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Modeling the Environmental Impact of Passenger Cars Driven on Hilly Roads in Austria: A More Accurate Valuation of Greenhouse Gas Emissions and Further Environmental Indicators for Integral Life Cycle Assessments of Road Infrastructures

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Abstract: Previous studies of road or railway infrastructures have shown that traffic emissions outweigh the environmental impacts of the product stage and construction stage over the entire life cycle. Traffic usage is therefore the main emitter over the life cycle (A1–C4). Due to the small number of sustainability assessment systems, the question of how to consider traffic emissions in detail in an integral life cycle assessment has arisen. This study examines Austrian car traffic and investigates environmental impacts beyond the scope of carbon dioxide and particulate matter. The results were determined for a selection of common impact indicators. In addition to driving in flat terrain, an approach is presented that enables the evaluation of emissions due uphill and downhill driving. Thus, route options and route closures/detours due to maintenance work can be evaluated in a simple way. During the analyses, a traffic calculator was developed, which can currently assess different cars depending on the route specifics (flat/hill). The tool can be expanded to include other road vehicles (buses, trucks, motorcycles) and trains as well. This will simplify evaluations and decision-making processes and provide optimal support for a future-proof sustainable built environment.

Keywords: cars driven in Austria; infrastructure; integral LCA studies; life cycle assessment; road vehicles; sustainability; traffic

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1. Introduction

Accounting for approximately 37% of global greenhouse gas emissions, the construction industry has a significant impact on the environment, the consumption of energy and the use of natural resources [1]. In view of new regulations at the European and national levels [2], and increased efforts towards sustainability, it is necessary to accurately quantify the emissions of new construction projects and maintenance measures over the entire life cycle (A1–C4).

The life cycle assessment (LCA) of buildings, but also of infrastructures, is becoming increasingly important in society and for decision-makers [3]. For the infrastructure sector in particular, the small number of standardized assessment systems has resulted in difficulties with the data basis and implementation [4]. With regard to the implementation of analyses, it should be noted that the lack of infrastructure assessment systems [3–5] often results in labor-intensive and costly individual studies. Current research is attempting to close the "markets gap" and develop life cycle tools [3–5].

When investigating the emissions of road infrastructures over their whole life cycle (A1-C4), i.e., from the production of materials (A1–A3), transportation to the site (A4), construction (A5), maintenance (B2–B8), to dismantling and disposal (C1–C4), it is essential to consider the direct operational emissions from traffic use (B1) of the infrastructure. In

addition to the emissions generated by construction and the materials used, previous studies have shown that these are only marginal compared to the operating emissions generated over the entire life cycle [6,7]. In other words, traffic/traffic use (B1) can be identified as the main emitter for traffic infrastructures. In the case of road infrastructures, these emissions can be attributed to emissions from road vehicles. However, this raises the question of which detailed and up-to-date results of traffic emissions are available and how these can be optimally prepared for integration into a life cycle assessment (LCA) or an assessment system for traffic infrastructures.

Ecological data for passenger cars are currently available on the market at the country-specific level for CO_2 values (pure CO_2 and CO_2 equivalents—abbr.: eq.) and particulate matter (PM) from various established assessment systems [8–11]. As these data are not sufficient for an integral LCA of a traffic infrastructure according to EN17472 [12], further investigations are required that consider other environmental impact indicators beyond the values of CO_2 and PM, according to ÖNORM EN15804 [13]. In addition to the results on air pollutants from the aforementioned assessment systems, eco-data are partly available from databases (e.g., ecoinvent) [14]. However, these only cover current vehicle populations and current technology standards (e.g., vehicle masses, battery sizes of electric cars, mileage, etc.) to a limited extent. In addition, the datasets in the databases are usually only targeted for larger regions (e.g., Europe, global, etc.) and cannot be further assigned to specific countries [14]. Similarly, no particular route specifics and route gradients can be taken into account in a detailed form in the sustainability assessment of the road infrastructure, as the currently available emission values only cover the average journey in the plain.

For these reasons, this study examines cars driven in Austria, considering the current Austrian vehicle stock in compliance with the standardized and established regulations according to ISO14040 [15], ISO14044 [16] and presents results for further impact indicators according to ÖNORM EN15804 [13], as well as for uphill and downhill journeys for an optimal integration into an integral life cycle assessment (LCA) of road infrastructures according to ÖNORM EN17472 [12]. Therefore, this basic study can be used to carry out ecological traffic analyses using the example of cars driven in Austria and the developed transport calculator, while incorporating different car types and route specifics.

The investigated results for the life cycle stage "B1 use" can be included in an integral LCA of a traffic infrastructure; therefore, holistic considerations, such as route variants (e.g., tunnel vs. mountain pass road), detour traffic or traffic scenarios, can be quantified in detail. This will make a further contribution to a more detailed consideration of the environmental effects of the use of road infrastructures (B1) and thus support future sustainable decision-making and, above all, the implementation of a future sustainable built environment.

Throughout the analysis and execution of the study, the car datasets of the ecoinvent 3.9 database [14] are used as a basis and are adapted accordingly to the Austrian market, updated, and also expanded to include the current technical status. While the traveled distance is logically directly linked to the generated number of emissions, it is also important for specific and realistic use cases to consider geographical conditions such as differences in altitude from uphill and downhill driving with regard to additional fuel/energy consumption in the sustainability assessment [7]. These additional consumptions and the associated environmental impacts are calculated for passenger cars. An adapted approach [17] for a skilled implementation in an integral LCA of a road infrastructure is presented below.

2. Background

Before starting the investigation and analysis of the environmental impacts of passenger cars, background information on the general sustainability issues of traffic and political regulations is given. A study of the current Austrian passenger car stock is presented and the study of some common vehicle evaluation systems on the market is discussed.

2.1. Sustainable Goals and Problems of Traffic

In fulfilling the climate objectives of the United Nations [18] and the European Commission [2], as well as in managing the transition to sustainable energy, the transportation sector, and particularly motor vehicle traffic, has a significant and presently notable impact on politics and media [19]. In light of the United Nations Environment Program—Global Status Report 2022 [1], it is clear that the transportation industry contributes 22% [1] of the world's greenhouse gas emissions and faces the challenge of contributing to climate change mitigation [19]. Currently, policymakers in Europe and Austria [2,19,20] are prioritizing the replacement of internal combustion engine cars (ICE) with battery electric vehicles (BEVs) [19]. By 2030, newly registered cars in Austria must be "emission-neutral" in accordance with the regulations of the Austrian federal government [20]. The changeover is viewed positively in terms of environmental friendliness by transport experts, as per a report by the Austrian automobile club ÖAMTC [19]. However, there are still concerns about range deficits and high costs associated with e-cars in comparison to traditional combustion engines [19]. On the flip side, the long charging times and inadequate charging infrastructure detract from the benefits [19]. To achieve a sustainable transition towards mobility, the focus must be on the technological advancement [19,21] of a fuel-efficient and emissions-neutral means of transportation. Nonetheless, setting up the requisite charging infrastructure is also crucial [19].

