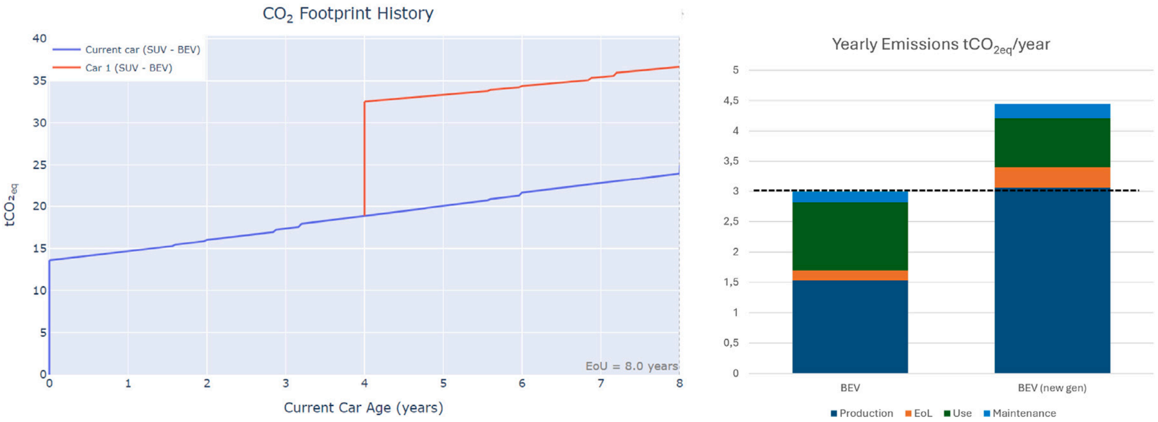


Fig. 11. Scenario 3 results. **Left:** Cumulative $CO_{2,eq}$ footprint over the observation window for the current vehicle and the replacement option. **Right:** Yearly $CO_{2,eq}$ emissions comparison between the current car and the new potential vehicle.

3.3. Scenario 3: High-mileage BEV SUV owner considering a new BEV SUV

In this scenario, a user who drives 25,000 km/year and already owns a BEV SUV considers switching to a new BEV SUV. The full potential of the proposed tool has been exploited to make the prediction more robust by introducing forward-looking assumptions. Specifically, the new BEV SUV is modeled with production, end-of-life, and use-phase footprints all reduced by 25% to simulate a plausible near-future context in which the automotive industry adapts to stricter environmental regulations for manufacturing and end-of-life processes, while the mean EU WTT electricity mix improves.

Nevertheless, as shown in Fig. 11, the yearly $CO_{2,eq}$ emissions remain 48% lower if the current vehicle is retained. This finding clearly demonstrates that, even in a scenario where cleaner production processes and a greener electricity mix are assumed, extending the lifespan of the current BEV through appropriate maintenance is a crucial strategy to minimize environmental impact.

3.4. Scenario 4: Lease contract user considering a switch from MHEV/FHEV to BEV

This scenario examines a user with an annual mileage of 12,000 km (EU mean) who operates under a lease contract, which provides the option to switch to a new car after three years or to keep the current one. The current vehicle is a Segment C Mild/Full Hybrid (MHEV/FHEV), and the alternative under consideration is a new Segment C BEV.

In this case, the production and EoL footprint of the new BEV is proportionally reduced to reflect the limited three-year ownership period. Despite this reduction, along with the lower $kgCO_{2,eq}/km$ use-phase impact of the BEV and the higher maintenance requirements of the current MHEV compared to the new vehicle, keeping the current MHEV remains the more sustainable option. As shown in Fig. 12, retaining the MHEV results in a 14% lower overall footprint than switching to the BEV.

