Life-cycle inventories for on-road vehicles

Authors
Romain Sacchi
Christian Bauer
Paul Scherrer Institut – Technology Assessment group
https://www.psi.ch/en/ta

Contact: romain.sacchi@psi.ch

Reviewed by
Brian Cox
INFRAS AG

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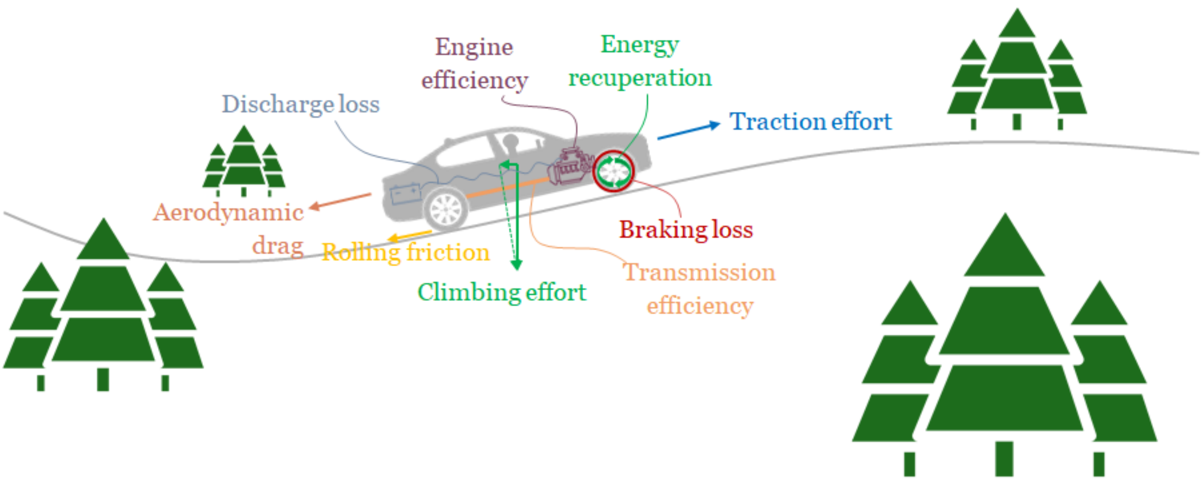

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Abbreviations

Vehicles

ICEV-p	Internal Combustion Engine Vehicle, powered with gasoline
ICEV-d	Internal Combustion Engine Vehicle, powered with diesel
ICEV-g	Internal Combustion Engine Vehicle, powered with compressed gas
HEV-p	Hybrid Engine Vehicle, powered with gasoline
HEV-d	Hybrid Engine Vehicle, powered with diesel
PHEV-p	Plugin Hybrid Engine Vehicle, powered with gasoline
PHEV-d	Plugin Hybrid Engine Vehicle, powered with diesel
BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicles

Emissions

CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
GHG	Greenhouse gas
HC	Hydrocarbon
N_2O	Nitrous oxide
NH_3	Ammonia
NMVOC	Non-methane Volatile Organic Compounds
NO_x	Nitrogen oxides
Pb	Lead
PM <2.5	Particulate matter with a width inferior to 2.5 micrometer
PM 2.5-10	Particulate matter with a width comprised between 2.5 and 10 micrometer
SO_2	Sulfur dioxide

Units

J	Joule
kg	kilogram
kWh	kilowatt hour
MJ	mega joule
pkm	person-kilometer
t	ton
tkm	ton-kilometer
vkm	vehicle-kilometer

Other

CH	Switzerland
EURO-x	European emission standard
GLO	World region
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HBEFA	Handbook for Emission Factors
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
RER	Region for geographical Europe
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

Summary

This report describes the modelling of life cycle inventories for current on-road vehicles. This includes vehicles for passenger transport as well as for the transport of goods.

For the transport of passengers, inventories for kick-scooters, bicycles, scooters, motorbikes, passenger cars, and city and coach buses are provided, with conventional, hybrid and electric powertrains.

For the transport of goods, inventories for delivery, medium- and heavy-duty trucks with conventional and electric powertrains are also included.

Additionally, fleet average vehicles (motorbikes, passenger cars and trucks) are modelled to represent the average performance of these vehicles in Switzerland and Europe in 2020.

The tables Table 1-Table 5 give an overview of the vehicles considered in this study.

Table 1 Fuel and battery options considered in this study

F_h	Energy provided by user (food intake not included)	E_{mix}	Low voltage Swiss consumption electricity mix
F_{g_CH}	Gasoline blend purchased in Switzerland (contains a certain amount of bioethanol)	E_{cert}	Low voltage label-certified Swiss electricity mix
F_{g_EU}	Gasoline blend purchased in Europe (contains a certain amount of bioethanol)	E_{mix_EU}	Low voltage European consumption electricity mix
F_{d_CH}	Diesel blend purchased in Switzerland (contains a certain amount of biodiesel)	B_{NMC}	Lithium-ion NMC battery
F_{d_EU}	Diesel blend purchased in Europe (contains a certain amount of biodiesel)	B_{NCA}	Lithium-ion NCA battery
F_{c_CH}	Compressed gas blend purchased in Switzerland (contains a certain amount of biomethane)	B_{LFP}	Lithium-ion LFP battery
F_{c_EU}	Compressed gas blend purchased in Europe (contains a certain amount of biomethane)	B_{LTO}	Lithium-ion LTO battery
F_{b_CH}	Compressed biomethane purchased in Switzerland	H_{elec_CH}	Hydrogen produced by means of electrolysis operated with E_{mix}
F_{b_EU}	Compressed biomethane purchased in Europe	$H_{elec\_cert\_CH}$	Hydrogen produced by means of electrolysis operated with E_{cert}
F_{mix}	Swiss fleet average-based fuel blend	H_{elec_EU}	Hydrogen produced by means of electrolysis operated with E_{mix_EU}
F_{mix_EU}	European fleet average-based fuel blend	H_{SMR}	Hydrogen produced by means of Steam Methane Reforming of natural gas

Table 2 Two-wheelers included in this study

		Kick-scooters	Bicycles					Scooters	Motorbikes			
			Conv.	< 25 km/h	< 45 km/h	Cargo	<4 kW	4-11 kW	4-11 kW	11-35 kW	> 35 kW	Fleet average
Non-motorized	n/a		F_h									
Gasoline	EURO-3						F_{g_CH}		F_{g_CH}			
	EURO-4											
	EURO-5											
	Fleet average											
Battery electric Slow, fast and rapid charge (<=150 kW) CHAdeMO, CCS, Type 1 and 2 chargers	2020	E_{mix}, E_{cert}, B_{NMC}, B_{NCA}, B_{LFP}		E_{mix}, E_{cert}, B_{NMC}, B_{NCA}, B_{LFP}			E_{mix}, E_{cert}, B_{NMC}, B_{NCA}, B_{LFP}					

Table 3 Passenger cars considered in this study

		Passenger cars			
		Compact	Medium	Large	Fleet average
Gasoline	EURO-3	F_{g_CH}, F_{g_EU}			F_{mix}, F_{mix_EU}
	EURO-4				
	EURO-5				
	EURO-6 a/b				
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				
Diesel	EURO-3	F_{d_CH}, F_{d_EU}			
	EURO-4				
	EURO-5				
	EURO-6 a/b				
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				
Compressed gas	EURO-3	F_{c_CH}, F_{b_CH}, F_{c_EU}, F_{b_EU}			
	EURO-4				
	EURO-5				
	EURO-6 a/b				
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				
Gasoline hybrid	EURO-5	F_{g_CH}, F_{g_EU}			
	EURO-6 a/b				
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				
Diesel hybrid	EURO-5	F_{d_CH}, F_{d_EU}			
	EURO-6 a/b				
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				
Gasoline plug-in hybrid	EURO-6 a/b	F_{g_CH} + E_{mix}, F_{g_CH} + E_{cert}, F_{g_EU} + E_{mix_EU}			
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				

		Passenger cars			
		Compact	Medium	Large	Fleet average
Diesel plug-in hybrid	EURO-6 a/b	$F_{d\_CH} + E_{mix}$, $F_{d\_CH} + E_{cert}$, $F_{d\_EU} + E_{mix\_EU}$			
	EURO-6 c				
	EURO-6 d-temp				
	EURO-6 d				
	Fleet average				
Battery electric Slow, fast and rapid charge (<=150 kW) CHAdeMO, CCS, Type 1 and 2 chargers	2020	E_{mix}, E_{mix_EU}, E_{cert}, B_{NMC}, B_{NCA}, B_{LFP}			
	Fleet average	E_{mix}, E_{mix_EU}, B_{NMC}			
Battery electric Continuous charge (50 kW) Overhead lines	2020				
Battery electric Continuous charge (200 kW) Type 3 chargers	2020				
Battery electric Ultra-fast charge (450 kW) Pantograph	2020				
Fuel cell electric	2020	H_{elec_CH}, H_{elec_EU}, H_{SMR}			
	Fleet average				

Table 4 City and coach buses considered in this study

		Buses					
		Midibus, 9m	Single deck, city bus, 13m	Single deck, city bus, 18m	Double deck, city bus, 13m	Single deck, coach, 13m	Double deck, coach, 13m
Diesel	EURO-III	F_{d_CH}, F_{d_EU}					
	EURO-IV						
	EURO-V						
	EURO-VI						
	Fleet average						
Compressed gas	EURO-III	F_{c_CH}, F_{b_CH}					
	EURO-IV						
	EURO-V						
	EURO-VI						
	Fleet average						
Diesel hybrid	EURO-V						
	EURO-VI	F_{d_CH}, F_{d_EU}					
	Fleet average						
Battery electric Continuous charge (50 kW) Overhead lines	EURO-VI/2020		E_{mix}, E_{cert}, B_{LTO}	E_{mix}, E_{cert}, B_{LTO}			
Battery electric Continuous charge (200 kW) Type 3 chargers	EURO-VI/2020	E_{mix}, E_{cert}, B_{NMC}, B_{NCA}, B_{LFP}					
Battery electric Ultra-fast charge (450 kW) Pantograph	EURO-VI/2020	E_{mix}, E_{cert}, B_{LTO}					
Fuel cell electric	EURO-VI/2020	H_{elec_CH}, $H_{elec\_cert\_CH}$, H_{SMR}					

Table 5 Medium and heavy-duty trucks considered in this study

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="6">Trucks, urban delivery</td><td colspan="6">Trucks, regional delivery</td><td colspan="6">Trucks, long haul</td><td></td></tr>
<tr><td>3.5t</td><td>7.5t</td><td>18t</td><td>26t</td><td>32t</td><td>40t</td><td>3.5t</td><td>7.5t</td><td>18t</td><td>26t</td><td>32t</td><td>40t</td><td>3.5t</td><td>7.5t</td><td>18t</td><td>26t</td><td>32t</td><td>40t</td><td>Fleet average</td></tr>
<tr><td>Non-motorized</td><td colspan="20"></td></tr>
<tr><td rowspan="5">Diesel</td><td>EURO-III</td><td rowspan="5" colspan="19">F_{d_CH}, F_{d_EU}</td></tr>
<tr><td>EURO-IV</td></tr>
<tr><td>EURO-V</td></tr>
<tr><td>EURO-VI</td></tr>
<tr><td>Fleet average</td></tr>
<tr><td rowspan="5">Compressed gas</td><td>EURO-III</td><td rowspan="5" colspan="19">F_{c_CH}, F_{b_CH}</td></tr>
<tr><td>EURO-IV</td></tr>
<tr><td>EURO-V</td></tr>
<tr><td>EURO-VI</td></tr>
<tr><td>Fleet average</td></tr>
<tr><td rowspan="3">Diesel hybrid</td><td>EURO-V</td><td rowspan="2" colspan="18">F_{g_CH}, F_{g_EU}</td><td rowspan="2"></td></tr>
<tr><td>EURO-VI</td></tr>
<tr><td>Fleet average</td><td rowspan="3" colspan="19"></td></tr>
<tr><td rowspan="2">Gasoline plug-in hybrid</td><td>EURO-VI</td></tr>
<tr><td>Fleet average</td></tr>
<tr><td rowspan="2">Diesel plug-in hybrid</td><td>EURO-VI</td><td colspan="18">$F_{d\_CH} + E_{mix}$, $F_{d\_CH} + E_{cert}$, $F_{d\_EU} + E_{mix\_EU}$</td><td></td></tr>
<tr><td>Fleet average</td><td colspan="19"></td></tr>
<tr><td>Battery electric
Continuous charge
(200 kW)
Type 3 chargers</td><td>EURO-VI/2020</td><td colspan="12">E_{mix}, E_{cert}, B_{NMC}, B_{NCA}, B_{LFP}</td><td colspan="7"></td></tr>
<tr><td rowspan="2">Fuel cell electric</td><td>EURO-VI/2020</td><td colspan="18">H_{elec_CH}, $H_{elec\_cert\_CH}$, H_{SMR}</td><td></td></tr>
<tr><td>Fleet average</td><td colspan="19"></td></tr>
</table>

The vehicle specifications and corresponding inventories supplied with this report are available for different LCI databases and software and are accessible via the following Data Object Identfier (DIO): https://doi.org/10.5281/zenodo.5156043.

Table of contents

I. Introduction

A. Goal and scope

This report aims to document all the energy and material resource inputs and associated output emissions that relate to the relevant life cycle phases of current on-road passenger and freight transportation services into a dataset-like structure to be further used for Life Cycle Assessment (LCA).

The resulting Life Cycle Inventories (LCI) have a Cradle-to-Grave scope. They encompass the following phases of the life cycle of the transportation service:

- the manufacture of the vehicle,
- its use and maintenance, including the supply of fuel,
- the construction and maintenance of the road and related infrastructure,
- as well as the disposal of the vehicle, its dismantling, and the treatment of its components.

1. Functional unit

One vehicle-kilometer is the functional unit used for individual means of transport (i.e., kick scooters, bicycles, scooters, motorbikes, and cars). The functional unit used for collective means of transport (i.e., urban and coach buses) is **one person-kilometer**.
The functional unit used for transporting goods (i.e., delivery, medium- and heavy-duty trucks) is **one ton-kilometer**.

In all instances, the functional unit of the vehicle performing the transportation service is **one vehicle unit**.

2. System boundaries

System boundaries generally encompass the following:

- the extraction and transformation of energy and materials needed for the vehicle components manufacture and assembly. This includes the potential environmental benefits of using materials with certain recycled content (e.g., steel, aluminum, plastics, etc.).
- the use and maintenance of the vehicle, including the entire energy chain,
- the construction and maintenance of the road and related infrastructure,
- and the vehicle dismantling and supply of material fractions to different waste treatment routes. Some waste treatment routes may include recycling processes for which the associated environmental load is considered (e.g., battery recycling and metal recovery via pyro-metallurgical treatment). However, the benefits of material recycling (i.e., primary production avoidance) are not considered.

B. Data sources and quality

Data sources for the different vehicles differ. Table 6 presents an overview of the various data sources used.

Table 6 Overview of data sources

	Vehicle components	Vehicle design and sizing	Energy chain	Fuel economy	Exhaust emissions	Non-exhaust emissions	Use-related parameters	Disposal
Two-wheelers	(Brian Cox et al. 2020)		UVEK:2018/ecoinvent	(spritmonitor.de 2021)	(European Environment Agency 2019)		(Brian Cox et al. 2020)	UVEK:2018/ecoinvent
Passenger cars	(B. Cox et al. 2020; R Sacchi et al., n.d.)		UVEK:2018/ecoinvent	(European Commission 2021)	(Notter, Keller, and Cox 2019; European Environment Agency 2019)	(European Environment Agency 2019)	(B. Cox et al. 2020; R Sacchi et al., n.d.)	
Urban and coach buses	(Romain Sacchi 2021)			(European Commission 2018)			(BAFU 2020; Brian Cox et al. 2020; ASTRA 2021)	
Medium and heavy-duty trucks	(Romain Sacchi, Bauer, and Cox 2021; Wolff et al. 2020)						Swiss Federal Statistical Office (SFO 2021b)	

For all other purposes, the data source is the life cycle inventory database the vehicle models link to (i.e., UVEK:2018 or ecoinvent 3.6/3.7.1/3.8 cut-off). Additional data sources, such as vehicle manufacturer specifications, are used for validation.

<u>Important remark</u>: fuel consumption values are based on *reported data* by vehicle owners for two-wheelers. They are *modeled* for the other vehicles and then validated with the EEA's database Monitoring of CO_2 emissions for passenger cars and the European Commission's software VECTO for buses and trucks.

Table *7* lists some of this study's most critical assumptions or limitations.

Table 7 Summary of potentially critical model limitations or data quality issues

	Use-related	**Vehicle Model**	**Inventory**	**Database**
Two-wheelers	* The driving pattern (urban, rural, motorway) associated with the reported energy use values is unknown. This limits how well exhaust and on-exhaust emissions are distributed over air compartments of different population densities. * The sample for electric scooters and motorbikes used to calculate energy use values is relatively small compared to gasoline scooters and motorbikes. * No data could be found to estimate the lifetime of electric	* Based on manufacturers' documentation, it is assumed that electric kick-scooters do not need to replace the battery over their lifetime. But the clear proof of that is lacking.	* ICE and EV motorbikes are modeled using a dataset for scooters	* UVEK:2018 does not list any datatsets to approximate the production of *nickel sulfate* and *manganese sulfate* for the electroplating of battery cathodes. Hence, inputs of nickel and manganese ores are used instead to the extent that matches the GWP intensity of *nickel*

	scooters and motorbikes. Hence, the values used for their gasoline counterparts are used.			*sulfate* and *manganese sulfate* production.
Passenger cars	* Energy consumption is calibrated against the EU database using the WLTP test cycle. Real-driving energy use can be 14% higher, according to (Dornoff, Tietge, and Mock 2020). * The electric utility factor for plugin hybrid vehicles is an observed average, and deviation from the norm can significantly alter results. A plugin hybrid vehicle with an electric utility factor of 0% is provided for sensitivity purposes.	* Some studies, including some based on experiments, report battery cycle lives for different chemistries. However, empirical data is missing. A correction factor of +50% is applied to the documented battery cycle life values to be consistent with what is broadly reported regarding battery replacement over the vehicle's lifetime.	* Dataset for the vehicle glider is from 2006 and does not reflect the current use of lightweight materials. The use and nature of lightweight materials used to reduce the glider's mass are modeled separately.	
Buses	* Energy use is modeled using VECTO driving cycles, further validated against HBEFA 4.1. Real-driving energy use may differ as the driving pattern may vary from what is considered in VECTO's driving cycles. * Occupancy rates are critical to collective means of transport results, and it is difficult to find a good source for those. Hence, current values used in Mobitool are re-used and adapted to new size classes. * The number of buses used per charging station is uncertain. However, we do not think this could critically change results. * The share of the trolley bus route equipped with overhead lines can differ across cities or itineraries, which can significantly increase the required onboard energy storage capacity.	* Battery electric and fuel cell buses are still yet to deploy in Europe, which means that energy use data is limited. We rely on modeling the drivetrain efficiency, calculate the energy use based on a VECTO driving cycle, and validate it against a few values from HBEFA 4.1. Hence, actual driving values may differ. * Some studies, including some based on experiments, report battery cycle lives for different chemistries. However, empirical data is missing. A correction factor of +50% is applied to the documented battery cycle life values to be consistent with what is broadly reported regarding battery replacement over the vehicle's lifetime.	* Inventories for fast and ultra-fast chargers are difficult to find. An old set of inventories for a public fast-charger has been re-scaled to match current ABB models.	
Trucks	* Energy use is modeled using VECTO driving cycles, further validated against HBEFA 4.1. Real-driving energy use may differ as the driving pattern may vary from what is considered in VECTO's driving cycles. * The required range autonomy values of 150, 400, and 800 km for urban, regional, and long-haul use have been chosen arbitrarily. Other values lead to resizing battery electric buses' onboard energy storage capacity. * Load factors (cargo mass) are critical to the performance of trucks. For Swiss trucks, the cargo mass cannot be distinguished across use types (i.e., urban delivery, long haul). This can introduce some	* Battery electric and fuel cell trucks are still yet to deploy in Europe, which means that energy use data is limited. We rely on modeling the drivetrain efficiency, calculate the energy use based on a VECTO driving cycle, and validate it against values claimed by manufacturers. Hence, actual driving values may differ. * The electric utility factor for plugin hybrid trucks relies on the specifications of the only commercial model available today. Hence, future models may lead	* Inventories for fast and ultra-fast chargers are difficult to find. An old set of inventories for a public fast-charger has been re-scaled to match current ABB models.	

	errors, as trucks may have different average load factors depending on the usage. For European trucks, the cargo mass is from the EU road survey data TRACCS (Papadimitriou et al. 2013). It is further corrected to reflect different usage types using numbers from the EU regulation on calculating the CO_2 emissions of trucks (European Commission 2020). Overall, both Swiss and European average load factors should be considered uncertain. Any significant deviation from these values will affect the results.	to reconsider this electric utility factor. * Some studies, including some based on experiments, report battery cycle lives for different chemistries. However, empirical data is missing. A correction factor of +50% is applied to the documented battery cycle life values to be consistent with what is broadly reported regarding battery replacement over the vehicle's lifetime.		

C. General information

1. Overview

This section briefly describes common assumptions and modeling approaches to all vehicle types.

2. Road demand

The demand for the construction and maintenance of road and road-related infrastructure is calculated on the following basis:

- Road construction: 5.37e-7 meter-year per kg of vehicle driving mass per km
- Road maintenance: 1.29e-3 meter-year per km, regardless of the vehicle mass

The driving mass of the vehicle consists of the mass of the vehicle in working order (including fuel) in addition to the mass of the passengers and cargo if any. In all instances, the mass of the passenger is 75 kilograms.

The demand rates used to calculate the required amounts for road construction and maintenance (based on vehicle driving mass per km and km, respectively) are obtained from (Spielmann and Scholz 2005).

Because roads are maintained by removing older surface layers than discarded, the disposal of road infrastructure is modeled in ecoinvent as a renewal rate over the year within the road construction dataset. In UVEK, the removal of the road (i.e., the excavation of the surface layer) is modeled separately. It is to note that no requirement for road maintenance is considered for kick-scooters and bicycles because of the negligible effect of their mass on the infrastructure.

3. Fuel properties

For all vehicles with an internal combustion engine, carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions are calculated based on the vehicle's fuel consumption and the carbon and sulfur concentration of the fuel observed in Switzerland and Europe. Sulfur concentration values are sourced from HBEFA 4.1 (Notter, Keller, and Cox 2019). Lower heating values and CO_2 emission factors for fuels are sourced from p.86 and p.103 of (Swiss Federal Office for the Environment 2021). The fuel properties shown in Table 8 are used for fuels purchased in Switzerland.

Table 8 Fuels characteristics

	Volumetric mass density [kg/l]	Lower heating value [MJ/kg]	CO_2 emission factor [kg CO_2/kg]	SO_2 emission factor [kg SO_2/kg]
Gasoline	0.737 (Bundesamt für Umwelt BAFU 2019)	42.6	3.14	1.6e-5
Bioethanol	0.785 (Muhaji and Sutjahjo 2018)	26.5	1.96	1.6e-5
Diesel	0.83 (Bundesamt für Umwelt BAFU 2019)	43	3.15	8.85e-4
Biodiesel	0.88 (Guo, Yang, and Gao 2016)	38	2.79	8.85e-4
Natural gas		47.5	2.68	
Bio-methane		47.5	2.68	

Because significant variations are observed in terms of sulfur concentration in biofuels, similar values to that of conventional fuels are used.

In addition, it is assumed that the physical and energetic properties of gasoline prepared for a 2-stroke engine (with a typical fuel-to-oil ratio of 1:32) are similar to that of regular gasoline. Finally, biofuel use in the gasoline blend (i.e., bioethanol) for 2-stroke engines is not considered because of the immiscibility of ethanol and oil (leading to lubrication issues).

4. Exhaust emissions

Emissions of regulated and non-regulated substances during driving are approximated using emission factors from HBEFA 4.1 (Notter, Keller, and Cox 2019). An exception to this is for two-wheelers, where emission factors from EEA/EMEP’s Air Pollutant Emission Inventory Guidebook 2019 (European Environment Agency 2019) – section 1.A.3.b.iv – are used instead. Emission factors are typically given in grams per km. Emission factors representing free-flowing driving conditions and urban and rural traffic situations are used for two-wheelers and passenger cars. For buses and trucks, emission factors of traffic situations specific to the vehicle application are used (e.g., emission factors for urban traffic situations for urban buses).

Also, for passenger cars, cold start emissions and running, evaporation, and diurnal losses are accounted for, sourced from HBEFA 4.1 (Notter, Keller, and Cox 2019).

For vehicles with an internal combustion engine, its use in Switzerland and Europe will be associated with a slightly different fuel quality. More specifically, the sulfur concentration values in the fuel can slightly differ across regions – although this remains somewhat limited within Europe. The values provided by HBEFA 4.1 and specified in Table 9 are used for Switzerland and Europe. The sulfur concentration values for France and Germany are used as an approximation for Europe.

Table 9 Sulfur concentration values for on-road fuel in Switzerland and Europe

Sulfur [ppm/fuel wt.]	**Switzerland**	**Europe**
Gasoline	8	8
Diesel	10	8

Additionally, the average fuel blends specified in Table 10 are considered. Switzerland, they are based on internal communications with the Swiss Federal Office for Environment and represent the situation in 2020. For Europe, they are sourced from the IEA's Extended World Energy Balances database (International Energy Agency (IEA) 2021). The biofuel used is produced from biomass residues (i.e., second-generation fuel): fermentation of whey and wood residues for bioethanol (50-50%), esterification of used vegetable oil for biodiesel and anaerobic digestion of sewage sludge for bio-methane.

Table 10 Specification of fuel blends for Switzerland and Europe

Biofuel share [% wt.]	**Switzerland**	**Europe**
Gasoline blend	2.6	4
Diesel blend	5.9	6
Compressed gas blend	27.3	9

a) NMVOC speciation

After NMVOC emissions are quantified, EEA/EMEP's 2019 Air Pollutant Emission Inventory Guidebook provides factors to further specify some of them into the substances listed in Table 11.

Table 11 NMVOC sub-species as fractions of the mass emitted

	All gasoline vehicles	**All diesel vehicles, except trucks and buses**	**Trucks and buses (diesel)**
	Wt. % of NMVOC	*Wt. % of NMVOC*	*Wt. % of NMVOC*
Ethane	3.2	0.33	0.03
Propane	0.7	0.11	0.10
Butane	5.2	0.11	0.15
Pentane	2.2	0.04	0.06
Hexane	1.6	0	0.00

Cyclohexane	1.1	0.65	0.00
Heptane	0.7	0.2	0.30
Ethene	7.3	10.97	0.00
Propene	3.8	3.6	0.00
1-Pentene	0.1	0	0.00
Toluene	11	0.69	0.01
m-Xylene	5.4	0.61	0.98
o-Xylene	2.3	0.27	0.40
Formaldehyde	1.7	12	8.40
Acetaldehyde	0.8	6.47	4.57
Benzaldehyde	0.2	0.86	1.37
Acetone	0.6	2.94	0.00
Methyl ethyl ketone	0.1	1.2	0.00
Acrolein	0.2	3.58	1.77
Styrene	1	0.37	0.56
NMVOC, unspecified	50.8	55	81.3

5. Non-exhaust emissions

Several emission sources besides exhaust emissions are considered. They are described in the following sub-sections.

a) Engine wear emissions

Metals and other substances are emitted during fuel combustion because of engine wear. These emissions are scaled based on fuel consumption, using the emission factors listed in Table 12, sourced from (European Environment Agency 2019).

Table 12 Emission factors for engine wear as fractions of the fuel mass combusted

	All gasoline vehicles	**All diesel vehicles, except trucks and buses**	**Trucks and buses (diesel)**
	kg/MJ fuel	*kg/MJ fuel*	*kg/MJ fuel*
PAH	8.19E-10	1.32E-09	1.82E-09
Arsenic	7.06E-12	2.33E-12	2.33E-12
Selenium	4.71E-12	2.33E-12	2.33E-12
Zinc	5.08E-08	4.05E-08	4.05E-08
Copper	9.88E-10	4.93E-10	4.93E-10
Nickel	3.06E-10	2.05E-10	2.05E-10
Chromium	3.76E-10	6.98E-10	6.98E-10
Chromium VI	7.53E-13	1.40E-12	1.40E-12

	All gasoline vehicles	All diesel vehicles, except trucks and buses	Trucks and buses (diesel)
Mercury	2.05E-10	1.23E-10	1.23E-10
Cadmium	2.54E-10	2.02E-10	2.02E-10

b) Abrasion emissions

We distinguish four types of abrasion emissions besides engine wear emissions:

1. brake wear emissions: from the wearing out of brake drums, discs, and pads
2. tires wear emissions: from the wearing out of rubber tires on the asphalt
3. road wear emissions: from the wearing out of the road pavement
4. and re-suspended road dust: dust on the road surface that is re-suspended due to passing traffic “due either to shear forces at the tire/road surface interface, or air turbulence in the wake of a moving vehicle” (Beddows and Harrison 2021).

(Beddows and Harrison 2021) provides an approach for estimating the mass and extent of these abrasion emissions. They propose to disaggregate the abrasion emission factors presented in the EMEP’s 2019 Emission inventory guidebook (European Environment Agency 2019) for two-wheelers, passenger cars, buses, and heavy good vehicles, to re-quantify them as a function of vehicle mass, but also traffic situations (urban, rural and motorway). Additionally, they present an approach to calculate re-suspended road dust according to the method shown in (US EPA 2011) – such factors are not present in the EMEP’s 2019 Emission inventory guidebook – using representative values for dust load on European roads.

The equation to calculate brake, tire, road, and re-suspended road dust emissions is the following:

$$EF = b.W^{\frac{1}{c}}$$

With:

- *EF* being the emission factor, in mg per vehicle-kilometer
- *W* being the vehicle mass, in tons
- *b* and *c* being regression coefficients, whose values are presented in Table 13.

Table 13 Regression coefficients to estimate abrasion emissions

	Tire wear						Brake wear						Road wear		Re-suspended road dust	
	Urban		Rural		Motorway		Urban		Rural		Motorway					
	b	c	b	c	b	c	b	c	b	c	b	c	b	c	b	c
PM 10	5.8	2.3	4.5	2.3	3.8	2.3	4.2	1.9	1.8	1.5	0.4	1.3	2.8	1.5	2	1.1
PM 2.5	8.2	2.3	6.4	2.3	5.5	2.3	11	1.9	4.5	1.5	1	1.3	5.1	1.5	8.2	1.1

The respective brake and tire wear emissions in urban, rural, and motorway driving conditions are weighted to represent the driving cycle used. The weight coefficients sum to 1, and the coefficients considered are presented in Table *14*. They have been calculated by analyzing the speed profile of each driving cycle, except for two-wheelers, for which no driving cycle is used (i.e., the energy consumption is from reported values) and where simple assumptions are made instead.

Table 14 Weighting coefficients to calculate representative abrasion emissions given a type of use/driving cycle

	Driving cycle	Urban	Rural	Motorway
Bicycle	Reported energy consumption – no specific driving cycle used.	1		
Scooter		0.5	0.5	
Motorbike <11kW		0.5	0.5	
Motorbike >11kW		0.33	0.33	0.33
Passenger car	WLTP	0.33	0.24	0.43
Truck, urban delivery	Urban delivery	1		
Truck, regional delivery	Regional delivery	0.16	0.32	0.52
Truck, long haul	Long haul			1
Urban bus	Urban	1		
Coach bus	Intercity	0.27		0.73

Finally, for electric and (plugin) hybrid vehicles (except for two-wheelers), brake wear emissions are reduced. This reduction is calculated as the ratio between the sum of energy recuperated by the regenerative braking system and the sum of negative resistance along the driving cycle. The logic is that the amount of negative resistance the regenerative braking system could not meet must be completed with mechanical brakes. This is illustrated in Figure *1*, where the distance between the recuperated energy and the total negative motive energy corresponds to the amount of energy that needs to be provided by mechanical brakes. Table *15* lists such reduction actors for the different vehicles of this study.

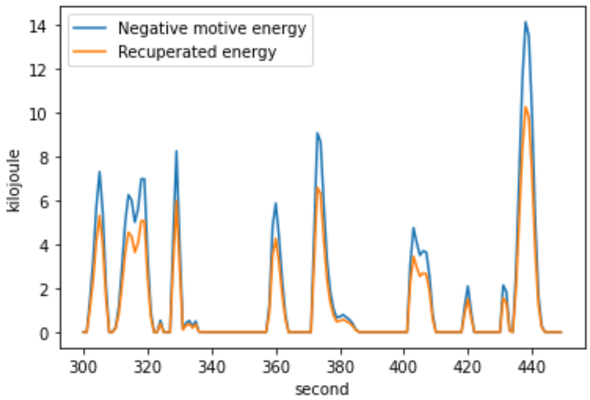


Figure 1 Negative motive energy and recuperated energy between the second 300 and 450 of the WLTC driving cycle.

Table 15 Approximate reduction factors for brake wear emissions. Values differ slightly across size classes.

	Driving cycle	Reduction factor for hybrid vehicles	Reduction factor for plugin hybrid vehicles	Reduction factor for battery and fuel cell electric vehicles
Passenger car	WLTP	-72%	-73%	-76%
Truck, urban delivery	Urban delivery	-20%	-82%	-82%
Truck, regional delivery	Regional delivery	-24%	-82%	-83%
Urban bus	Urban	-22%		-85%

The sum of PM 2.5 and PM 10 emissions is used as the input for the UVEK:2018/ecoinvent v.3.x LCI datasets indicated in Table *16*. For convenience, the datasets for abrasion emissions of passenger cars in UVEK:2018/ecoinvent v.3.x are also used for two-wheelers to approximate the composition of these emissions – not the quantity emitted. The same applies to buses: we use datasets meant initially for trucks.

Table 16 LCI datasets used to approximate PM emissions composition and emissions to air, soil, and water.

<table>
<tr><th></th><th>Tire wear</th><th>Brake wear</th><th>Road wear</th><th>Re-suspended road dust</th></tr>
<tr><td>Two-wheeler</td><td rowspan="2">Tire wear emissions, passenger car</td><td rowspan="2">Brake wear emissions, passenger car</td><td rowspan="2" colspan="2">Road wear emissions, passenger car</td></tr>
<tr><td>Passenger car</td></tr>
<tr><td>Truck</td><td rowspan="2">Tire wear emissions, lorry</td><td rowspan="2">Brake wear emissions, lorry</td><td rowspan="2" colspan="2">Road wear emissions, lorry</td></tr>
<tr><td>Bus</td></tr>
</table>

Finally, we assume that the composition of the re-suspended road dust is evenly distributed between brake, road, and tire wear particles.

c) Refrigerant emissions

The use of HFC refrigerant for onboard air conditioning systems is considered for passenger cars, trucks, and buses until 2017(FOEN 2022). The supply of refrigerant gas R134a is accounted for until 2017, replaced by CO_2 afterward (i.e., as a proxy for the new refrigerant HFO-12324yf, which has a similar global warming potential of approximately 1). Similarly, the leakage of the refrigerant is also considered. For this, the calculations from (Stolz, Messmer, and Frischknecht 2016) are used. Such emission is included in the transportation dataset of the corresponding vehicle. The overall supply of refrigerant amounts to the initial charge plus the amount leaked throughout the vehicle's lifetime, both listed in Table 17.

Table 17 Use and loss of refrigerant gas for onboard air conditioning systems

	Passenger cars (except Micro)	Buses	Trucks
Initial charge [kg per vehicle lifetime]	0.55	7.5	1.1
Lifetime loss [kg per vehicle lifetime]	0.75	16	0.94

Important assumption: it is assumed that electric and plugin electric vehicles also use a compressor-like belt-driven air conditioning system, relying on refrigerant gas. An increasing, but still minor, share of electric vehicles now use a (reversible) heat pump to provide cooling.

Important remark: Microcars do not have an air conditioning system. Hence, no supply or leakage of refrigerant is considered for those.

d) Noise emissions

Noise emissions are represented in two different ways. The implementation presented in (Stolz, Messmer, and Frischknecht 2016) and already implemented in UVEK:2018 is considered, where average noise emission factors per vehicle-kilometer (i.e., dB(A) per km) are included as natural output flows in the transport activity dataset, and normalized by the load if needed. The Ecological Scarcity 2013/2021 impact assessment method can characterize those noise emission factors described in Table 18. Only the Simapro implementation of the Ecological Scarcity 2013 impact assessment method has characterization factors for noise emissions.

Table 18 Noise emission factors as implemented for UVEK:2018 datasets. UF = electric utility factor (share of the distance driven in battery-depleting mode).