2.2. The Austrian Car Stock

When looking at the Austrian vehicle stock [21–24], it becomes clear that cars with internal combustion engines (ICE) are widely used in Austria. Approximately 94% (according to the data collection of 31 December 2022) [22] of the Austrian car stock are cars with pure diesel or petrol engines. The remaining 6% comprises hybrid (HEV) or plug-in hybrid vehicles (PHEV) with petrol/electricity (2.9%), electric cars (BEV) (2.1%), diesel/electric cars (0.8%) and about 0.1% natural gas (NG) cars [22,23] (see Figure 1).

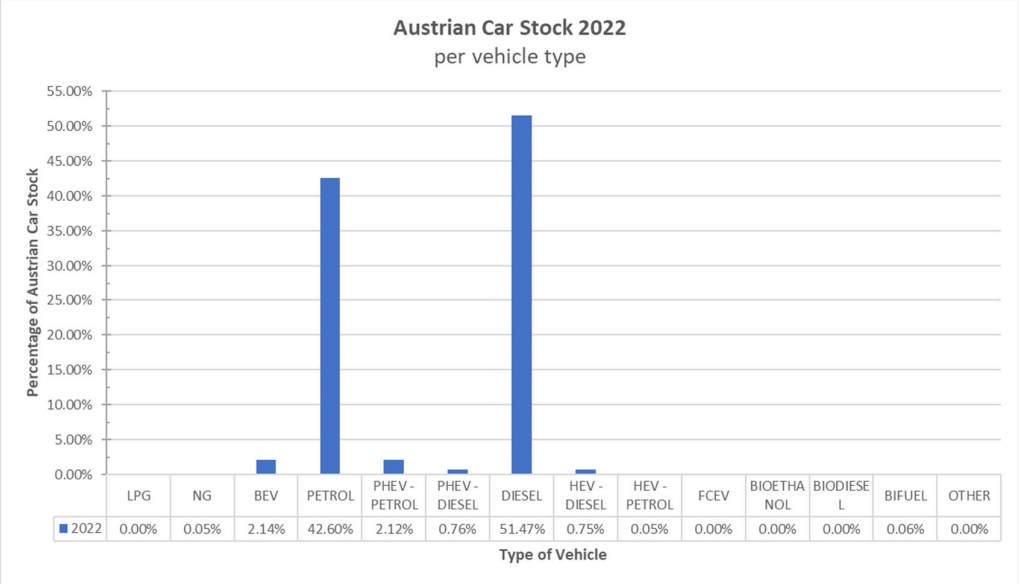


Figure 1. The Austrian car stock for the year 2022 per vehicle type.

By analyzing the development of the Austrian vehicle population, clear trends can be identified [21,22]. For instance, the diesel combustion engine (ICE diesel), which has enjoyed widespread popularity in Austria for many years, has been losing ground since 2018. A drop of 4.5% in diesel-powered vehicles can be attributed to the diesel emissions scandal [19]. Conversely, significant growth rates have been observed for alternative drive systems. The number of battery electric vehicles (BEVs) in Austria has surged from 3386 in

2014 to 110,225 in eight years [21,22]. Nevertheless, hybrid electric vehicles (HEVs) with both a combustion engine and an electric range are currently in high demand. Plug-in hybrid electric vehicles (PHEV), which are hybrids that can recharge externally through a power socket, are particularly popular at present [21,22] (refer to Figure 2). Other alternative driving systems, such as LPG cars and hydrogen or fuel cell cars (HYD_FCELL), have seen a slight increase in numbers. However, there is no significant volatility in the population of cars in Austria in total.

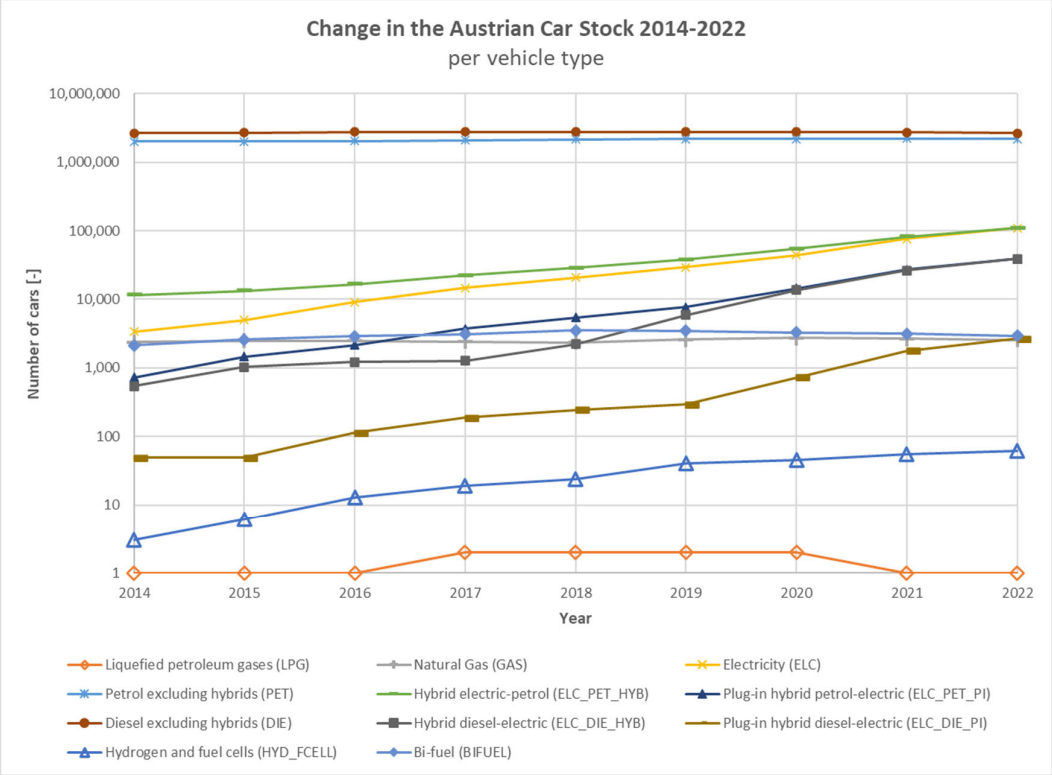


Figure 2. The numerical changes in the Austrian car stock per vehicle type from 2014 to 2022.

In order to determine the vehicle population in Austria, the age distribution of the vehicles on the roads is essential. This is particularly significant for cars with combustion engines as the date of manufacture corresponds to European emission classes (EURO classes). Due to the amounts of emissions released into the air, these EURO classes are decisive for a subsequent life cycle assessment (LCA) and integral LCA implementation. The Austrian Federal Statistical Office [22] recorded the age structure of passenger cars in Austria. Following the guidelines of the European Union [25] and using the known dates of manufacture from the vehicle registration information [26], the vehicles can now be assigned to specified EURO emission classes [25,27]. For cars in Austria, approximately 19% were assigned to EURO 3, 12% to EURO 4, 29% to EURO 5, and 40% to EURO 6 emission classes.

Based on the current inventory of vehicles, the LCA for various passenger cars can now considered for a life cycle assessment (LCA) integration of a traffic infrastructure. However, the question arises as to how to evaluate the vehicles from an ecological point of view, and which evaluation system (e.g., HBEFA, TREMOD, TREMOVE, COPERT etc.) [8–10,28–30] or database (e.g., ecoinvent etc.) [14,31] should be used. For a better understanding, some systems and approaches established on the market are explained before the methodological approach of this study is discussed.