3.5. Methodological advantages, limitations, and future developments

The results presented above highlight the potential of the proposed tool as a decision-support framework for evaluating vehicle replacement versus retention under tailored usage conditions. To the best of the authors' knowledge, this is one of the few tools that enables a direct comparison between alternative scenarios defined at the level of the individual user, rather than relying on average values representative of broad population categories. In particular, the tool explicitly accounts for parameters such as annual mileage, geographical location, ownership duration, and vehicle condition (new, used, or leased), as well as aspects that are often neglected in the literature, including partial ownership allocation and second-hand vehicle dynamics. This level of customization allows for a more realistic representation of real-world decision-making processes.

At the same time, the methodology relies on a number of simplifying assumptions that should be acknowledged. First, the analysis is currently limited to a single impact category, namely climate change expressed in $kgCO_{2,eq}$. While this indicator is widely recognized as a key metric for assessing environmental performance, it does not capture the full spectrum of environmental impacts. For instance, certain

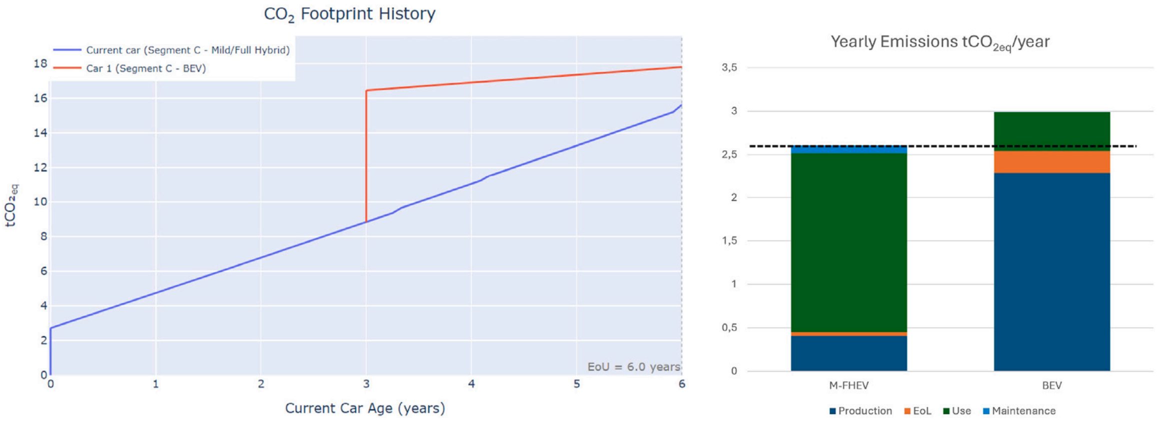


Fig. 12. Scenario 4 results. **Left:** Cumulative $CO_{2,eq}$ footprint over the observation window for the current vehicle and the replacement option. **Right:** Yearly $CO_{2,eq}$ emissions comparison between the current car and the new potential vehicle.

processes or components (e.g., battery end-of-life management) may have a limited contribution in terms of greenhouse gas emissions but could be significantly more critical when evaluated using other impact categories, such as toxicity or resource depletion.

A natural extension of the present work is therefore the inclusion of additional impact categories within a multi-indicator LCA framework, allowing for a more comprehensive environmental assessment. Furthermore, the integration of Life Cycle Costing (LCC) would represent a valuable enhancement, enabling the simultaneous evaluation of environmental and economic sustainability, which is of primary importance for end users when making vehicle-related decisions.

From a software perspective, the maintainability of the tool is ensured through the modular structure of the internal database, which allows for periodic updates of key parameters. In particular, emission factors (especially those related to the electricity grid mix) are updated regularly to reflect evolving energy systems, while other parameters characterized by slower dynamics (e.g., average vehicle mass and specific consumption by category) are planned to be revised in future versions of the tool. Ongoing developments also aim to expand the scope of the database and improve the flexibility of the computational framework.

Overall, while the current version of the tool provides a robust and user-oriented approach to carbon footprint-based decision-making, future developments will focus on extending its methodological scope and enhancing its applicability to a broader set of sustainability indicators.