	Noise emission factor [dB(A)/km]	Comment
Bicycle, conventional		
Bicycle, electric		
Scooter, gasoline	2	Previously implemented
Scooter, electric	0.5	Newly added in this study
Motorbike, gasoline	2	
Motorbike, electric	0.5	
Passenger car, with internal combustion engine	1	Previously implemented
Passenger car, with electric motor	0.5	
Passenger car, plugin hybrid	(0.5 * UF) + /1 * UF)	
Truck, with internal combustion engine	1 / cargo mass [t]	
Truck, with electric motor	0.5 / cargo mass [t]	Newly added in this study
Truck, plugin hybrid	(1 * 1 – (UF)) + (0.5 * UF) / cargo mass [t]	
Bus, with internal combustion engine	1 / passengers [unit]	
Bus, with electric motor	0.5 / passengers [unit]	

Noise emissions along the driving cycle of the vehicle are also quantified using the method developed within the CNOSSOS project (Stylianos Kephalopoulos, Marco Paviotti 2012), which are expressed in joules for each of the 8 octaves. The mid-and endpoint impact assessment methods presented in (Cucurachi et al. 2019) can be used to characterize these emissions into Pascal.person per second and DALY, respectively.

6. Electric energy storage

Battery electric vehicles can use different battery chemistries (Li-ion NMC, Li-ion LFP, Li-ion NCA, and Li-LTO) depending on the manufacturer’s preference or the location of the battery supplier. Unless specified otherwise, all battery types are produced in China. Several sources, among which BloombergNEF (Veronika Henze 2020), indicate that more than 75% of the world’s cell capacity is manufactured there.

Accordingly, the electricity mix used for battery cell manufacture and drying, and the provision of heat is assumed to represent the country (i.e., the corresponding providers are selected from the LCI background database).

The battery-related parameters considered in this study are shown in Table 19. For LFP batteries, “blade battery” or “cell-to-pack” battery configurations are considered, as introduced by CATL (Xinhua 2019) and BYD (Mark 2020), two major LFP battery suppliers in Asia. This dramatically increases the cell-to-pack ratio and the gravimetric energy density at the pack level.

Overall, the gravimetric energy density values at the cell and system levels in Table 19 are considered conservative. Some manufacturers perform significantly better than the average, and these values tend to change rapidly over time, as it is the focus of much R&D.

Table 19 Specifications for the different battery types

	Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) — NMC[1]	Lithium Iron Phosphate($LiFePO_4$) — LFP	Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) — NCA	Lithium Titanate (Li_2TiO_3) — LTO	Source
Cell energy density [kWh/kg]	0.2	0.15	0.23	0.07	(BatteryUniversity 2021)
Cell-to-pack ratio	0.6	0.8	0.6	0.6	(Yang, Liu, and Wang 2021)
Pack-level gravimetric energy density [kWh/kg]	0.12	0.12	0.14	0.04	Calculated from the two rows above
Cell manufacture energy [kWh/kg]	8				(Dai et al. 2019; B. Cox et al. 2020)
of which electricity [kWh/kg]	4				
Share of cell mass in battery system [%]	70% (two-wheelers), 60 to 80% (others, depending on the chemistry, see third row above)				(B. Cox et al. 2020; Yang, Liu, and Wang 2021)
Maximum state of charge [%]	100%	100%	100%	90%	(Göhlich et al. 2018; BatteryUniversity 2021)
Minimum state of charge [%]	20%	20%	20%	40%	
Cycle life to reach 20% initial capacity loss (80%-20% SoC charge cycle)	2’000	7’000+	1’000	5,000-7,000	(Preger et al. 2020)
Corrected cycle life	3’000	7’000	1’500	7’000	Assumption
Charge efficiency	85% for passenger cars, 88% for buses and trucks for slow and fast charging, and 76.5% for buses for ultra-fast charging. For two-wheelers, we do not explicitly model the vehicle's energy consumption: the battery charge efficiency is not needed as the reported electricity consumption is used directly (it includes already losses related to battery charge).				(B. Cox et al. 2020; Brian Cox et al. 2020) for two-wheelers and passenger cars. (Schwertner and Weidmann 2016) for buses and trucks. (Rantik 1999) for battery charge efficiency when ultra-fast charging.
Discharge efficiency	88% for passenger cars, buses, and trucks. For two-wheelers, the battery discharge efficiency is not needed as the reported electricity consumption is used directly (it includes already losses related to battery discharge).				(B. Cox et al. 2020; Schwertner and Weidmann 2016)

On account of that:

- the battery cycle life values were obtained in the context of an experiment (Preger et al. 2020),

[1] The NMC battery cell used here corresponds to a so-called NMC 6-2-2 chemistry: it exhibits three times the mass amount of Ni compared to Mn, and Co, while Mn and Co are present in equal amount. Development aims at reduing the content of Cobalt and increasing the Nickel share.

- with a loss of 20% of the initial capacity, the battery may still provide enough energy to complete the intended route.
- batteries meant to equip buses and trucks are likely to be fitted with better onboard battery management systems to preserve their service life,

cycle life values for NMC and NCA battery chemistries are corrected by +50%.

For all vehicles with limited mileage (i.e., two-wheelers, passenger cars), the number of battery replacements is based on what is being observed today and considered (Brian Cox et al. 2020). It is noted that the energy consumption values for kick-scooters and bicycles used in (Brian Cox et al. 2020) are based on manufacturers' data and are lower than those used in this study. Nevertheless, the additional charge cycles associated with this higher energy consumption should not lead to a battery replacement.

For buses and trucks, for which the mileage varies across size classes and application types, the number of battery replacements is calculated based on the required number of charge cycles (which is itself conditioned by the battery capacity and the total mileage over the lifetime), in relation with the cycle life of the battery (which differs across chemistries – see Table 19). Li-LTO batteries are limited to opportunity- and in-motion charging electric buses.

Important assumption: The environmental burden associated with spare manufacturing batteries is entirely allocated to vehicle use, and the number of battery replacements is rounded up.

Beyond the chemistry-specific resistance to degradation induced by charge-discharge cycles, the calendar aging of the cells for batteries that equip buses and trucks is also considered. Regardless of the charging type, there is a minimum of one replacement of the battery during the vehicle's lifetime.

Table 20 gives an overview of the number of battery replacements assumed for the different electric vehicles in this study.

Table 20 Number of battery replacements assumed or calculated for each vehicle type

	NMC	LFP	NCA	LTO
Kick-scooter, electric	0	0	0	
Bicycle, electric	1	1	1	
Scooter, electric	1	1	1	
Motorbike, electric	1	1	1	
Passenger car, electric	0	0	0	
Bus, opportunity charging				1
Bus, motion charging				1-2
Bus, depot charging	1	1	2	
Medium/heavy duty truck, urban delivery	1	1	1	

Medium/heavy duty truck, regional delivery	1	1	1	

7. Fuel cell stack

All fuel cell electric vehicles use a proton exchange membrane (PEM)-based fuel cell system.

Table 21 lists the specifications of the fuel cell stack and system used in this study. The durability of the fuel cell stack, expressed in hours, is used to determine the number of replacements needed – the expected kilometric lifetime and the average speed specified by the driving cycle give the number of hours of operation. The environmental burden associated with manufacturing spare fuel cell systems is entirely allocated to vehicle use, as no reuse channels seem to be implemented for fuel cell stacks.

Table 21 Specifications for fuel cell stack systems

	Passenger cars	Buses and trucks	Source
Power [kW]	65 - 140	30 - 140	Calculated.
Fuel cell stack efficiency [%]	55-58%		(B. Cox et al. 2020)
Fuel cell stack own consumption [% of kW output]	15%		
Fuel cell system efficiency [%]	45-50%		
Power density [W/cm2 cell]	0.9	0.45	For passenger cars, (Simons and Bauer 2015). For trucks and buses, the power density is assumed to be half that of passenger cars to reflect increased durability.
Specific mass [kg cell/W]	0.51	1.02	
Platinum loading [mg/cm2]	0.13		
Fuel cell stack durability [hours to reach 20% cell voltage degradation]	4’000	17’000	(Eudy and Post 2020; Kurtz et al. 2018)
Fuel cell stack lifetime replacements [unit]	1	0 - 2	Calculated.

8. Lightweight

The automotive industry has increasingly used lightweight materials to replace steel in engine blocks, chassis, wheel rims, and powertrain components (Ducker Frontier 2019). However, vehicle light-weighting has not reduced overall curb mass for passenger cars and trucks, as additional safety equipment compensates for it. According to (Mock 2017), passenger cars in the EU in 2016 were, on average, 10% heavier than in 2000, while light-duty vehicles were 10% heavier in the same period.

The dataset used to represent the chassis of passenger cars (i.e., “glider, for passenger car”) does not reflect today’s use of lightweight materials, such as aluminum and advanced high-strength steel (AHSS).

A report from the Steel Recycling Institute (Sebastian and Thimons 2017) indicates that every kilogram of steel in a car glider can be substituted by 0.75kilogramsm of AHSS or 0.68kilogramsm of aluminum. Looking at the material composition of different car models three years apart, (Hottle et al. 2017) show that steel is, in fact, increasingly replaced by a combination of both aluminum and AHSS. However, they also show that AHSS is generally preferred to aluminum as its mass reduction-to-cost ratio is preferable.

Hence, it is considered that, for a given mass reduction to reach, two-thirds of the mass reduction comes from using AHSS, and one-third comes from using aluminum. This means that one kilogram of mass reduction is achieved by replacing 3.57 kilograms of steel by:

- 1.76 kilogram of AHSS
- 0.8 kilogram of aluminium

Additionally, as Section III.B.2 explains, additional efforts are made to ensure that the final aluminum content in the chassis corresponds to what is found in current passenger car models, according to (Ducker Frontier 2019).

While ecoinvent v.3.7 and UVEK:2018 have an LCI dataset for the supply of aluminum, it is not the case for AHSS. However, an LCA report from the World Steel Insitute (World Steel Association 2015) indicates that AHSS has a similar carbon footprint to conventional primary low-alloyed steel from a basic oxygen furnace route (i.e., 2.3 kg CO2-eq./kg). We will therefore use traditional steel to represent the use of AHSS.

9. Migration to UVEK:2018

The life cycle inventories are generated initially to link to ecoinvent 3.6, 3.7.1, and 3.8 (Wernet et al. 2016). A mapping procedure is necessary to relink the inventories to UVEK:2018. Annex A of this report presents the correspondence table between ecoinvent 3.7.1 and UVEK:2018 datasets.

10. Supply chains and transport distances

In the absence of market datasets in the UVEK:2018 database, transport operations are added from the regional storage to the assembly plant, following the distances and means of transport indicated in Table 4.2 p. 13 of the ecoinvent v.2 report (Frischknecht et al. 2007).

Two-wheelers are assumed to be assembled in Asia. This study considers shipping the vehicles from the assembly plant (believed to be in China) to the Netherlands by container ship. A further distribution step between the Netherlands and Switzerland via road truck is also considered. This results in 15’900 km by ship and 1’000 km by truck.

Passenger cars, buses, and trucks are assumed to be produced in Europe, and the transport to market in such cases is neglected. However, for the batteries manufactured in China, their transport is accounted for (15’900 km by ship and 1’000 km by truck).

11. Vehicle specifications and datasets

Specifications for all the vehicles presented in this study and the corresponding LCI datasets are available using the following Data Object Identifier: https://doi.org/10.5281/zenodo.5156043.

II. Two-wheelers

A. Overview

The vehicles included in the two-wheelers category are:

- Kick scooters, electric
- Bicycles, conventional
- Bicycles, electric, with a top speed of 25 km/h
- Bicycles, electric, with a top speed of 45 km/h
- Bicycles, electric, cargo type
- Scooters, gasoline
- Scooters, electric
- Motorbikes, gasoline
- Motorbikes, electric

Some of these vehicles are defined across several power categories and powertrain types.

Table 22 Overview of vehicles included in the two-wheelers category.

	Gasoline	Electric	<1 kW	1-4 kW	4-11 kW	11-35 kW	> 35 kW
Kick scooters		X	X				
Electric bicycles (< 25 km/h)		X	X				
Electric bicycles (< 45 km/h)		X	X				
Electric bicycles, cargo		X	X				
Scooters	X	X		X	X		
Motorbikes	X	X			X	X	X

The power intervals chosen correspond roughly to the required driving license types in Europe and Switzerland. AM, A1, A2, and A-type driving licenses are required for vehicles with an engine power inferior to 4 kW (including scooters), between 4 and 11 kW, between 11 and 35 kW, and above 35 kW, respectively.

B. Modeling considerations applicable to all two-wheelers

- For all vehicles, the passenger mass is 75 kilograms.
- For all vehicles, the vehicle datasets use one vehicle unit as a functional unit, and the corresponding transport activity uses one vehicle-kilometer as a functional unit.

C. Modeling considerations applicable to internal combustion engine vehicles

Emission factors for CO_2 and SO_2 are detailed in Table 8-Table 9. Biofuel shares in the fuel blend are described in Table 10.

Several fuel-related emissions other than CO_2 and SO_2 are considered using the EMEP EEA's 2019 Air Pollutant Emissions Inventory Guidebook (European Environment Agency 2019).

Two sources of emissions are considered:

- Exhaust emissions: emissions from fuel combustion during operation, and their concentration relates to fuel consumption and the vehicle's emission standard.
- Other non-exhaust emissions: brake, tire, and road wear emissions, emissions of refrigerant, and noise.

Exhaust emissions per vehicle-kilometer for two-wheelers are summarized in Table 23.

Table 23 Exhaust emissions for two-wheelers, in grams per vehicle-kilometer

Gram/vehicle-kilometer	CO_2	CO_2, bio	SO_2	CH_4	CO	N_2O	NH_3	NO_x	$PM_{2.5}$	NMVOC
Scooter, gasoline, <4kW, EURO-3	101.692	0.000	0.001	0.038	4.022	0.002	0.002	0.145	0.011	0.676
Scooter, gasoline, <4kW, EURO-4	95.935	0.000	0.000	0.036	3.794	0.002	0.002	0.137	0.010	0.638
Scooter, gasoline, <4kW, EURO-5	94.976	0.000	0.000	0.036	3.756	0.002	0.002	0.135	0.010	0.632
Scooter, gasoline, 4-11kW, EURO-3	77.060	0.936	0.000	0.029	3.418	0.001	0.001	0.111	0.003	0.308
Scooter, gasoline, 4-11kW, EURO-4	76.297	0.927	0.000	0.029	3.384	0.001	0.001	0.110	0.003	0.305
Scooter, gasoline, 4-11kW, EURO-5	75.534	0.917	0.000	0.029	3.350	0.001	0.001	0.109	0.003	0.302
Motorbike, gasoline, 4-11kW, EURO-3	74.724	0.908	0.000	0.050	0.703	0.002	0.002	0.096	0.004	0.029
Motorbike, gasoline, 4-11kW, EURO-4	73.984	0.899	0.000	0.056	0.822	0.002	0.002	0.027	0.005	0.042
Motorbike, gasoline, 4-11kW, EURO-5	73.244	0.890	0.000	0.056	0.712	0.002	0.002	0.018	0.005	0.024
Motorbike, gasoline, 11-35kW, EURO-3	108.381	1.316	0.001	0.022	0.221	0.001	0.001	0.026	0.002	0.044
Motorbike, gasoline, 11-35kW, EURO-4	107.308	1.303	0.001	0.028	0.140	0.001	0.001	0.014	0.002	0.015
Motorbike, gasoline, 11-35kW, EURO-5	106.235	1.290	0.001	0.027	0.122	0.001	0.001	0.009	0.002	0.009
Motorbike, gasoline, >35kW, EURO-3	143.714	1.746	0.001	0.017	0.294	0.001	0.001	0.031	0.002	0.058
Motorbike, gasoline, >35kW, EURO-4	142.292	1.728	0.001	0.021	0.186	0.001	0.001	0.014	0.003	0.020
Motorbike, gasoline, >35kW, EURO-5	140.869	1.711	0.001	0.021	0.161	0.001	0.001	0.009	0.003	0.012

Figure 2 shows the calculated abrasion emissions for two-wheeled vehicles in mg per vehicle-kilometer, following the approach presented in Section I.C.5.b.

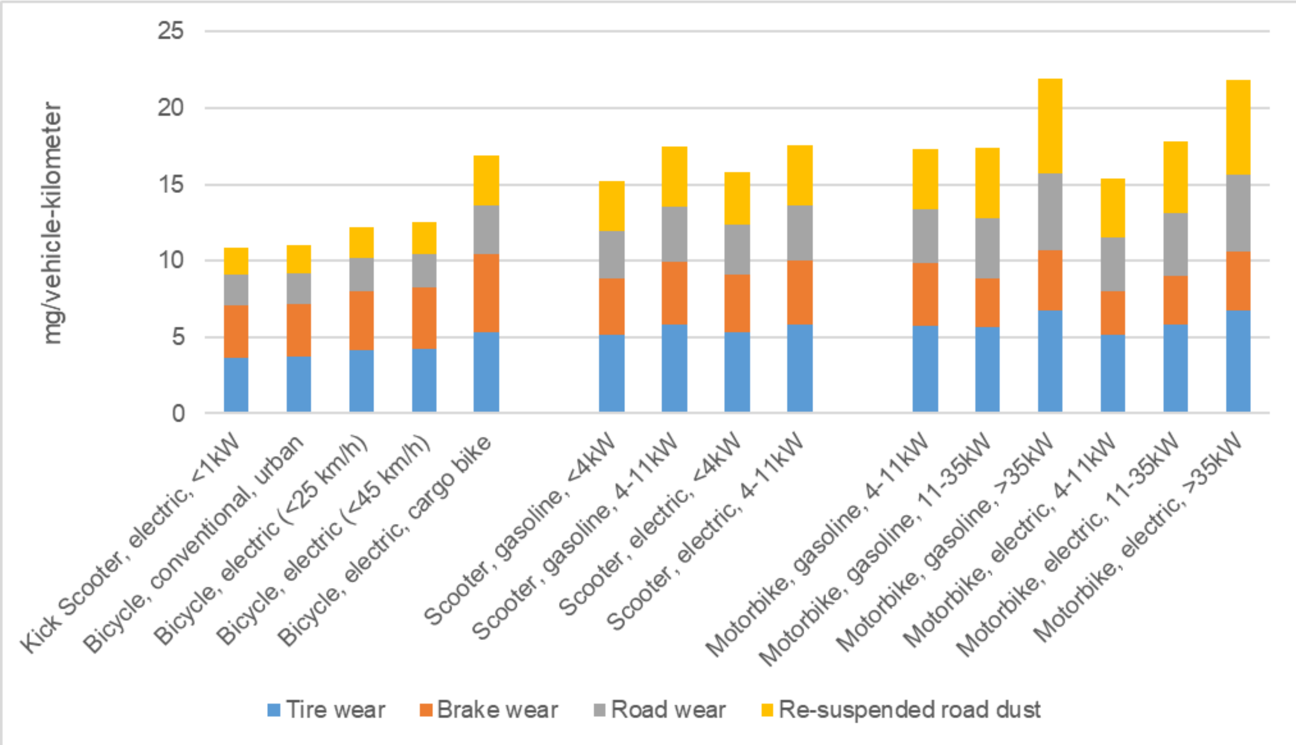


Figure 2 Total particulate matter emissions (<2.5 μm and 2.5-10 μm) in mg per vehicle-kilometer for two-wheeled vehicles.

D. Kick-scooters, electric

Illustrations of available models of electric kick-scooters considered in this study:


Ninebot Mini Pro by Segway


Mi Pro 2 by xiaomi

Specifications (i.e., curb mass, motor power, battery capacity) for commercially available electric kick-scooters are available in Annex B. Specifications used to represent an average kick-scooter are detailed in Table 24. Kick-scooter energy consumption values are not modeled but extracted from spritmonitor.de, where kick-scooter users have reported their electricity consumption.

The UVEK:2018/ecoinvent v.3 datasets for manufacturing a 17 kg heavy bicycle (Leuenberger and Frischknecht 2010a) is used as a proxy for the supply of the glider. The transport of the vehicle from the assembly plant to the intended market is included: 15’900 km by transoceanic container ship and 1’000 km by truck (with a fleet-average vehicle). No requirement for road maintenance is attributed to the vehicle due to its lightweight and small size, following the previous implementation in UVEK:2018/ecoinvent v.3 for bicycles.

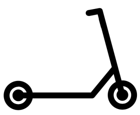
The dataset for the AC charger is based on the UVEK:2018/ecoinvent v.3 dataset “charger production, for electric scooter”. It has been scaled down to represent a power output of 100 Watts.

Important assumption: No maintenance operation (incl. parts replacement) or battery replacement is assumed throughout the vehicle's lifetime. The energy consumption values in Table 24 are about twice as high as those used in (Brian Cox et al. 2020), based on manufacturers’ claimed range autonomy and battery size. However, even with such values, the cumulated electricity required over the vehicle's lifetime is about 42 kWh. A usable battery capacity of 0.2 kWh represents a bit more than 210 charge cycles, which should not require a second battery. The absence of battery replacement differs from what is assumed in (Leuenberger and Frischknecht 2010b) and is currently implemented in (BAFU 2020), where one replacement is considered.

Important assumption: It is believed that the energy consumption values represent the consumption at the “wall plug” level, including charger loss and losses occurring at the battery level during charge. Suppose the energy use values reported by spritmonitor.de users are, in fact, at “battery level”. In that case, the electricity use values considered in this study are potentially underestimated by approximately 5% (i.e., battery charge losses).

Important remark: based on energy consumption values reported by users to spritmonitor.de, and considering a maximum depth of discharge of 80%, the range autonomy obtained is significantly different from what is claimed by manufacturers (i.e., 8 to 10 km calculated, as opposed to >20 km according to manufacturers – see Annex B).
Important remark: No requirement for road maintenance is attributed to the vehicle due to its lightweight, as previously considered for conventional and electric bicycles (Leuenberger and Frischknecht 2010b).

Table 24 Specifications for kick-scooters

	Kick Scooter, electric, <1kW - 2020	Comment	Source
Lifetime [km]	1’785	Lifetime, annual mileage, and energy consumption values were calculated from actual usage values reported to spritmonitor.de, based on a sample of 10 (8’945 km cumulated).	(spritmonitor.de 2021)
Annual kilometers [km]	890		
Energy consumption [MJ/km] (kWh/100 km)	0.086 (2.6)		
Passenger mass [kg]	75	Standard assumption.	
Cargo mass [kg]	0		

Curb mass [kg]	12[2]	Based on manufacturers' data.	Segway Ninebot, iWatt, Xiaomi
Driving mass [kg]	87[2]	Calculated.	
Power [kW]	0.25	Based on manufacturers' data.	Segway Ninebot, iWatt, Xiaomi
Electric energy stored [kWh]	0.25	Based on manufacturers' data.	
Range autonomy [km]	8-10	Calculated.	
Depth of discharge [%]	80%	Standard assumption to preserve battery lifetime.	Similar assumptions used by (Brian Cox et al. 2020)
Battery replacement [unit]	0	Standard assumption for this type of vehicle.	
Servicing per lifetime [unit]	0	Standard assumption for this type of vehicle.	

[2] Mass values considering a Li-NMC battery. Mass values will slightly change with Li-LFP and Li-NCA batteries due to a different cell energy density. Refer directly to the implemented dataset.

E. Bicycle, conventional

Examples of available models of urban bicycles considered in this study:

MINT model by CANDY

Commuter 5 by Canyon

Regarding the expected kilometric lifetime and annual mileage, the values from (Leuenberger and Frischknecht 2010b) are used. These values are used in Mobitool v.2.1 (BAFU 2020): 15’000 km over 15 years, giving an annual mileage of 1’000 km.

Datasets for conventional bicycle production present in UVEK:2018/ecoinvent v.3, initially from (Leuenberger and Frischknecht 2010b), are used. However, its use has been scaled down to fit the mass of current average bicycles (i.e., 12 kg, against 17 kg initially). The transport of the vehicle from the assembly plant to the intended market is included: 15’900 km by transoceanic container ship and 1’000 km by a fleet-average truck.

Specifications used to represent an average conventional bicycle are detailed in Table 25.

Table 25 Specifications for conventional bicycles

	Bicycle, conventional, urban - 2020	Comment	Source
Lifetime [km]	15’000	Standard assumption (1’000 km/year)	A similar assumption is used in (Leuenberger and Frischknecht 2010b) and is currently used in Mobitool v.2.1 (BAFU 2020)
Annual kilometers [km]	1’000		
Passenger mass [kg]	75	Standard assumption.	
Cargo mass [kg]	1	Standard assumption.	
Curb mass [kg]	12	Based on manufacturers’ data.	
Driving mass [kg]	88	Calculated.	
Servicing per lifetime [unit]	1	The original UVEK:2018/ecoinvent v.3 datasets for maintenance (Leuenberger and Frischknecht 2010b) is valid for the entire lifetime of the bicycle (which is 15’000 km). Note that despite a lighter weight (12 kg against 17 kg), we do not adjust the requirements for maintenance.	(lc-inventories 2018)

F. Bicycle, electric

Illustrations of available models of urban electric bicycles considered in this study:

Zouma Supreme+ S model by Diamant (max. 45 km/h)

Cult EVO model by Atala (max. 25 km/h)

Cargo Bike by RadWagon

Annual mileage values are collected from spritmonitor.de. They deviate by a factor of 2 to 3 from the yearly mileage values previously used in (Leuenberger and Frischknecht 2010b): 2’000, 3’000, and 2’000 kilometers per year for the slow (max. speed <25 km/h), fast (max. speed <45 km/h) and electric cargo bicycles respectively, against 1’000 km in the report from Leuenberger and Frischknecht.
In addition, electric bicycles are generally designed to have a longer kilometric lifetime comparatively to conventional bicycles, with an overall heavier chassis and reinforced tires. But the onboard electronics and battery management system cannot possibly last 15 years on average – as previously assumed in (Leuenberger and Frischknecht 2010b) – given such annual mileage. Hence, the calendar lifetime is reduced to 10 years to obtain a kilometric lifetime of 20’000 km, 30’000 km, and 20’000 km for the slow, fast, and cargo electric bicycles, respectively.

The frame and mechanical powertrain are modeled using an input from the UVEK:2018/ecoinvent dataset for electric bicycle production, from which the inputs for the electric motor and battery have been removed to size them separately. The input required from the electric bicycle production dataset is scaled on the driving mass minus the mass of the electric motor and battery, as this mass differs from what is initially considered in the dataset: 24 kg, against 23, 27, and 46 kg considered here for the slow, fast and cargo electric bicycles, respectively.

The transport of the vehicle from the assembly plant to the intended market is included: 15’900 km by ship and 1’000 km by truck. Abrasion emissions are scaled on the driving mass, but the datasets for abrasion emissions of passenger cars in UVEK:2018/ecoinvent are used to approximate their composition.

A 500W charger dataset has been created based on the UVEK:2018/ecoinvent dataset for an electric scooter charger, and it has been scaled down accordingly based on the power output. This follows the approach used by (Brian Cox et al. 2020).

The disposal of the bicycle is specified separately.

Important remark: No requirement for road maintenance is attributed to the vehicle due to its lightweight and small size, as previously considered in (Leuenberger and Frischknecht 2010b).

Important remark: based on energy consumption data reported to spritmonitor.de, and considering a maximum depth of discharge of 80%, range autonomy values are found to be twice to thrice as low as what is claimed by manufacturers (e.g., 32 km for 45 km/h electric bicycles, as opposed to >90 km according to manufacturers – see Annex A).

Specifications (i.e., curb mass, motor power, battery capacity, and range autonomy) for commercially available electric bicycles in Annex A. Specifications for electric bicycles considered in this study are presented in Table 26.

Table 26 Specifications for electric bicycles

	Bicycle, electric (<25 km/h) - 2020	Bicycle, electric (<45 km/h) - 2020	Bicycle, electric (cargo)	Comment	Source
Lifetime [km]	20’000	30’000	20’000	Annual mileage and energy consumption values calculated from actual usage values reported to spritmonitor.de, based on a sample of 69 for “slow” electric bicycles (350’000 km cumulated), 21 for “fast” electric bicycles (230’000 km cumulated) and 4 for electric cargo bikes (8,200 km cumulated). The lifetime has been estimated by multiplying the annual mileage by ten years	(spritmonitor.de 2021)
Annual kilometers [km]	2’000	3’000	2’000		
Energy consumption [MJ/km] (kWh/100 km)	0.025 (0.75)	0.045 (1.38)	0.035 (1.06)		
Passenger mass [kg]	75	75	75	Standard assumption.	
Cargo mass [kg]	1	1	50		
Curb mass [kg]	23[3]	27[2]	45[2]	Based on manufacturers’ data.	Cube, Haibike, Raleigh, Fischer
Driving mass [kg]	99[2]	103[2]	170	Calculated.	
Power [kW]	0.25	0.5	0.25	Based on manufacturers’ data.	Cube, Haibike, Raleigh, Fischer, Babboe
Electric energy stored [kWh]	0.5	0.5	0.5	Based on manufacturers’ data.	
Range autonomy [km]	60	32	40	Calculated.	
Depth of discharge [%]	80%	80%	80%	Standard assumption to preserve the battery lifetime.	Similar assumptions were used by (Brian Cox et al. 2020).
Battery replacement [unit]	1	1	1	Standard assumption for this type of vehicle.	

[3] Mass values considering a Li-NMC battery. Mass values will slightly change with Li-LFP and Li-NCA batteries due to a different cell energy density. Refer to the implemented dataset directly.

	Bicycle, electric (<25 km/h) - 2020	Bicycle, electric (<45 km/h) - 2020	Bicycle, electric (cargo)	Comment	Source
Servicing per lifetime [unit]	1.33	2	1.33	The original UVEK:2018/ecoinvent dataset for maintenance assumes a lifetime of 15’000km, yielding a factor superior to 1.	

G. Scooter, gasoline

Examples of available models of gasoline scooters considered in this study:

Vespa Primavera model by Piaggio (50 cm3, <4 kW)

PCX 125 model by Honda (125 cm3, 4-11 kW)

Fuel consumption values are extracted from spritmonitor.de over a cumulated mileage of 6.6 million vehicle-kilometers.

The national vehicle registry (MOFIS) from (ASTRA 2021) is used to obtain the age of gasoline scooters when discarded. The road transport survey data from TRACCS (Papadimitriou et al. 2013) for Switzerland in 2010 is used to get the annual mileage of mopeds/scooters. The values calculated are presented in Table 27.

Table 27 Kilometric and calendar lifetime values for gasoline scooters

	Age of decommissioning (i.e., calendar lifetime) [years]	**Cumulated mileage reached at the age of decommissioning (i.e., kilometric lifetime) [km]**
Source	MOFIS registry (ASTRA 2021)	TRACCS 2010 survey data for Switzerland (Papadimitriou et al. 2013)
Comment	Outliers have been removed (i.e., <5 years and >30 years). Corresponds to gasoline-fueled “kleinmotorrad” in the registry.	Annual mileage values for “Mopeds” and “2-s motorcycles”.
Sample size	14’520	
Scooter, gasoline, <4 kW	16	25’000
Scooter, gasoline, 4-11 kW	16	30’000

The glider and the mechanical powertrain of the scooter are modeled using the UVEK:2018/ecoinvent dataset “motor scooter production” and scaled to mass accordingly, as the original dataset is meant to represent a 90 kg heavy scooter. The fuel tank is modeled separately, using an input of injection-molded high-density polyethylene.

Market development indicates a preference for 2-stroke engines for engines with a small displacement volume (which allows extracting more power out of an otherwise small engine). In contrast, most engines with a displacement volume superior to 50 cm^3 are 4-stroke (more reliable). In this study, engines with a power output inferior to 4 kW are assumed to be 2-stroke, while engines for which the power output is between 4 and 11 kW are considered 4-stroke.

Emission factors from the EMEP EEA’s 2019 Air Pollutant Emissions Inventory Guidebook (European Environment Agency 2019) are used for the emission standards, with the additional distinction between 2-stroke and 4-stroke engines (see Table 23). Accordingly, 2-

stroke engine vehicles are supplied with fuel from the dataset “petrol blending for two-stroke engines” which contains a certain amount of lubricating motor oil.

The transport of the vehicle from the assembly plant to the intended market is included: 15’900 km by transoceanic container ship and 1’000 km by a fleet-average truck.

Abrasion emissions are scaled on the driving mass, but the dataset for abrasion emissions of passenger cars in UVEK:2018 is used to approximate their composition.

The disposal of the scooter is included in the “motor scooter production” dataset.

Scooters manufactured in 2006, 2016, and 2020 are modeled to represent the emission standards EURO 3, 4, and 5, respectively. Specifications for gasoline scooters considered in this study are presented in Table 28.

Table 28 Specifications for gasoline scooters

	Scooter, gasoline, <4 kW, EURO-3 - 2006	Scooter, gasoline, <4 kW, EURO-4 - 2016	Scooter, gasoline, <4 kW, EURO-5 - 2020	Scooter, gasoline, 4-11 kW, EURO-3 - 2006	Scooter, gasoline, 4-11 kW, EURO-4 - 2016	Scooter, gasoline, 4-11 kW, EURO-5 - 2020	Comment	Source
Lifetime [km]	25’000	25’000	25’000	30’000	30’000	30’000	See Table 27.	(ASTRA 2021; Papadimitriou et al. 2013)
Annual kilometers [km]	1’570	1’570	1’570	1’870	1’870	1’870		
Energy consumption [MJ/km] (L gasoline/100 km)	1.38 (3.25)	1.3 (3.07)	1.29 (3.04)	1.06 (2.5)	1.05 (2.47)	1.04 (2.45)	Energy consumption is calculated from actual usage values reported to spritmonitor.de, based on a sample of 165 vehicles representing over 6.6 million kilometers.	(spritmonitor.de 2021)
Passenger mass [kg]	75	75	75	75	75	75	Standard assumption.	
Cargo mass [kg]	4	4	4	4	4	4		
Curb mass [kg]	94	92	91	133	131	130	Based on manufacturers’ data.	Peugeot, Piaggio, NRG
Driving mass [kg]	173	171	171	212	210	209	Calculated.	
Power [kW]	2.8	2.8	2.8	8.8	8.8	8.8	Based on manufacturers’ data.	Peugeot, Piaggio, NRG
Range autonomy [km]	160	170	173	270	273	276	Calculated.	
Servicing per lifetime [unit]	1	1	1	1	1	1	The original ecoinvent dataset for	ecoinvent

	Scooter, gasoline, <4 kW, EURO-3 - 2006	Scooter, gasoline, <4 kW, EURO-4 - 2016	Scooter, gasoline, <4 kW, EURO-5 - 2020	Scooter, gasoline, 4-11 kW, EURO-3 - 2006	Scooter, gasoline, 4-11 kW, EURO-4 - 2016	Scooter, gasoline, 4-11 kW, EURO-5 - 2020	Comment	Source
							maintenance for motor scooters is valid for the vehicle's entire lifetime.	

H. Scooter, electric

Examples of available models of electric scooters considered in this study:

NQi Pro model by NIU (<4 kW)

VX-1 model by Vectrix (4-11 kW)

The national vehicle registry (MOFIS) from (ASTRA 2021) is used to obtain the age of electric scooters when discarded. However, as Table 29 indicates, the lifetime values obtained are substantially lower than that of gasoline scooters (Table 27). The road transport survey data from (Papadimitriou et al. 2013) for Switzerland in 2010 is used to obtain the annual mileage of mopeds/scooters, and the values calculated are presented in Table 27.

<u>Important assumption</u>: because electric scooters are relatively recent on the market, the lifetime values obtained (i.e., nine years, see Table 29) probably underrepresent the performances expected from electric scooters manufactured in 2020. Hence, <u>a similar lifetime value as for gasoline scooters is assumed</u> instead – without any good data to support this. Time will confirm whether this assumption is correct or whether electric scooters are discarded earlier than their gasoline counterparts (e.g., when the first battery needs replacement). It is noted that Leuenberger and Frischknecht (2010) also assumed 25’000 km for electric scooters.

Table 29 Kilometric and calendar lifetime values for electric scooters

	Age of decommissioning (i.e., calendar lifetime) [years]	**Corrected age of decommissioning [years]**	**Cumulated mileage reached at the age of decommissioning (i.e., kilometric lifetime) [km]**
Source	MOFIS registry (ASTRA 2021)		TRACCS 2010 survey data for Switzerland (Papadimitriou et al. 2013)
Comment	Outliers have been removed (i.e., <5 years and >30 years). Corresponds to electricity-powered “kleinmotorrad” in the registry.	Current electric scooters are assumed to last as long as their gasoline counterpart.	Annual mileage values for “Mopeds” and “2-s motorcycles”.
Sample size	1’036		
Scooter, gasoline, <4 kW	9	16	25’000
Scooter, gasoline, 4-11 kW	9	16	30’000

The UVEK:2018/ecoinvent datasets for glider and electric powertrain for an electric scooter are used (Leuenberger and Frischknecht 2010b) – these datasets refer to 1 kilogram of glider and electric powertrain, respectively. The dataset for the electric powertrain production does not contain the battery, which is modeled separately.