2.3. Discussion of Evaluation Systems

The quantification of road transport vehicle emissions is an already established field of research that is widespread and used by regulatory agencies and national governments. Different evaluation systems are used worldwide for the calculation of emissions inventories. Here, the evaluation systems COPERT, TREMOD and HBEFA are discussed to obtain a short overview of the input data for the following LCA study. Although these systems vary both in complexity and approach, they are used in common databases (e.g., the ecoinvent-database) [14].

COPERT is a computer program that has been in development since 1989 for the calculation of road vehicle emissions. Financing and development are secured through the European Environmental Agency (EEA), while scientific support is provided by the Joint Research Center (JRC) of the European commission. Central to its modelling approach is the average velocity of different vehicle types and their emission factors on a road or corridor. This results in values for a wide variety of parameters, from greenhouse gas emissions (e.g., CO_2, CH4) to fuel consumption and pollutants (PM, NMHC). The following vehicle categories and fuel types are considered by COPERT for passenger cars, light-duty vehicles, motorcycles, busses, and heavy-duty vehicles (HDV). Fuels like petrol, diesel, LPG, CNG, E10 and E85 are considered. Input parameters, such as the fleet composition, driving characteristics (i.e., average velocity), road gradient, vehicle load factor (only for HDV), environmental conditions (e.g., temperature, humidity) and fuel quality, are accounted for. COPERT is used by 22 EU member states to calculate national and regional emission inventories [10]. The advantage of COPERT is its consideration of all major pollutants, different vehicle categories and application potentials in Asia, South America, Oceania, and Europe for the years between 1970 and 2050. However, COPERT is not designed for predictive modelling and is not based on a calibrated baseline. Furthermore, it is only used for road traffic.

TREMOD is a road traffic emissions model developed in 1997 by the Institute for Energy and Environmental Research (IFEU) on behalf of the German Environmental Agency (UBA). The model is regularly updated every 2 years. It calculates emissions for different road categories and traffic situations based on emission factors according to the Handbook Emission Factors for Road Transport (HBEFA). This is conducted in conjunction with traffic activity data. TREMOD uses fleet compositions, driving behaviors, road gradients, vehicle load factors, environmental conditions, and fuel qualities as inputs and provides data on fuel consumptions, greenhouse gas emissions and organic pollutants. TREMOD also includes non-road vehicles, e.g., trains, airplanes, and river barges. It is used in Germany for the calculation of national emission inventories. The advantage of TREMOD is that it can be used for predictive modelling. However, as TREMOD is specifically developed for the situation in Germany, it cannot be directly used for the emission inventories of other countries.

The calculated emission factors of the Handbook Emission Factors for Road Transport (HBEFA) are used by several valuation systems [11]. It has been under ongoing development by INFRAS AG, on behalf of numerous national environmental agencies, including Germany, Austria, Switzerland, Norway, Sweden, and France since 1995. Like COPERT, it is supported by the JRC. It is composed of two versions. Whereas the public version only contains the emission factors for 276 predefined traffic situations and approximately 400 different vehicles, the expert version also contains a more detailed fleet and emission model. The investigated traffic situations include urban and rural, highway and city streets and different levels of service (e.g., free-flowing, congested, stop and go). In combination with roller dynamometer measurements, a passenger car and a heavy-duty emission model are fed to calculate the emission factors for each vehicle type, road gradient, traffic situation and ambient temperature. These emission factors include all regulated air pollutants, energy consumptions, and CO_2-emissions. Therefore, the HBEFA emission factors are used as the basis for several emission models (e.g., COPERT, TREMOD) [10].

As mentioned above, the results of the emission models are partly used in the datasets of the ecoinvent database as input parameters. Due to the fact that the following LCA study is based on the ecoinvent approaches, data from TREMOD, HBEFA, etc., are also involved in this study.

3. Methods—Life Cycle Assessment for the Cars Driven in Austria

The LCA is based on ISO14040 [15], ISO14044 [16] but also takes the building-specific standards ÖNORM EN15804 [13] and ÖNORM EN17472 [12] into account. Hence, compatibility with other sustainability assessments for civil engineering works is ensured [12]. The study's methodological steps are outlined in detail below.

3.1. Goals

Based on the transport and emissions calculation models mentioned above [8–10,28,29], the aim of this study is to calculate the environmental impacts of passenger cars driven in Austria according to ÖNORM EN15804 [13] and to display them using several environmental indicators. The results will subsequently be measured using various environmental indicators to expand beyond the pure results outputted from the traffic emission models, which only account for greenhouse gas and particulate matter emissions. Additionally, the pure operational emissions are expanded to account for indirect environmental effects stemming from wear and tear of materials (such as brakes and tires), vehicle manufacturing, repairs, and disposal, on a proportional basis per route unit. This will enable the Austria-specific and current results presented in this study to be integrated into a holistic, integral LCA analysis of a traffic infrastructure (e.g., a bridge, a section of road, etc.). In addition to determining, analyzing, and investigating the environmental impacts of cars powered by diesel, petrol, electricity, natural gas, and liquefied petroleum gas (LPG), the results for diesel/electric and petrol/electric hybrid cars are also determined. Furthermore, this study presents a clear and concise approach to considering traffic emissions from uphill and downhill driving for the LCA at the life cycle stage "B1 Use Stage" according to ÖNORM EN17472 [12] and ÖNORM EN15804 [13].

3.2. Scope of the Study

3.2.1. Functional Unit

This study employs the established approach [14] of using 1 km driven as a functional unit.

3.2.2. System Boundaries

A "cradle to cradle" approach was used in the study, as many of the vehicle components are recycled and reused. Additionally, the production of vehicles primarily relies on European manufacturing processes and companies. The ecoinvent database 3.9.1 (system model: cut off by classification) [14,32] was used as a data source to evaluate the manufacturing, maintenance, and disposal procedures, which were tailored to the Austrian car population.

Throughout this study, all life cycle stages, ranging from the production of raw materials (A1) to disposal (C4) [12], were considered. Particular attention was paid to stage "B1 use", as well as additional consumption and emissions attributable to uphill and downhill driving. However, it should be noted that with regards to system limitations, the straightforward approach [17] for the inclusion of uphill and downhill gradients is applicable only under certain boundary conditions. When ascending a hill, the effectiveness of Liebl, Lederer et al.'s approach [17] depends on consistent acceleration without gear reduction and with a typical engine workload. For downhill driving, it is important to use the potential energy generated by the difference in altitude to persist against air resistance and friction [33], rather than transforming it into heat via braking [17]. These situations appear to be rare in real road traffic. In reality, it may be assumed that the fuel consumption is generally slightly higher. However, the approach of considering height

difference consumption in an integral LCA, as detailed by [7,17], appears to be practical, straightforward, and beneficial.

The Austrian national border was chosen for the geographical system boundary of this LCA, as it corresponds to the current Austrian car population [22,26]. It should be noted that the application of the results, presented below, may lead to results that differ from reality in other countries and geographic areas.

3.3. Life Cycle Inventory (LCI)

3.3.1. General

In order to accurately calculate the environmental results of a LCA, the Life Cycle Inventory (LCI) is a key step in the quantification process, where all energy inputs and outputs [34,35] as well as the material consumption etc., are collected. Due to the complex and extensive data collection for all manufacturing, maintenance, replacement, and disposal processes, the ecoinvent 3.9.1 database [14] was used for the current life cycle inventory (LCI) of vehicles in Austria. The passenger car datasets were subsequently modified and adapted to align with the current Austrian passenger car fleet [22,23,26]. As detailed in Section 2.2, parameters such as fuel consumption, vehicle mass, mileage, and battery size were therefore updated. Due to the current state of the art [25], EURO 6 vehicles were also modeled for the internal combustion engines (ICE). Results were also obtained for diesel/electric and petrol/electric hybrid vehicles.