4. Conclusions

The tool developed in this study allows for a comprehensive and case-specific assessment of the mobility-related carbon footprint associated with the choice between retaining a current vehicle or switching to a new one. Unlike many existing studies, which often rely on average user profiles and new vehicle comparisons, the present approach enables the analysis of specific, non-average cases, including users with annual mileage or ownership patterns that deviate significantly from the mean.

A key feature of the tool is its ability to include existing vehicles, for which production and end-of-life emissions are already past events and therefore no longer relevant to the decision-making process. This capability is critical to realistically evaluate the environmental consequences of keeping older vehicles in operation, as demonstrated in the four scenarios analyzed. The results show that in several situations—particularly for users with lower-than-average annual mileage and/or shorter-than-average vehicle lifespans—it is environmentally preferable to keep the current vehicle on the road rather than replacing it, even with more efficient alternatives.

The analysis also highlights the crucial role of maintenance. Proper and timely maintenance helps keep per-kilometer emissions stable and ensures that vehicles can achieve their expected lifespans. This is especially relevant in all cases where extending the vehicle's life avoids the need for premature production of new vehicles, thereby preventing the associated environmental burden.

The tool also provides a transparent and quantitative way to visualize the effects of different scenarios through both break-even point (BEP) analysis and yearly emissions comparison, with the latter being preferred as a more informative metric. Future developments may include the integration of economic sustainability assessments alongside environmental impact analysis, as well as the extension to other impact categories beyond climate change, in order to better inform user decisions with a multi-criteria perspective.

CRediT authorship contribution statement

Chiara Gastaldi: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Luca Cibrario:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] European Commission. Directorate General for Communication, European Green Deal :Delivering on Our Targets, Publications Office, 2021, http://dx.doi.org/10.2775/373022.

[2] European Commission, Directorate-General for Climate Action, Proposal for a regulation of the European parliament and of the council amending regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the union's increased climate ambition, 2021.

[3] M.Z. Hauschild, M. Goedkoop, J. Guinée, R. Heijungs, M. Huijbregts, O. Jolliet, M. Margni, A. De Schryver, S. Humbert, A. Laurent, S. Sala, R. Pant, Identifying best existing practice for characterization modeling in life cycle impact assessment, Int. J. Life Cycle Assess. 18 (3) (2012) 683–697, http://dx.doi.org/10.1007/s11367-012-0489-5.

[4] S. Hellweg, L. Milà i Canals, Emerging approaches, challenges and opportunities in life cycle assessment, Science 344 (6188) (2014) 1109–1113, http://dx.doi.org/10.1126/science.1248361.

[5] C. Samaras, K. Meisterling, Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy, Environ. Sci. Technol. 42 (9) (2008) 3170–3176, http://dx.doi.org/10.1021/es702178s.

[6] T.R. Hawkins, O.M. Gausen, A.H. Strømman, Environmental impacts of hybrid and electric vehicles—a review, Int. J. Life Cycle Assess. 17 (8) (2012) 997–1014, http://dx.doi.org/10.1007/s11367-012-0440-9.

[7] R. Faria, P. Marques, P. Moura, F. Freire, J. Delgado, A.T. de Almeida, Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles, Renew. Sustain. Energy Rev. 24 (2013) 271–287, http://dx.doi.org/10.1016/j.rser.2013.03.063.

[8] C. Bauer, J. Hofer, H.-J. Althaus, A. Del Duce, A. Simons, The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework, Appl. Energy 157 (2015) 871–883, http://dx.doi.org/10.1016/j.apenergy.2015.01.019.

[9] G. Puig-Samper Naranjo, D. Bolonio, M.F. Ortega, M.-J. García-Martínez, Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain, J. Clean. Prod. 291 (2021) 125883, http://dx.doi.org/10.1016/j.jclepro.2021.125883.

[10] H. Oda, H. Noguchi, M. Fuse, Review of life cycle assessment for automobiles: A meta-analysis-based approach, Renew. Sustain. Energy Rev. 159 (2022) 112214, http://dx.doi.org/10.1016/j.rser.2022.112214.