The transport of the vehicle from the assembly plant to the intended market is included: 15’900 km by transoceanic container ship and 1’000 km by a fleet-average truck.

Abrasion emissions are scaled on the driving mass, but the dataset for abrasion emissions of passenger cars in UVEK:2018 is used to approximate their composition.

The disposal of the scooter (incl. the batteries) is not included in either of the datasets for the glider or electric powertrain and is therefore added separately. Specifications for electric scooters considered in this study are presented in Table 30.

Table 30 Specifications for electric scooters

	Scooter, electric, <4 kW - 2020	Scooter, electric, 4-11 kW - 2020	Comment	Source
Lifetime [km]	25’000	30’000	See Table 29.	(ASTRA 2021; Papadimitriou et al. 2013)
Annual kilometers [km]	1,570	1’870		
Energy consumption [MJ/km] (kWh/100 km)	0.133 (4.08)	0.189 (5.79)	Energy consumption is calculated from actual usage values reported to spritmonitor.de, based on a sample of 83 vehicles, with a cumulative mileage of 500’000 kilometers.	(spritmonitor.de 2021)
Passenger mass [kg]	75	75	Standard assumption.	
Cargo mass [kg]	4	4		
Curb mass [kg]	100[4]	130[3]	Based on manufacturers’ data.	Piaggio, NIU, Gogoro, Pink
Driving mass [kg]	179[3]	209[3]	Calculated.	
Power [kW]	2.6	6.1	Based on manufacturers’ data.	Piaggio, NIU, Gogoro, Pink
Battery capacity [kWh]	2.3	3.3		
Depth of discharge [%]	80	80	Standard assumption to preserve battery lifetime.	Similar assumptions were used by (Brian Cox et al. 2020).
Battery replacement unit [unit]	1	1	Standard assumption for this type of vehicle.	
Range autonomy [km]	50	50	Calculated.	
Servicing per lifetime [unit]	1	1.2	The original UVEK:2018/ecoinvent dataset for maintenance for motor scooters is valid for a lifetime of 25’000.	(Leuenberger and Frischknecht 2010b)
Abrasion emissions (tire, brake, and road wear) [kg/km]	6e-6, 6.39e-6, 6.18e-6			(European Environment Agency 2019)

[4] Mass values considering a Li-NMC battery. Mass values will slightly change with Li-LFP and Li-NCA batteries due to a different cell energy density. Refer to the implemented dataset directly.

I. Motorbike, gasoline

Examples of available models of gasoline motorbikes considered in this study:

Seventy models by MASH (4-11 kW)

G 310 R model by BMW (11-35 kW)

Ninja model by Kawasaki (>35 kW)

The national vehicle registry (MOFIS) from (ASTRA 2021) is used to obtain the age of gasoline motorbikes when discarded.

While annual mileage values can also be obtained, as with scooters, from the 2010 TRACCS survey data, the more recent 2015 Swiss Mobility census (FSO and ARE 2017) seems a better option. In the micro census report, the annual mileage for motorcycles, excluding light motorcycles (i.e., scooters), is presented by engine displacement volume: “up to 125 cm^3”, “126-749 cm^3”, and “750-999 cm^3” are used to represent “4-11 kW”, “11-35 kW” and “>35 kW” respectively.

Important remark: the kilometric lifetime values obtained differ significantly from those used by (B. L. Cox and Mutel 2018). Cox and Mutel considered a lifetime of 28-69’000 and 145’000 km for small (i.e., 4 and 11 kW) and large (50 kW) motorbikes, respectively, against 25’000 and 40’500 km in this study.

A dataset specific to motorbike production with the characteristics listed in Table 31 could not be obtained. Hence, the dataset from UVEK:2018/ecoinvent “motor scooter production” is used instead to approximate the energy and material requirements for manufacturing the glider and the mechanical part of the powertrain. The dataset initially refers to a 90 kg heavy scooter. The same approach is adopted for vehicle maintenance, where the dataset for scooter maintenance is used.

The disposal of the vehicle is already included in the “motor scooter production” dataset.

Vehicle specifications used in this study for gasoline motorbikes are presented in Table 32-Table 34.

Table 31 Kilometric and calendar lifetime values for gasoline motorbikes

	Age of decommissioning (i.e., calendar lifetime) [years]	**Annual mileage [km/year]**	**Cumulated mileage reached at the age of decommissioning (i.e., kilometric lifetime) [km]**
Source	MOFIS registry (ASTRA 2021)	(FSO and ARE 2017)	
Comment	Outliers have been removed (i.e., <5 years and >30 years). Corresponds to gasoline-powered	The micro census categories “up to 125 cm^3”, “126-749 cm^3”, and “750-999 cm^3” are used to represent “4-11 kW”, “11-35	

	Age of decommissioning (i.e., calendar lifetime) [years]	**Annual mileage [km/year]**	**Cumulated mileage reached at the age of decommissioning (i.e., kilometric lifetime) [km]**
	"motorrad" in the registry.	kW", and ">35 kW" motorcycles, respectively	
Sample size	205'513		
Motorbike, gasoline, 4-11 kW	14	1'776	25'000
Motorbike, gasoline, 11-35 kW	16	2'405	38'500
Motorbike, gasoline, >35 kW	14	2'896	40'500

1. 4-11 kW

Table 32 Specifications for gasoline motorbikes, 4-11 kW

	Motorbike, gasoline, 4-11 kW, EURO-3 - 2006	Motorbike, gasoline, 4-11 kW, EURO-4 - 2016	Motorbike, gasoline, 4-11 kW, EURO-5 - 2020	Comment	Source
Lifetime [km]	25,000	25'000	25'000	See Table 31.	(ASTRA 2021; FSO and ARE 2017)
Annual kilometers [km]	1'776	1'776	1'776		
Energy consumption [MJ/km] (L gasoline/100 km)	1.03 (2.42)	1.02 (2.4)	1.01 (2.37)	Energy consumption is calculated from actual usage values reported to spritmonitor.de, based on a sample of 34 vehicles representing over 1.6 million kilometers.	(spritmonitor.de 2021)
Passenger mass [kg]	75	75	75	Standard assumption. The passenger occupancy values are similar to those used in (BAFU 2020)	
Number of passengers [unit]	1.1	1.1	1.1		
Cargo mass [kg]	6	6	6		
Curb mass [kg]	122	120	119	Based on manufacturers' data.	
Driving mass [kg]	211	209	208	Calculated.	
Power [kW]	9	9	9	Based on manufacturers' data.	
Range autonomy [km]	279	282	285	Calculated.	
Servicing per lifetime [unit]	1	1	1	The original ecoinvent dataset for maintenance for motor scooters is valid for a vehicle lifetime of 25'000 km.	(Leuenberger and Frischknecht 2010b)

2. 11-35 kW

Table 33 Specifications for gasoline motorbikes, 11-35 kW

	Motorbike, gasoline, 11-35 kW, EURO-3 - 2006	Motorbike, gasoline, 11-35 kW, EURO-4 - 2016	Motorbike, gasoline, 11-35 kW, EURO-5 - 2020	Comment	Source
Lifetime [km]	38’500	38’500	38’500	See Table 31.	(ASTRA 2021; FSO and ARE 2017)
Annual kilometers [km]	2’405	2’405	2’405		
Energy consumption [MJ/km] (L gasoline /100 km)	1.49 (3.51)	1.47 (3.48)	1.46 (3.44)	Energy consumption is calculated from actual usage values reported to spritmonitor.de, based on a sample of 138 vehicles representing over 6.7 million kilometers.	
Passenger mass [kg]	75	75	75	Standard assumption.	
Number of passengers [unit]	1.1	1.1	1.1		
Cargo mass [kg]	6	6	6		
Curb mass [kg]	160	158	156	Based on manufacturers’ data.	
Driving mass [kg]	248	246	244	Calculated.	
Power [kW]	20	20	20	Based on manufacturers’ data.	
Range autonomy [km]	327	330	334	Calculated.	
Servicing per lifetime [unit]	1.54	1.54	1.54	The original ecoinvent dataset for maintenance for motor scooters is valid for a vehicle lifetime of 25’000 km.	(Leuenberger and Frischknecht 2010b)

3. >35 kW

Table 34 Specifications for gasoline motorbikes, > 35 kW

	Motorbike, gasoline, >35 kW, EURO-3 - 2006	Motorbike, gasoline, >35 kW, EURO-4 - 2016	Motorbike, gasoline, >35 kW, EURO-5 - 2020	Comment	Source
Lifetime [km]	40’500	40’500	40’500	See Table 31.	(ASTRA 2021; FSO and ARE 2017)
Annual kilometers [km]	2’896	2’896	2’896		
Energy consumption [MJ/km] (L gasoline /100 km)	1.97 (4.65)	1.95 (4.61)	1.93 (4.56)	Energy consumption was calculated from actual usage values reported to spritmonitor.de, based on a sample of 148 vehicles representing over 13.7 million kilometers.	
Passenger mass [kg]	75	75	75	Standard assumption.	

	Motorbike, gasoline, >35 kW, EURO-3 - 2006	Motorbike, gasoline, >35 kW, EURO-4 - 2016	Motorbike, gasoline, >35 kW, EURO-5 - 2020	Comment	Source
Number of passengers [unit]	1.1	1.1	1.1		
Cargo mass [kg]	6	6	6		
Curb mass [kg]	262	259	257	Based on manufacturers' data.	
Driving mass [kg]	351	347	345	Calculated.	
Power [kW]	91	91	91	Based on manufacturers' data.	
Range autonomy [km]	290	293	296	Calculated.	
Servicing per lifetime [unit]	1.62	1.62	1.62	The original ecoinvent dataset for maintenance for motor scooters is valid for a vehicle lifetime of 25'000 km.	(Leuenberger and Frischknecht 2010b)

4. Fleet average

The fleet composition data of HBEFA 4.1 provides enough details to build a fleet-average motorbike. There are, however, several limitations to using HBEFA fleet data:

- According to HBEFA's fleet composition, 33% of the total fleet vehicle-kilometers are driven by motorcycles with an emission standard anterior to EURO-3, which are not vehicle models considered in this study. The share of vehicle-kilometers driven by these old motorbikes is allocated instead to EURO-3 motorbikes, with the risk of underestimating the emission of exhaust pollutants, notably CO.
- 7% of the fleet vehicle-kilometers are driven with 2-stroke engines, not vehicle models considered in this study (only small scooters). Hence, the 4-stroke counterpart will be used instead to represent this share of vehicle-kilometer. In practice, however, 2-stroke motorbikes have almost completely disappeared from the market today as they are not allowed to drive on the road in many countries (i.e., they mainly do not comply with noise and emission limits), with only a few models of off-road and racing motorbikes left. Hence, substituting 4-stroke engine motorbikes for 2-stroke ones is reasonable.
- A last limitation is that HBEFA's vehicle labeling does not precisely match the vehicles considered here. Besides the emission standard, the distinction is made between motorbikes with an engine displacement inferior or superior to 250 cm^3. The "4-11 kW" category is used to represent HBEFA's vehicles with an engine displacement below 250 cm^3, while the fleet share represented by vehicles with an engine displacement superior to 250 cm^3 is represented evenly by the "11-35 kW" and ">35 kW" categories.

Based on this, the fleet composition presented in Table 35 characterizes a fleet-average gasoline motorbike.

Table 35 Fleet composition data for gasoline motorbikes in Switzerland in 2020

		Vehicle-km share in the 2020 Swiss gasoline motorbike fleet		
		4-11 kW	**11-35 kW**	**>35 kW**
Gasoline	**2006**	21.5%	23.75%	23.75%
	2016	8.25%	11.38%	11.38%

J. Motorbike, electric

A dataset specific to electric motorbikes production with the characteristics listed in Table 37 above could not be obtained. Hence, the dataset “glider production, for electric scooter” is used instead to approximate the energy and material requirements for manufacturing the glider and the mechanical part of the powertrain. In addition, the dataset “electric powertrain production, for electric scooter” is used to approximate the manufacture of the electric part of the powertrain (incl. the electric motor) – the battery is modeled separately from the powertrain. The energy consumption values are based on reported values from users on spritmonitor.de.

The disposal of the vehicle is specified separately.

Important assumption: The national vehicle registry (MOFIS) from (ASTRA 2021) does not have a sample of decommissioned electric motorbikes large enough to be used. Hence, a similar lifetime value to gasoline motorbikes is assumed instead – without any good data to support this. Similarly, the annual mileage values from the 2015 Swiss micro-census on mobility (FSO and ARE 2017) are used.

Table 36 Kilometric and calendar lifetime values for electric motorbikes

	Age of decommissioning (i.e., calendar lifetime) [years]	**Annual mileage [km/year]**	**Cumulated mileage reached at the age of decommissioning (i.e., kilometric lifetime) [km]**
Source	MOFIS registry (ASTRA 2021)	(FSO and ARE 2017)	
Comment	Assumed similar to gasoline motorbikes	Assumed similar to gasoline motorbikes	
Sample size	205’513		
Motorbike, electric, 4-11 kW	14	1’776	25’000
Motorbike, electric, 11-35 kW	16	2’405	38’500
Motorbike, electric, >35 kW	14	2’896	40’500

Specifications for the electric motorbikes considered in this study are presented in Table 37.

Table 37 Specifications for electric motorbikes

	Motorbike, electric, 4-11 kW - 2020	Motorbike, electric, 11-35 kW - 2020	Motorbike, electric, >35 kW - 2020	Comment	Source
Lifetime [km]	25’000	38’500	40’500	See Table 31.	(ASTRA 2021; FSO and ARE 2017)
Annual kilometers [km]	1’776	2’405	2’896		
Energy consumption [MJ/km]	0.182	0.246	0.275	Energy consumption is calculated from actual usage values reported to spritmonitor.de, based on a sample of 42 vehicles representing over 520’000 kilometers.	(spritmonitor.de 2021)
Passenger mass [kg]	75	75	75	Standard assumption.	
Cargo mass [kg]	6	6	6		

	Motorbike, electric, 4-11 kW - 2020	Motorbike, electric, 11-35 kW - 2020	Motorbike, electric, >35 kW - 2020	Comment	Source
Curb mass [kg]	105[5]	166[4]	255[4]	Based on manufacturers' data.	Super Soco, Horwin, Ox Rider, Zero motorcycles, Energica
Driving mass [kg]	194[4]	255[4]	3430[4]	Calculated.	
Power [kW]	5	14	49	Based on manufacturers' data.	Super Soco, Horwin, Ox Rider, Zero motorcycles, Energica
Battery capacity [kWh]	2.9	8.1	16.5		
Depth of discharge [%]	80%	80%	80%	Standard assumption to preserve battery lifetime.	Similar assumptions were used by (Brian Cox et al. 2020).
Battery replacement unit [unit]	1	1	1	Standard assumption for this type of vehicle.	
Range autonomy [km]	46	95	173	Calculated.	
Servicing per lifetime [unit]	1	1.54	1.62	The original ecoinvent dataset for maintenance for electric scooters is valid for a vehicle lifetime of 25'000 km.	(Leuenberger and Frischknecht 2010b)

[5] Mass values considering a Li-NMC battery. Mass values will slightly change with Li-LFP and Li-NCA batteries due to a different cell energy density. Refer to the implemented dataset directly.

III. Passenger cars

The LCA tool for passenger cars named *carculator* is used, for which the source code is made available at https://github.com/romainsacchi/carculator. The tool generates inventories of passenger cars for different powertrain types, size classes, and years of manufacture. The tool builds on the following publications:

- Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D., and Mutel, C. Applied Energy. 2020. DOI: 10.1016/j.apenergy.2020.115021
- carculator: When, where, and how can the electrification of passenger cars reduce greenhouse gas emissions? Sacchi R., Bauer C., Cox B., Mutel C. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2022.112475

A. Overview

Inventories for the following powertrain types are provided:

- Gasoline-run internal combustion engine vehicle (ICEV-p)
- Diesel-run internal combustion engine vehicle (ICEV-d)
- Gas-run internal combustion engine vehicle (ICEV-g)
- Gasoline-run hybrid electric vehicle (HEV-p)
- Diesel-run hybrid electric vehicle (HEV-d)
- Gasoline-run plugin hybrid electric vehicle (PHEV-p)
- Diesel-run plugin hybrid electric vehicle (PHEV-d)
- Battery electric vehicle (BEV)
- Fuel cell electric vehicle (FCEV)
- Fleet-based powertrain average vehicle

Initially, *carculator* defines seven size classes, namely: Micro, Mini, Small, Lower medium, Medium, Large, SUV, Large SUV, and Van, according to the following criteria, adapted from the work of (Thiel et al. 2014) and shown in Table 38.

Table 38 Criteria for size classes

EU segment	EU segment definition	carculator	Minimum footprint [m2]	Maximum footprint [m2]	Minimum curb mass [kg]	Maximum curb mass [kg]	Examples
L7e	Microcars/Heavy quadricycles	**Micro**			400	600	Renault Twizzy, Microlino
A	Mini cars	**Mini**		3.4		1050	Renault Twingo, Smart ForTwo, Toyota Aygo
B	Small cars	**Small**	3.4	3.8	900	1'350	Renault Clio, VW Polo, Toyota Yaris
C	Medium cars	**Lower medium**	3.8	4.3	1250	1500	VW Golf, Ford Focus, Mercedes Class A
C		**Medium**	3.9	4.4	1500	1750	VW Passat, Audi A4, Mercedes Class C
D	Large/Executive	**Large**	4.4		1'450	2'000	Tesla Model 3, BMW 5 Series, Mercedes E series
J	Sport Utility	**Medium SUV**	Defined by body type as well as mass and footprint.				Toyota RAV4, Peugeot 2008, Dacia Duster
J	Sport Utility	**Large SUV**	Defined by body type as well as mass and footprint.				Audi Q7, BMW X7, Mercedes-Benz GLS, Toyota Landcruiser, Jaguar f-Pace
M	Multi-Purpose Vehicles	**Van**	Defined by body type rather than mass and footprint.				VW Transporter, Mercedes Sprinter, Ford Transit

Example of Microcar

Example of Mini car

Example of Small car

Example of Lower medium car

Example of Medium car

Example of Large car

Example of Medium SUV

Example of Large SUV

Example of Van

However, in this study, to keep the number of datasets low, the following size classes are provided instead:

- Micro: corresponding to **Micro** vehicles
- Compact: by merging **Mini** and **Small** vehicles
- Medium: by combining **Lower medium** and **Medium** vehicles
- Large: by combining **Large** and medium-sized **SUV** vehicles
- Large SUV: corresponding to **Large SUV** vehicles
- Fleet-based size average vehicle

This results in the classification criteria shown in Table 39.

Table 39 Size classes criteria used in this study.

EU segment	EU segment definition	This study	Minimum footprint [m2]	Maximum footprint [m2]	Minimum curb mass [kg]	Maximum curb mass [kg]	Examples
L7e	Microcars/Heavy quadricycles	**Micro**		3.4	400	600	Renault Twizzy, Microlino
B	Mini and Small cars	**Compact**	3.5	3.8	900	1’350	Renault Clio, VW Polo, Toyota Yaris
C	Medium cars	**Medium**	3.8	4.4	1’250	1’750	VW Golf, Ford Focus, Mercedes Class A, VW Passat, Audi A4
D	Large cars and medium-sized Sport utility cars	**Large**	4.4		1’450	2’000	Tesla Model 3, BMW 5 Series, Mercedes E series
J	Sport utility cars	**Large SUV**	6		2’000	2’500+	Audi Q7, BMW X7, Mercedes-Benz GLS, Toyota Landcruiser, Jaguar i-Pace

Important remark: Microcars are not considered passenger cars in the Swiss and European legislation, but heavy quadricycles. We, however, assimilate them to passenger cars in this study, and they are modeled with a battery-electric powertrain.

Important remark: Sport Utility Vehicles (SUVs) are considered more as a body type than a size class. These vehicles have distinct aerodynamic properties, but their curb mass can be as light as that of a VW Polo or a Renault Clio (i.e., the Dacia Duster or Peugeot 2008 have a curb mass of 1’150 kg, against 1’100-1’300 kg for a VW Polo) or as heavy as a Mercedes Class E (i.e., the Audi Q7 has a minimum curb mass of 2’000 kg, against 1’900 kg for a Mercedes Class E). To some extent, the reader could assimilate the impacts of a moderate-sized SUV to that of the “Large” size class used in this study. And to assess the implications of very large vehicles, the “Large SUV” category has been added to represent SUV models with a very high curb mass (2’000 kg and above) and footprint.

For most powertrain-size segments, the following conditions of use are considered:

- In Switzerland
- In Europe

Vehicles with an electric powertrain are only defined for use in Switzerland. In practice, however, the electricity supply within the transport dataset can be switched to another electricity mix from the inventory background database to obtain a reasonably good approximation.

Finally, for each powertrain-size-geography combination, several emission standards are considered. For simplicity, it is assumed that the vehicle manufacture year corresponds to the registration year, as shown in Table 40.

Table 40 Correspondence between manufacture year and emission standards used in this study

	Start of registration	**End of registration (incl.)**	**Manufacture year in this study**
EURO-3	2001	2005	**2003**
EURO-4	2006	2010	**2008**
EURO-5	2011	2014	**2013**
EURO-6 a/b	2015	2017	**2016**
EURO-6 c	2018	2018	**2018**
EURO-6 d (temp)	2019	2020	**2019**
EURO-6 d	2021	-	**2021**

B. Modeling approach applicable to all vehicle types

1. Use-related parameters

The 2015 Swiss survey on mobility (FSO and ARE 2017) indicates an average annual mileage of 11’828 km for passenger cars. The European database ODYSSEE shows an average yearly mileage of 11’964 km for passenger cars in the EU27+1 (Enerdata 2018). For simplicity, the annual mileage for Swiss and European passenger cars is assumed to be 12’000 km.

Regarding the expected lifetime of the vehicles, the Swiss vehicles registry MOFIS from the Swiss Federal Road Office (ASTRA 2021) is used. Average lifetime values for the most recent one million decommissioned passenger cars in Switzerland are derived and presented in

Table 41. Vehicles with a lifetime below six years or above 30 years are considered outliers and omitted. Gasoline and diesel hybrid vehicles have a significantly lower lifetime than conventional diesel and gasoline powertrains. However, this may be because such powertrain technologies are not yet mature. The weighted average lifetime value is 13.5 years and is used for all vehicle powertrains and size classes. This yields a kilometric lifetime for all vehicles of 162’000 km in Switzerland. To account for the vehicle usage not visible in MOFIS (e.g., vehicle use after export), a kilometric lifetime for all passenger cars of 200’000 km, as recommended by (Weymar and Finkbeiner 2016), was chosen.

Table 41 Kilometric lifetime values for passenger vehicles

	Gasoline-powered passenger cars	Diesel-powered passenger cars	Compressed gas-powered passenger cars	Gasoline hybrid passenger cars	Diesel hybrid passenger cars	Source	Comment
Count	748'680	283'764	1'352	165	99	MOFIS vehicles registry (ASTRA 2021)	Outliers have been removed (with a lifetime inferior to 6 years or superior to 30 years).
Average lifetime [years]	14	11	10.6	8.5	7.2		
Average weighted lifetime value used in this study [years]	13.5						The weighted average lifetime value is considered.
Lifetime [kilometer]	162'000						Calculated from the two rows above.

Important assumption: Use data is lacking for microcars. Because of their limited speed and autonomy compared to other passengers, we assume that micro cars are used daily about 16.5 km for ten years, yielding an annual mileage of 6'000 km and a kilometric lifetime of 60'000 km.

2. Size and mass-related parameters and modeling

The vehicle sizing is depicted in Figure 3. The vehicle glider and its components (powertrain, energy storage, etc.) are sized according to engine power, which is conditioned by the curb mass of the vehicle. The curb mass of the car is the sum of the vehicle components (excluding the driver and possible cargo), an iterative process that stops when the curb mass of the vehicle converges. For each iteration, the tank-to-wheel energy consumption of the vehicle is calculated (i.e., to size the energy storage components).

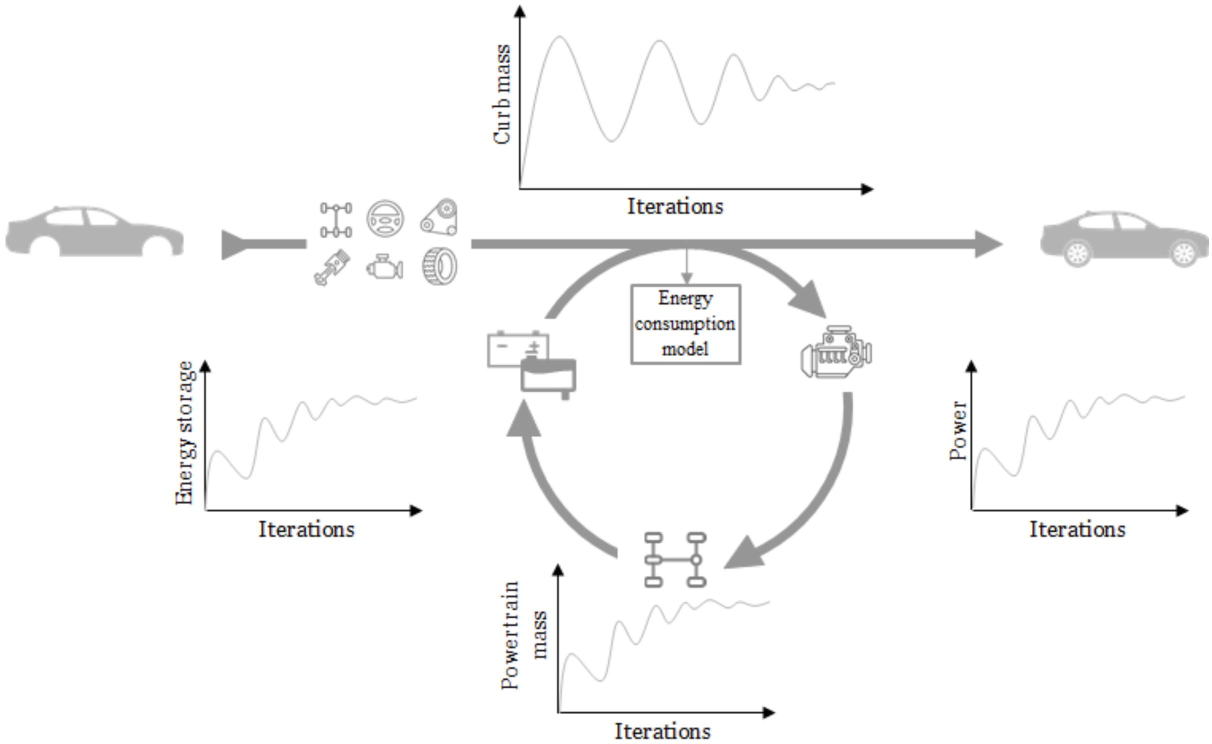


Figure 3 Representation of the sizing of the passenger car model

Because the LCI dataset used to represent the glider of the vehicle is not representative of today's use of lightweight materials, such as aluminum (i.e., the dataset "glider for passenger cars" only contains 0.5% of its mass in aluminum) and advanced high strength steel (AHSS), an amount of such light-weighting materials is introduced to substitute conventional steel and thereby reduce the mass of the glider.

As explained in Section I.C.8, the glider's mass is reduced by replacing steel with a mix of aluminum and AHSS. Hence, the amounts of lightweight materials introduced depend on the rate of glider lightweight in 2020 relative to 2000 (approximately 11% for combustion engine vehicles). The amount of aluminum introduced is further cross-checked with the amounts indicated in (Ducker Frontier 2019) and listed in Table *42* and comes in addition to the aluminum already contained in the LCI datasets for the engine and transmission.

Important remark: the lightweight rate is for most vehicles approximately 11% relative to 2000. However, battery-equipped vehicles are an exception to this: Medium, Large, and Large SUV vehicles have significantly higher lightweighting rates to compensate for the additional mass of their batteries partially. To match the battery capacity and the curb mass of their respective size class, their lightweighting rate is increased to 14, 28, and 30%, respectively. This trend is also confirmed by (Ducker Frontier 2019), showing that battery electric vehicles have 85% more aluminum than combustion engine vehicles, partly going into the battery management system and partly into the chassis to compensate for the extra mass represented by the battery.
These lightweighting rates have been finely adjusted to match the curb mass of a given size class while preserving the battery capacity. For example, a large SUV's curb mass should be approximately 2'200 kg, with an 80-kWh battery weighing 660 kg (e.g., Jaguar i-Pace). This is possible with a 30% lightweighting rate, introducing around 460 kg of aluminum in the chassis (roughly matching the value for an Audi e-Tron in Table 42) and 1'008 kg of AHSS instead of 2'034 kg of regular steel.

Table 42 Amount of aluminum in European passenger cars. Source: (Ducker Frontier 2019)

Used in source	Basic	Sub-Compact	Compact	Midsize	Large	Audi e-Tron
Used in this study	Compact			Medium	Large	Large SUV (BEV)
Average aluminum content per vehicle [kg]	77	98	152	266	442	804
Share of aluminum mass in components other than engine and transmission [%]	66%					
Aluminum added to the glider [%]	65			175	292	530

The final curb mass obtained for each vehicle is calibrated against the European Commission's database for CO_2 emission tests for passenger cars (hereafter called EC-CO2-PC) using the NEDC/WLTP driving cycles (European Commission 2021). Each vehicle registered in the European Union is tested, and several vehicle attributes are reported (e.g., dimension, curb mass, driving mass, CO_2 emissions, etc.). This has represented about 15+ million vehicles per year for the past five years.

The figure below shows such calibration for the years 2010, 2013, 2016, 2018, 2019, and 2020 -- to be representative of EURO-4, -5, 6 a/b, 6-c, and 6-d-temp vehicles. No measurements for 2003 (EURO-3) or 2021 (EURO-6-d) are available. After cleaning the data from the EC-CO2-PC database, it represents 27 million points to calibrate the curb mass of the vehicles. Green vertical bars represent 50% of the curb mass distribution, and the red dots are the curb mass values modeled by *carculator*.

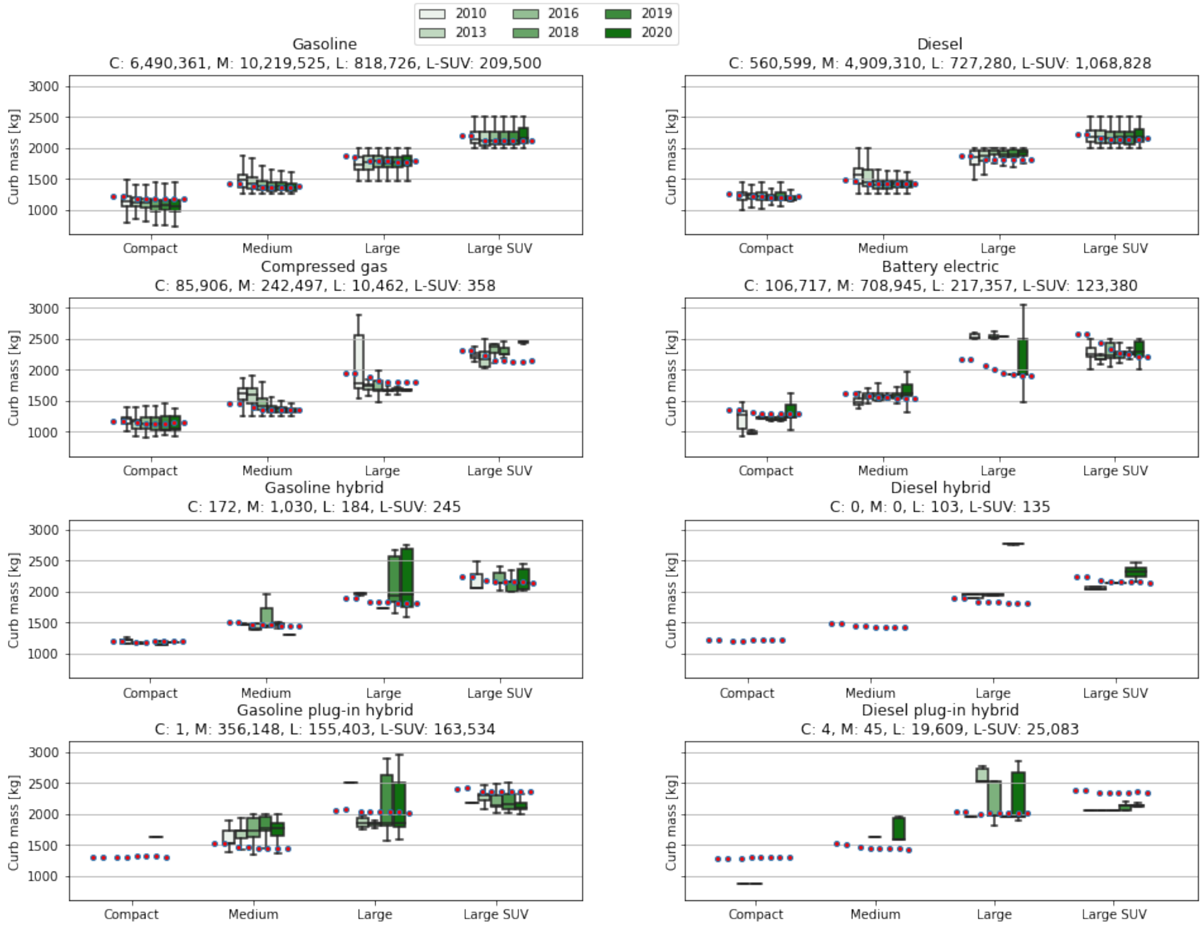


Figure 4 Calibration of the curb mass of the passenger car model against the EC-CO2-PC database. Red dots: values modeled by carculator. Green box-and-whiskers: values distribution from the EC-CO2-PC database (box: 50% of the distribution, whiskers: 90%). Microcars are not represented in the EC-CO2-PC database.

Table *43* shows the mass distribution for gasoline and battery electric passenger cars resulting from the calibration. Mass information on other vehicles is available in the vehicles' specifications spreadsheet.

Table 43 Mass distribution for gasoline and battery electric passenger cars in 2021

	Gasoline				**Battery electric**				
in kilograms	Compact	Medium	Large	Large SUV	Micro	Compact	Medium	Large	Large SUV
Glider base mass	998	1'170	1'550	1'900	350	998	1'170	1'550	1'900
Lightweighting	-110	-129	-171	-209	-35	-140	-164	-434	-570
Glider mass	888	1'041	1'380	1'691	315	858	1'006	1'116	1'330
Powertrain mass	96	106	132	140	42	67	77	94	100
Engine or motor mass	111	125	157	168	29	61	73	96	102
Energy storage mass	72	85	104	104	120	276	360	580	660
Electronics mass	3	4	5	7	23	23	23	23	23
Curb mass	**1'170**	**1'361**	**1'777**	**2'110**	**529**	**1'285**	**1'540**	**1'910**	**2'215**
Passenger mass	120	120	120	120	120	120	120	120	120
Cargo mass	20	20	20	20	20	20	20	20	20
Driving mass	1'310	1'501	1'917	2'250	669	1'425	1'680	2'050	2'355

The energy consumption model of *carculator* calculates the energy required at the wheels by considering different types of resistances. Some of these resistances are related to the vehicle size class. For example, the frontal area of the vehicle influences the aerodynamic drag. Also, the kinetic energy to overcome the vehicle's inertia is influenced by the car's mass (which partially correlates with the size class or body type) and by the acceleration required by the driving cycle. Other resistances, such as the climbing effort, are instead determined by the driving cycle (but the vehicle mass also plays a role here). Once the energy required at the wheels is known, the model calculates the energy needed at the tank level by considering additional losses along the drive train (i.e., axles, gearbox, and engine losses). The different types of resistance considered are depicted in Figure 5.

Powertrains that are partially or fully electrified can recuperate some of the energy spent for propulsion during deceleration or braking. The round-trip battery energy loss (the sum of the charge and discharge battery loss, described in Table 19) is subtracted from the recuperated energy. For hybrid vehicles (i.e., HEV-p, HEV-d), this allows to downsize the combustion engine and improves the overall tank-to-wheel efficiency, as explained in (B. Cox et al. 2020; R Sacchi et al., n.d.).