As discussed at the beginning of this paper, an approach [17] to integrating additional consumption when driving uphill and downhill was included in the LCA.

Further elaboration on the individual key adaptations and implementation of additional consumption through uphill and downhill driving is provided below.

3.3.2. LCI of the Cars Driven in Austria

To generate the LCI for each car type, all relevant processes must be considered. This process starts with the elementary flow, or production flow [34], which represents the most elementary unit. The ecoinvent database [14] accounts for all procedures involved in car datasets, comprising fuel consumption (including the proportionate production per 1 km), the proportionate production of the vehicle, average maintenance and repairs broken down to 1 km of driving, as well as the emissions from the general use of the car, and brake and tire wear emissions, per 1 km. Additionally, the ecoinvent dataset [14] covers the construction and maintenance of the road infrastructure in proportion. The current study does not regard the infrastructure, as it is presented in a more detailed way in the integral LCA of the traffic infrastructure.

To ensure clarity, Figure 3 summarizes the essential main parameters of the LCI.

The parameters (inputs and outputs) shown in Figure 3 were adapted on the basis of the current car fleet and data surveys for cars driven Austria. The average vehicle mass [22,23,26] (see Table 1) was used as the main input parameter for the adaptation.

Table 1. Average mass per vehicle type for cars driven in Austria.

Car Type	Total Avg. Mass [kg]
Diesel	1694.25
Petrol	1309.42
(P) HEV-Diesel/Electric	2345.32
(P) HEV-Petrol/Electric	1985.4
Electric	1864.0
Natural Gas	1362.6
LPG	1205.0

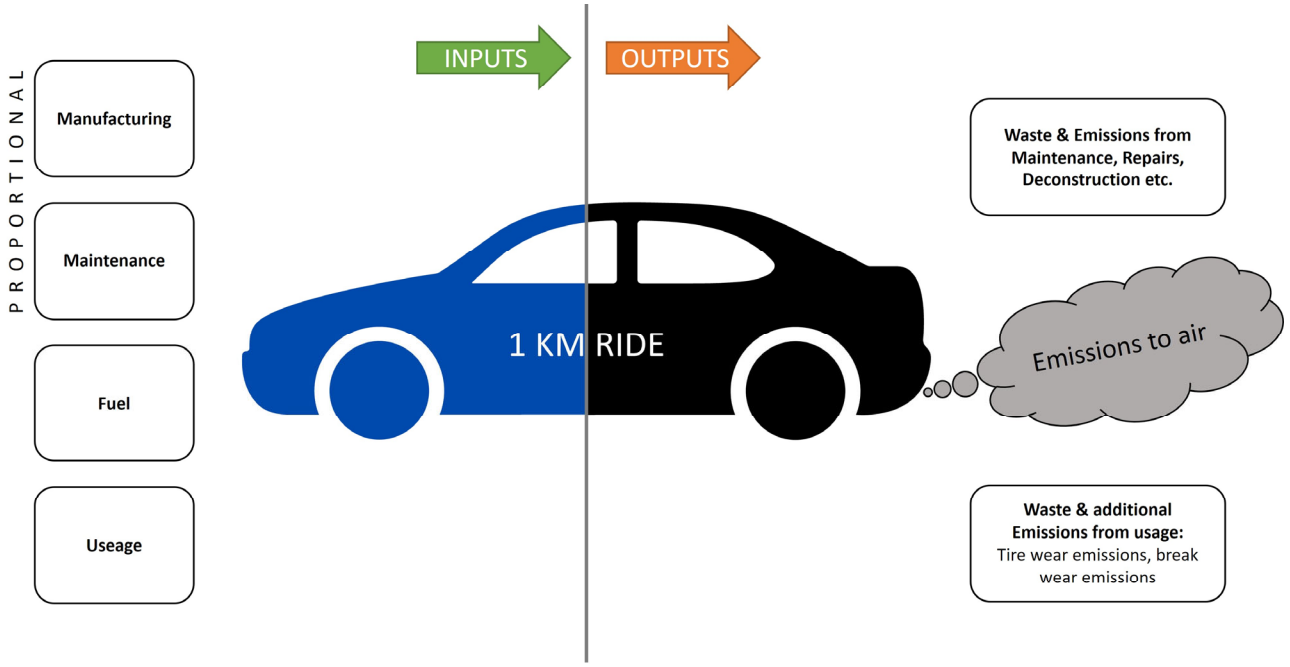


Figure 3. Overview of the main input and output parameters of the car life cycle inventory (LCI).

Based on the vehicle weight, the fuel consumption data in ecoinvent sourced from the TREMOVE model [8,9] were adapted to the average engine type/vehicle type and EURO emission class (3, 4, 5) in Austria through the implementation of ecoinvent's scaling factor [14]. This methodology applies to all passenger cars featuring internal combustion engines (ICE). In addition, the emissions stored in ecoinvent for 1 km of driving can be adjusted, using given scaling factors, unless they directly depend on the EURO emission class. This is applicable to nitrogen oxides (NO_x) and particulates <2.5 µm (PM). The NO_x and PM values are taken from the Handbook of Emission Factors for Road Transport (HBEFA) [10,11] and are adjusted to 1.915×10^{-6} kg/km for PM and 6.773×10^{-4} kg/km for NO_x, based on the diesel car's engine capacity as specified [14]. According to ecoinvent, there is no need to adjust the NO_x and PM values for petrol and gas passenger cars.

However, due to the non-existence of a EURO 6 car in the ecoinvent database, a corresponding dataset was modeled using a EURO 5 car for diesel, petrol, and natural gas cars. The modeling process started by adjusting the consumption factor stored in ecoinvent through an iterative method until the carbon dioxide (CO_2) emissions from pure operation aligned with those from the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) [36,37]. Once the fuel consumption was computed, the other emissions were adjusted based on the determined factor and modified to the atmosphere.

For the electric car (BEV), the average consumption of electricity is 0.1746 kWh/1 km [26], on the basis of data collected either by the registration authorities or from the European Environment Agency database. Additionally, the battery size and weight of the BEV are adjusted to current technological standards resulting in an average range of 414.29 km [26]. The lithium-ion (Li-Ion) battery weighs approximately 400 kg, considering an average energy content of around 180 Wh/kg.

The petrol/electric and diesel/electric hybrid vehicles were designed using the EURO 6 diesel or EURO 6 petrol as a basis and incorporating components of the BEV. The technological aspect is the addition of the components of the lithium-ion battery (production and disposal) and the electric motor with proportional production and disposal. The percentages of the components in both the combustion engine and electric car are considered within a range estimation. An average range of approximately 954 km can be estimated for a diesel-ICE and approximately 1027 km for a petrol-ICE, assuming a tank volume of 55 L as typical for hybrid vehicles [38]. According to the EEA survey [26], the electric range

is 63.69 km for diesel/electric and 55.59 km for petrol/electric. The battery weight can be calculated as 100 kg for diesel/electric and 60 kg for petrol/electric, based on the energy content of the Li-ion battery, which is similar to that of a BEV. The inputs and outputs of each component within the electric technosphere, including production, maintenance, repair, and disposal, were adjusted and added to the ICE dataset based on the achievable ranges. For instance, an estimated 15% increase in maintenance activities for the accumulator and electric motor for the diesel/electric and about 13% increase for the petrol/electric car have been considered.

For battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), it is assumed that only Austrian electricity is used. Therefore, the Austrian electricity mix for low voltages (<1 kV) [39] was used to calculate the operating emissions of these vehicles. Furthermore, an average battery life of 150,000 driven km [19] was assumed. After this lifetime, the Li-ion battery is removed from the BEV and PHEV, recycled and replaced with a new battery. The replacement process is factored proportionally into the LCA, taking the mileage into account as described below.

In addition to the vehicle mass, the mileage of the cars (i.e., the assumed service life of the cars) is decisive for the proportionate consideration of manufacturing, maintenance, and disposal processes. Presently, LCA databases [14] adopt a mileage estimate of 150,000 km for passenger cars. Recent studies [19,40,41] indicate that this value does not align with current technology standards. An analysis of traffic volume, including a 2025+ forecast for Austria [40], shows that the mileage should be increased. This finding is also confirmed by reports from both the Austrian automobile club [19] and the federal environment agency [41]. The Austrian traffic forecast for 2025+ [40] covers two scenarios that calculate the total car mileage for 2025. In 2025, it is estimated that either 79.44 billion km or, in scenario 2, 65.70 billion km, will be driven [40]. Based on the calculated number of approximately 5075 million cars for 2025+ in Austria [40], the average distance covered per car is estimated to be around 13,000 km per year. With a realistic and achievable service life of 15 years [19,40], this leads to a total mileage per vehicle of approximately 200,000 km. To allocate environmental impacts of the mentioned manufacturing processes etc., to the functional unit (FU), these processes are divided by the lifetime mileage of 200,000 km to consider them on a proportional basis per kilometer.

3.3.3. LCI of Driving Uphill/Downhill

In addition to updating the datasets to the current state of the art, an approach to investigating how the traffic utilization of the roads can be considered for an integral LCA study or implementation within a life cycle tool was also developed. Investigating different route variants and including gradients, is of particular interest for this type of study. In the LCA of traffic emissions, it is necessary to include the effects of uphill and downhill driving that exceed the average emissions. This study employs the approach of Liebl, Lederer et al. [17] for the LCA. Therefore, the extra fuel or electricity consumption is calculated for each engine type based on the difference in altitude traveled. Based on this result, the consumption values for the respective route section are included in the LCI. It is important to note that the calculated additional consumption increases as the longitudinal gradient increases. Although traveling downhill theoretically compensates the additional consumption due to reduced potential energy [7], in reality, only 50% [7] of the consumption from the uphill journey is compensated due to the need for braking maneuvers [7]. The additional fuel consumed is calculated using the following formula [17]:

$$Fuel_{height}\left[\frac{l \text{ or } kWh}{100\ km}\right] = vehicle\ mass[kg] * height\ difference[m] * 9.81\left[\frac{m}{s^2}\right] * \frac{1}{1000*3600} * \nu_{Pe} * \frac{100}{distance[km]} * \frac{1}{0.98}$$
$$\nu_{Pe}\left[\frac{l}{kWh}\ or\ kWh\right] \ldots consumption\ efficiency; \nu_{Pe} = 0.264\ for\ petrol, 0.220\ for\ diesel, 1\ for\ electricity,\ 0.205\ for\ gas \quad (1)$$

3.4. Life Cycle Impact Assessment

To evaluate the environmental impact of driving 1 km with a passenger car, the results are presented using common and selected impact indicators according to ÖNORM EN15804 [13] for total (direct and indirect) driving emissions.

The considered impact indicators are [13]:

- Global Warming Potential—total (GWP-total) [kg CO_2 eq.];
- Ozone Depletion Potential (ODP) [kg CFC 11 eq.];
- Acidification Potential (AP) [mol H^+ eq.];
- Eutrophication Potential aquatic freshwater (EP-freshwater) [kg PO_4 eq.];
- Eutrophication Potential aquatic marine (EP-marine) [kg N eq.];
- Eutrophication Potential terrestrial (EP-terrestrial) [mol N eq.];
- Formation Potential of Tropospheric ozone (POCP) [kg NMVOC eq.];
- Abiotic depletion potential for non-fossil resources (ADP-minerals & metals) [kg Sb eq.];
- Abiotic depletion for fossil resources potential (ADP-fossil) [MJ, net calorific value];
- Water (user) deprivation potential, deprivation-weighted water consumption (WDP) [m^3 world eq. deprived];
- Potential incidence of disease due to particulate matter emissions (PM) [Disease incidence];
- Potential Comparative Toxic Unit for ecosystems (ETP-fw) [CTUe];
- Potential Comparative Toxic Unit for humans (HTP-c) [CTUh];
- Potential Comparative Toxic Unit for humans (HTP-nc) [CTUh];
- Potential soil quality index (SQP) [dimensionless];
- Total use of renewable primary energy resources (PERT) [MJ, net calorific value];
- Total use of non-renewable primary energy resources (PENRT) [MJ, net calorific value];
- Use of secondary material (SM) [kg];
- Materials for recycling (MFR) [kg];

4. Results

4.1. General

The environmental impacts of selected impact indicators were calculated for a variety of cars driven in Austria according to ÖNORM EN15804. To gain a general understanding, pure operating (direct) emissions per kilometer driven and also the total (direct and indirect) emissions were further presented.

As the GWP impact indicator is currently of great importance, the GWP results are presented and discussed by means of an example using a graph for the operating emissions and for the overall view.

Examining the results in Figure 4, it becomes apparent that diesel cars in Austria emit an average of 0.170 kg CO_2 eq./km while petrol cars emit 0.184 kg CO_2 eq./km. The emission class distribution, as indicated at the beginning, forms the basis of these findings. The facts show that petrol cars emit more on average due to the composition of the vehicle fleet and their age distribution in Austria. Hybrid cars eject lower overall CO_2 eq. emissions due to the e-share of driving. Regarding BEVs, pure operating emissions rely extensively on the mix of electricity used. As previously outlined in Section 3.3.2, the results and analysis presented here rely on the Austrian electricity mix. The available electricity mix of the Austrian market is very environmentally friendly due to the large number of hydropower plants, other renewable energy sources from domestic generation, and the low amount of fossil energy used in Austria. The emissions for gas-powered vehicles with ICE depend on the origin of the natural gas source as well as the EURO emission classes. On average, cars driven in Austria emit 172 g CO_2 eq./km, with consideration for vehicle distribution (refer to Figure 1) and EURO emission class composition (see Section 2.2).