[11] K. Danilecki, P. Smurawski, K. Urbanowicz, Optimization of car use time for different maintenance and repair scenarios based on life cycle assessment, Appl. Sci. 13 (17) (2023) 9843, http://dx.doi.org/10.3390/app13179843.

[12] M. Manuguerra, R. Marini, M. Germani, A machine learning-enhanced life cycle assessment framework for sustainable product design, J. Clean. Prod. 450 (2024) 142308, http://dx.doi.org/10.1016/j.jclepro.2024.142308.

[13] S. Bressan, M. Marconi, M. Germani, An eco-design decision support tool for electric vehicles in early design stages, J. Ind. Inf. Integr. 41 (2024) 100605, http://dx.doi.org/10.1016/j.jii.2024.100605.

[14] A. Raimondi, G. Girotti, G.A. Blengini, D. Fino, LCA of petroleum-based lubricants: state of art and inclusion of additives, Int. J. Life Cycle Assess. 17 (8) (2012) 987–996, http://dx.doi.org/10.1007/s11367-012-0437-4.

[15] Y. Dong, Y. Zhao, M.U. Hossain, Y. He, P. Liu, Life cycle assessment of vehicle tires: A systematic review, Clean. Environ. Syst. 2 (2021) 100033, http://dx.doi.org/10.1016/j.cesys.2021.100033.

[16] R. Kawamoto, H. Mochizuki, Y. Moriguchi, T. Nakano, M. Motohashi, Y. Sakai, A. Inaba, Estimation of CO2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA, Sustainability 11 (9) (2019) 2690, http://dx.doi.org/10.3390/su11092690.

[17] M. Negri, G. Bieker, Life-Cycle Greenhouse Gas Emissions from Passenger Cars in the European Union: A 2025 Update and Key Factors to Consider, Report, International Council on Clean Transportation (ICCT), 2025, URL https://theicct.org/publication/electric-cars-life-cycle-analysis-emissions-europe-jul25/, Sales-weighted LCA of EU passenger cars, comparing fuels and powertrains.

[18] T.R. Smith, V. Kersey, T. Bidwell, The effect of engine age, engine oil age and drain interval on vehicle tailpipe emissions and fuel efficiency, in: SAE Technical Paper Series, in: FFL, SAE International, 2001, http://dx.doi.org/10.4271/2001-01-3545.

[19] S.I. Tseregounis, M.L. Mcmillan, Engine oil aging effects on fuel economy as measured by the EPA FTP vehicle dynamometer test in a GM engine, in: SAE Technical Paper Series, in: SFL, SAE International, 2002, http://dx.doi.org/10.4271/2002-01-1635.

[20] S. Chandra, V. Balali, A study on vehicle tire inflation and fuel consumption, 2021, URL https://transweb.sjsu.edu/sites/default/files/2006-Chandra-RB-Tire-Inflation-Fuel-Consumption.pdf.

[21] A. Varghese, Influence of Tyre Inflation Pressure on Fuel Consumption, Vehicle Handling and Ride Quality: Simulation and Modeling, (Master's thesis), Chalmers University of Technology, 2013, URL https://publications.lib.chalmers.se/records/fulltext/193515/193515.pdf, Chalmers University of Technology, Applied Mechanics, Thesis 2013:24.

[22] M. Messagie, F. Boureima, N. Sergeant, J.M. Timmermans, C. Macharis, J.V. Mierlo, Environmental breakeven point: an introduction into environmental optimization for passenger car replacement schemes, 2012, Mobility, Logistics and Automotive Technology Research Centre (MOBI), Vrije Universiteit Brussel, Analysis of life cycle emissions in scrappage policies.

[23] F. Del Pero, M. Delogu, M. Pierini, Life cycle assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car, Procedia Struct. Integr. 12 (2018) 521–537, http://dx.doi.org/10.1016/j.prostr.2018.11.066.