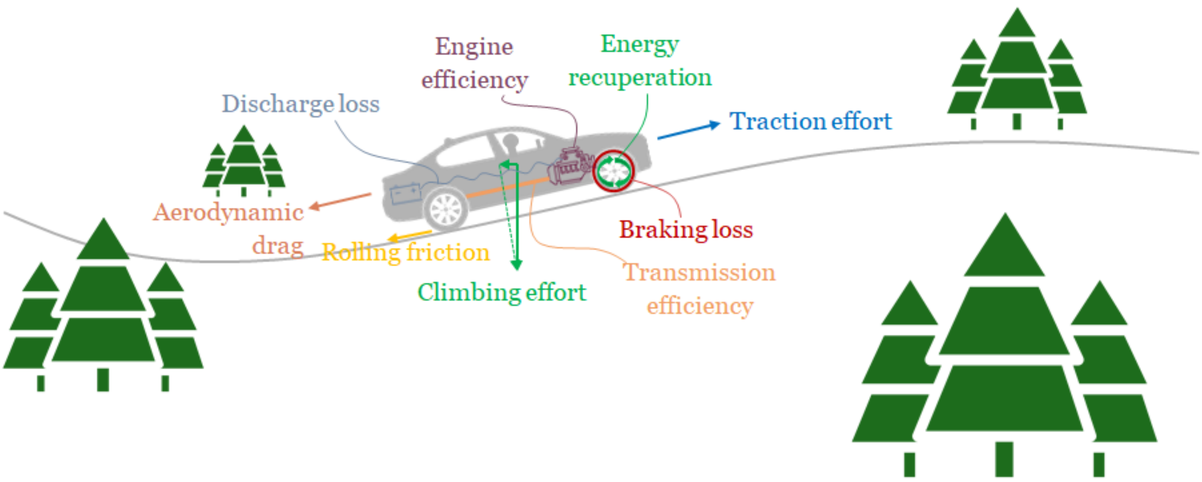


Figure 5 Representation of the different types of resistance considered.

Finally, the auxiliary power load is considered for each second of the driving cycle. It comprises an auxiliary base power load (i.e., to operate onboard electronics) and the power load from heating and cooling. While electric vehicles provide energy from the battery to supply heating and cooling (i.e., thereby decreasing the available energy available for traction), combustion vehicles recover enough waste engine heat to provide adequate heating. The values considered for the auxiliary base power load and the power load for heating and cooling are presented in Table 44. These values are averaged yearly based on maximum demand and operation share.

Table 44 Auxiliary power demand

	Auxiliary power base demand [W]	**Heating power demand [W]**					**Cooling power demand [W]**				
		Micro	**Compact**	**Medium**	**Large**	**Large SUV**	**Micro**	**Compact**	**Medium**	**Large**	**Large SUV**

ICEV, HEV, PHEV	94		Provided by engine					250	320	350	350
BEV, FCEV	75	200	250	320	350	350	0	250	320	350	350

Important remark: Microcars are equipped with an air conditioning system. Hence, their cooling energy requirement is set to zero.

A driving cycle calculates the tank-to-wheel energy required to drive over one kilometer. For example, the WLTC driving cycle comprises a mix of urban, suburban, and highway driving. It is assumed to be representative of the average Swiss and European driving profile – although this would likely differ in the case of Intensive Mountain driving.
Figure 6 exemplifies a calculation for a medium battery electric passenger car manufactured in 2020 using the WLTC driving cycle.

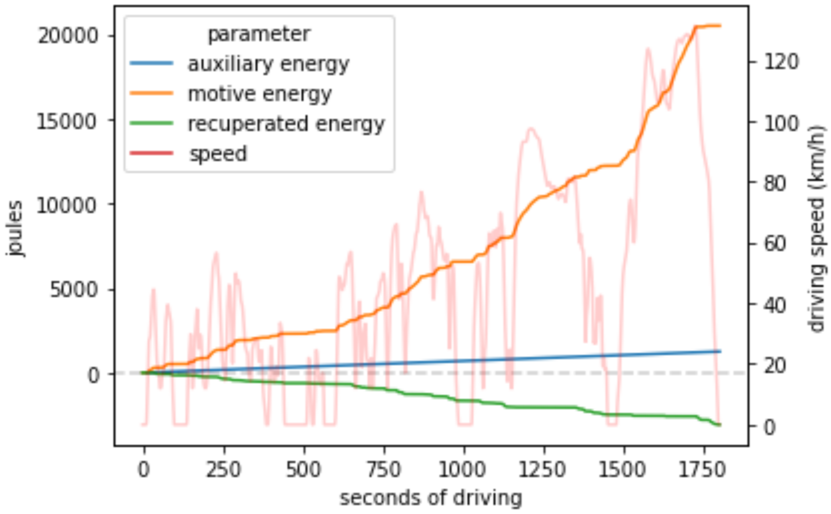


Figure 6 Cumulated tank-to-wheel energy consumption, along the WLTC driving cycle, for a medium battery electric vehicle from 2020.

There are no fuel consumption measurements available for fuel cell vehicles. Values found in the literature and from manufacturers' data are used to approximate the engine and transmission efficiency.

For diesel and gasoline hybrid vehicles, which are ICE vehicles equipped with a small electric motor to allow for energy recuperation and reduce the engine size, the drivetrain and engine efficiency are based on (B. Cox et al. 2020; R Sacchi et al., n.d.). The amount of energy recuperated is determined by the driving cycle and the round-trip efficiency between the wheels and the engine. It cannot be superior to the power output of the engine.

3. Abrasion emissions

Figure 7 shows the calculated abrasion emissions for passenger cars in mg per vehicle-kilometer, following the approach presented in Section I.C.5.b.

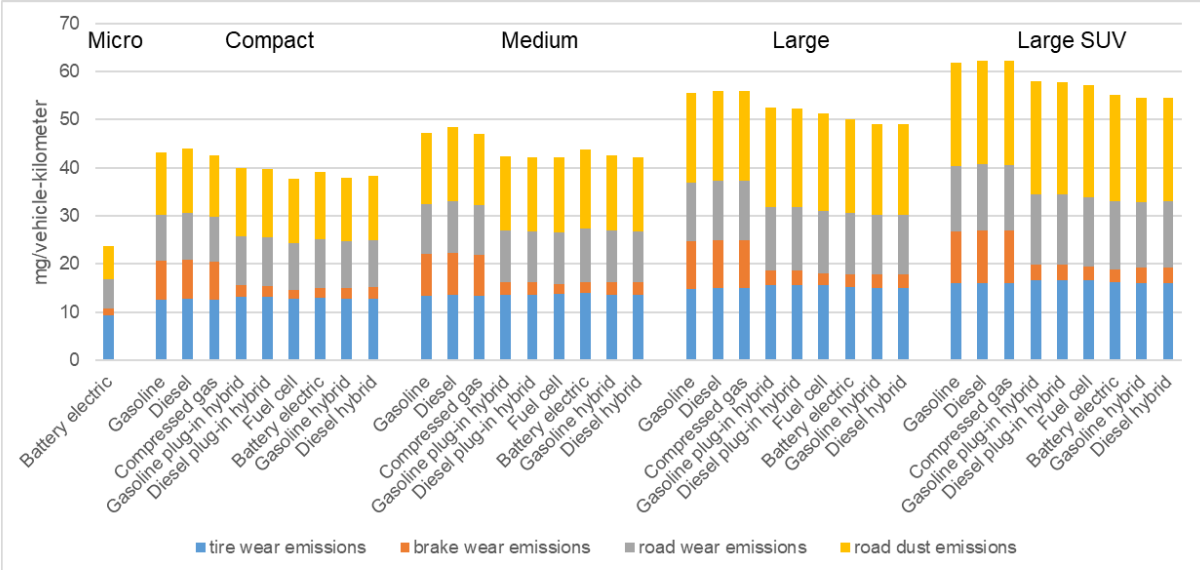


Figure 7 Total particulate matter emissions (<2.5 µm and 2.5-10 µm) in mg per vehicle-kilometer for passenger cars.

Re-suspended road dust emissions are assumed to be evenly composed of brake wear (33.3%), tire wear (33.3%), and road wear (33.3%) particles.

4. Fleet average vehicles for Switzerland

Fleet-average vehicles were built based on fleet statistics for Switzerland in 2020. Two sources of data are used for this purpose.

The updated fleet composition data for Switzerland from HBEFA 4.1 based on the ExPost Analysis for 2020 (Infras; Prognos; TEP Energy; 2015) is used. It contains the respective share in vehicle-kilometer for each sub-segment (where a sub-segment is defined as a powertrain type, a size class if specified, and an emission standard).
From the sub-segment, the powertrain type and the approximate registration year (based on the emission standard) are inferred, as shown in Table 45.

Table 45 Fleet composition data given by HBEFA 4.1 (updated) for passenger cars

Sub-segment	Share vehicle-km	Powertrain type (inferred)	Year (inferred)
PC petrol Euro-3	1.94%	ICEV-p	2003
PC petrol Euro-4	11.24%	ICEV-p	2008
PC petrol Euro-5	17.66%	ICEV-p	2010
PC petrol Euro-6ab	16.38%	ICEV-p	2015
PC petrol Euro-6c	3.09%	ICEV-p	2018
PC petrol Euro-6d-temp	4.65%	ICEV-p	2019
…	…		…

However, no information is given on how the vehicle-kilometer contribution for a given sub-segment is **split between different size classes**, as size classes are not given for passenger cars.

Hence, data from the Swiss Statistical Office (SFO 2021d) is used to help complete the fleet composition. It provides the number of vehicles per interval of registration years, fuel type, and curb mass, which allows inferring the powertrain type, manufacture year, and size class.

Table 46 Passenger cars stock composition data from the Swiss Federal Statistical Office

Registration year	Fuel	Mass	Number of vehicles	Powertrain (inferred)	Size (inferred)	Year (inferred)
2000-2004	Petrol	Up to 1000 kg	2550	ICEV-p	Small	2003
2005-2009	Diesel	1001-1500 kg	3800	ICEV-d	Lower medium	2008
2010-2014	Petrol-Electric	1501-2000	590	HEV-p	Medium	2013
2016	Gas	2001-2050	890	ICEV-g	Large	2016
...	...	...	...	...	...	

We use the following mapping to link the vehicle mass given by the Swiss Statistical Office to the size classes we use in this study:

- Up to 1’000 kg: Compact
- 1001-1500 kg: Medium
- 1501-2000 kg: Large
- 2001-2500 kg: Large SUV
- More than 2500: Large SUV

Note that this mapping is imperfect since there could be large sedan cars with a curb mass above 2’000 kg. Also, since SUV is a body type rather than a size class, some could be found with a curb mass below 2’000 kg.

Combining these two sources allows us to obtain a fleet composition per powertrain type, size class, and manufacture year, for 2020, regarding vehicle-kilometer contribution. Doing so, however, implies that **the vehicle-kilometer contribution of a given sub-segment is split between size classes in proportion to their respective representation in the fleet** (i.e., in terms of the number of vehicles), which may not be accurate. For example, larger vehicles may be driven more on average than smaller ones.

The fleet composition for Switzerland in 2020, in reference to their contribution to transport performance, is presented in Table 47 (sums to 100%).

<u>**Important remark:**</u> Note that 1.4% of the vehicle-kilometer in the Swiss fleet, as given by HBEFA for 2020, are represented by vehicles older than the emission standard EURO-3. Because we do not have datasets to represent vehicles with such emission standards, <u>this 1.4% is added to EURO-3 vehicles</u> (from 2003).

Table 47 Fleet composition data for Switzerland in 2020, all powertrain types and size classes

		Vehicle-kilometer share within the 2020 Swiss fleet						
powertrain	size	2003	2008	2013	2016	2018	2019	2020
Battery electric	Compact							0.00%
	Large							0.51%
	Large SUV							0.14%

	Medium							0.11%
Diesel	Compact	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%
	Large	0.49%	2.84%	9.07%	9.74%	1.52%	2.07%	0.35%
	Large SUV	0.15%	0.84%	2.18%	3.18%	0.55%	0.92%	0.18%
	Medium	0.28%	1.12%	2.94%	2.52%	0.24%	0.22%	0.04%
Compressed gas	Compact		0.00%	0.00%	0.00%			
	Large		0.02%	0.02%	0.02%			
	Large SUV		0.00%	0.00%	0.00%			
	Medium		0.02%	0.03%	0.10%			
Gasoline	Compact	0.22%	0.76%	1.05%	0.91%	0.13%	0.14%	0.02%
	Large	0.86%	3.32%	4.84%	4.84%	1.15%	1.96%	0.36%
	Large SUV	0.07%	0.31%	0.41%	0.48%	0.13%	0.20%	0.04%
	Medium	2.03%	6.85%	11.36%	10.14%	1.68%	2.34%	0.41%
Gasoline plugin hybrid	Compact							0.00%
	Large			0.03%	0.27%			0.02%
	Large SUV			0.00%	0.13%			0.01%
	Medium							

5. Fleet average vehicles for Europe

Fleet composition data for Europe (understood as EU 27 + United Kingdom) is based initially on the TRACCS database and post-processed and made available (Rottoli et al. 2021). Vehicle sub-segments were grouped into size classes according to curb mass and engine power. The results for the European fleet composition in 2020 are shown in Table 48 (sums to 100%). Some values are shown as "0.00%" as they are too small to display.

Table 48 Fleet composition data for the EU 27 + the United Kingdom in 2020, all powertrain types and size classes

		Vehicle-kilometer share within the 2020 European fleet						
		2003	2008	2013	2016	2018	2019	2020
Battery electric	Large			0.02%	0.02%	0.03%	0.02%	0.03%
	Medium			0.05%	0.04%	0.08%	0.05%	0.07%
	Compact			0.03%	0.03%	0.05%	0.04%	0.04%
Fuel cell electric	Large			0.01%	0.00%	0.00%	0.00%	0.00%
	Medium			0.02%	0.01%	0.01%	0.00%	0.00%
	Compact			0.01%	0.01%	0.01%	0.00%	0.00%
Diesel hybrid	Large	0.01%	0.02%	0.10%	0.08%	0.15%	0.10%	0.13%
	Medium	0.02%	0.05%	0.23%	0.20%	0.35%	0.24%	0.27%
	Compact	0.01%	0.03%	0.15%	0.13%	0.24%	0.16%	0.18%
Gasoline hybrid	Large		0.01%	0.04%	0.03%	0.05%	0.03%	0.05%
	Medium		0.02%	0.10%	0.08%	0.13%	0.08%	0.10%
	Compact		0.01%	0.06%	0.05%	0.09%	0.06%	0.07%
Diesel	Large	0.48%	1.45%	4.55%	2.04%	1.87%	0.91%	1.19%
	Medium	1.21%	3.62%	11.34%	5.09%	4.68%	2.27%	2.20%

		Vehicle-kilometer share within the 2020 European fleet						
		2003	2008	2013	2016	2018	2019	2020
	Compact	0.97%	2.92%	9.07%	4.07%	3.75%	1.82%	1.32%
Compressed gas	Large			0.01%	0.00%	0.00%	0.00%	0.00%
	Medium			0.02%	0.01%	0.01%	0.00%	0.00%
	Compact			0.02%	0.01%	0.01%	0.00%	0.00%
Gasoline	Large	0.23%	0.68%	1.93%	0.76%	0.66%	0.32%	0.48%
	Medium	0.57%	1.71%	4.80%	1.88%	1.64%	0.80%	0.90%
	Compact	0.46%	1.38%	3.84%	1.50%	1.32%	0.64%	0.54%
Diesel plugin hybrid	Large	0.01%	0.02%	0.06%	0.03%	0.04%	0.02%	0.03%
	Medium	0.02%	0.04%	0.15%	0.08%	0.08%	0.05%	0.05%
	Compact	0.01%	0.03%	0.10%	0.05%	0.06%	0.03%	0.03%
Gasoline plugin hybrid	Large		0.01%	0.03%	0.01%	0.01%	0.01%	0.01%
	Medium		0.02%	0.06%	0.03%	0.03%	0.02%	0.02%
	Compact		0.01%	0.04%	0.02%	0.02%	0.01%	0.01%

C. Modeling approach applicable to internal combustion engine vehicles

1. Exhaust emissions

Emission factors for CO_2 and SO_2 are detailed in Table 8-Table 9. Biofuel shares in the fuel blend are described in Table 10.

Several fuel-related emissions other than CO_2 and SO_2 are considered using the HBEFA 4.1 database (INFRAS 2019).

Six sources of emissions are considered:

- Exhaust emissions: emissions from fuel combustion during operation. Their concentration relates to fuel consumption and the vehicle's emission standard.
- Cold start emissions: emissions when starting the engine. The factor is given in grams per engine start. 2.3 engine starts per day are considered (Swiss Federal Office for the Environment 2021) and an annual mileage of 12’000 km.
- Diurnal emissions: fuel evaporation due to a temperature increase in the vehicle. The factor is given in grams per day. Emissions are distributed evenly along the driving cycle, based on an annual mileage of 12’000 km per year.
- Hot soak emissions: evaporative emissions occurring after the vehicle has been used. The factor is given in grams per trip. The emission is added at the end of the driving cycle.
- In addition, running loss emissions are emissions related to fuel evaporation (i.e., not combusted) during operation. The factor is given in grams per km, and emissions are distributed evenly along the driving cycle.
- Other non-exhaust emissions: brake, tire road wear, re-suspended road dust emissions, as well as emissions of refrigerant.

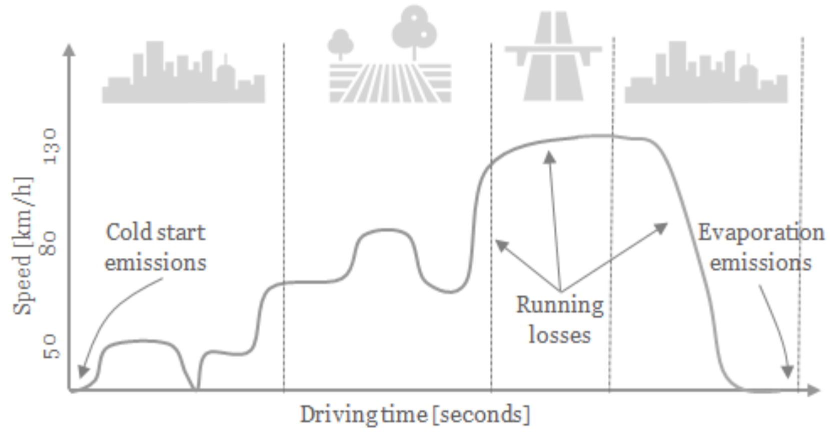


Figure 8 Representation of the different sources of emission other than exhaust emissions

For exhaust emissions, factors based on the fuel consumption are derived by comparing emission data points for different traffic situations (i.e., grams emitted per vehicle-km) in a free-flowing driving situation, with the fuel consumption corresponding to each data point (i.e., MJ of fuel consumed per km), as illustrated in Figure 9 for a diesel-powered engine. The aim is to obtain emission factors expressed in grams of a substance emitted per MJ of fuel consumed to model emissions of passenger cars of different sizes and fuel efficiency and for different driving cycles.

Important remark: the degradation of anti-pollution systems for diesel and gasoline cars (i.e., catalytic converters) is accounted for as indicated by HBEFA, by applying a degradation factor on the emission factors for CO, HC, and NO_x for gasoline cars, as well as on CO and NO_x for diesel cars. These factors are shown in Table 49 for passenger cars with a mileage of 200’000 km. The degradation factor corresponding to half of the vehicle kilometric lifetime is used to obtain a lifetime-weighted average degradation factor.

Table 49 Degradation factors at 200'000 km for passenger cars

Degradation factor at 200’000 km	**Gasoline passenger cars**			**Diesel passenger cars**	
	CO	**HC**	**NO_x**	**CO**	**NO_x**
EURO-1	1.9	1.59	2.5		
EURO-2	1.6	1.59	2.3		1.25
EURO-3	1.75	1.02	2.9		1.2
EURO-4	1.9	1.02	2	1.3	1.06
EURO-5	2		2.5	1.3	1.03
EURO-6	1.3		1.3	1.4	1.15

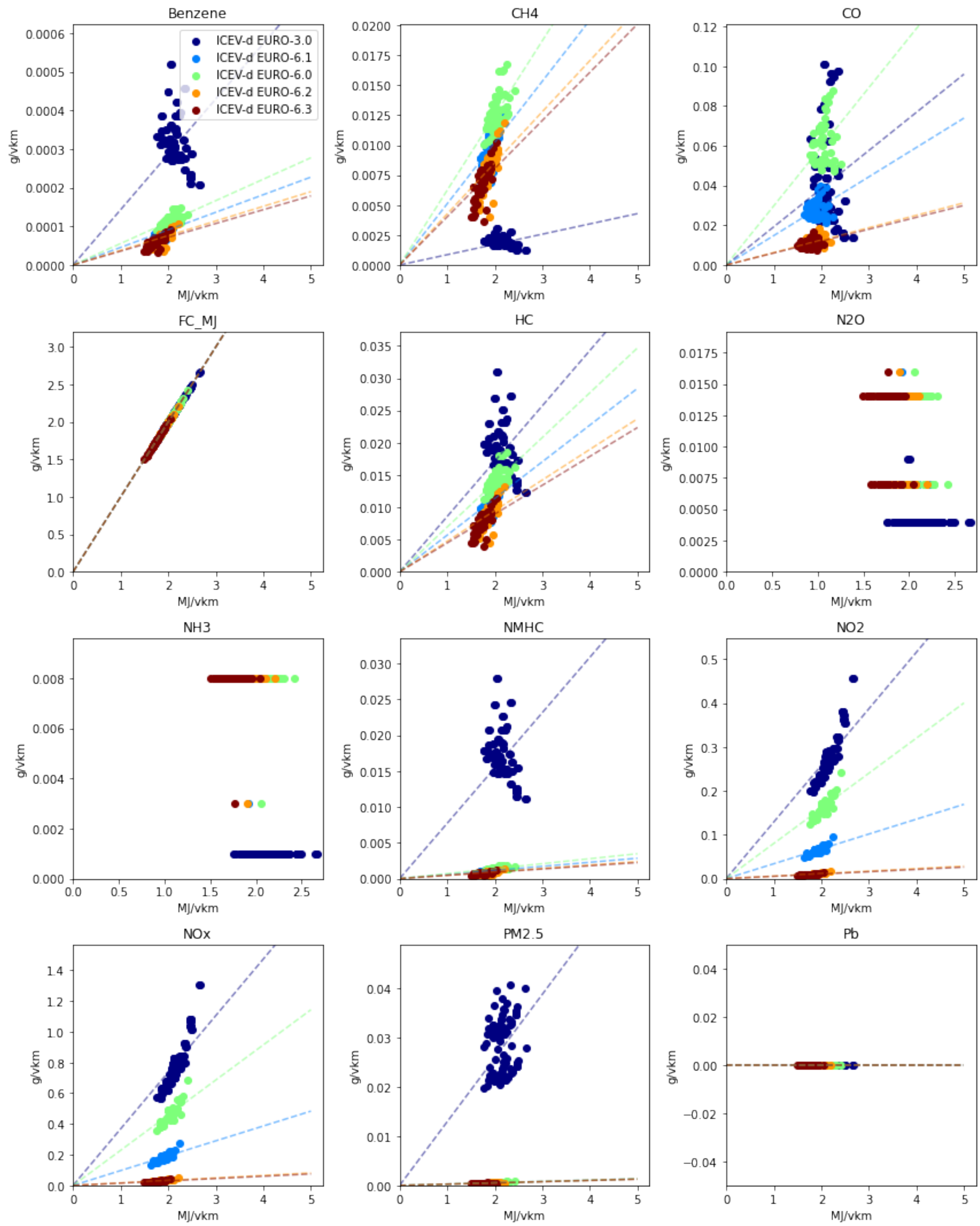


Figure 9 Relation between emission factor and fuel consumption for a diesel-powered passenger car. Dots represent HBEFA 4.1 emission factors for different traffic situations for a diesel engine with varying emission standards.

However, as Figure 9 shows, the relation between amounts emitted and fuel consumption is not always apparent. Using a linear association between amounts emitted and fuel consumption can potentially be incorrect. In addition, emissions of ammonia (NH_3) and

Nitrous oxides (N_2O) seem to be related to the emission standard (e.g., use of urea solution) and engine temperature rather than fuel consumption.

To confirm that this approach does not yield kilometric emissions too different from the emission factors per vehicle-kilometer proposed by HBEFA 4.1, Figure 10 compares the emissions obtained by *carculator* using the WLTC driving cycle over one vehicle-km (red dots) with the distribution of the emission factors for different traffic situations (green box-and-whiskers) as well as the traffic situation-weighted average emission factor (yellow dots) given by HBEFA 4.1 for various emission standards for a medium diesel-powered passenger car.

There is some variation across traffic situations, but the emissions obtained remain, for most substances, within 50% of the distributed HBEFA values across traffic situations. Also, the distance between the modeled emission and the traffic-situation-weighted average is reasonable.

Important remark: NO_x emissions for emission standards EURO-4 and 5 tend to be underestimated compared to HBEFA's values. It is also important to highlight that, in some traffic situations, HBEFA's values show that emissions of CO, HC, NMHC, and PMs for vehicles with early emission standards can be much higher than what is assumed in this study. Overall, a good agreement exists between traffic situation-weighted average emission factors and those used in this study.

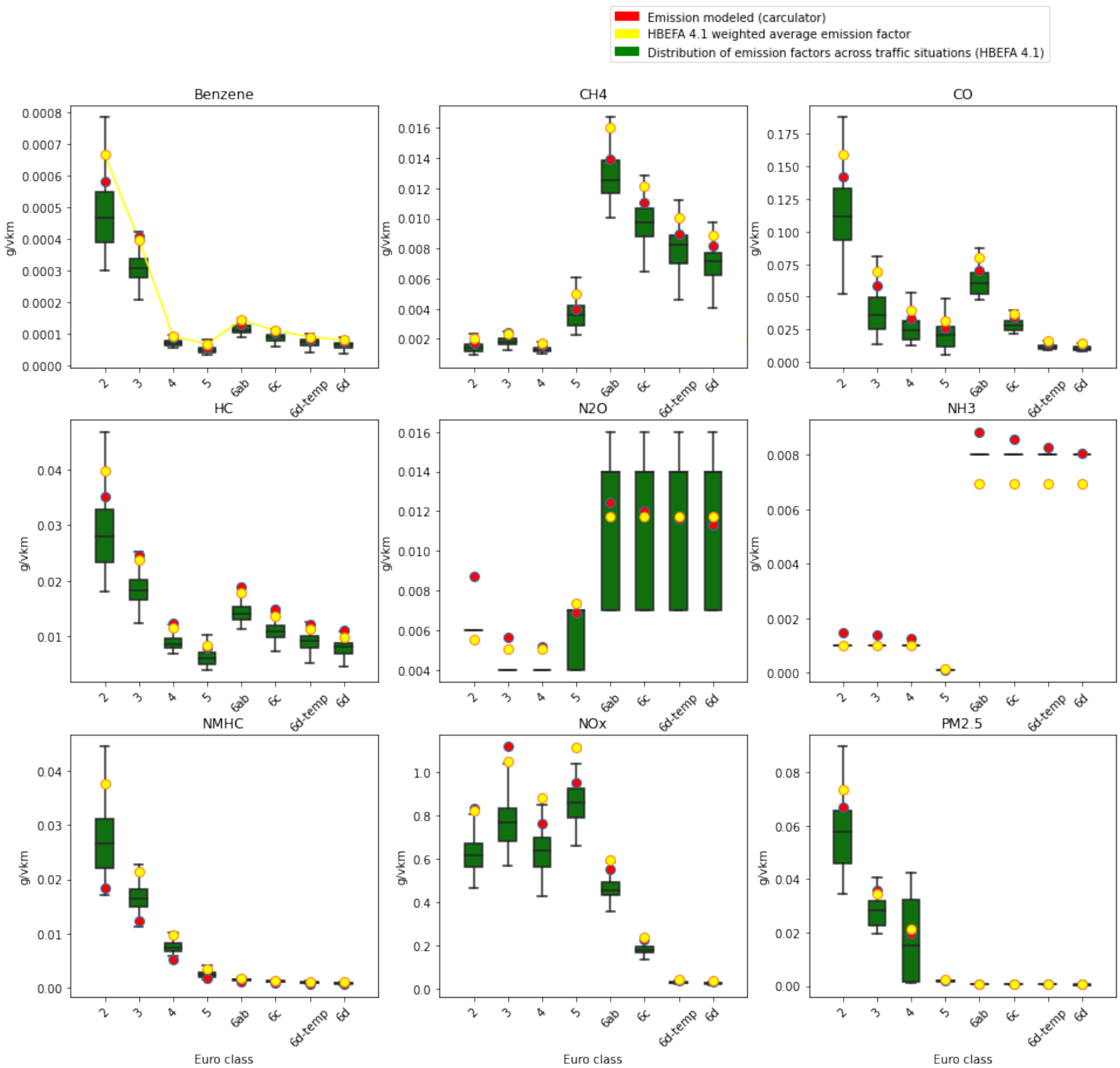


Figure 10 Validation of the exhaust emissions model with the emission factors provided by HBEFA 4.1 for a medium size diesel-powered passenger car. Box-and-whiskers: distribution of HBEFA's emission factors for different traffic situations (box: 50% of the distribution, whiskers: 90%). Yellow dots: traffic situation-weighted average emission factors. Red dots: modeled emissions calculated by *carculator* with the WLTC cycle, using the relation between fuel consumption and amounts emitted.

The following sections present the vehicles and the parameters used to derive life cycle inventories.

D. Modeling approach applicable to electric vehicles

1. Sizing of battery

The sizing of batteries for battery electric vehicles is conditioned by the battery mass, defined as an input parameter for each size class. The battery masses given for the different size classes are presented in Table 50 using the battery chemistry NMC. They are based on representative battery storage capacities available today on the market and displayed in relation to the curb mass in Figure 11. The data is collected from the vehicle's registry of Touring Club Switzerland.

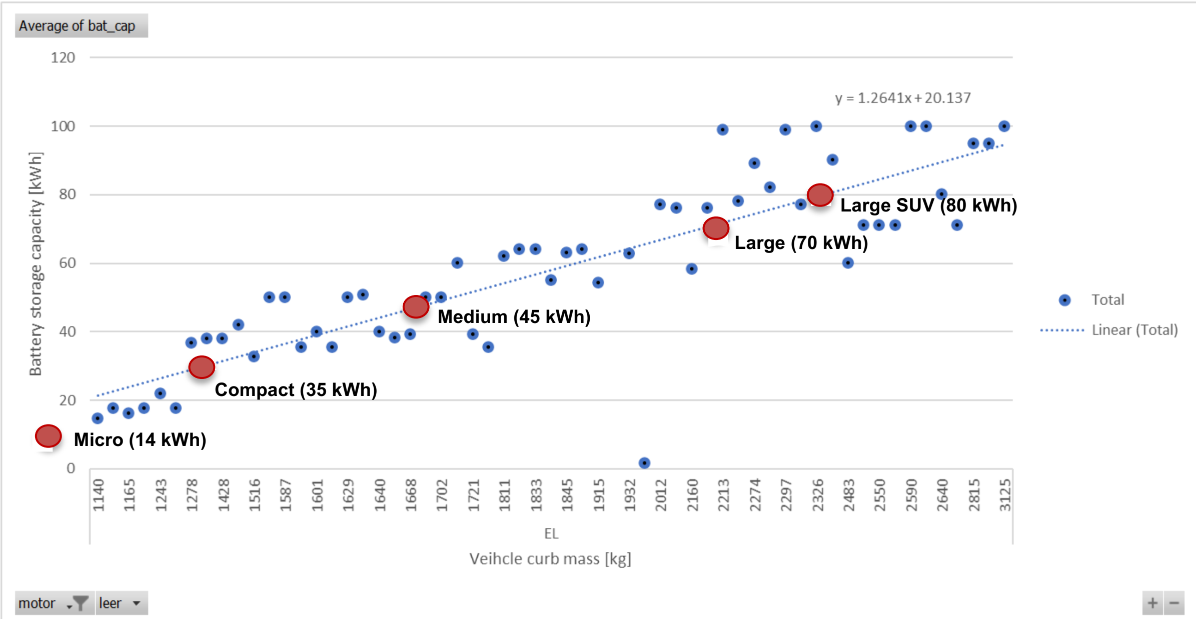


Figure 11 Energy storage capacity for current battery electric cars, shown in relation to curb mass. Red dots are the energy storage capacities used for Compact, Medium, and Large battery electric vehicles in this study.

Sixty percent of the overall battery mass is assumed to be represented by the battery cells in the case of NMC and NCA batteries. Given the energy density of the battery cell considered (which is defined for the different chemistries in Table 19), this yields the battery's storage capacity. A typical depth of discharge of 80% is used to calculate the available storage capacity.

Table 50 Parameters for battery sizing for battery electric vehicles using NMC battery chemistry

	Unit	Micro	Compact	Medium	Large	Large SUV
Storage capacity (reference)	kWh	14	35	45	70	80
Commercial models with similar energy storage capacity		Microlino, Renault Twizzy	VW e-Up!, BMW i3	Citroën ë-C4, DS 3 E.Tense, Peugeot 2008, Peugeot 208, Opel Corsa-e, VW ID.3	Audi e-Tron, Tesla Model 3	Jaguar i-Pace
Battery mass (system)	Kilogram	120	291	375	583	660
Battery cell mass	%	~60%				
Battery cell mass	Kilogram	72	175	225	330	400
Balance of Plant mass	Kilogram	48	116	150	233	260
Energy density	kWh/kg	0.2				
Storage capacity	kWh		35	45	70	80
Depth of discharge	%	80%				
Storage capacity (available)	kWh	14	28	36	56	65

Similarly, plugin hybrid vehicles are dimensioned to obtain an energy storage capacity of the battery that corresponds with the capacity of models available today. The sizing of the battery is similar to what is described above for battery-electric vehicles. The battery's energy storage capacity is essential for plugin hybrid vehicles, as it influences the electric utility factor – the share of kilometers driven in battery-depleting mode – which calculation is described in the next section.

Table 51 Parameters for battery sizing for plugin hybrid vehicles using NMC battery chemistry

	Unit	Compact	Medium	Large	Large SUV
Battery storage capacity (reference)	kWh	9	13	18	
Commercial models with similar electric and fuel storage capacity		Kia Niro, Kia Xceed	Skoda Octavia, VW Golf, Cupra Leon	Suzuki Across, VW Touareg	
Battery mass (system)	Kilogram	80	105	160	
Battery cell mass	%	60%			
Battery cell mass	Kilogram	48	63	96	
Balance of Plant mass	Kilogram	32	42	64	
Energy density	kWh/kg	0.2			
Battery storage capacity	kWh	9	13	19	
Depth of discharge	%	80%			
Battery storage capacity (available)	kWh	7.2	10.4	15.6	
Fuel tank storage capacity	L	45	52	64	

Note that plugin hybrid vehicles are only modeled with an NMC battery in this study.

Important remark: although fuel cell electric vehicles have a small battery to recover braking energy, we do not model it. For example, the Toyota Mirai has a 1.6 kWh nickel-based battery.

2. Electric utility factor

Diesel and gasoline plugin hybrid vehicles are modeled as a composition of an ICE vehicle and a battery electric vehicle to the extent determined by the share of km driven in battery-depleting mode (also called "electric utility factor").

An electric utility factor of 47% is used. It is based on a report from the ICCT (Plötz et al. 2022), which provides measured electricity utility factors for 5'808 PHEV **private** owners in Europe (mainly Germany) for vehicles built between 2011 and 2021. According to this report, a 45-49% electric utility factor was observed for privately-owned PHEV vehicles, bringing the average fuel consumption to 4-4.4 L/100 km.

We equally provide datasets for plugin hybrid diesel and gasoline cars with an electric utility factor of 0% for sensitivity.

E. Validation

To validate the energy consumption values calculated by the model, they are compared with those found in the EU-CO2-PC database for the years 2010, 2013, 2016, 2018, 2019, and 2020. However, note that the NEDC driving cycle is used for the validation exercise. It is the only driving cycle common to all the years in the database (i.e., the WLTC driving cycle started being used only in 2018).

Once the energy consumption model is calibrated, the WLTC driving cycle is used instead to obtain the final energy consumption – as it is deemed more representative of actual driving conditions than those represented by the NEDC driving cycle. The results of the calibration are shown in the figure below: red dots are energy consumption values modeled by *carculator* using the NEDC driving cycle for 2010, 2013, 2016, 2018, 2019, and 2020, while orange dots are energy consumption values calculated using the WLTC driving cycle – which tend to lead to values about 15-20% higher, in line with the findings of (Dornoff, Tietge, and Mock 2020).

According to that report, an analysis of a sample of 526 vehicles exhibited fuel consumption values 14% higher on spritmonitor.de (considered "real" consumption values) than in the EU-CO2-PC database using the WLTP driving cycle test. However, the sample size is likely too small to draw any robust conclusion, and such a correction factor cannot be used with enough confidence.