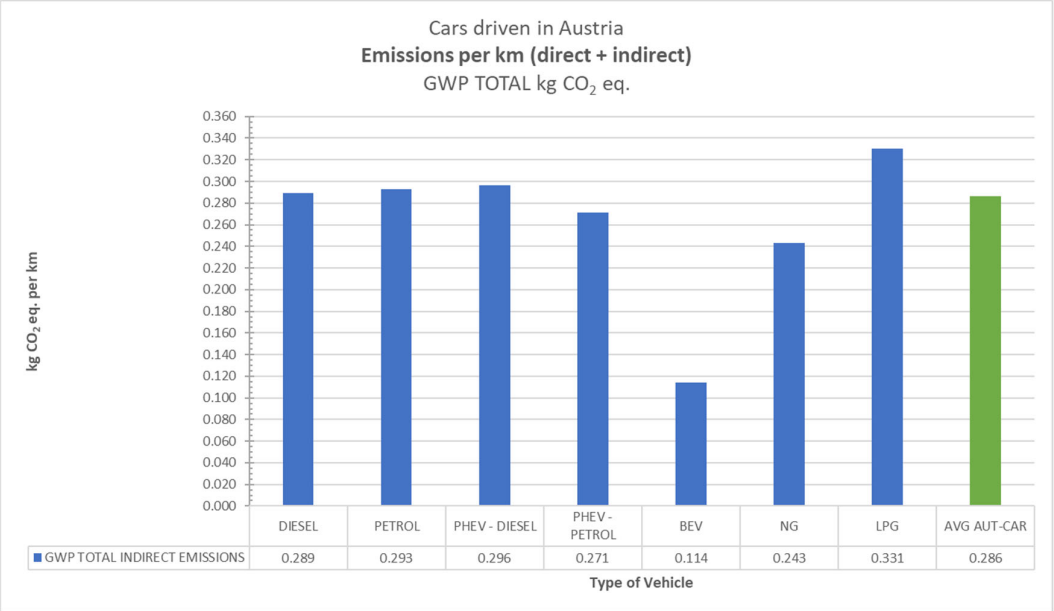


Figure 4. Average Austrian operational emissions presented for the Global Warming Potential (GWP) in kg CO_2 eq. per km and car type (blue bars), as well as for the average passenger car driven in Austria (green bar).

To conduct an LCA analysis for operating emissions according to ÖNORM EN 15804, it is essential to consider additional impact indicators. Table 2 presents detailed results for several common environmental indicators [42].

Table 2. Average Austrian operational emissions presented for several environmental impact indicators per km and car type.

Impact Indicator	Unit	Diesel	Petrol	Diesel/ Electric	Petrol/ Electric	BEV	NG	LPG	AVG AUT-CAR
GWP-total	kg CO_2 eq	1.697×10^{-1}	1.838×10^{-1}	1.443×10^{-1}	1.373×10^{-1}	3.225×10^{-2}	1.451×10^{-1}	1.763×10^{-1}	1.716×10^{-1}
ODP	kg CFC11 eq	0.000	0.000	3.224×10^{-10}	2.645×10^{-10}	5.155×10^{-9}	0.000	0.000	1.205×10^{-10}
AP	mol H^+ eq	4.817×10^{-4}	3.360×10^{-5}	4.125×10^{-4}	2.522×10^{-5}	1.109×10^{-4}	4.621×10^{-5}	3.081×10^{-5}	2.690×10^{-4}
EP-freshwater	kg P eq	0.000	0.000	6.729×10^{-7}	5.520×10^{-7}	1.076×10^{-5}	0.000	0.000	2.515×10^{-7}
EP-marine	kg N eq	2.512×10^{-4}	1.438×10^{-5}	2.130×10^{-4}	9.136×10^{-6}	2.390×10^{-5}	4.875×10^{-6}	1.333×10^{-5}	1.381×10^{-4}
EP-terrestrial	mol N eq	2.762×10^{-3}	1.784×10^{-4}	2.343×10^{-3}	1.163×10^{-4}	2.860×10^{-4}	2.061×10^{-4}	1.692×10^{-4}	1.527×10^{-3}
POCP	kg NMVOC eq	6.667×10^{-4}	1.511×10^{-4}	5.655×10^{-4}	1.013×10^{-4}	7.401×10^{-5}	8.358×10^{-5}	1.595×10^{-4}	4.170×10^{-4}
ADP-minerals & metals	kg Sb eq	0.000	0.000	3.678×10^{-8}	3.018×10^{-8}	5.882×10^{-7}	0.000	0.000	1.375×10^{-8}
ADP-fossil	MJ	0.000	0.000	2.780×10^{-2}	2.281×10^{-2}	4.445×10^{-1}	0.000	0.000	1.039×10^{-2}
WDP	m^3 depriv.	0.000	0.000	3.274×10^{-4}	2.686×10^{-4}	5.235×10^{-3}	0.000	0.000	1.224×10^{-4}
PM	disease inc.	4.174×10^{-9}	3.038×10^{-10}	1.299×10^{-9}	2.504×10^{-10}	7.290×10^{-10}	2.864×10^{-10}	1.065×10^{-10}	2.314×10^{-9}
ETP-fw	CTUe	5.289×10^{-3}	4.526×10^{-3}	4.268×10^{-2}	3.467×10^{-2}	6.122×10^{-1}	2.096×10^{-3}	4.974×10^{-3}	1.910×10^{-2}
HTP-c	CTUh	7.732×10^{-11}	1.245×10^{-11}	6.486×10^{-11}	9.807×10^{-12}	1.990×10^{-11}	1.742×10^{-12}	1.359×10^{-11}	4.637×10^{-11}
HTP-nc	CTUh	1.297×10^{-9}	6.593×10^{-10}	1.099×10^{-9}	3.475×10^{-10}	5.111×10^{-10}	1.206×10^{-9}	7.980×10^{-10}	9.798×10^{-10}
SQP	Pt	0.000	0.000	3.211×10^{-2}	2.634×10^{-2}	5.134×10^{-1}	0.000	0.000	1.200×10^{-2}

To analyze the environmental impact of transportation processes and emissions holistically according to ÖNORM EN17472, the extended effects per kilometer must be evaluated across the entire life cycle (A1–C4 or D). As described in Section 3.3.2, the inclusion of indirect driving effects, e.g., the proportional manufacturing or the accruing waste, must be considered. By examining the GWP results (presented in Figure 5), the GWP outcomes are, on average, roughly 60% higher than the direct operation emissions.

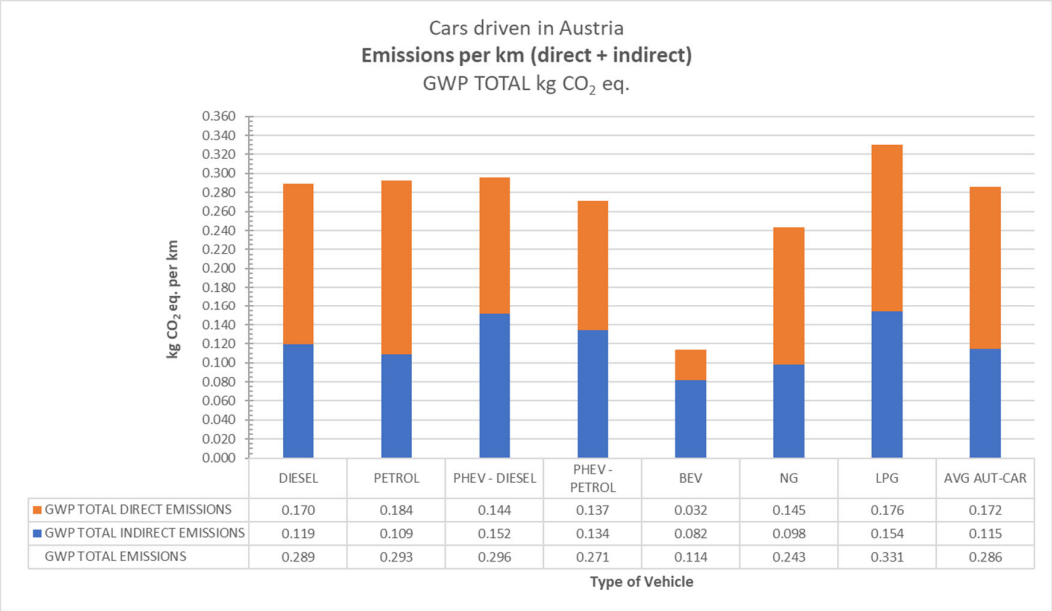


Figure 5. Average Austrian (total driving) emissions presented for the Global Warming Potential (GWP) in kg CO_2 eq. per km and car type.