[24] S. Schaubroeck, T. Schaubroeck, P. Baustert, T. Gibon, E. Benetto, When to replace a product to decrease environmental impact?—a consequential LCA framework and case study on car replacement, Int. J. Life Cycle Assess. 25 (8) (2020) 1500–1521, http://dx.doi.org/10.1007/s11367-020-01758-0.

[25] M. Spielmann, H.-J. Althaus, Can a prolonged use of a passenger car reduce environmental burdens? Life Cycle analysis of Swiss passenger cars, J. Clean. Prod. 15 (11–12) (2007) 1122–1134, http://dx.doi.org/10.1016/j.jclepro.2006.07.022.

[26] P. Girardi, A. Gargiulo, P.C. Brambilla, A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study, Int. J. Life Cycle Assess. 20 (8) (2015) 1127–1142, http://dx.doi.org/10.1007/s11367-015-0903-x.

[27] C. Tagliaferri, S. Evangelisti, F. Acconcia, T. Domenech, P. Ekins, D. Barletta, P. Lettieri, Life cycle assessment of future electric and hybrid vehicles: A cradle-to-grave systems engineering approach, Chem. Eng. Res. Des. 112 (2016) 298–309, http://dx.doi.org/10.1016/j.cherd.2016.07.003.

[28] L. Lombardi, L. Tribioli, R. Cozzolino, G. Bella, Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA, Int. J. Life Cycle Assess. 22 (12) (2017) 1989–2006, http://dx.doi.org/10.1007/s11367-017-1294-y.

[29] Ecoinvent v3.11, 2024, URL https://ecoinvent.org/database/.

[30] A. Nordelöf, S. Poulikidou, M. Chordia, F. Bitencourt de Oliveira, J. Tivander, R. Arvidsson, Methodological approaches to end-of-life modelling in life cycle assessments of lithium-ion batteries, Batteries 5 (3) (2019) 51, http://dx.doi.org/10.3390/batteries5030051.

[31] A. Accardo, G. Dotelli, F. Miretti, E. Spessa, End-of-life impact on the cradle-to-grave LCA of light-duty commercial vehicles in Europe, Appl. Sci. 13 (3) (2023) 1494, http://dx.doi.org/10.3390/app13031494.

[32] L. Roberson, S. Pantha, J.P. Helveston, Battery-powered bargains? Assessing electric vehicle resale value in the United States, Environ. Res. Lett. 19 (5) (2024) 054053, http://dx.doi.org/10.1088/1748-9326/ad3fce.

[33] A.D. Green, Vehicle price depreciation: An empirical study onused EVs vs ICEVs in the United States, 2025.

[34] H. Yau, Car depreciation calculator, 2025, URL https://calculator.now/car-depreciation-calculator/.

[35] Auto Advocate, Inc., Car edge depreciation tool, 2025, URL https://caredge.com/.

[36] D. Hall, N. Lutsey, Effects of battery manufacturingon electric vehicle life-cyclegreenhouse gas emissions, 2018.

[37] M. Clemente, P. Maharjan, M. Salazar, T. Hofman, Meta-analysis of life cycle assessments for Li-ion batteries production emissions, 2025, http://dx.doi.org/10.48550/ARXIV.2506.05531.

[38] European Commission. Joint Research Centre, JEC Well-To-Tank Report V5: JEC Well to Wheels Analysis : Well to Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Publications Office, 2020, http://dx.doi.org/10.2760/100379.

[39] European Environment Agency, Greenhouse gas emission intensity of electricity generation in Europe, 2025, Indicator published 27 June 2025; values expressed in $\mathrm{g\,CO_{2,eq}}$/kWh, https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1.

[40] A. Bauen, A. Harris, C. Sim, N. Gudde, M. Prussi, N. Scarlat, CORSIA lower carbon aviation fuels: An assessment of the greenhouse gas emission reduction potential, Appl. Sci. 12 (22) (2022) 11818, http://dx.doi.org/10.3390/app122211818.