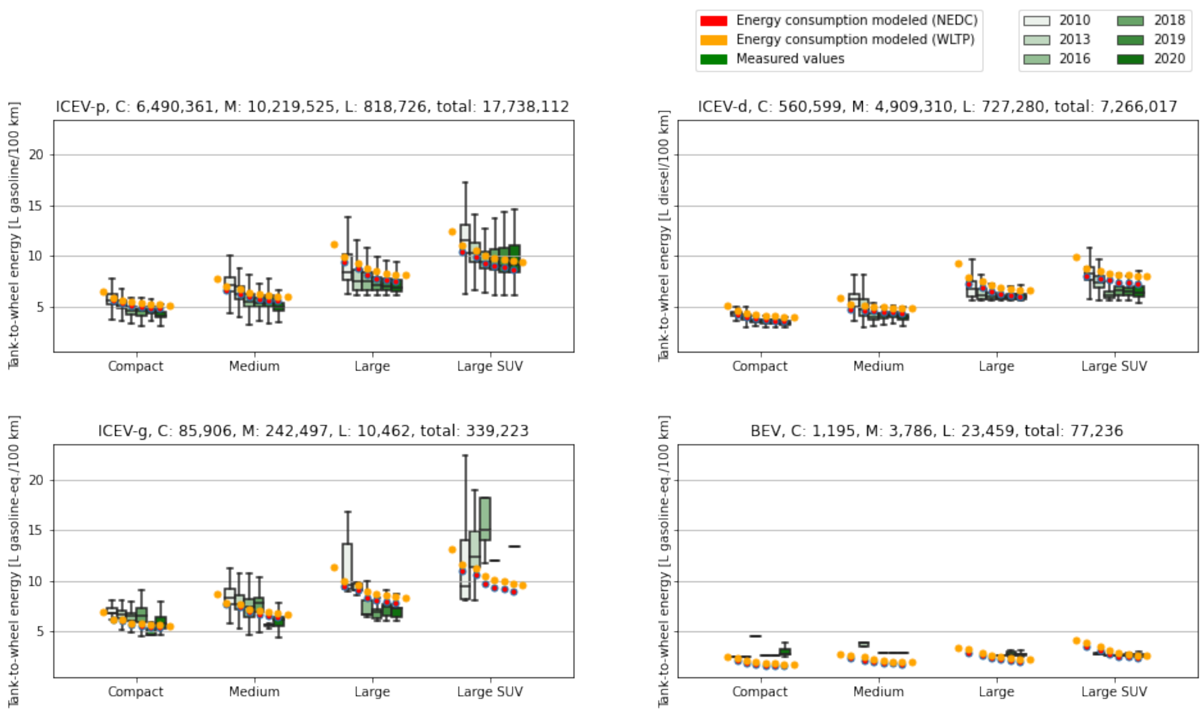


Figure 12 Energy consumption model calibration and validation against the EU-CO2-PC database. Vertical greens bars: 50% of the measured energy consumption values distribution using the NEDC driving cycle. Red dots: modeled by *carculator* using the NEDC driving cycle. Orange dots: modeled by *carculator* using the WLTC driving cycle. The energy consumption values assumed for EURO-3 and EURO-6-d vehicles correspond to the first and last orange dots. The energy consumption values are expressed in liters of gasoline equivalent per 100 km for battery electric and compressed gas vehicles. Microcars are not represented in the EU-CO2-PC database.

The energy consumption of EURO-3 vehicles is linearly approximated based on the documented efficiency of passenger cars from the year 2000 on one end (Mock et al. 2013) – given as a relative change to 2010 – and the efficiency of EURO-4 vehicles as indicated in the EU-CO2-PC database on the other end. Similarly, the energy consumption of EURO-6-d cars is assumed to be very close to that of EURO-6-temp vehicles (as only two years separate their introduction to the market).

Table 52 shows the fuel and electricity consumption of this calibration and validation exercise.

Table 52 Energy consumption for passenger cars in 2020 (EURO-d-temp or equivalent), in liters of gasoline-eq. (31.95 MJ/L gasoline), using the WLTC test cycle.

size	**powertrain**	**Fuel consumption**	**Electricity consumption** (incl. approx. 15% charger and battery charge loss)	**Gasoline-eq. consumption**
		L gasoline-eq./100 km	*kWh/100 km*	*L gasoline-eq./100 km*
Micro	**Battery electric**		12.7	1.4
Small	**Gasoline**	5.3		5.3
	Diesel	4.5		4.5
	Compressed gas	5.8		5.8
	Gasoline plugin hybrid	2.2	11.8	3.6
	Diesel plugin hybrid	2.0	11.8	3.3
	Fuel cell	3.4		3.4
	Battery electric		19.2	2.2
	Gasoline hybrid	4.5		4.5
	Diesel hybrid	3.7		3.7
Lower medium	**Gasoline**	6.2		6.2
	Diesel	5.5		5.5
	Compressed gas	7.0		7.0
	Gasoline plugin hybrid	2.1	14.3	3.7
	Diesel plugin hybrid	1.9	14.3	3.6
	Fuel cell	3.9		3.9
	Battery electric		21.4	2.4
	Gasoline hybrid	5.4		5.4
	Diesel hybrid	4.5		4.5
Large	**Gasoline**	8.3		8.3
	Diesel	7.4		7.4
	Compressed gas	8.6		8.6
	Gasoline plugin hybrid	2.3	19.6	4.5
	Diesel plugin hybrid	2.0	19.6	4.2
	Fuel cell	4.7		4.7
	Battery electric		24.6	2.8
	HEV-p	7.1		7.1
	Gasoline hybrid	6.1		6.1
Large SUV	**Diesel hybrid**	9.7		9.7
	Diesel	9.0		9.0
	Compressed gas	10.0		10.0
	Gasoline plugin hybrid	3.1	21.4	5.5
	Diesel plugin hybrid	3.0	21.4	5.4

	Fuel cell	5.5		5.5
	Battery electric		28.5	3.2
	Gasoline hybrid	8.2		8.2
	Diesel hybrid	7.5		7.5

IV. Buses

The LCA tool for urban and coach buses named *carculator_bus* is used, for which the source code is available at: https://github.com/romainsacchi/carculator_bus. The tool generates bus inventories for different powertrain types, size classes, and years of manufacture.

A. Overview

Inventories for the following powertrain types are provided:

- Diesel-run internal combustion engine vehicle (ICEV-d)
- Gas-run internal combustion engine vehicle (ICEV-g)
- Diesel-run hybrid electric vehicle (HEV-d)
- Battery electric vehicle (BEV):
    - overnight charging at depot (BEV-depot)
    - opportunity charging (BEV-opp)
    - motion-charging (BEV-motion), also commonly referred to as trolleybuses
- Fuel cell electric vehicle (FCEV)

Several size classes are available for each powertrain type, as indicated in Table 53. Some powertrain-size class combinations are not commercially available or technologically mature and are therefore not considered.

Table 53 Powertrain-size class combinations considered in this study

<table>
<tr><th>size/powertrains</th><th>ICEV-d</th><th>ICEV-g</th><th>HEV-d</th><th>FCEV</th><th>BEV-depot</th><th>BEV-opp</th><th>BEV-motion</th></tr>
<tr><td>9m (midibus)</td><td>x</td><td>x</td><td>x</td><td colspan="3" rowspan="2">Only for 2020</td><td>Not available</td></tr>
<tr><td>13m, single deck, city</td><td>x</td><td>x</td><td>x</td><td>Only for 2020</td></tr>
<tr><td>13m, single deck, coach</td><td>x</td><td>x</td><td>x</td><td colspan="3">Not available</td><td rowspan="3">Not available</td></tr>
<tr><td>13m, double deck, city</td><td>x</td><td>x</td><td>x</td><td colspan="3">Only for 2020</td></tr>
<tr><td>13m, double deck, coach</td><td>x</td><td>x</td><td>x</td><td colspan="3">Not available</td></tr>
<tr><td>18m, articulated, city</td><td>x</td><td>x</td><td>x</td><td colspan="4">Only for 2020</td></tr>
</table>

Example of midibus, 9m

Example of a single deck, city bus, 13m

Example of double deck, city bus, 13m

Example of a single deck, coach bus, 13m

Example of double deck, coach bus, 13m

Example of a single-deck city bus, 18m

Finally, for each ICE vehicle, several emission standards are considered. For simplicity, it is assumed that the vehicle manufacture year corresponds to the registration year, as indicated in Table 54.

Table 54 Buses emission standards and year of manufacture

	Start of registration	End of registration (incl.)	Manufacture year in this study
EURO-3	2000	2004	**2002**
EURO-4	2005	2007	**2006**
EURO-5	2008	2012	**2010**
EURO-6	2013	-	**2020**

B. Modeling considerations applicable to all vehicle types

1. Sizing of the base frame

The sizing of the base frame is mainly based on p.17-19 of (Hill et al. 2015). Detailed weight composition is obtained for a **Midibus, 12t,** and a **Single deck, coach, 19t**. Curb mass is obtained for all size classes. The rest is an adjusted function of the gross mass, as indicated in Table 55. These bus models correspond to the baseline year of 2010. A 2% light weighting factor, as shown in the same report, is applied to represent the industry's efforts in reducing vehicle weight in 2020.

The following components are common to all powertrains:

- Frame
- Suspension
- Brakes
- Wheels and tires,
- Electrical system
- Transmission
- Other components

Table 55 Mass of urban bus and coach systems and components

		Midibus, 12t	**Single deck, city bus, 19t**	**Single deck, city bus, 28t**	**Double deck, city bus, 26t**	**Single deck, coach, 19t**	**Double deck, coach, 26t**
	Type	rigid, 2 axles	rigid, 2 axles	articulated, 3 axles	rigid, 3 axles	rigid, 2 axles	rigid, 3 axles
in kilograms	Gross weight	12’000	19’000	28’000	26’000	19’000	26’000
Powertrain	Engine system	399	931	1’121	1’121	1’121	1’200
	Coolant system	84	116	168	130	140	182
	Fuel system	46	66	96	74	80	104
	Exhaust system	60	98	142	110	118	153
	Transmission system	451	395	571	443	476	618
Electrical system		135	183	264	205	220	286
Chassis system	Frame	472	695	1’004	778	837	1’087
	Suspension	1’032	1’490	2’153	1’669	1’795	2’331
	Braking system	149	272	393	305	328	426
	Wheels and tires	245	576	832	645	694	901
Cabin	Cabin	0	0	0	0	0	0
	Body system	4’270	5’570	8’045	6’238	6’709	8’714
Other		607	858	1’462	882	1’033	1’598
Curb mass		7’950	11’250	16’250	12’600	13’551	17’600
Payload		4’050	5’750	9’750	13’400	5’450	8’400

2. Other size-related parameters

Passenger occupancy is essential, as environmental impacts are normalized to a passenger-kilometer unit. The current version of Mobitool factors v.2.1 (BAFU 2020) uses the following occupancy values:

- “City bus”: 10 passengers
- “Autocar” (coach): 21 passengers
- “Trolleybus” (18m): 19 passengers

Similar values are used for “Single deck, city bus, 13m”, “Single deck, coach, 13m” and “Single deck, city bus, 18m” respectively. But the following occupancy values are also inferred for the remaining size classes:

- Midibus, 9m: 5 passengers (based on a 16% load factor for “Single deck, city bus, 13m”)

- Double deck, city bus, 13m: 13 passengers (based on a 16% load factor for “Single deck, city bus, 13m”)
- Double deck, coach bus, 13m: 26 passengers (based on a 38% load factor for “Single deck, coach, 13m”)

Regarding the expected lifetime of the vehicles, the Swiss vehicles registry MOFIS from the Swiss Federal Road Office (ASTRA 2021) is used. Average lifetime values for decommissioned buses in Switzerland are derived and presented in Table 56. Vehicles with a lifetime below ten years or above 30 years are considered outliers and omitted. Because the lifetime values obtained are very close to one another for all bus types but trolleybuses, 14 years is considered for those. For trolleybuses, the average value obtained is 21 years, but the sample of decommissioned vehicles is small (3). However, all of them were decommissioned at least after 20 years of use. Moreover, out of the 321 trolleybuses still in operation in 2021, a third are already 14 years or older. Hence, a lifetime value of 20 years seems representative.

Table 56 Kilometric lifetime values for urban buses and coaches

	Midibus	Single-decker, 13m	Articulated, 18m	Trolleybus (BEV-motion)	Source	Comment
Count	50	18	316	3	MOFIS vehicles registry (ASTRA 2021)	Outliers have been removed (with a lifetime inferior to 10 years or superior to 30 years).
Average lifetime [years]	15.05	14.7	14.2	21		
Lifetime value used in this study [years]	14	14	14	20		

To estimate the annual mileage driven by the different bus types, the amount of vehicle-kilometers driven by buses and trolleybuses is compared with the number of corresponding vehicles in Switzerland for that same year, as provided by the Swiss Federal Statistical Office (SFO 2021e). The results of this comparison are shown in Table 57.

Table 57 Annual mileage for buses and trolleybuses

	Year	Transport service [million vehicle-kilometer]	Vehicle stock [unit]	Annual mileage [kilometer per year]
Buses	2005	229	4’685	48’844
	2006	233	4’586	50’775
	2007	230	4’786	47’977
	2010	244	4’871	50’092
	2015	272	5’410	50’357
Trolleybuses (BEV-motion)	2005	27	606	44’490
	2006	27	606	43’913
	2007	26	596	43’216
	2010	27	606	44’554
	2015	27	548	49’507

Based on this data, an annual mileage of 50’000 km is considered for all bus types.

Other size-related parameters are listed in
Table 58. Some have been obtained or calculated from manufacturers’ data, which is available in Annex C of this report.

Table 58 Use and size parameters for urban buses and coaches.

	unit	Midibus, 9m	Single deck, city bus, 13m	Single deck, city bus, 18m	Double deck, city bus, 13m	Single deck, coach, 13m	Double deck, coach, 13m	Source
Lifetime	year	14	14 (20 for BEV-motion)	14 (20 for BEV-motion)	14	14	14	Derived from the MOFIS vehicles registry (ASTRA 2021), a similar value used by (Brian Cox et al. 2020) for buses
Annual kilometers	km	50’000	50’000	50’000	50’000	50’000	50’000	(SFO 2021e)
Lifetime	km	700’000	700’000 (1’000’000 for BEV-motion)	700’000 (1’000’000 for BEV-motion)	700’000	700’000	700’000	Calculated from the two rows above.
Average length	meter	9	13	18	13	13	13	Manufacturer s’ data.
Number of axles	unit	2	2	3 (1 driven)	3 (1 driven)	2	3 (1 driven)	
Axles load distribution	% of the total load	60% back, 40% front	60% back, 40% front	60% back, 20% middle, 20% front	60% back, 20% middle, 20% front	60% back, 40% front	60% back, 20% middle, 20% front	(European Commission 2018)
Rolling resistance coefficient	unitless, per tire	0.0055	0.0055	0.0055	0.0055	0.0055	0.0055	
Number of tires per axle	unit	2 per non-driven axle, 4 per driven axle						(European Commission 2018)
85% of tire load capacity	N	20’850						
Frontal area	square meter	6.06	8.07	8.07	9.45	8.07	9.45	Calculated from manufacturer s’ data.
Passengers capacity	unit	34	64	150	83	55	70	Manufacturer s’ data.
Passengers occupancy	unit	5	10	19	13	21	26	Inferred from Mobitool factors v.2.1 values
Load factor		16%	16%	13%	16%	38%	38%	Calculated from the two rows above.
Average passenger mass	kilogram	75						Standard assumption
Passenger luggage mass	kilogram	17						(Schoemake r 2007).

The number of axles influences several aspects of the bus's performance, notably its overall rolling resistance and the emissions associated with tire, brake, and road wear. The rolling resistance is calculated considering the number of axles, the relative load per axle, the number of tires per axle, and the driving mass of the vehicle, as presented in the documentation of VECTO (European Commission 2018).

3. Auxiliary power demand

The auxiliary power demand comprises the base power demand, the power demand from the battery management system, and the power demand from the HVAC system.

a) Base power demand

The *auxiliary power base demand* represents the power drawn from operating non-traction equipment such as the air compressor, the ticket vending machines, trip information displays, the steering compressor, etc. Vepsäläinen et al. (2019) estimate the base power load of a regular 13m-long single-decker. Considering the air compressor, the steering and braking systems, and other devices, the instant base power load ranges between 2 and 7 kW (as not all devices work simultaneously). Göhlich et al. (2018) confirm the value of 7 kW, but only when all devices work simultaneously. In the present study, a further assumption is made that such values for the base power demand are probably correlated to the size of the vehicle, as well as to the type of use (e.g., coach buses do not need to open and close doors as frequently as do urban buses). Hence, the values presented in Table 59 are considered.

Table 59 Auxiliary base power demand for different bus sizes

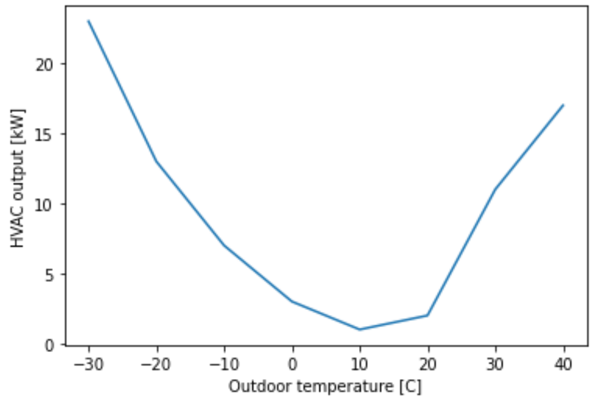
	Power base demand [kW]	Source
Midibus, 9m	2.25	From (Vepsäläinen et al. 2019) estimates the base power load to be 2 to 7kW. It is further scaled on the gross weight.
Single deck, city bus, 13m Double deck, city bus, 13m Single deck, city bus, 18m	5	
Single deck, coach, 13m Double deck, coach, 13m	3.5	

b) Battery management system power demand

According to (Göhlich et al. 2018), the battery management system requires 2.75 kW on hot summer days to cool the battery down and 0.5 kW on cold winter days to keep it warm. The average monthly daytime temperature for Switzerland is used (i.e., 12 values for the year) together with the values mentioned above (i.e., 2.75 kW and 0.5 kW) to calculate the additional load from the battery management system when the ambient temperature is above 20 degrees Celsius and below 5 degrees Celsius, respectively.

4. HVAC power demand

Estimating heating and cooling needs is a complicated matter, and unfortunately, it is also essential for BEV buses. In this study, a simplified approach is used. The following relation between HVAC power draw and ambient temperature from (Vepsäläinen et al. 2019) is used, based on a 24 kW HVAC system fitted on a 12m city bus in Finland.



Outdoor temperature [C]	-30	-20	-10	0	10	20	30	40
HVAC power output [kW]	23	13	7	3	1	2	11	17

Figure 13 Relation between ambient outdoor temperature and HVAC system power output

The HVAC system is sized according to the bus size class (i.e., from 10 kW for the midibus to 24 kW for the double-deck or articulated buses). This curve is adapted to the different bus size classes using the power load-to-maximum HVAC power ratio depicted above.

For BEV-buses, the HVAC is fitted with a heat pump, with the following Coefficients of Performance (CoP), taken from (Suh et al. 2015):

- CoP of 2.3 for heating
- CoP of 1.3 for cooling

For ICE buses, it is assumed that the excess heat from the engine is sufficient to warm the passengers' cabin to a comfortable temperature.

Important assumption: Although data cannot confirm this, coach buses likely have lower HVAC power requirements. They do not open doors as frequently and are generally better insulated (notably through double-glazed windows). Hence, coach buses are assumed to have an overall HVAC power requirement **20%** lower than city buses.

Figure 14 compares the different auxiliary energy components between a 13m single-deck BEV and ICEV-d bus for city and intercity use, the outdoor ambient temperature function.

Important remark: the 13m single-deck BEV intercity bus (i.e., coach) is only shown for this purpose, as the model would not validate such a bus (at least, not in 2020, as the battery would make the bus heavier than its permitted gross mass when fully occupied).

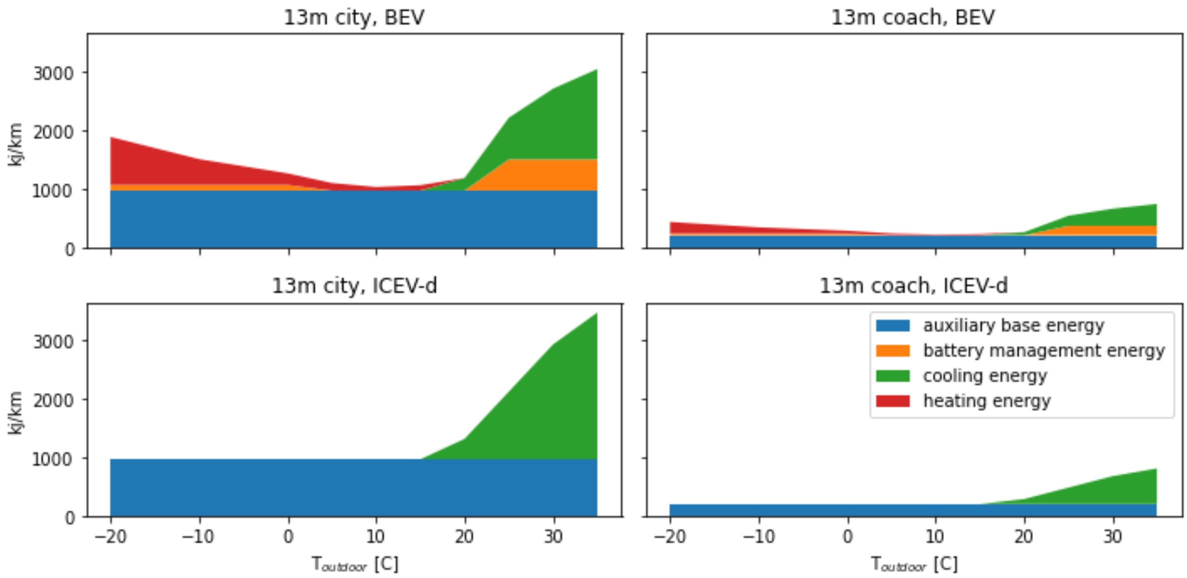


Figure 14 Auxiliary energy consumption as a function of outdoor ambient temperature

Because the auxiliary energy depends on time and not on distance, it is more of an issue for city buses when normalized per km, as they have an average speed of 2-to-3 times as low as that of a coach bus.

However, buses do not constantly operate at -20°C or +30°C. This is why pre-set monthly daylight average temperature series are used.

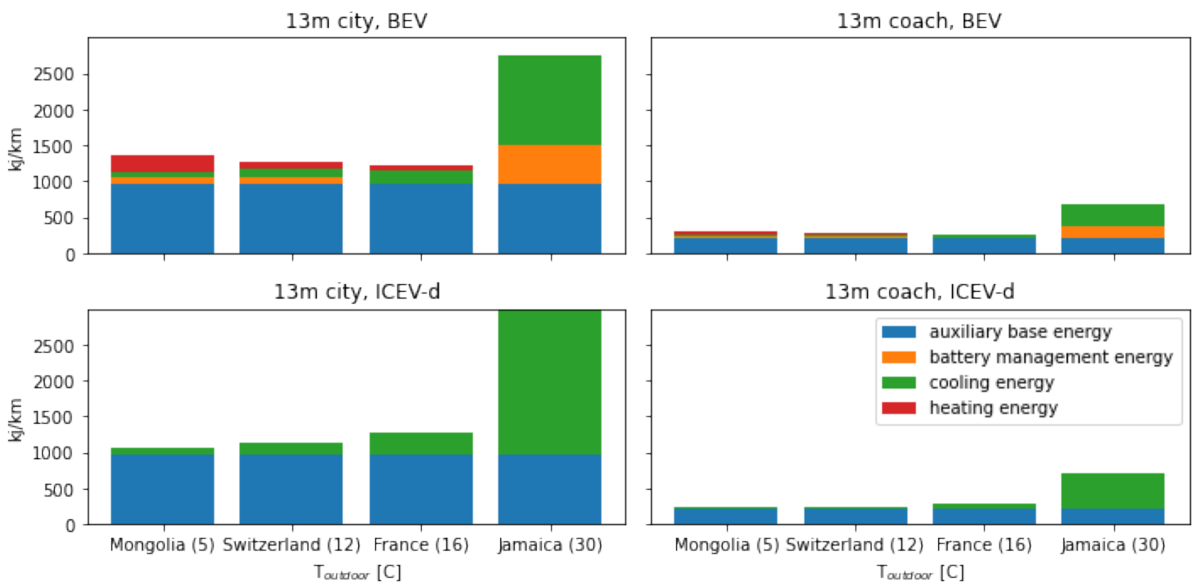


Figure 15 Auxiliary energy consumption for different countries, based on their yearly average daytime temperature

But does this matter compared to the traction energy?

Figure 16 shows the energy consumption[6] of a 13m-long single-deck bus for urban and intercity use, including the traction energy. The values are normalized to one vehicle-kilometer as a function of the ambient temperature.

It seems that the power draw from the HVAC system can potentially be an issue, but primarily for urban electric buses and, to a lesser extent, inter-city electric buses (provided they are a viable option, which they are not currently). It seems auxiliary energy represents 25% of the tank-to-wheel energy consumption in normal conditions and goes up to 30% and 40% in very cold and hot conditions, respectively. This is as much energy not available for traction purposes (i.e., which directly affects the vehicle's range autonomy).

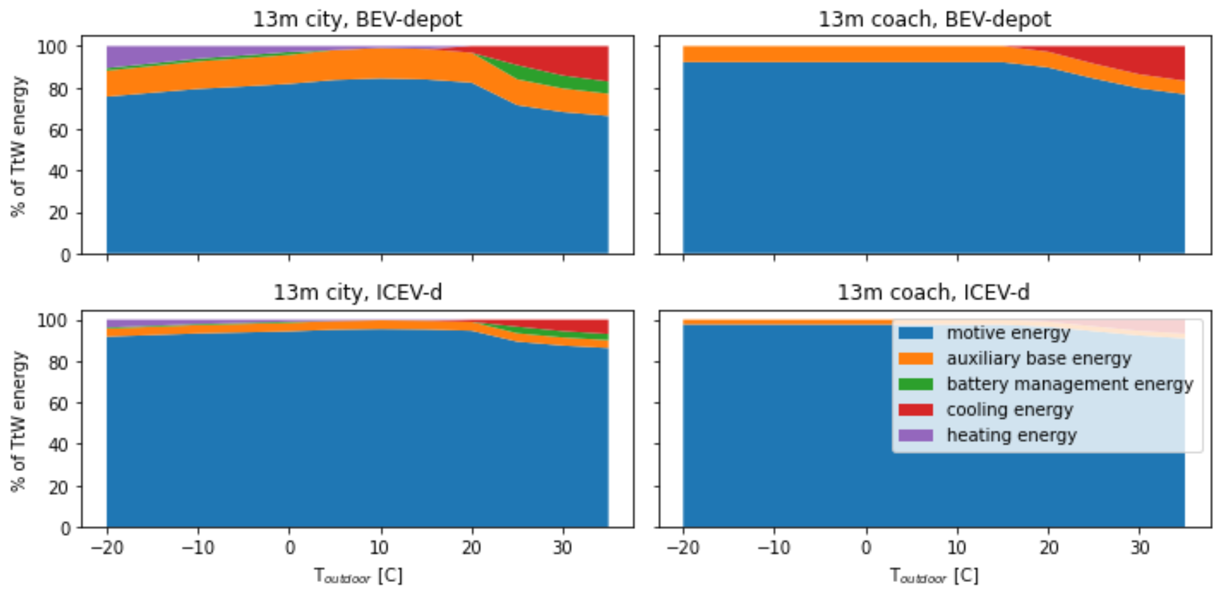


Figure 16 Distribution of the tank-to-wheel energy use for a single-deck 13m bus function of the ambient outdoor temperature

5. Abrasion emissions

Figure 17 shows the calculated abrasion emissions for buses in mg per vehicle-kilometer, following the approach presented in Section I.C.5.b.

[6] The modeling of the traction energy is explained in the next section.

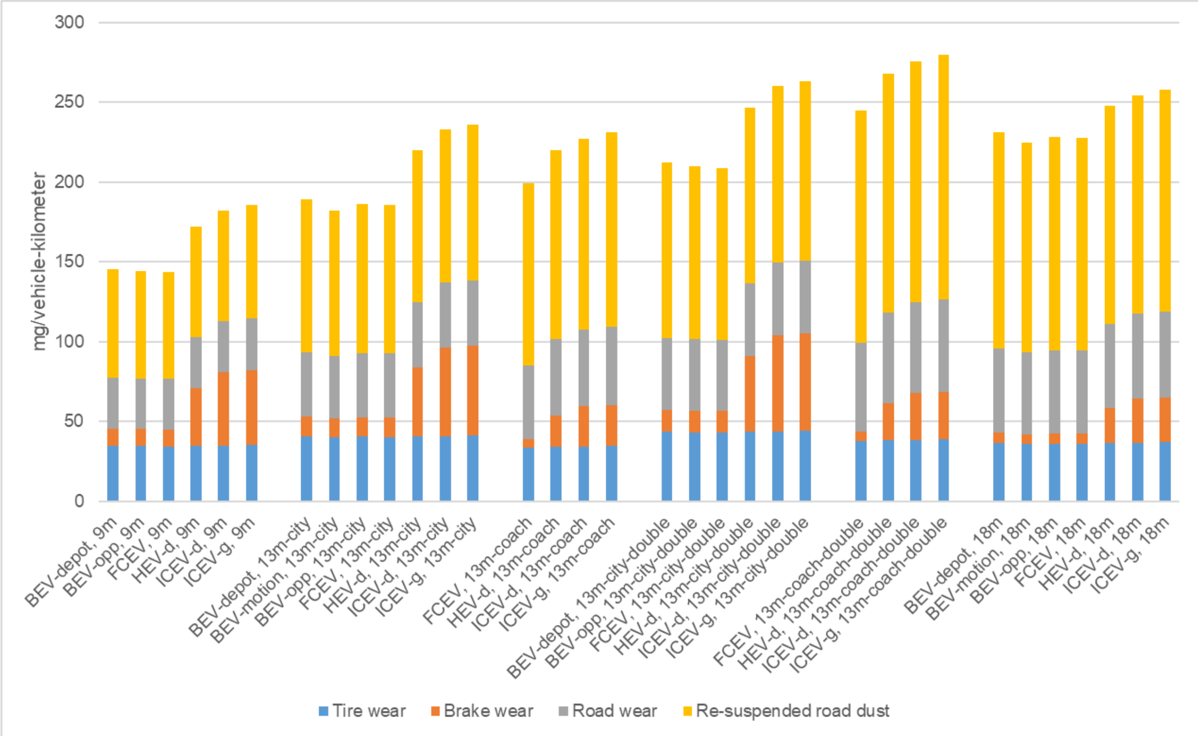


Figure 17 Total particulate matter emissions (<2.5 µm and 2.5-10 µm) in mg per vehicle-kilometer for buses.

C. Modeling approach applicable to internal combustion engine vehicles

1. Traction energy

The traction energy for city buses is calculated based on the "Urban" driving cycle for buses provided by VECTO (European Commission 2018). Simulations in VECTO are run with buses modeled as closely as possible to those of this study to obtain the performance along the driving cycle (e.g., speed, friction losses, and fuel consumption, among others). Figure 18 shows the first two hundred seconds of that driving cycle, distinguishing the target speed from the actual speed managed by the different vehicles. The power-to-mass ratio influences how much a vehicle manages to comply with the target speed.

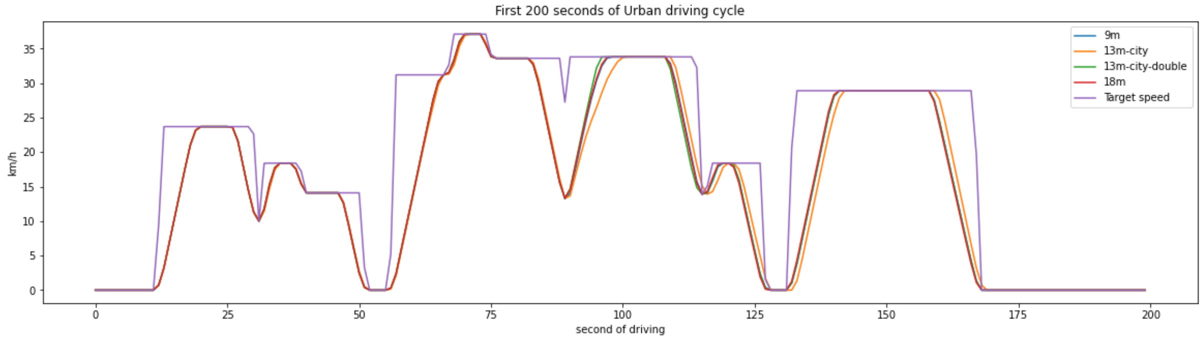


Figure 18 VECTO's Urban driving cycle (first two hundred seconds)

Road gradients are also considered. Figure 19 shows the road gradient profile of the urban driving cycle.

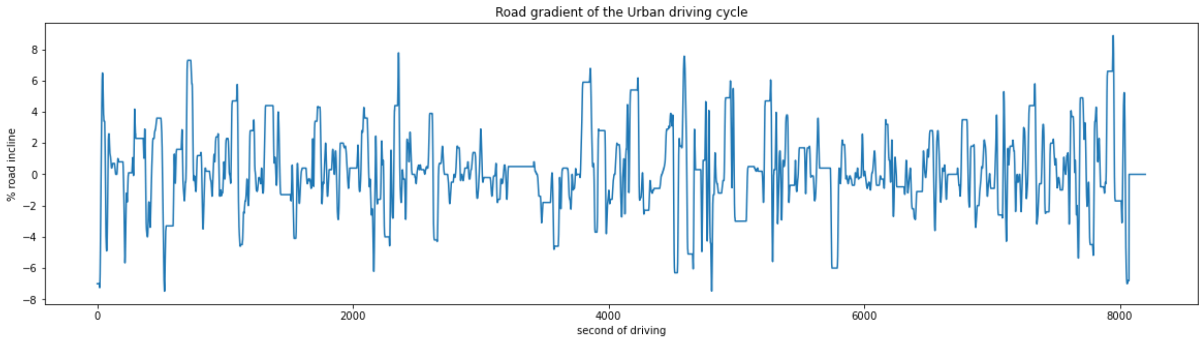


Figure 19 Road gradients corresponding to VECTO's urban driving cycle.

For coach buses, VECTO's "Intercity" driving cycle is used. This cycle has fewer stops and less fluctuation in terms of speed levels, and it also has a higher average speed level and lasts much longer. The first two hundred seconds of that driving cycle are depicted in Figure 20.

Figure 20 VECTO's Intercity driving cycle (first two hundred seconds)

Table 60 compares some of the parameters of both driving cycles.

Table 60 Parameters for "Urban" and "Intercity" driving cycles

	Average speed [km/h]	**Distanc e [km]**	**Driving time [s]**	**Idling time [s]**	**Mean positive acceleration [m.s^2]**
Midibus, 9m Single deck, city bus, 13m Double deck, city bus,	26	40	~7'700	~2'730	0.56

13m Single deck, city bus, 18m					
Single deck, coach, 13m Double deck, coach, 13m	57	275	~18'000	~390	0.29

The energy consumption model is similar to that of passenger cars: the sum of the different resistances at the wheel is calculated, after which friction-induced losses along the drivetrain are considered to obtain the energy required at the tank level.

VECTO's simulations are again used to calibrate the engine and transmission efficiency of diesel and compressed gas buses. Similar to the modeling of delivery, medium- and heavy-duty trucks, the relation between the efficiency of the drivetrain components (i.e., engine, gearbox, and axle) and the power load-to-peak-power ratio is used.

A calibration exercise with VECTO for the diesel-powered 13m city bus is shown in Figure 21. After calibration, the tank-to-wheel energy consumption value obtained from VECTO and *carculator_bus* for diesel-powered buses differ by less than 1 percent over the entire driving cycle.