For detailed average results per environmental indicator and vehicle type, kindly refer to Table 3.

Table 3. Average Austrian emissions presented for several environmental impact indicators per km and car type including direct and indirect emissions.

Impact Indicator	Unit	Diesel	Petrol	Diesel/ Electric	Petrol/ Electric	BEV	NG	LPG	AVG AUT-CAR
GWP-total	kg CO_2 eq	2.890×10^{-1}	2.927×10^{-1}	2.961×10^{-1}	2.714×10^{-1}	1.141×10^{-1}	2.429×10^{-1}	3.306×10^{-1}	2.863×10^{-1}
ODP	kg CFC11 eq	7.052×10^{-9}	6.475×10^{-9}	3.224×10^{-10}	6.888×10^{-9}	7.571×10^{-9}	1.078×10^{-8}	7.309×10^{-9}	6.760×10^{-9}
AP	mol H^+ eq	1.105×10^{-3}	6.173×10^{-4}	8.450×10^{-4}	8.616×10^{-4}	7.028×10^{-4}	4.499×10^{-4}	9.708×10^{-4}	8.792×10^{-4}
EP-freshwater	kg P eq	3.065×10^{-5}	2.538×10^{-5}	6.729×10^{-7}	5.249×10^{-5}	5.791×10^{-5}	2.534×10^{-5}	4.228×10^{-5}	2.937×10^{-5}
EP-marine	kg N eq	3.590×10^{-4}	1.099×10^{-4}	4.386×10^{-4}	1.526×10^{-4}	1.267×10^{-4}	8.446×10^{-5}	1.809×10^{-4}	2.425×10^{-4}
EP-terrestrial	mol N eq	3.821×10^{-3}	1.111×10^{-3}	4.823×10^{-3}	1.431×10^{-3}	1.217×10^{-3}	1.051×10^{-3}	1.866×10^{-3}	2.548×10^{-3}
POCP	kg NMVOC eq	1.402×10^{-3}	8.178×10^{-4}	1.164×10^{-3}	8.983×10^{-4}	8.586×10^{-4}	5.945×10^{-4}	1.131×10^{-3}	1.125×10^{-3}
ADP-minerals & metals	kg Sb eq	2.527×10^{-6}	2.085×10^{-6}	3.678×10^{-8}	6.149×10^{-6}	6.470×10^{-6}	2.151×10^{-6}	3.611×10^{-6}	2.507×10^{-6}
ADP-fossil	MJ	3.737	3.459	2.780×10^{-2}	3.264	1.474	3.452	4.398	3.526
WDP	m^3 depriv.	1.976×10^{-2}	1.654×10^{-2}	3.274×10^{-4}	2.565×10^{-2}	2.629×10^{-2}	1.613×10^{-2}	2.707×10^{-2}	1.854×10^{-2}
PM	disease inc.	1.276×10^{-8}	8.464×10^{-9}	2.636×10^{-9}	1.128×10^{-8}	8.727×10^{-9}	6.569×10^{-9}	1.158×10^{-8}	1.072×10^{-8}
ETP-fw	CTUe	2.125	1.880	4.735×10^{-2}	2.143	1.382	7.662×10^{-1}	2.703	1.988
HTP-c	CTUh	2.456×10^{-10}	1.499×10^{-10}	1.327×10^{-10}	2.367×10^{-10}	2.234×10^{-10}	1.432×10^{-10}	2.529×10^{-10}	2.031×10^{-10}
HTP-nc	CTUh	4.369×10^{-9}	3.307×10^{-9}	2.237×10^{-9}	5.281×10^{-9}	4.298×10^{-9}	3.602×10^{-9}	4.844×10^{-9}	3.924×10^{-9}
SQP	Pt	3.789×10^{-1}	3.370×10^{-1}	3.211×10^{-2}	4.912×10^{-1}	8.340×10^{-1}	2.109×10^{-1}	4.984×10^{-1}	3.712×10^{-1}

4.2. Driving Uphill/Downhill

To implement the approach outlined by Liebl, Lederer et al. [17] in Section 3.3.3, the extra consumption can be calculated from the values used for distance, altitude difference, fuel efficiency and vehicle mass. Additionally, to account for the environmental effects of driving uphill, the extra consumption can be multiplied by the analyzed values (see Table 4), considering the composition of the EURO emission classes. This provides a straightforward and manageable approach to assessing the environmental impact of uphill and downhill driving in a comprehensive life cycle assessment of a traffic route, in accordance with ÖNORM EN17472 and ÖNORM EN15804 indicators. It should be noted that during downhill driving, the compensation for 50% of the energy used during the uphill journey is factored into the additional consumption calculation (refer to Section 3.3.3). Additionally, changes in elevation must be taken into consideration with the appropriate polarities (+/−).

Table 4. Average Austrian emissions presented for several environmental impact indicators per km and different power units for the application of the approach of Liebl, Lederer et al. to consider driving in gradients.

Impact Indicator	Unit	1 L DIESEL	1 L PETROL	1 m³ GAS	1 kWh AUT-Electricity
GWP-total	kg CO_2 eq	3.538	3.352	2.685	1.847×10^{-1}
ODP	kg CFC11 eq	7.441×10^{-8}	6.429×10^{-8}	1.259×10^{-7}	2.953×10^{-8}
AP	mol H^+ eq	1.035×10^{-2}	4.406×10^{-3}	2.089×10^{-3}	6.355×10^{-4}
EP-freshwater	kg P eq	4.371×10^{-5}	4.554×10^{-5}	3.457×10^{-5}	6.163×10^{-5}
EP-marine	kg N eq	4.192×10^{-3}	8.075×10^{-4}	4.689×10^{-4}	1.369×10^{-4}
EP-terrestrial	mol N eq	4.458×10^{-2}	7.843×10^{-3}	7.658×10^{-3}	1.638×10^{-3}
POCP	kg NMVOC eq	1.630×10^{-2}	7.866×10^{-3}	4.904×10^{-3}	4.239×10^{-4}
ADP-minerals & metals	kg Sb eq	5.248×10^{-7}	5.592×10^{-7}	5.479×10^{-7}	3.369×10^{-6}
ADP-fossil	MJ	4.584×10^{1}	3.964×10^{1}	3.983×10^{1}	2.546
WDP	m^3 depriv.	6.121×10^{-2}	5.406×10^{-2}	4.340×10^{-2}	2.999×10^{-2}
PM	disease inc.	8.836×10^{-8}	3.974×10^{-8}	1.242×10^{-8}	4.176×10^{-9}
ETP-fw	CTUe	2.086×10^{1}	1.802×10^{1}	2.110	3.507
HTP-c	CTUh	1.358×10^{-9}	4.217×10^{-10}	3.054×10^{-10}	1.140×10^{-10}
HTP-nc	CTUh	2.643×10^{-8}	1.498×10^{-8}	1.723×10^{-8}	2.928×10^{-9}
SQP	Pt	2.533	2.314	4.659×10^{-1}	2.941