[41] D.C. Action, EC, determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, 2020.

[42] European Commission. Joint Research Centre. Institute for Environment and Sustainability, Well-To-Wheels Analysis of Future Automotive Fuels and Power Trains in the European Context: Report Version 3c, July 2011, Publications Office, 2011, http://dx.doi.org/10.2788/79018.

[43] J.L. Sullivan, R.E. Baker, B.A. Boyer, R.H. Hammerle, T.E. Kenney, L. Muniz, T.J. Wallington, CO2 emission benefit of diesel (versus gasoline) powered vehicles, Environ. Sci. Technol. 38 (12) (2004) 3217–3223, http://dx.doi.org/10.1021/es034928d.

[44] Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers), 2013.

[45] MPG and cost calculator and tracker, 2025, URL https://www.spritmonitor.de/en/.

[46] alVolante.it, Vi spieghiamo le nostre prove, 2019, URL https://www.alvolante.it/da_sapere/le-prove-di-alvolante-come-si-svolgono-365596.

[47] G. Fontaras, B. Ciuffo, N. Zacharof, S. Tsiakmakis, A. Marotta, J. Pavlovic, K. Anagnostopoulos, The difference between reported and real-world CO 2 emissions: How much improvement can be expected by WLTP introduction? Transp. Res. Procedia 25 (2017) 3933–3943, http://dx.doi.org/10.1016/j.trpro.2017.05.333.

[48] J.G.W. David L. Greene, The impact of increased fuel economy for light-DutyVehicles on the distribution of income in the U.S.:A retrospective and prospective analysis, 2017.

[49] F. Lamin, A. Omar, N.K. Alias, A. Hamzah, S.B. Ismail, M.R. Md Berhannudin, M.R.B. Abdul Razak, M. Loman, Effects of vehicle age on fuel economy for urban driving cycles, J. Kejuruter. si6 (2) (2023) 211–217, http://dx.doi.org/10.17576/jkukm-2023-si6(2)-22.

[50] G. Lammel, H. Graßl, Greenhouse effect of NOX, Environ. Sci. Pollut. Res. 2 (1) (1995) 40–45, http://dx.doi.org/10.1007/bf02987512.

[51] Intergovernmentlal Panel on Climate Change, IPCC fourth assessment report: Climate change, 2007.

[52] Ø. Hodnebrog, S.B. Dalsøren, G. Myhre, Lifetimes, direct and indirect radiative forcing, and global warming potentials of ethane (C2H6), propane (C3H8), and butane (C4H10), Atmospheric Sci. Lett. 19 (2) (2018) http://dx.doi.org/10.1002/asl.804.

[53] N.D. Rivera-Campoverde, J.L. Muñoz-Sanz, B.d.V. Arenas-Ramirez, Estimation of pollutant emissions in real driving conditions based on data from OBD and machine learning, Sensors 21 (19) (2021) 6344, http://dx.doi.org/10.3390/s21196344.

[54] Electric vehicle database, 2025, URL https://ev-database.org/.

[55] A. Ryan, Electric vehicle charging cable care: what you need to know, 2025, URL https://www.fleetnews.co.uk/features/ev-charging-cable-care-what-you-need-to-know,

[56] P. Plötz, S. Link, H. Ringelschwendner, M. Keller, C. Moll, J.D. Georg Bieker, P. Mock, Real-world usage of plug-in hybrid vehicles in Europe, 2022, URL https://theicct.org/wp-content/uploads/2022/06/real-world-phev-use-jun22-1.pdf.

[57] Elektromobilität.NRW, CO_2-Bilanz | Elektromobilität.NRW – CO_2-Rechner, 2025, URL https://www.elektromobilitaet.nrw/infos/co2-bilanz/, Interactive CO_2 calculator for electric and combustion vehicles, Online tool.