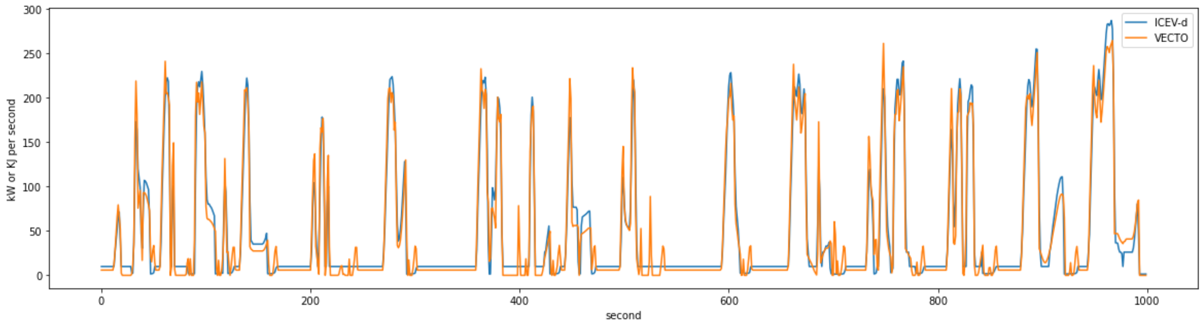


Figure 21 Calibration of carculator_bus energy model against VECTO simulations for a single deck 13m long diesel bus (first 1'000 seconds shown)

Unfortunately, VECTO does not have a model for compressed gas-powered buses. Therefore, correction factors for fuel efficiency relative to diesel buses are derived from HBEFA 4.1 and presented in Table 61. They are calculated from the average difference in fuel efficiency between compressed gas and diesel buses across similar traffic situations and size classes.

Table 61 Difference in fuel economy between diesel and compressed gas urban and coach buses for similar traffic situations

HBEFA size class	Urban traffic situations	Rural traffic situations
Midi <15t	**+10%** (applicable to " Midibus, 9m")	
15-18t	**+3%** (relevant to "Single deck, city bus, 13m")	**+20%** (relevant to "Single deck, coach, 13m")
>18t	**+1%** (relevant to "Single deck, city bus, 18m" and "Double deck, city bus, 13m")	**+20%** (relevant to "Double deck, coach, 13m")

Important remark: the engine and gearbox efficiencies (and the resulting tank-to-wheel consumption) are calibrated against VECTO's simulations, but the relative change in efficiency throughout time (i.e., along emission standards) is calibrated against HBEFA's data.

2. Exhaust emissions

Emission factors for CO_2 and SO_2 are detailed in Table 8-Table 9. Biofuel shares in the fuel blend are described in Table 10.

As with passenger cars and trucks, several fuel-related emissions other than CO_2 or SO_2 are considered. The emission factors of the HBEFA 4.1 database are used.

For buses, two sources of emissions are considered:

- Exhaust emissions: emissions from the combustion of fuel during operation. Their concentration relates to fuel consumption and the vehicle's emission standard.
- Non-exhaust emissions: brake, tire, and road wear emissions, as well as emissions of refrigerant and noise.

For exhaust emissions, factors based on the fuel consumption are derived by comparing emission data points for different traffic situations (i.e., grams emitted per vehicle-km) in free-flowing driving conditions, with the fuel consumption corresponding to each data point (i.e., MJ of fuel consumed per km), as illustrated in Figure 22 for a diesel-powered engine. The aim is to obtain emission factors expressed as grams of a substance emitted per MJ of fuel consumed to model emissions of buses of different sizes and mass operating on different driving cycles.

Important remark: the degradation of anti-pollution systems for EURO-6 diesel buses (i.e., catalytic converters) is accounted for, as indicated by HBEFA 4.1, by applying a degradation factor on the emission factors for NO_x. These factors are shown in Table 62 for buses with a mileage of 890’000 km. Since the diesel buses in this study have a kilometric lifetime of 700’000 km, degradation factors are interpolated linearly (with a degradation factor of 1 at Km 0). The degradation factor corresponding to half of the vehicle kilometric lifetime is used to obtain a lifetime-weighted average degradation factor.

Table 62 Degradation factors at 890'000 km for diesel buses

Degradation factor at 890’000 km	
	NO_x
EURO-6	1.3

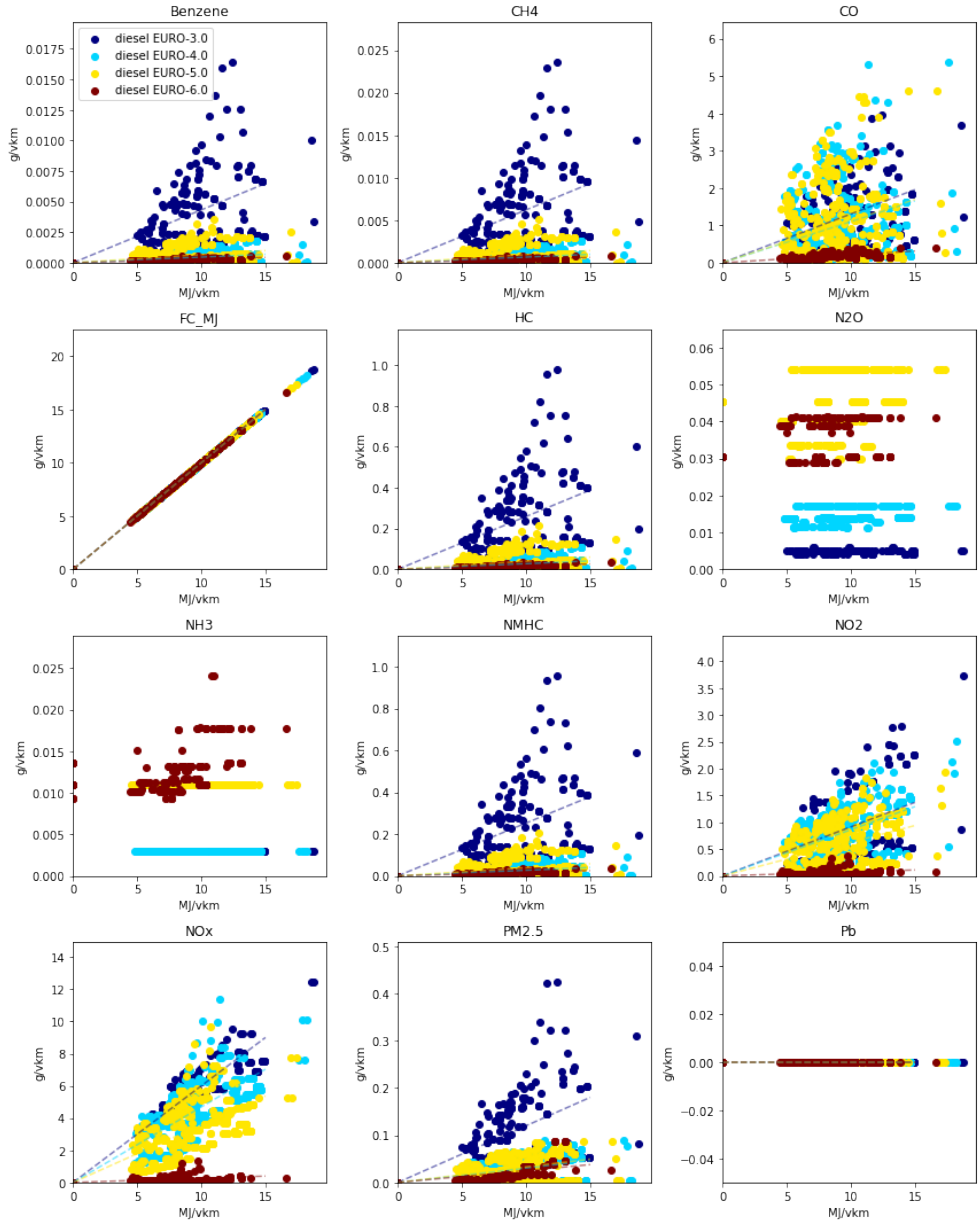


Figure 22 Relation between emission factors and fuel consumption for a diesel-powered urban bus for several “urban” traffic situations

Using these fuel-based emissions factors, emissions for each second of the driving cycle for each substance are calculated.

To confirm that such approach does not yield kilometric emissions too different from the emission factors per vehicle-kilometer proposed by HBEFA 4.1, Figure 23 compares the emissions obtained by *carculator_bus* using VECTO's "Urban" driving cycle over one vehicle-km (red dots) for the "Single deck, city bus, 13m" with the distribution of the emission factors across different "urban" traffic situations (green box-and-whiskers) as well as the traffic-situation-weighted average emission factors (yellow dots) given by HBEFA 4.1 for various emission standards for a bus with a gross mass of 15-18 tons.

There is some variation across HBEFA's urban traffic situations. Still, the emissions obtained remain, for most substances, within 50% of the distributed HBEFA values across traffic situations, except for N_2O and NO_x, which are slightly under and overestimated, respectively. Those two substances are also underestimated compared to the traffic situation-weighted average emission factors given by HBEFA 4.1, especially for early emission standards. These deviations can be explained by a different underlying driving cycle to calculate fuel consumption and related emissions. The comparison between the model's emission results for the intercity driving cycle using coach buses and HBEFA's emission factors for "rural" traffic situations shows a similar picture.

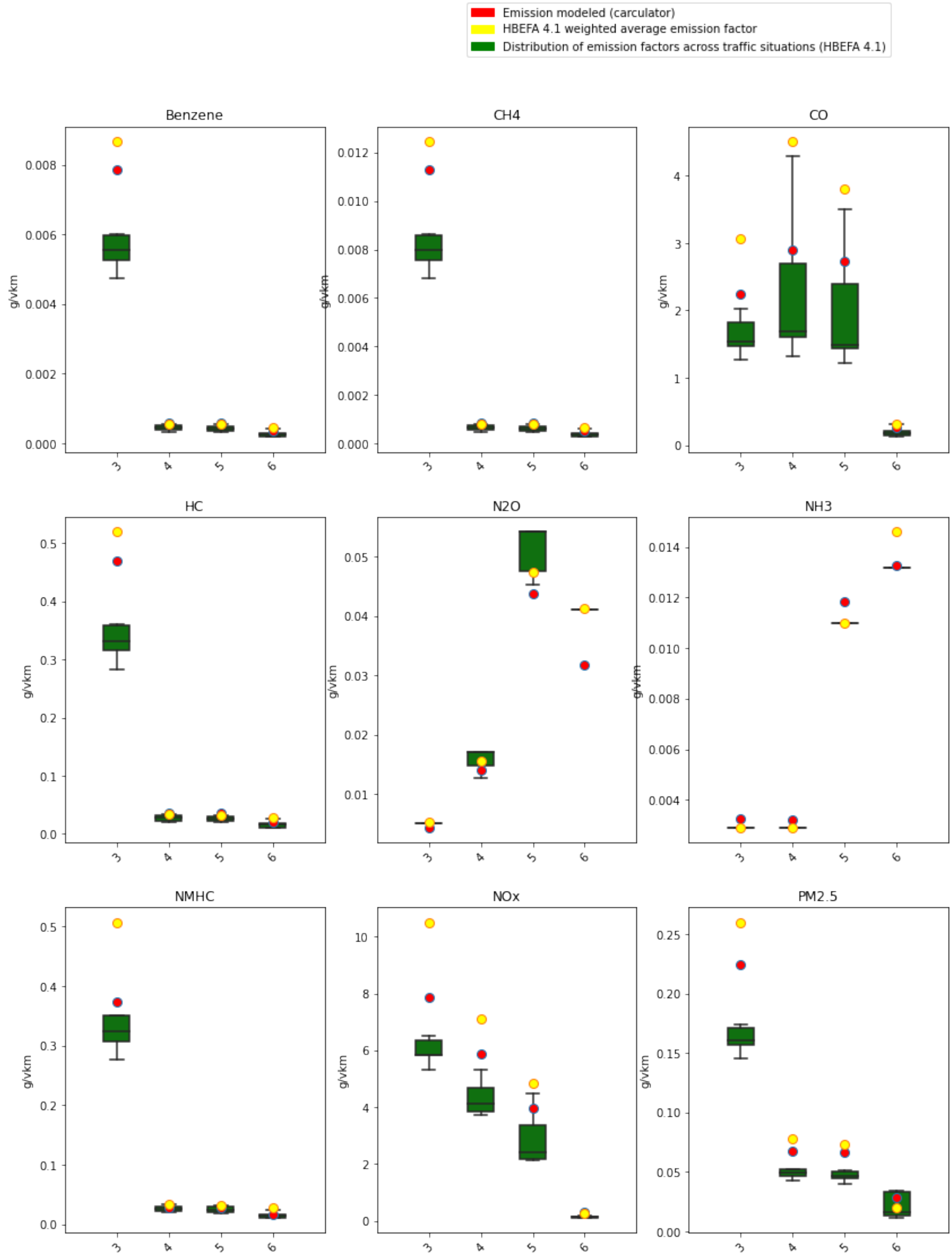


Figure 23 Validation of the exhaust emissions model with the emission factors provided by HBEFA 4.1 for urban buses in traffic situations of “urban” type. Box-and-whiskers: distribution of HBEFA’s emission factors for different “urban” traffic situations (box: 50% of the distribution, whiskers: 90%). Yellow dots: traffic situation-weighted average emission

factor given by HBEFA 4.1. Red dots: modeled emissions calculated by *carculator_bus* with the “Urban” driving cycle for a 13m single deck urban bus, using the relation between fuel consumption and amounts emitted.

D. Modeling approach applicable to electric vehicles

1. City bus itinerary parameters

For electric buses, a few parameters affect their charging strategy and the sizing of the battery, and they are crucial to detail.

The second edition of the ZeEUS eBus project report (Guida and Abdulah 2017) extracts statistics on routes serviced by electric city buses in Europe, presented in Table 63. It is found that motion-charging buses are operated significantly longer than depot- and opportunity-charging buses per shift (a shift is understood as the operation time between two deep charges at the bus depot). It is also found that opportunity-charging buses are operated over a slightly longer distance than depot-charging buses, although not to a significant extent. Based on the average distance driven per shift, the average operation time for each electric bus type is calculated. Because the resulting values for opportunity- and depot-charging buses are very close (i.e., 6.5 hours against 6 hours), a similar operation time of 6 hours is assumed. All these parameters are presented in Table 64.

	BEV-opp	BEV-depot	BEV-motion	Source	Comment
Route count	23	31	12	(Guida and Abdulah 2017)	
Average distance driven per shift [km]	170	156	310		
Average operation time per shift (in motion) [h]	6	6	12		Calculated based on the average speed of VECTO’s driving cycle for city buses.

Table 63 Statistics on electric bus routes in Europe

For coach buses, it is assumed they drive 9 hours per day (corresponding to the limit set by the EU and Swiss legislation if only one driver is present).

Finally, using a pantograph system, opportunity-charging electric buses (BEV-opp) can charge once per trip. In-motion-charging electric trolleybuses (BEV-motion) follow an itinerary where 40% to 70% of the trip distance is equipped with overhead electrical lines to allow for charging, based on (Randacher, Lokalbahnen, and Steiner 2015) but also based on the battery capacity featured on current models on the market.

Table 64 Use-related parameters for the different electric buses

		City			**Source**	**Comment**
powertrain	***unit***	**BEV-opp**	**BEV-depot**	**BEV-motion**		
Operation time per shift (in motion)	hours	12	6	6	Based on statistics from (Guida and Abdulah 2017)	As shown above.
Distance per shift	km	310	~155	~155		
Number of trips per shift	unit	8	5	8		Calculated.

		City			Source	Comment
powertrain	***unit***	**BEV-opp**	**BEV-depot**	**BEV-motion**		
Average speed	km/h	26	26	26	VECTO (European Commission 2018)	Given by the driving cycle.
Distance per trip	km	40	40	40		Given by the driving cycle.
Charging opportunity per trip	unit	1	-	-		Assumed.
Share of trip distance with catenary	ratio	-	-	0.4 - 0.7	Based on (Randacher, Lokalbahnen, and Steiner 2015) but further adjusted to match the battery sizes observed on the market.	

2. Traction energy

a) Electric vehicles

VECTO does not have a model for battery or fuel-cell electric buses. Therefore, constant efficiency values for the engine and drivetrain for electric buses in driving and recuperation mode from (Schwertner and Weidmann 2016) are used. They are detailed in Table 65 and Table 66.

Table 65 Efficiency values along the drivetrain of electric buses in driving mode

Eff. of subsystem	**Fuel cell bus**	**BEV bus**	**Trolleybus**
Fuel tank	0.98		
Energy storage		0.92	
Fuel cell stack	0.55		
Converter		0.98	
Rectifier			
Inverter	0.98	0.98	0.98
Electric motor	0.93	0.93	0.93
Reduction gear	0.95	0.95	0.95
Drive axle	0.94	0.94	0.94
Total	0.44	0.73	0.81

Table 66 Efficiency values along the drivetrain of electric buses in recuperation mode

Eff. of subsystem	**Fuel cell bus**	**BEV bus**	**BEV-motion**
Drive axle	0.94	0.94	0.94
Reduction gear	0.95	0.95	0.95
Electric motor	0.93	0.93	0.93
Rectifier	0.98	0.98	0.98
Converter	0.98	0.98	
Energy storage	0.85	0.85	0.85
Converter	0.98	0.98	
Inverter	0.98	0.98	0.98

Eff. of subsystem	Fuel cell bus	BEV bus	BEV-motion
Electric motor	0.93	0.93	0.93
Reduction gear	0.95	0.95	0.95
Drive axle	0.94	0.94	0.94
Total	0.54	0.54	0.56

3. Energy storage

a) Battery electric buses

The sizing of the energy storage unit for battery electric buses is sensitive to a few parameters, such as the operation time per shift, the number of charging opportunities per trip, the share of the bus line length equipped with overhead lines, and of course, the specific energy density of the battery cells and the amplitude of charge cycles. Furthermore, a 20% margin on the battery capacity is added for emergency or unexpected use.

Important remark: *carculator_bus* models all buses. However, suppose a battery electric vehicle (or other) has an energy storage unit mass leading to a fully occupied driving mass superior to the maximum allowed gross mass. In that case, it will not be processed for LCI quantification, which is typically the case for battery electric coach buses.

Important remark: overnight charging vehicles (BEV-depot) use a **Li-NMC battery** by default (but inventories with an NCA and LFP battery are also considered), while opportunity- (BEV-opp) and in motion-charging (BEV-motion) vehicles use a **Li-LTO** battery. According to (Göhlich et al. 2018), Li-LTO batteries are better suited for general ultra-fast charging and under extreme temperatures in particular. This is also confirmed by recent trends, although some models designed for ultra-fast charging can use Li-NMC and Li-LFP batteries.

Important remark: According to (Xiao 2019), Li-LFP batteries equip electric buses in Europe, but the vast majority are used in Asia, China in particular. 95% of the battery electric buses in China are equipped with Li-LFP batteries. Outside of China, it is 47% only. Sill according to (Xiao 2019), the European market seems to favor depot-charging buses with large Li-NMC batteries over opportunity- or motion-charging buses. In 2018, China accounted for 98% of the new battery-electric buses registered globally.

The expected battery lifetime (and the need for replacement) is based on the expected battery cycle life, based on theoretical values given by (Göhlich et al. 2018) as well as some experimental ones from (Preger et al. 2020). Although the specifications of the different battery chemistries are presented in Table 19, they are also repeated in

Table 67.

Table 67 Parameters for different battery chemistries for battery electric buses

	unit	LFP	LTO	NMC	NCA
Cell voltage	V	3.2	2.3	3.6	3.6
Cell capacity	Ah	1.4-4.5	2.0-6.5	3.7-5.3	4.8
Energy density	Wh/kg cell	115-146	76-77	175-200	200-230
Charge rate		1C	4C-10C	2C-3C	2C-3C
Cycle life (at 100% DoD)	unit	7000+	5’000-7’000	2’000	1’000
Corrected cycle life	unit	7’000	7’000	3’000	1’500

Given the vehicle's energy consumption and the required battery capacity, *carculator_bus* calculates the number of charging cycles needed and the resulting number of battery replacements, given the chemistry-specific cycle life of the battery. As discussed at the beginning of this report, the expected cycle life is corrected.

Considering the chemistry-specific cycle life values, there is a difference in the extent battery cell degrades over charging cycles. It is explained by the fact that Li-LTO batteries are charged with a smaller charge cycle amplitude (about 40-50%, against 80% for Li-NMC batteries). This also leads to an important sizing factor. The Li-NMC battery of the BEV-depot bus needs replacing multiple times during the vehicle's lifetime, while the Li-LTO battery of ultra-fast charging buses only requires one replacement. The number of replacements is even higher when using Li-NCA batteries, as the expected cycle life is comparatively lower.

Table 68 shows the battery sizing factors considered.

Table 68 Sizing factors used for different battery chemistries

	Ultra-fast charging (pantograph, induction, overhead wires)	Fast-charging (plug-in station)
Battery chemistries	**LTO**	**NMC, NCA, LFP**
Maximum SoC	90%	100%
Maximum DoD	40%	20%
Sizing factor	2	1.25
Additional margin in capacity	+20%	+20%

The effect of switching the battery chemistry for each type of electric bus can be quantified, as Figure 24 illustrates. While Li-LFP and Li-LTO batteries lead to fewer replacements, they are also heavier and result in higher energy consumption – and the necessity to increase the battery storage capacity consequently.

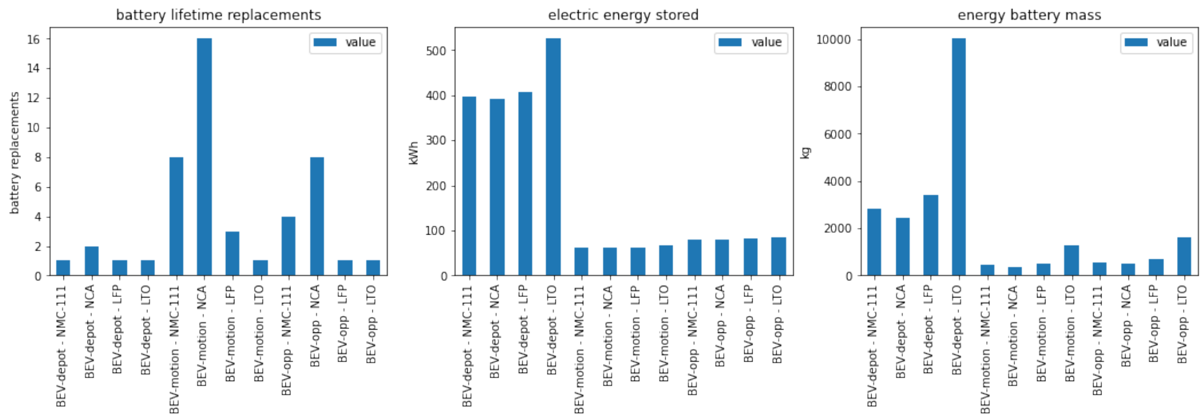


Figure 24 Effect of battery chemistry on the number of replacements, battery capacity, and mass for a 13m long single deck city bus.

Table 69 indicates the number of battery replacements considered for each type of battery chemistry.

Table 69 Lifetime battery replacements for different battery chemistries

	NMC	LFP	NCA	LTO
Bus, opportunity charging				1
Bus, motion charging				1
Bus, depot charging	1	1	2	

b) Fuel cell electric buses

The energy storage unit of fuel cell electric buses is sized based on the required amount of hydrogen onboard (i.e., defined by the required range autonomy). The relation between hydrogen and tank mass is derived from manufacturers' specifications – mainly from (Hua et al. 2010; Quantum 2019), as shown in Figure 41.

We start from the basis that fuel cell electric buses are equipped with 650 liters cylinders, which contain 14.4 kg hydrogen at 700 bar, for an (empty) mass of 178 kg. The required size and mass of the tank eventually depend on the number of hours of service but should not exceed 300 kg, excluding the hydrogen.

The hydrogen tank is of type IV, a carbon fiber-resin (CF) composite-wrapped single tank system, with an aluminum liner capable of storing 5.6 kg usable hydrogen, weighting 119 kg per unit (of which 20 kg is carbon fiber), which has been scaled up to 178 kg for a storage capacity of 14.4 kg to reflect current models on the market (Quantum 2019). The inventories are initially from (Hua et al. 2010). The inventories for the carbon fiber supply are from (Benitez et al. 2021). Note that alternative hydrogen tank designs exist, using substantially more carbon fiber (up to 70% by mass): this can potentially impact results as carbon fiber is very energy-intensive to produce.

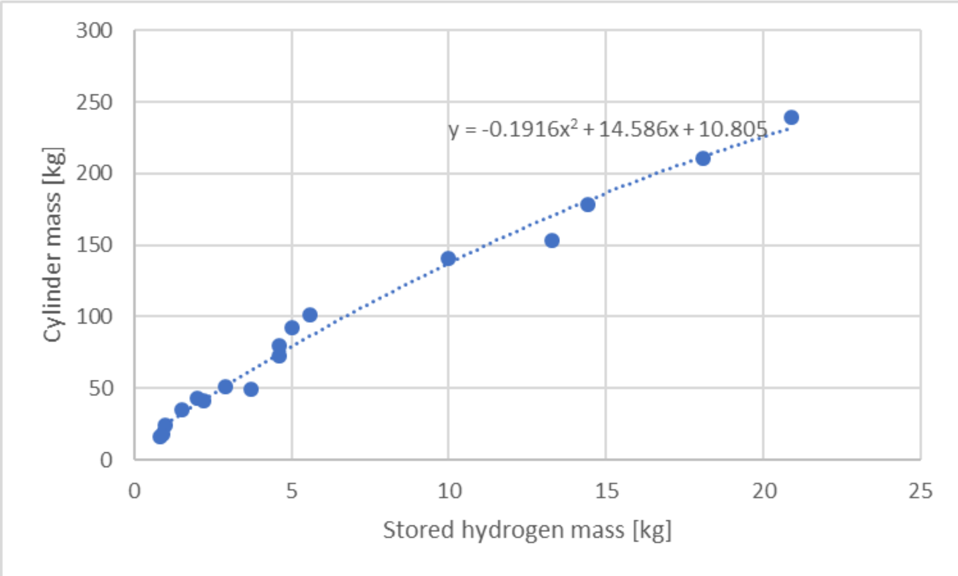


Figure 25 Relation between stored hydrogen mass and hydrogen storage cylinder mass

Inventories for Type IV hydrogen tanks from (Benitez et al. 2021) are used to that effect.

Important remark: a battery is also added to fuel cell electric buses. Based on the manufacturer's specification, its storage capacity represents approximately 9% of the storage capacity of the hydrogen cylinders, with a minimum capacity of 20 kWh.

c) Compressed gas buses

For compressed gas buses, the energy storage is in a four-cylinder configuration, with each cylinder containing up to 57.6 kg of compressed gas – 320 liters at 200 bar.

The relation between the compressed gas and the cylinder mass is depicted in Figure 26. This relation is based on manufacturers' data – mainly from (Daimler Trucks 2017; QTWW 2021).

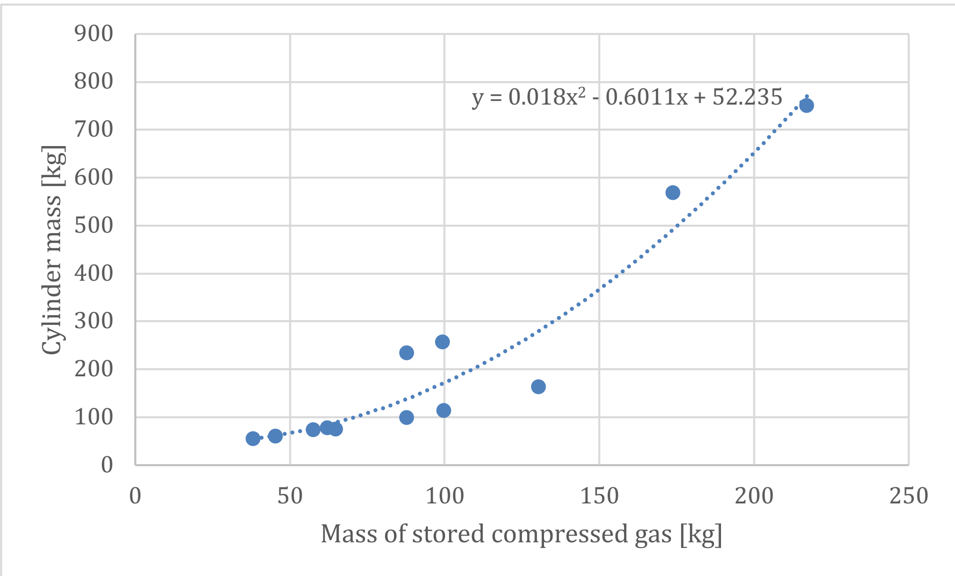


Figure 26 Relation between the mass of stored compressed gas and cylinder mass

Inventories for a Type II 200-bar compressed gas tank with a steel liner are from (Candelaresi et al. 2021).

4. Charging stations

The parameters for the different charging stations modeled are presented in Table 70.

Table 70 Parameters of the different charging stations for battery electric buses

	EV charger, level 3, plug-in	**EV charger, level 3, with pantograph**	**Catenary system**
Bus type	BEV-depot	BEV-opp	BEV-motion
Power [kW]	200	450	48
Efficiency [%]	95	90	95
Source for efficiency	(Chlebis et al. 2014)		(Schulte and Ny 2018)
Lifetime [years]	24	24	40
Number of buses allocated per charging system	2	10	60
Source for inventories	(ABB 2019; Nansai et al. 2001)		(Schulte and Ny 2018)
Comment	Assumed lifetime of 24 years. It is upscaled to a 200 kW Level-3 charger by scaling the charger component up based on a mass of 1’290 kg given by AAB's 200 kW bus charger.	The total mass is from AAB's 450 kW pantograph charger (1340 kg x 3) plus the charging interface (500 kg). But the material composition is extrapolated from the Level-2 charger (Nansai et al. 2001).	

E. Finding solutions and validation

Very much like *carculator* and *carculator_truck*, *carculator_bus* iterates until:

- the change in curb mass of the vehicles between two iterations is below 1%

All while considering the **following constraints**:

- For **all buses**, the driving mass when fully occupied cannot be superior to the gross mass of the vehicle (this is specifically relevant for BEV buses)
- For all buses, but particularly relevant for electric buses, the curb mass should be so low as to allow a 50% increase in the average number of passengers (i.e., during peak hours), all while staying under the permissible gross weight limit.
- **Coach buses** cannot be considered for opportunity and in-motion charging strategies.
- For **BEV-depot** buses, the capacity of the battery must be so that it gives enough time to charge it overnight to be ready for the next shift.

F. Validation

1. Manufacturer's specifications

The bus models generated by *carculator_bus* are validated against the specifications found in the literature and manufacturers' data – available in Annex C of this report. For electric buses, most of the specifications obtained (i.e., battery capacity, motor power, curb mass) are from the ZEeus project report (Guida and Abdulah 2017).

Important remark: the sample size for *fuel cell* electric buses is very low (i.e., n=2).

The model returns curb masses and engine and electric motor power output values that largely agree with current European models, as shown in Figure *27* and Figure 28 respectively.

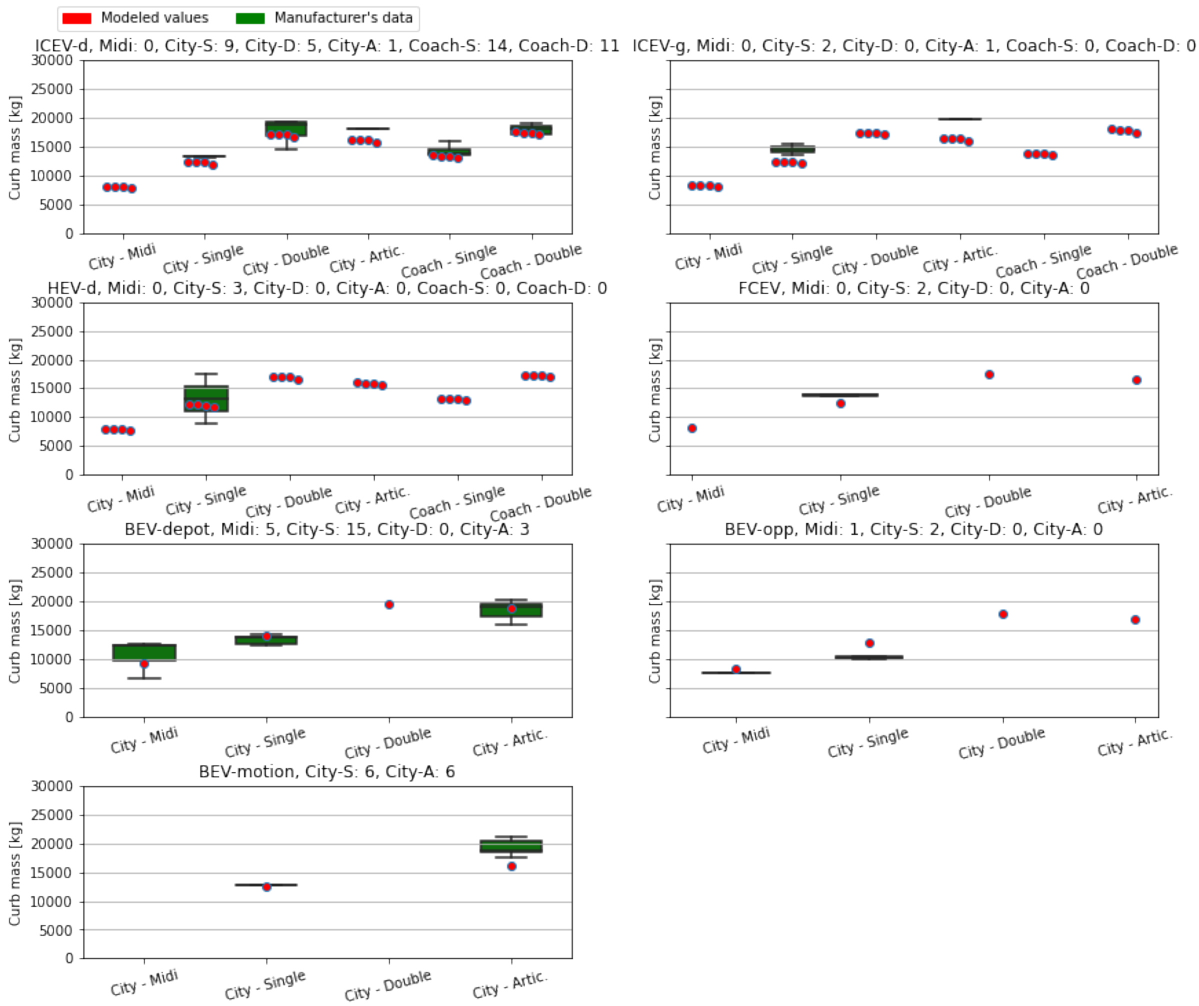


Figure 27 Validation of the vehicles' curb mass against manufacturers' data. Above each plot, the sample size is indicated for each size class.

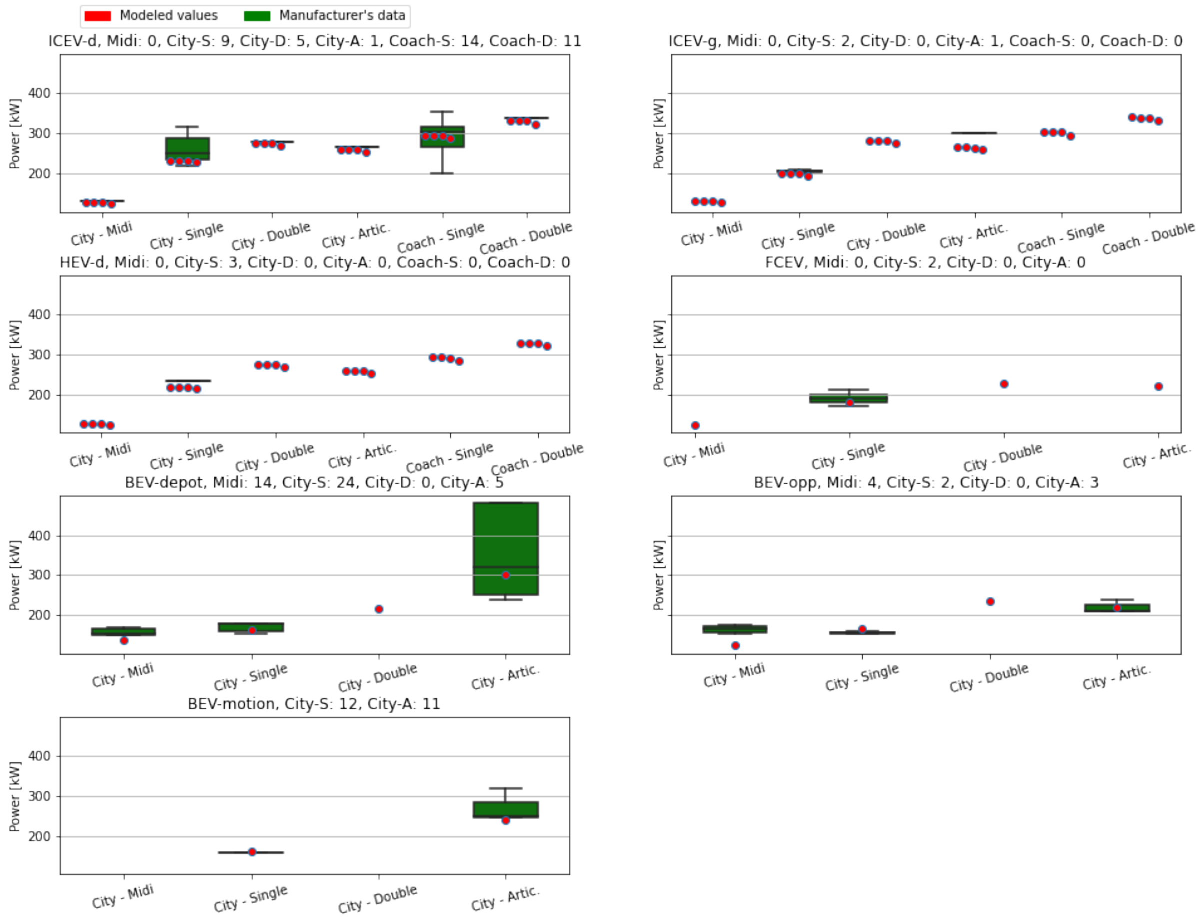


Figure 28 Validation of the vehicles' engine power against manufacturers' data. Above each plot, the sample size is indicated for each size class.