5. Discussion and Conclusions

This study examined the life cycle assessment of cars driven in Austria in detail. Results of the study showed that while a large number of assessment systems [8–11] are available on the market, in most cases, emissions data are only available for CO_2 values and particulate matter (PM). In certain LCA databases, such as the ecoinvent database [14], well-founded and detailed results can be calculated for various impact indicators for cars, but these background data are only aimed at certain superordinate regions (global, Europe) and are not accessible on a country-specific basis. However, it is apparent that some of the stored data no longer correspond to current technology standards (vehicle mass, battery sizes, lifetime mileage, etc.). Furthermore, the available approaches make it difficult to display emissions data for journeys beyond flat terrain, i.e., uphill and downhill driving, for impact indicators in accordance with EN15804.

Hence, this study addressed these problems in order to calculate current eco-data for Austrian car traffic and to prepare the results in a form that allows them to be included in a life cycle assessment of traffic infrastructure for the life cycle stage "B1". In the process, various car types with different driving systems were evaluated. In addition to pure driving (direct emissions from movement), all upstream environmental impacts from the production, maintenance, repair and disposal of vehicle parts, including the associated logistical processes, were taken into account in a "cradle to cradle" approach. An examination of the global warming potential shows that the average car driven in Austria t emits 286 g of CO_2 equivalents per kilometer.

Furthermore, the approach of Liebl and Lederer et al. was used to calculate the additional consumption of fuel and energy when driving uphill and downhill, and the possibility of taking these data into account in the life cycle assessment was considered. Corresponding eco-results of fuels and energy for use in this approach were calculated and presented. An individual and flexible assessment, which is only dependent on the distance, the difference in altitude and the energy source, can thus be guaranteed in a simple way; however, the limitations of this approach, such as a constant driving process without downshifting and a normal engine load etc., must be mentioned. Although the approach has some limitations it appears to be a good way to consider incline and decline effects in a life cycle assessment.

A further aim of this study was to provide a basis for the creation of Austrian data values for car traffic and for an integration into sustainability assessments of traffic infrastructures. As has been shown, traffic usage is the main emitter over the entire life

cycle. It is therefore essential that detailed values are available to ensure that roads can be assessed over their whole life cycle and can be compared with other route options. The results presented were therefore quantified according to the impact indicators of EN15804 and prepared for an assessment of traffic infrastructure according to EN17472. To further support the life cycle assessment of road infrastructures, a simple Excel-based transport calculator (see Figure 6) was developed over the course of the analysis. After entering the distance, the difference in altitude and the respective vehicle composition, it calculates the emitted environmental impact. An extension for other means of transport (trucks, buses, motorcycles and trains) is planned by using the same methodical approach. The intention is to ensure that the results can be used not only for road infrastructures, but also to evaluate rail routes and generally to assess the life cycle stage "B1 use". As the analyses continue, difficulties could arise in the collection of data for freight transport by truck or freight train, as the usual unit of the measurement are ton-kilometers (tkm) instead of normal kilometers. It will certainly be more challenging to collect data for Austria-specific values than for cars, where large volumes of data are available.

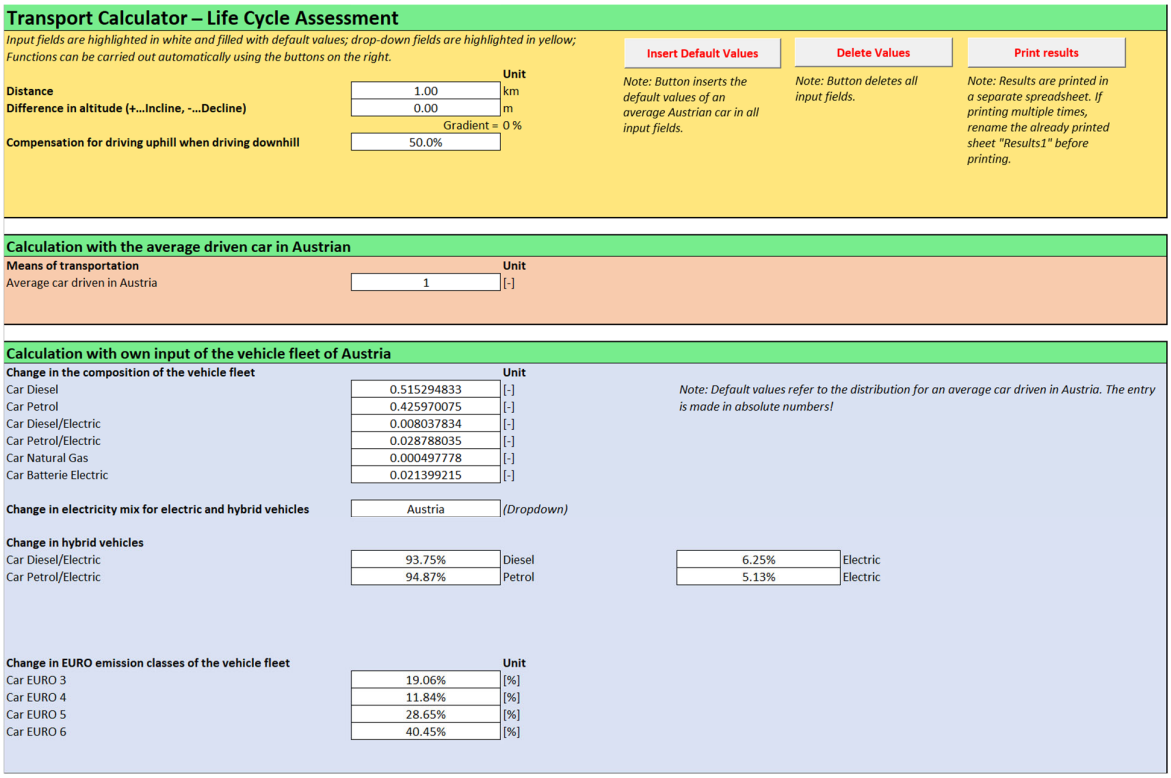


Figure 6. Input mask of the LCA transport calculator for passenger cars driven in Austria.

In summary, this paper has created an ecological data basis for cars driven in Austria, which is available for pure traffic analyses, but also for further integration into overall sustainability assessments of traffic infrastructures. At the same time, a method was presented that can be applied to other means of transportation. The results and approaches are intended to provide an initial data basis that can subsequently be integrated into a life cycle tool called "LZinfra" [4] that is currently being developed in Austria, which can then assess the sustainability of traffic infrastructures in total.

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Data Availability Statement: The data presented in this study are not publicly available due to ongoing research activities and license regulations of the ecoinvent-database.

Conflicts of Interest: Author Jounes Lutterbach was employed by the company VCE Vienna Consulting Engineers ZT GmbH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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