The comparison between the modeled battery energy storage capacity for battery electric buses and what is currently found on the market in Europe is shown in Figure 29. For BEV-depot buses, the model returns a battery capacity significantly higher than the median for European buses: based on personal communication with INFRAS, there is a tendency in Switzerland to purchase depot-charging electric buses with a battery capacity higher than average. It is, for example, the case with MAN’s Lion’s City electric bus models, which feature a 480 kWh and 640 kWh battery for the 12-meter and 18-meter versions, respectively. This overestimate is an attempt to reflect that trend partially.

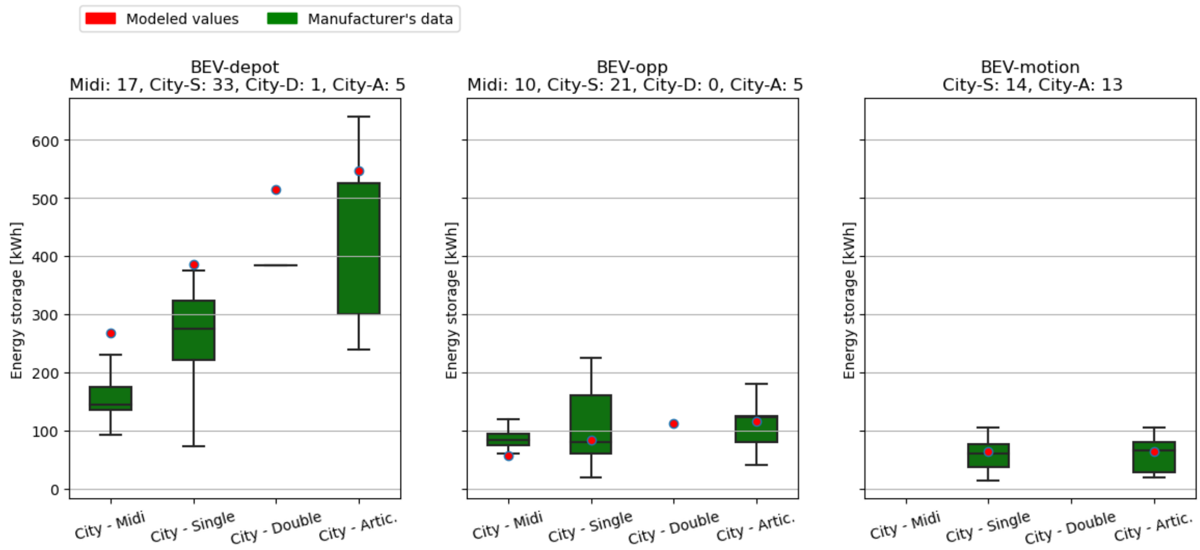


Figure 29 Validation of the energy storage capacity of the battery electric buses against manufacturers' data. Above each plot, the sample size is indicated for each size class.

The resulting curb mass for each bus model is within the range given by the different models operated in Europe, as shown in Figure 30.

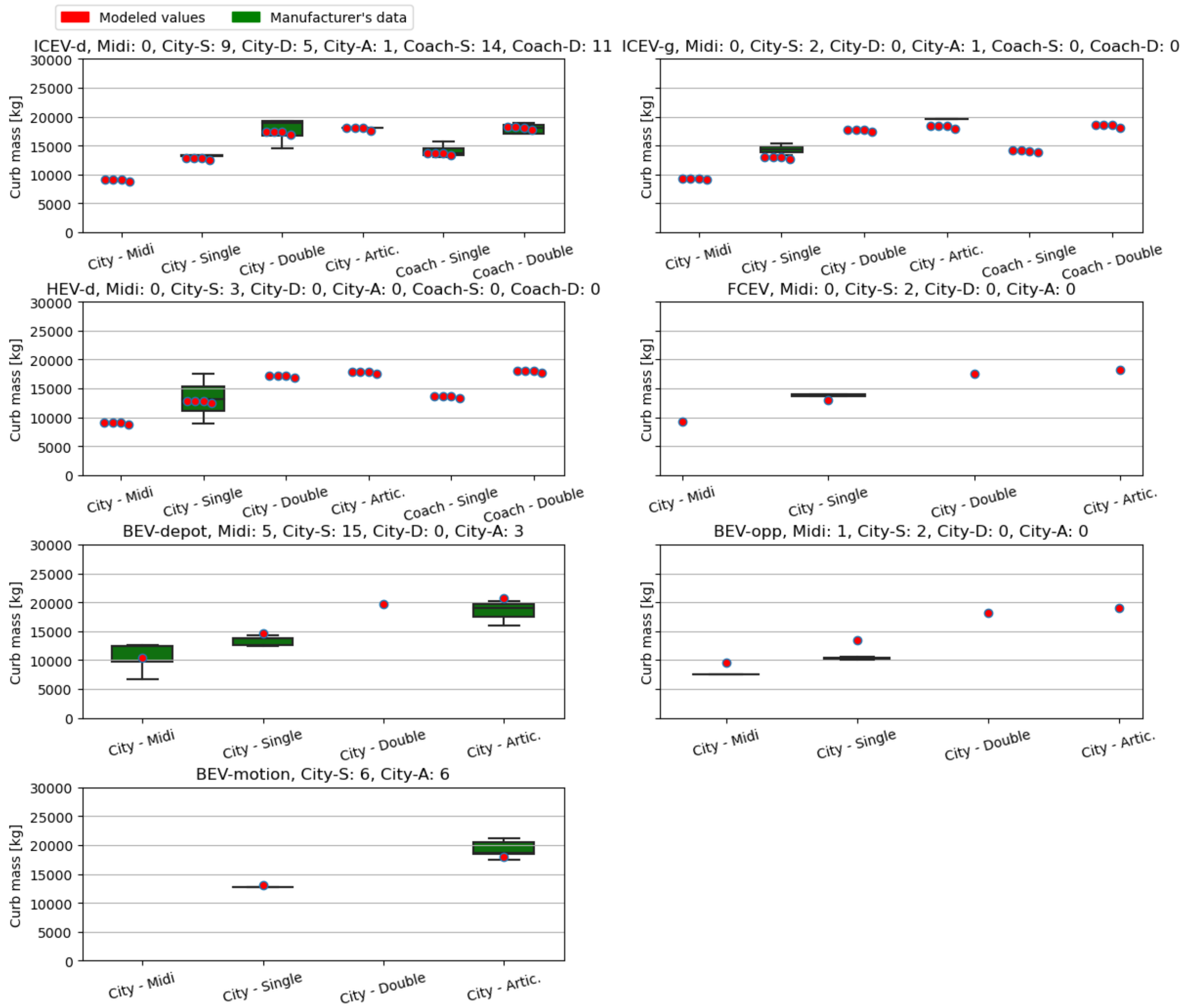


Figure 30 Validation of the vehicles' curb mass against manufacturers' data. Above each plot, the sample size is indicated for each size class.

2. HEBFA's data

Figure 31 compares the tank-to-wheel energy consumption modeled for urban buses with the values obtained from HBEFA 4.1 for urban traffic situations. HBEFA's size class "Midi <= 15t" corresponds in this case to "Midibus, 9m", "<= 18t" and "15-18t" to "Single deck, city bus, 13m", and ">18t" to "Single deck, city bus, 18m". Overall, *carculator*_bus provides slightly higher energy consumption numbers for diesel and compressed gas city buses than those collected from HBEFA 4.1. This could be explained by the driving cycle from VECTO being more demanding in accelerations and stops.

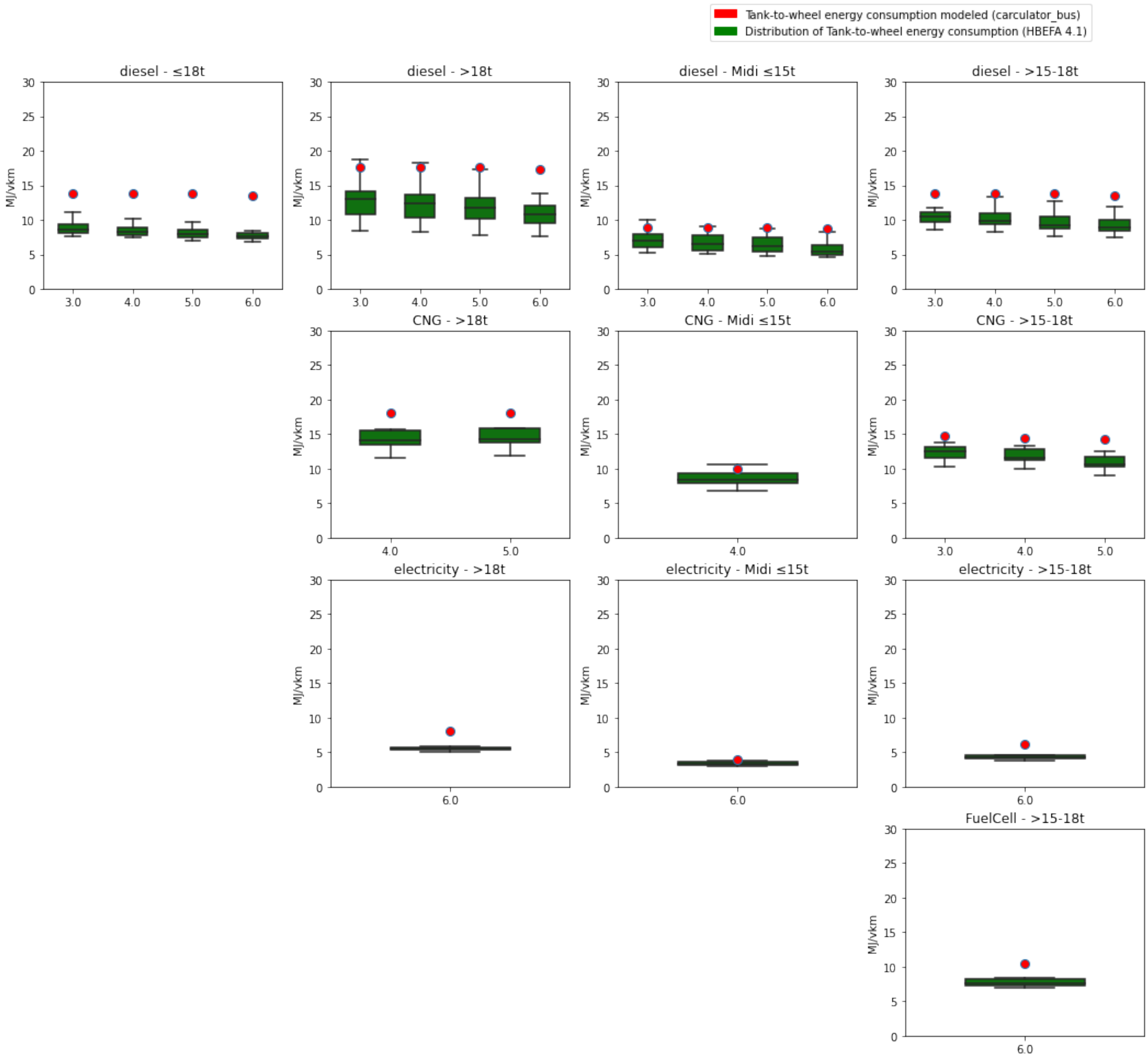


Figure 31 Compares modeled tank-to-wheel energy consumption for city buses and values reported from HBEFA 4.1 for urban traffic situations. X-axis labels correspond to the European emission standard (except for electric powertrains).

Figure 32 compares the tank-to-wheel energy consumption modeled for coach buses with the values reported from HBEFA 4.1 for rural traffic situations. HBEFA's size "<= 18t" and "15-18t" are matched with "Single deck, coach bus, 13m" and ">18t" to "Double deck, coach bus, 13m". There is a good agreement between the energy consumption values for coach buses modeled by *carculator_bus* and those from HBEFA 4.1.

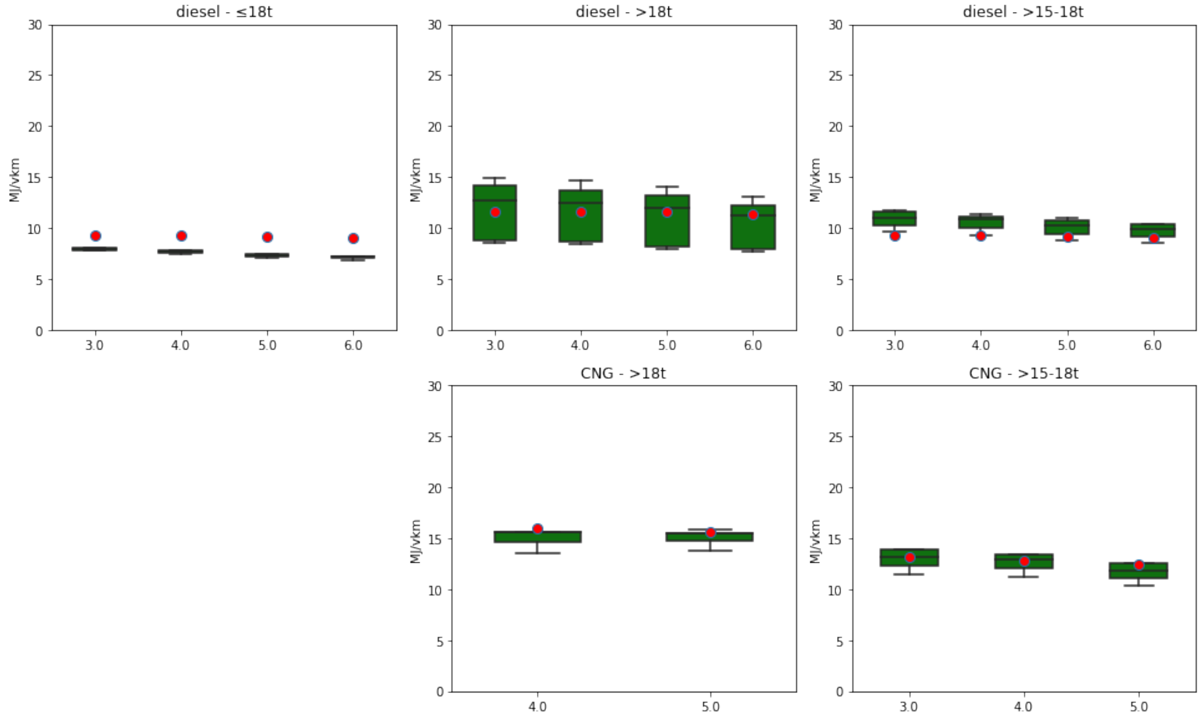


Figure 32 Compares modeled tank-to-wheel energy consumption for coach buses and values reported from HBEFA 4.1 for rural traffic situations. X-axis labels correspond to the European emission standard.

V. Trucks

The LCA tool for medium and heavy-duty trucks named *carculator_truck* is used, for which the source code is made available at https://github.com/romainsacchi/carculator_bus. The tool generates inventories for trucks of different powertrain types, size classes, and years of manufacture. The reader can refer to the following publication for more details:

- Sacchi R, Bauer C, Cox BL. Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium and Heavy-Duty Vehicles. Environ Sci Technol 2021. https://doi.org/10.1021/acs.est.0c07773.

A. Overview

Inventories for the following powertrain types are provided:

- Diesel-run internal combustion engine vehicle (ICEV-d)
- Gas-run internal combustion engine vehicle (ICEV-g)
- Diesel-run hybrid electric vehicle (HEV-d)
- Diesel-run plugin hybrid electric vehicle (PHEV-d)
- Battery electric vehicle (BEV)
- Fuel cell electric vehicle (FCEV)
- Fleet-based powertrain average vehicle

Several size classes are available for each powertrain type. They refer to the maximum permissible gross weight of the vehicle (e.g., 32 tons). In addition, several application-specific designs are available for each powertrain-size class combination: *urban delivery*, *regional delivery,* and *long haul*. They are associated with a given range autonomy: *150* km, *400* km, and *800* km, respectively. This is particularly relevant for sizing the onboard energy storage unit. Some powertrain-size class-application combinations are not commercially available or technologically mature and are therefore not considered.

Because trucks with a gross weight of 60 tons are currently limited to Sweden and Finland, they are not considered in this study. In addition, vehicles with partially electrified powertrains (i.e., HEV-d, PHEV-d) are not considered for regional delivery and long-haul applications, as it would provide very little sense to use such vehicles where the possibility for energy recovery is limited. The size of batteries would yield a very low electric utility factor.

Finally, battery electric vehicles are only considered for 2020 and urban and regional delivery use in 2020, as the volumetric density of batteries does not currently allow range autonomies superior to 400 km.

The combinations of powertrain types and size classes considered in this study are presented in Table 71.

Table 71 Powertrain-size class combinations for medium and heavy-duty trucks considered in this study

Application	Gross weight	**ICEV-d**	**ICEV-g**	**HEV-d**	**PHEV-d**	**FCEV**	**BEV**
Urban delivery (150 km)	3.5t	X	x	Only for 2020			
	7.5t	X	X				
	18t	X	X				
	26t	X	X				
	32t	X	X				
	40t	x	X				
	60t	Not available in Switzerland					
Regional delivery (400 km)	3.5t	X	X	Only for 2020	Not available	Only for 2020	Only for 2020
	7.5t	X	X				
	18t	X	X				
	26t	X	X				
	32t	X	X				
	40t	X	X				
	60t	Not available in Switzerland					
Long haul (800 km)	3.5t	X	X	Only for 2020	Not available	Only for 2020	Not available
	7.5t	X	X				
	18t	X	X				
	26t	X	X				
	32t	X	X				
	40t	X	X				
	60t	Not available in Switzerland					

For ICE vehicles, several emission standards are considered. For simplicity, it is assumed that the vehicle manufacture year corresponds to the registration year, and those are presented in Table 72.

Table 72 Emission standards and year of manufacture for medium and heavy/duty trucks

	Start of registration	**End of registration (incl.)**	**Manufacture year in this study**
EURO-3	2000	2004	**2002**
EURO-4	2005	2007	**2006**
EURO-5	2008	2012	**2010**
EURO-6	2013	-	**2020**

Example of 3.5t truck, rigid, 2 axles, box body

Example of 7.5t truck, rigid, 2 axles, box body

Example of 18t truck, rigid, 2 axles, box body

Example of 26t truck, rigid, 3 axles, box body

Example of 32t truck, semi-trailer, 2+3 axles, curtain-sider

Example of 40t truck, tipper-trailer, 2+4 axles

Example of 60t truck, semi-trailer + trailer, 2+4+2 axles, curtain-sider*

* Not considered in this study

B. Modeling considerations applicable to all vehicle types

1. Sizing of the base frame

The sizing of the base frame is based on p. 17-19 of (Hill et al. 2015). Detailed weight composition is obtained for a **12t rigid truck** and a **40t articulated truck**. Curb mass and payload are obtained for all size classes, the rest being adjusted function of the gross mass. The masses of the vehicles and their subsystems are detailed in Table 73. These truck models have 2010 as the baseline year. A 2% and 5% weight reduction factors are applied on rigid and articulated trucks, respectively, as the same report indicates.

The following components are common to all powertrains:

- Frame
- Suspension
- Brakes
- Wheels and tires,
- Electrical system
- Transmission
- Other components

Table 73 Mass distribution of components for medium- and heavy-duty trucks

		Rigid truck, 3.5t	**Rigid truck, 7.5t**	**Rigid truck, 12t**	**Rigid truck, 18t**	**Rigid truck, 26t**	**Articulated truck, 32t**	**Articulated truck, 40t**	**Articulated truck, 60t***
	Type	rigid, 2 axles, box body	rigid, 2 axles, box body	rigid, 2 axles, box body	rigid, 2 axles, box body	rigid, 3 axles, box body	semi-trailer, 2+3 axles, curtain-sider	semi-trailer, 2+4 axles, curtain-sider	semi-trailer + trailer, 2+4+2 axles, curtain-sider
in kilograms	Gross weight	3500	7500	12000	18000	26000	32000	40000	60000
Powertrain	Engine system	151	324	518	777	1122	899	1124	1686
	Coolant system	11	23	37	56	80	112	140	210
	Fuel system	14	29	47	71	102	64	80	120
	Exhaust system	44	94	150	225	325	176	220	330
	Transmission system	83	177	283	425	613	446	558	837
Electrical system		24	52	83	125	180	212	265	398
Chassis system	Frame	120	256	410	615	888	2751	3439	5159
	Suspension	310	665	1064	1596	2000	2125	2656	3984
	Braking system	24	52	83	125	180	627	784	1176
	Wheels and tires	194	416	665	998	1100	1138	1422	2133
Cabin	Cabin	175	375	600	900	1300	922	1153	1730
	Body system/trailer	583	1250	2000	3000	4333	1680	2100	3150
Other		119	256	409	614	886	847	1059	1589
Curb mass, incl. Trailer		1852	3968	6349	9524	13110	12000	15000	22500

Payload		1648	3532	5651	8477	12890	20000	25000	37500

* Not considered in this study

2. Other use and size-related parameters

Regarding the expected lifetime of the Swiss vehicles, the Swiss vehicles registry MOFIS from the Swiss Federal Road Office (ASTRA 2021) is used. Average lifetime values for decommissioned trucks in Switzerland are derived and presented in Table 74, based on a sample of approximately 200’000 vehicles. Vehicles with a lifetime below ten years or above 30 years are considered outliers and omitted, as well as vehicles with an engine power output unknown or below 80 kW. The gross mass of the vehicles is not given. Instead, the following intervals regarding the engine power output of up to 200 kW, between 200 and 300 kW, and above 300 kW are used to approximate light delivery trucks (i.e., 3.5t and 7.5t of gross mass), medium-duty trucks (i.e., 18t and 26t of gross mass) and heavy-duty trucks (i.e., 32t and 40t of gross mass).

Table 74 Kilometric lifetime values for delivery trucks, medium- and heavy-duty trucks

	<= 200 kW	200 – 300 kW	>= 300 kW	Source	Comment
Count	20’000	100’000	80’000	MOFIS vehicles registry (ASTRA 2021)	Outliers have been removed (with a lifetime inferior to 10 years or superior to 30 years).
Average lifetime [years]	15	16.5	12.5		

To estimate the annual mileage driven by the different truck types, the amount of vehicle-kilometers driven by trucks is divided by the number of corresponding vehicles in Switzerland for that same year, as provided by the Swiss Federal Statistical Office (SFO 2021a). The results of this division are shown in Table 75. The resulting calendar and kilometric lifetime values for Swiss trucks are presented in Table 76.

Table 75 Annual mileage for Swiss medium- and heavy-duty trucks

	Year	Transport service [million vehicle-kilometer]	Vehicle stock [unit]	Annual mileage [kilometer per year]
Delivery trucks, rigid trucks, and trailer tractors up to 3.5t	2019	4’668	387’991	12’000
Rigid trucks and trailer tractors between 3.5t and 7.5t	2019	58	5’266	11’000
Rigid trucks and trailer tractors between 7.5t and 18t	2019	976	25’047	42,000
Rigid trucks and trailer tractors between 18t and 26t	2019	396	11’387	35’000
Rigid trucks and trailer tractors above 26t	2019	310	11’104	28’000

Table 76 Calendar and kilometric lifetime values for Swiss medium- and heavy-duty trucks

-	**unit**	3.5t	7.5t	18t	26t	32t	40t	**Source**
Lifetime	year	15	15	16.5	16.5	12.5	12.5	See Table 74.
Annual kilometers	km	12’000	11’000	42’000	35’000	28’000	28’000	See Table 75.
Kilometric lifetime	km	180’000	165’000	693’000	700’000	350’000	350’000	Obtained by multiplying the lifetime (in years) by the annual mileage.

Also, from the Swiss Statistical Federal Office (SFO 2021c), the loads transported (in ton-kilometers) per type of vehicle and gross mass are normalized by the corresponding distance driven (in vehicle-kilometers) to obtain the average load per vehicle type as shown in Table 77. The average loads shown in Table 77 are used to normalize the results per ton-kilometer and are adapted to the different size classes used in this study and shown in Table *78*. Not all truck technologies have the same cargo-carrying capacity within the same size class. It is typically the case for battery electric trucks, which tend to be heavier than trucks with a combustion engine because of the battery. Applying the same load to all the trucks within the same size class implies that the load factor varies across powertrain technologies.

Table 77 Average distance-weighted load for Swiss medium- and heavy-duty trucks

	Year	Transport service [million vehicle-kilometer]	Load transported [thousand ton-kilometer]	Average weighted load [kilogram]
Delivery trucks, up to 3.5t	2013	1’501	522’317	348
Rigid trucks and trailer tractors between 3.5t and 7.5t	2019	58	36’806	635
Rigid trucks and trailer tractors between 7.5t and 18t	2019	976	2’976’800	3’050
Rigid trucks and trailer tractors between 18t and 26t	2019	396	2’770,000	7’662
Rigid trucks and trailer tractors above 26t	2019	310	3’342,000	8’833

Table 78 Average loads for Swiss medium- and heavy-duty trucks

Size class in this study		3.5t	7.5t	18t	26t	32t	40t	
Cargo carrying capacity	ton	~1.3	~3.5	~10.1	~17.0	~20.1	~25.5	Manufacturers’ data.
Cargo mass	tons	0.35	0.64	3.05	7.66	8.83	8.83	See Table 77.
Average Load factor	%	~27%	~18%	~30%	~45%	~44%	~35%	Calculated from Cargo

								carrying capacity and cargo mass

On the other hand, HBEFA 4.1 is used as a source to estimate the calendar and kilometric lifetime values for European diesel trucks. Those are presented in Table 79.

Table 79 Kilometric and calendar lifetimes for European trucks

Size class in this study		3.5t	7.5t	18t	26t	32t	40t	**Source**
HBEFA vehicle segments	Unit	RigidTruck <7,5t	RigidTruck 7,5-12t	RigidTruck >14-20t	RigidTruck >26-28t	TT/AT >28-34t	TT/AT >34-40t	
Yearly mileage at Year 1	Km	32'526	47'421	37'602	69'278	31'189	118'253	HBEFA 4.1
Relative annual decrease in annual mileage		5.5%				7%		Estimated from HBEFA 4.1
Calendar lifetime	Year	12				12	8	Estimated from HBEFA 4.1
Kilometric lifetime	km	272'000	397'000	315'000	580'000	227'000	710'000	Calculated from the rows above

Average loads for European trucks for long haul use are from the TRACCS road survey data for the EU-28 (Papadimitriou et al. 2013). We differentiate loads across driving cycles and use correction factors based on the representative loads suggested in Annex I of European Commission regulation 2019/1242. Such average loads are presented in Table 80.

Table 80 Average loads for European medium- and heavy-duty trucks

Size class in this study		3.5t	7.5t	18t	26t	32t	40t	
Cargo carrying capacity	ton	~1.3	~3.5	~10.1	~17.0	~20.1	~25.5	Manufacturers' data.
Cargo mass (urban delivery)	tons	0.26	0.52	1.35	2.05	6.1	6.1	Long haul cargo mass, further corrected based on EC regulation 2019/1242
Cargo mass (regional delivery)	tons	0.26	0.52	1.35	2.05	6.1	6.1	Long haul cargo mass, further corrected based on EC regulation 2019/1242

Cargo mass (long haul)	ton	0.8	1.6	4.1	6.2	9.1	9.1	TRACCS (Papadimitriou et al. 2013) for EU28

Other size-related parameters are listed in Table 81. Some have been obtained or calculated from manufacturers' data, which is available in Annex D of this report.

Table 81 Size-related parameters common to Swiss and European trucks

Size class in this study		3.5t	7.5t	18t	26t	32t	40t	**Source**
Number of axles	unit	2	2	2	3	5	6	Manufacturers' data.
Rolling resistance coefficient	unitless	0.055	0.055	0.055	0.055	0.055	0.055	(Meszler et al. 2018)
Frontal area	square meter	4.1	5.3	7.5	7.5	8	8	Manufacturers' data.
Passengers occupancy	unit	1	1	1	1	1	1	Inferred from Mobitool factors v.2.1 values
Average passenger mass	kilogram	75						Standard assumption

3. Fleet average vehicles for Switzerland

Fleet composition data from HBEFA 4.1 is used for the delivery, medium- and heavy-duty trucks for Switzerland in 2020. Vehicles with emission standards older than Euro-3, representing 0.85% of the vehicle-kilometer driven by the fleet, are removed.
The correspondence described in Table 82 is used to map the size classes used in HEBFA with those used in *carculator_truck*:

Table 82 Correspondence between vehicle size classes in HEBFA and carculator_truck

HBEFA size classes	**carculator_truck size class**
RT ≤7,5t	7.5t
RT >7,5-12t	7.5t
RT >12-14t	18t
RT >14-20t	18t

RT >20-26t	26t
RT >26-28t	26t
RT >28-32t	32t
RT >32t	40t
TT/AT ≤7,5t	7.5t
TT/AT >20-28t	26t
TT/AT >28-34t	32t
TT/AT >34-40t	40t

The resulting fleet composition for the characterization of a fleet average diesel truck per size class, and all size classes considered, is presented in Table 83.

Table 83 Fleet composition for trucks in Switzerland in 2020

		Vehicle-km share in the 2020 Swiss diesel truck fleet				
		7.5t	**18t**	**26t**	**32t**	**40t**
Diesel	**2002**	0.60%	0.85%	0.45%	1.05%	0.50%
	2006	0.10%	0.16%	0.11%	0.24%	0.34%
	2010	2.70%	4.35%	3.53%	6.47%	8.12%
	2020	4.53%	8.08%	9.41%	9.73%	38.67%

4. Abrasion emissions

Figure 33 shows the calculated abrasion emissions for trucks in mg per vehicle-kilometer, following the approach presented in Section I.C.5.b.

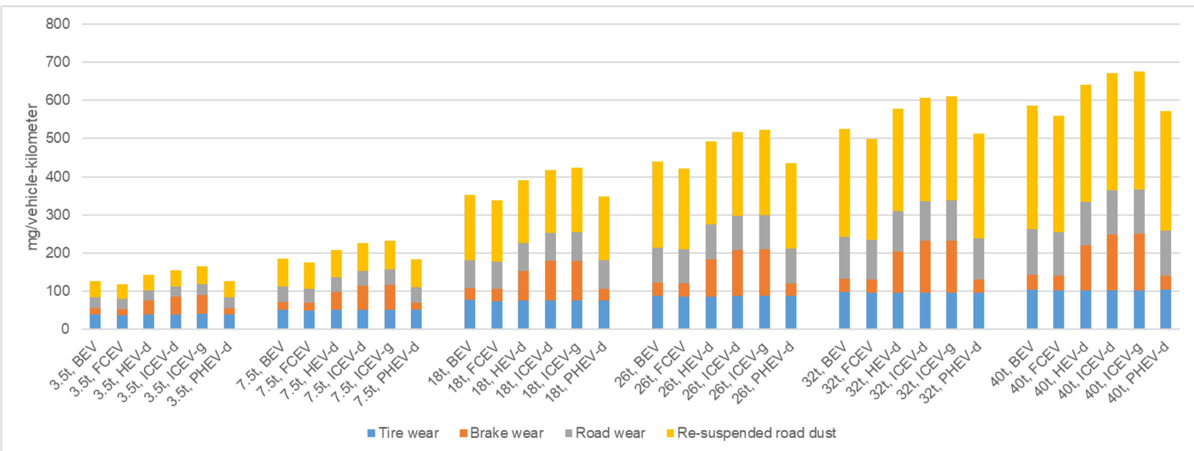


Figure 33 Total particulate matter emissions (<2.5 μm and 2.5-10 μm) in mg per vehicle-kilometer for trucks.

5. Fleet average vehicles for Europe

The truck fleet modeling work of Rottoli et al. (2021) is used to characterize a European fleet average diesel truck per size class and all size classes considered. The fleet composition is presented in Table 84.

Important remark: originally in (Rottoli et al. 2021), the fleet model lumps trucks older than 2010 together. Here, they are disaggregated back, assuming 50% of the vehicle-kilometers were driven by trucks from 2010 (EURO-V), 35% by trucks from 2006 (EURO-IV), and 15% by trucks from 2002 (EURO-III).

Table 84 Fleet composition for trucks in Europe in 2020 (sums to 100%)

		Vehicle-km share in the 2020 European diesel vehicle fleet		
		7.5t	**26t**	**40t**
Diesel	**2002**	0.13%	1.99%	1.6%
	2006	0.29%	4.64%	3.75%
	2010	0.42%	6.63%	5.35%
	2011	0.26%	4.03%	3.24%
	2012	0.28%	4.24%	3.39%
	2013	0.29%	4.39%	3.49%
	2014	0.30%	4.49%	3.55%
	2015	0.31%	4.57%	3.59%
	2016	0.31%	4.67%	3.79%
	2017	0.30%	4.59%	3.84%
	2018	0.29%	4.50%	3.88%
	2019	0.28%	4.41%	3.93%

C. Modeling approach applicable to internal combustion engine vehicles

1. Traction energy

The traction energy for medium- and heavy-duty trucks is calculated based on the driving cycles for trucks provided by VECTO. Simulations are run in VECTO with trucks modeled as closely as possible to those of this study to obtain performance indicators along the driving cycle (e.g., speed and fuel consumption, among others).

Figure 34 shows the first two hundred seconds of the “Urban delivery” driving cycle. It distinguishes the target speed from the actual speed the different vehicles manage. The power-to-mass ratio influences how much a vehicle manages to comply with the target speed.

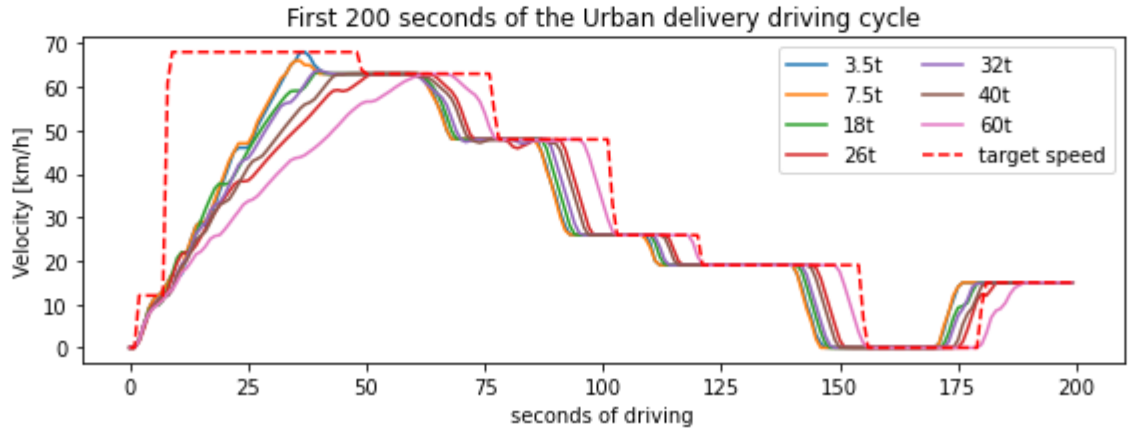


Figure 34 VECTO's "Urban delivery" driving cycle (first two hundred seconds)

Road gradients are also considered. Figure 35 shows the road gradient profile of the "Urban delivery" driving cycle.

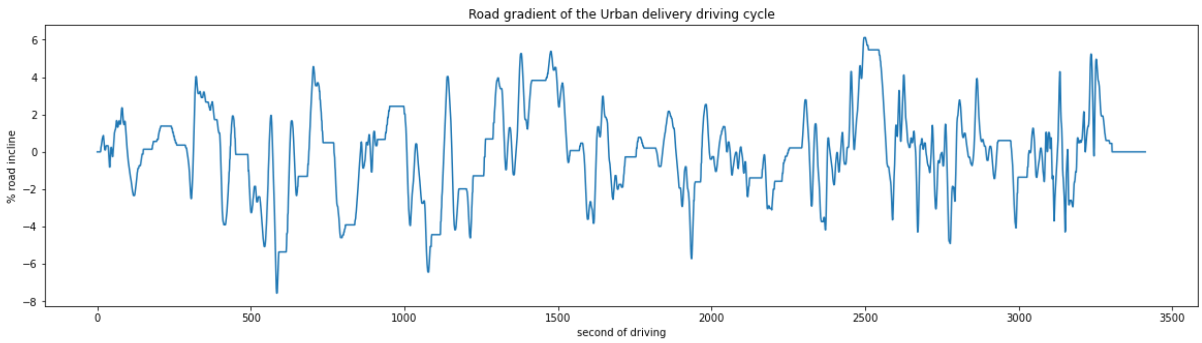


Figure 35 Road gradients corresponding to VECTO's "Urban delivery" driving cycle

The "Regional delivery" and "Long haul" driving cycles of VECTO are used for regional delivery and long haul use, respectively. They contain fewer stops and fewer fluctuations in terms of speed levels. The "Long haul" driving cycle has a comparatively higher average speed and lasts much longer. Figure 36 shows the first two hundred seconds of the "Long haul" driving cycle.

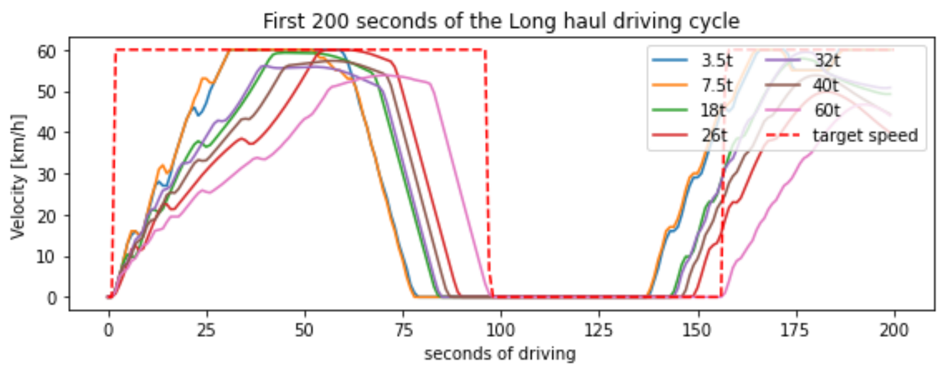


Figure 36 VECTO's "Long haul" driving cycle (first two hundred seconds)

Table 85 shows a few parameters about the three driving cycles considered. Value intervals are shown for some parameters as they vary across size classes.

Important remark: unlike the modeling of passenger cars, the vehicles are designed to satisfy a given range of autonomy. The range autonomy specific to each driving cycle is specified in the last column of Table 85. This is particularly relevant for battery electric vehicles: their energy storage unit is sized to allow them to drive the required distance on a single battery charge. While this also applies to other powertrain types (i.e., the diesel fuel tank or compressed gas cylinders are sized accordingly), the consequences in terms of vehicle design are not as significant. The required range autonomy shown in Table 85 is not defined by VECTO but set as desirable range values by the authors of this study.

Table 85 Parameters of driving cycles used for medium- and heavy-duty trucks

Driving cycle	Average speed [km/h]	Distance [km]	Driving time [s]	Idling time [s]	Mean positive acceleration [m.s2]	Required range autonomy [km]
Urban delivery	9.9 - 10.7	28	~10'000	614 - 817	0.26 - 0.55	150
Regional delivery	16.5 - 17.8	26	~5'500	110 - 220	0.21 - 0.52	400
Long haul	19.4 - 21.8	108	~19'400	240 - 868	0.13 - 0.54	800

The energy consumption model is similar to that of passenger cars: different resistances at the wheels are calculated, after which friction-induced losses along the drivetrain are considered to obtain the energy required at the tank level.

VECTO's simulations are used to calibrate diesel trucks' engine and transmission efficiency. Similar to the modeling of buses, the relation between the efficiency of the drivetrain components (engine, gearbox) and the power load-to-peak-power ratio is used.

A calibration exercise with VECTO for the diesel-powered 40t truck is shown below against the "Urban delivery" driving cycle. After calibration, the tank-to-wheel energy consumption value obtained from VECTO and *carculator_truck* for diesel-powered trucks differ by less than 1 percent over the entire driving cycle.

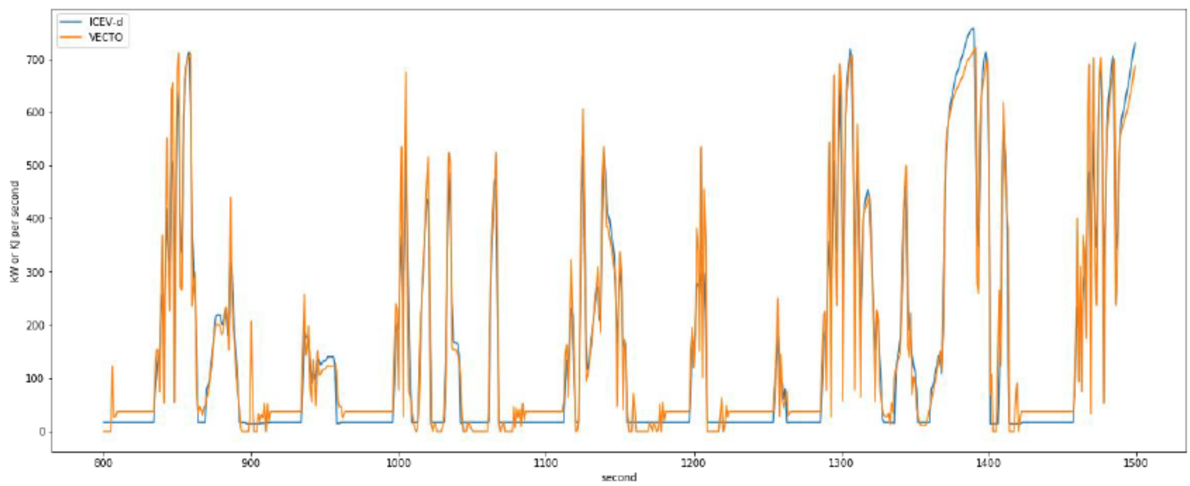


Figure 37 Calibration of carculator_truck energy model against VECTO simulations for a 40t articulated truck diesel truck (first 1'500 seconds shown)

Unfortunately, VECTO does not have a model for compressed gas-powered trucks, and the calibrated model for diesel-powered buses is used. A penalty factor of 10% is applied based on findings from a working paper from the ICCT (Ragon and Rodríguez 2021) showing that compressed gas-powered trucks have an engine efficiency between 8 to 13% lower than that of diesel-powered trucks.

2. Exhaust emissions

a) Other pollutants

Emission factors for CO_2 and SO_2 are detailed in Table 8-Table 9. Biofuel shares in the fuel blend are described inTable 10.

Several fuel-related emissions other than CO_2 or SO_2 are also considered.

For trucks, two sources source of emissions are considered:

- Exhaust emissions: emissions from the combustion of fuel during operation. Their concentration relates to fuel consumption and the vehicle's emission standard.
- Non-exhaust emissions: abrasion emissions such as brake, tire, and road wear, but also emissions of refrigerant and noise.

For exhaust emissions, factors based on the fuel consumption are derived by comparing emission data points for different traffic situations (i.e., grams emitted per vehicle-km) in free-flowing driving conditions, with the fuel consumption corresponding to each data point (i.e., MJ of fuel consumed per km), as illustrated in for a diesel-powered engine. The aim is to obtain emission factors expressed as grams of a substance emitted per MJ of fuel consumed, to model exhaust emissions of trucks of different sizes and masses operating on different driving cycles and with various load factors.

Important remark: the degradation of anti-pollution systems for EURO-6 diesel trucks (i.e., catalytic converters) is accounted for, as indicated by HBEFA 4.1, by applying a degradation factor on the emission factors for NO_x. These factors are shown in Table 86 and Table 49 for trucks with a mileage of 890’000 km. Since the trucks in this study have a kilometric lifetime of 180-700’000 km, degradation factors are interpolated linearly (with a degradation factor of 1 at Km 0). The degradation factor corresponding to half of the vehicle kilometric lifetime is used to obtain a lifetime-weighted average degradation factor.

Table 86 Degradation factors at 890'000 km for diesel trucks

Degradation factor at 890’000 km	
	NO_x
EURO-6	1.3

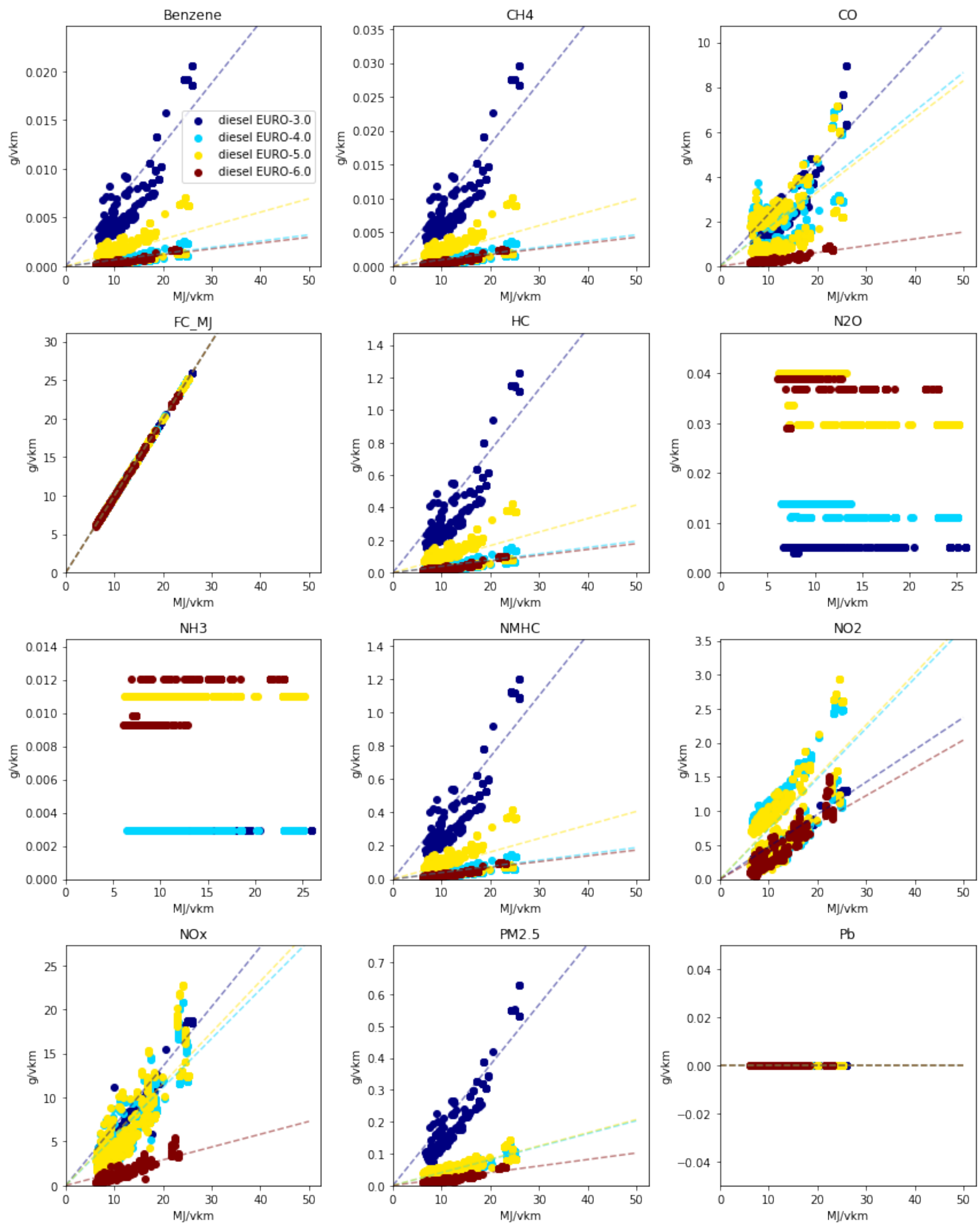


Figure 38 Relation between emission factors and fuel consumption for a diesel-powered truck for several "urban" and "rural" traffic situations for different emission standards.

Using these fuel-based emission factors, emissions for each second of the driving cycle for each substance are calculated.

To confirm that such approach does not yield kilometric emissions too different from the emission factors per vehicle-kilometer proposed by HBEFA 4.1, Figure 23 compares the emissions obtained by *carculator_truck* using VECTO's "Urban delivery" driving cycle over one vehicle-km (red dots) for an 18t rigid truck with the distribution of the emission factors across different "urban" traffic situations (green box-and-whiskers) given by HBEFA 4.1, as well as its weighted average (yellow dots) for various emission standards for a rigid truck with a gross mass of 14-20 tons.

There is some variation across HBEFA's urban traffic situations, but the emissions obtained remain, for most substances, within 50% of the distributed HBEFA values across traffic situations. Special attention must be paid to EURO-III vehicles, for which emissions tend to be slightly over-estimated by *carculator_truck*. The comparison between the model's emission results for the regional and long-haul driving cycles using trucks of different size classes and HBEFA's emission factors for "rural" and "motorway" traffic situations shows a similar picture.

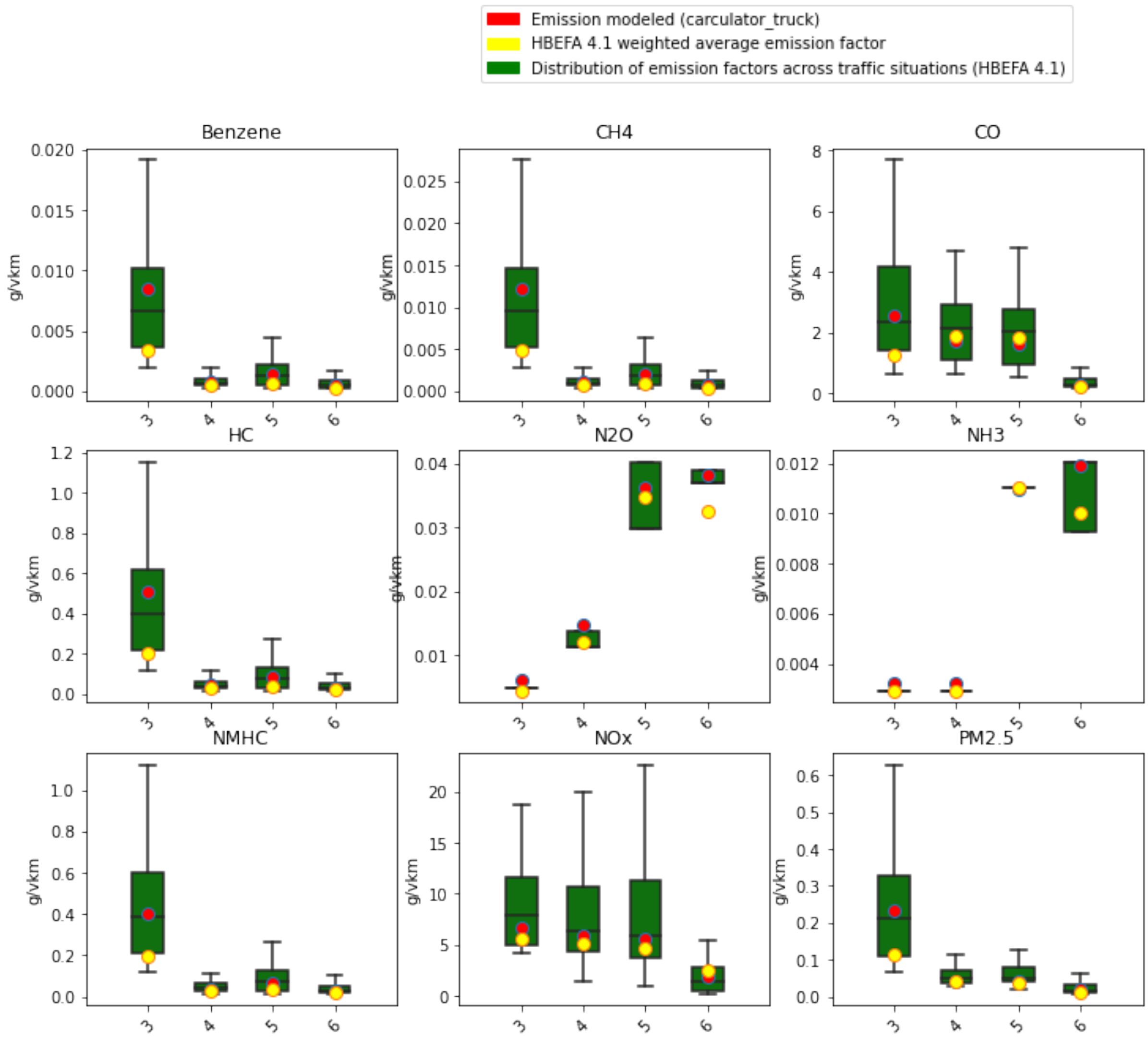


Figure 39 Validation of the exhaust emissions model with the emission factors provided by HBEFA 4.1 for medium-duty trucks in urban and rural traffic situations for different service levels. Box-and-whiskers: distribution of HBEFA's emission factors (box: 50% of the distribution, whiskers: 90%). Yellow dots: traffic situations-weighted average emission factors. Red dots: modeled emissions calculated by *carculator_truck* with the "Urban

delivery" driving cycle for an 18t rigid truck, using the relation between fuel consumption and amounts emitted.

D. Modeling approach applicable to electric vehicles

1. Traction energy

a) Electric vehicles

VECTO does not have a model for battery or fuel cell electric buses that can be used. Therefore, similarly to the modeling of buses, constant engine, and drivetrain efficiency values are used. These values are based on (Schwertner and Weidmann 2016) and are presented in Table 87-Table 88.

Table 87 Efficiency values along the drivetrain of electric trucks in driving mode

Eff. of subsystem	Fuel cell bus	BEV bus	Trolleybus
Fuel tank	0.98		
Energy storage		0.92	
Fuel cell stack	0.55		
Converter		0.98	
Rectifier			
Inverter	0.98	0.98	0.98
Electric motor	0.93	0.93	0.93
Reduction gear	0.95	0.95	0.95
Drive axle	0.94	0.94	0.94
Total	0.44	0.73	0.81

Table 88 Efficiency values along the drivetrain of electric trucks in recuperation mode

Eff. of subsystem	Fuel cell bus	BEV bus	BEV-motion
Drive axle	0.94	0.94	0.94
Reduction gear	0.95	0.95	0.95
Electric motor	0.93	0.93	0.93
Rectifier	0.98	0.98	0.98
Converter	0.98	0.98	
Energy storage	0.85	0.85	0.85
Converter	0.98	0.98	
Inverter	0.98	0.98	0.98
Electric motor	0.93	0.93	0.93
Reduction gear	0.95	0.95	0.95
Drive axle	0.94	0.94	0.94
Total	0.54	0.54	0.56

2. Energy storage

a) Battery electric trucks

The sizing of energy storage for BEV trucks is sensitive to the required range autonomy specific to each driving cycle.

Important remark: technically speaking, *carculator_truck* will model all trucks. However, if a vehicle has an energy storage unit mass that reduces cargo carrying capacity beyond a reasonable extent, it will not be processed for LCI quantification. This is why battery electric trucks are not considered for long haulage (i.e., with a required range autonomy of 800 km).

The expected battery lifetime (and the need for replacement) is based on the battery's expected cycle life, based on theoretical values given by (Göhlich et al. 2018) as well as some experimental ones from (Preger et al. 2020). Although the specifications of the different battery chemistries are presented in Table 19, they are also repeated in Table 89.

Table 89 Parameters for different battery chemistries for battery electric trucks

	unit	**LFP**	**LTO**	**NMC**	**NCA**
Cell voltage	V	3.2	2.3	3.6	3.6
Cell capacity	Ah	1.4-4.5	2.0-6.5	3.7-5.3	4.8
Energy density	Wh/kg cell	115-146	76-77	175-200	200-230
Charge rate		1C	4C-10C	2C-3C	2C-3C
Cycle life (at 100% DoD)	unit	7000+	5’000-7’000	2’000	1’000
Corrected cycle life	unit	7’000	7’000	3’000	1’500

Given the vehicle's energy consumption and the required battery capacity, *carculator_truck* calculates the number of charging cycles needed and the resulting number of battery replacements, given the cycle life of the chemistry used. As discussed at the beginning of this report (see Section I.C.6), the expected cycle life is corrected. There is also a minimum replacement for all vehicles to account for the calendric aging of the battery.

The effect of changing the battery chemistry, using a required range autonomy of 150 km on a 32t articulated truck, is shown in Figure 40. The difference across chemistries is not significant. The higher gravimetric energy density of NCA batteries slightly increases the available payload of the vehicle.

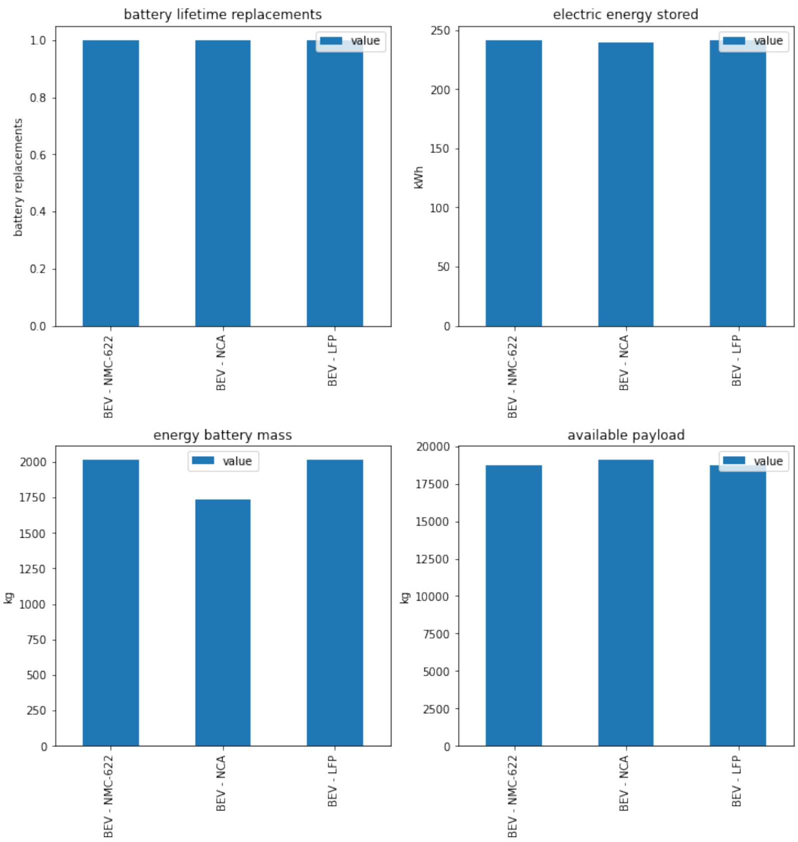


Figure 40 Effect of battery chemistry on the number of replacements, battery capacity, mass, and available payload for a 32t articulated truck with a required range autonomy of 150 km.

b) Plugin hybrid trucks

The number of commercial models of plugin hybrid trucks is limited. This study mostly modeled plugin hybrid trucks after Scania's PHEV tractor (Scania 2020). According to the manufacturer, it comes with three 30 kWh battery packs, giving it a range autonomy in the battery-depleting mode of 60 km. These specifications in terms of battery capacity are used to model plugin hybrid trucks of different size classes (i.e., roughly based on their respective gross mass).

Knowing the vehicle battery storage capacity and its tank-to-wheel efficiency when powered on battery, it is possible to calculate its resulting range autonomy in battery-depleting mode. Furthermore, it is assumed that, in urban delivery, the truck is used in a battery-depleting mode in priority, resorting to the combustion mode to complete the driving cycle (i.e., 150 km). This approach is used to calculate the *electric utility factor* for these vehicles. Energy storage capacities and electric utility factors for plugin hybrid trucks are described in Table 90.

Table 90 Energy storage and electric utility factor of plugin hybrid trucks

Size class	Battery capacity	Range autonomy in battery-depleting mode	Required range autonomy	Electric utility factor	Comment
	kWh	km	km	%	The km driven in combustion mode complete the distance the range
3.5t	20	50	150	35	
7.5t	30	47		33	
18t	70	50		35	
26t	90	45		33	
32t	95	45		32	

40t	110	48		33	autonomy requires.

c) Fuel cell electric trucks

The energy storage unit of fuel cell electric trucks is sized based on the required amount of hydrogen onboard (defined by the required range autonomy). The relation between hydrogen and tank mass is derived from manufacturers' specifications, as shown in Figure 41.

We start from the basis that fuel cell electric trucks are equipped with 650 liters cylinders, which contain 14.4 kg hydrogen at 700 bar, for an (empty) mass of 178 kg. Hence, the requirement in terms of tank mass for a long haul fuel cell electric truck that needs 74 kg of hydrogen is $0.1916^2 + 14.586*14.4 + 10.8 * (74/14.4) = 1'068$ kg, excluding the hydrogen mass.

The hydrogen tank is of type IV, a carbon fiber-resin (CF) composite-wrapped single tank system, with an aluminum liner capable of storing 5.6 kg usable hydrogen, weighting 119 kg per unit (of which 20 kg is carbon fiber), which has been scaled up to 178 kg for a storage capacity of 14.4 kg to reflect current models on the market (Quantum 2019). The inventories are initially from (Hua et al. 2010). The inventories for the carbon fiber supply are from (Benitez et al. 2021). Note that alternative hydrogen tank designs exist, using substantially more carbon fiber (up to 70% by mass): this can potentially impact results as carbon fiber is very energy-intensive to produce.

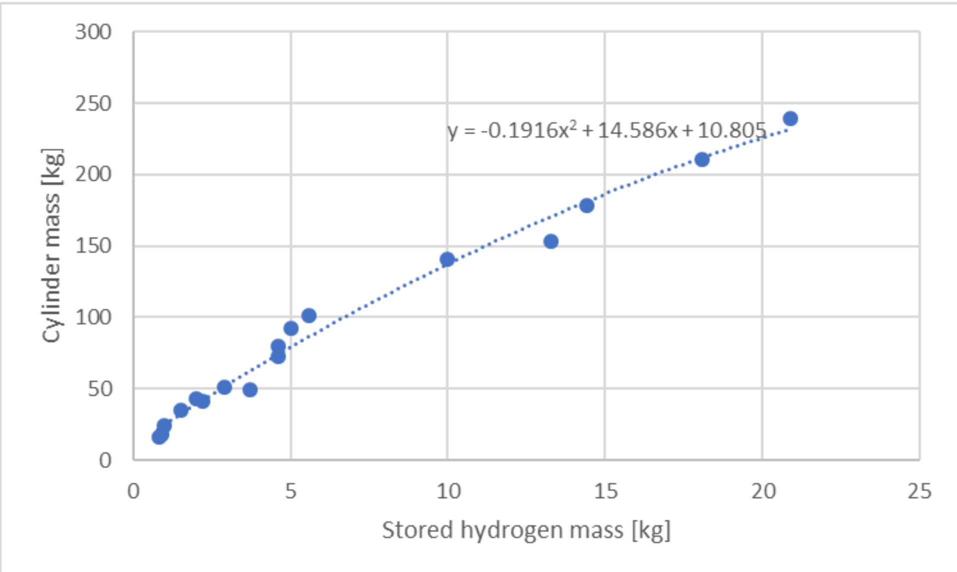


Figure 41 Relation between stored hydrogen mass and hydrogen storage cylinder mass

Important remark: a battery is also added to fuel cell electric trucks. Based on the manufacturer's specification, its storage capacity represents approximately 6% of the storage capacity of the hydrogen cylinders, with a minimum of 20 kWh.

d) Compressed gas trucks

For compressed gas trucks, the energy storage is in a four-cylinder configuration, with each cylinder containing up to 57.6 kg of compressed gas – 320 liters at 200 bar.

The relation between the compressed gas and the cylinder mass is depicted in Figure 26. This relation is based on manufacturers' data – mainly from (Daimler Trucks 2017; QTWW 2021).

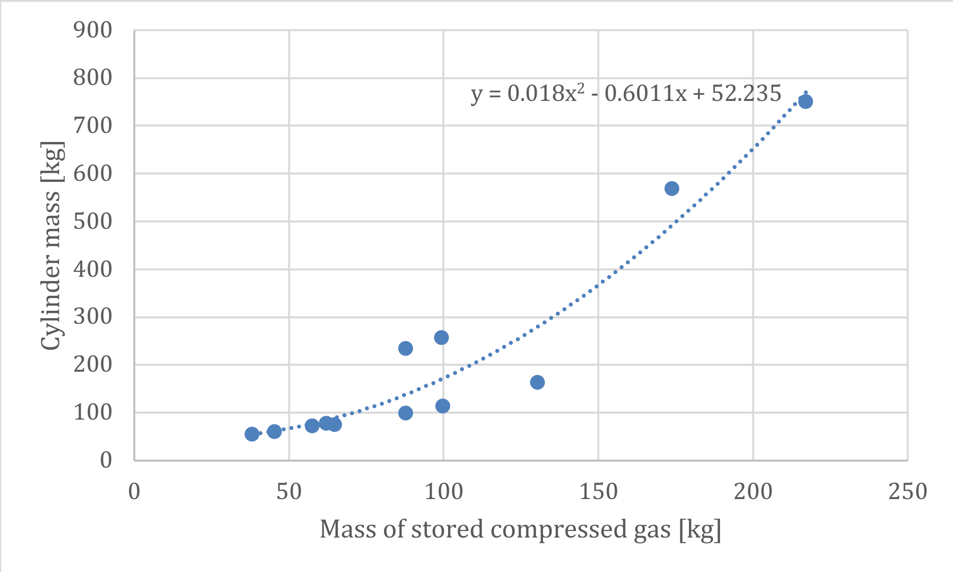


Figure 42 Relation between the mass of stored compressed gas and cylinder mass

Inventories for a Type II 200-bar compressed gas tank with a steel liner are from (Candelaresi et al. 2021).

3. Charging stations

The parameters for the fast charging station used for battery electric trucks are presented in Table 91. The number of vehicles serviced by the charging station daily is defined by the battery capacity of the vehicles it serves. Theoretically, level-3 chargers can fast-charge 2'100 kWh daily if operated within a safe SoC amplitude or about five trucks with a 350 kWh battery pack.

Table 91 Parameters of the charging station for battery electric trucks

	EV charger, level 3, plugin
Bus type	BEV-depot
Power [kW]	200
Efficiency [%]	95
Source for efficiency	(Chlebis et al. 2014)
Lifetime [years]	24
Number of trucks allocated per charging system	2'100 [kWh/day] / energy storage cap. [kWh]

Share of the charging station allocated to the vehicle	1 / (24 [years] * no. trucks * annual mileage [km/day] * cargo mass [ton])
Source for inventories	(ABB 2019; Nansai et al. 2001)
Comment	Assumed lifetime of 24 years. It is upscaled to represent a 200 kW Level-3 charger by scaling the charger component up based on a mass of 1’290 kg given by AAB's 200 kW bus charger.

E. Finding solutions

Very much like *carculator* and *carculator_bus*, *carculator_truck* iterates until:

- The change in curb mass of the vehicles between two modeling iterations is below 1%. This indicates that the vehicle model and the size of its components have stabilized, and further iterating will not affect its mass or fuel consumption.

All while considering the **following constraints**:

- For **all trucks**, the driving mass when fully occupied cannot be superior to the gross mass of the vehicle (this is specifically relevant for battery electric vehicles)
- Particularly relevant to battery electric vehicles, the curb mass (including the battery mass) should be so low as to allow it to retain at least 10% of the initial cargo-carrying capacity while staying under the permissible gross weight limit.

F. Validation

1. Diesel trucks

Figure 43 compares the fuel economy of trucks of different size classes modeled by *carculator_truck* with those found in HBEFA and ecoinvent v.3.

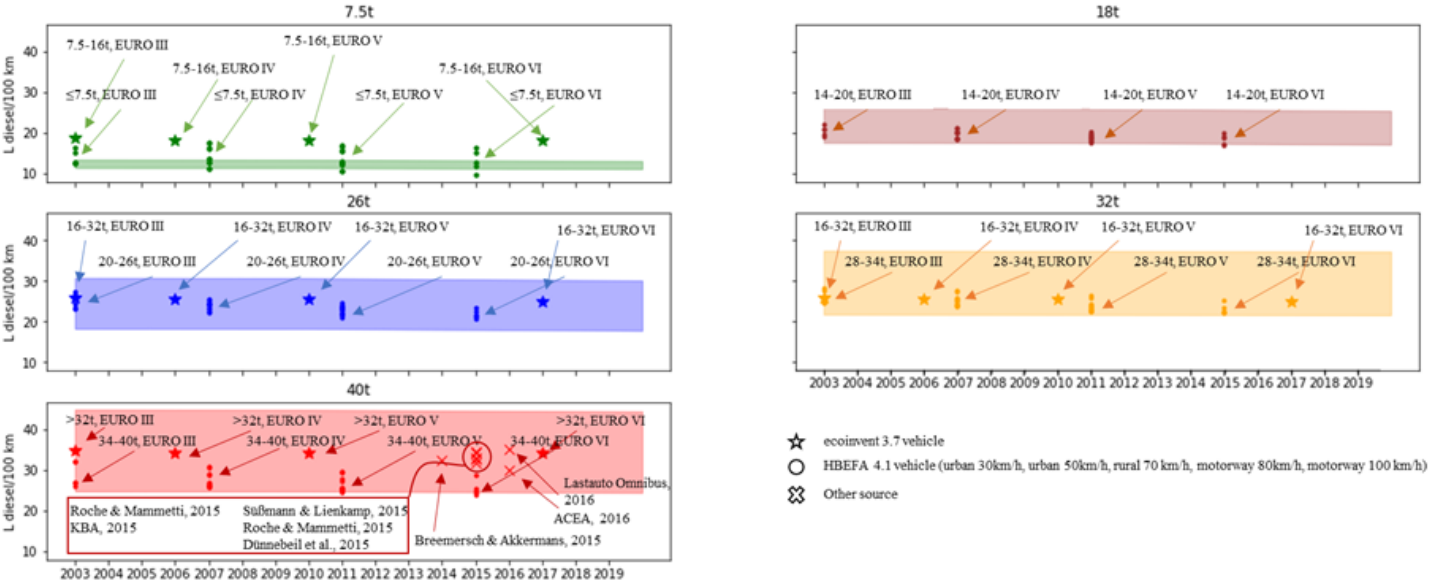
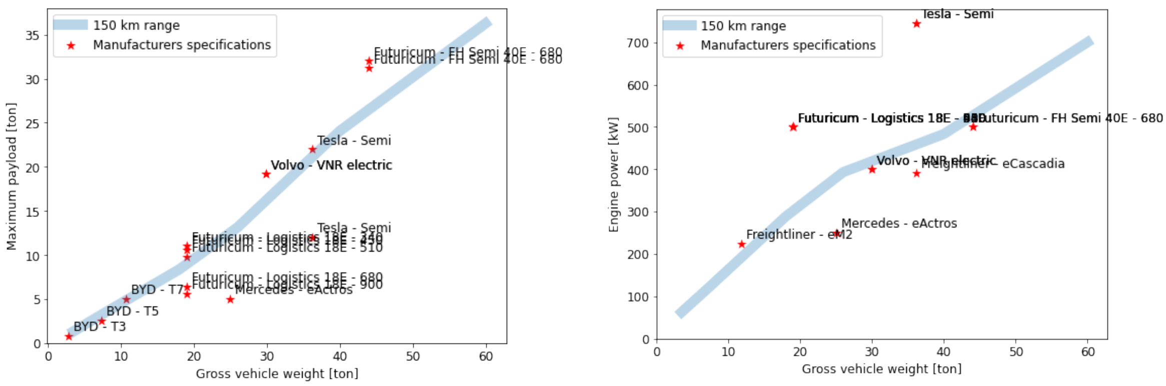


Figure 43 Fuel consumption for diesel trucks in L diesel per 100 km, against literature data. Shaded areas: the upper bound is calculated with the “Urban delivery” driving cycle with a load factor of 80%, and the lower bound is calculated with the “Long haul” driving cycle with a load factor of 20%.

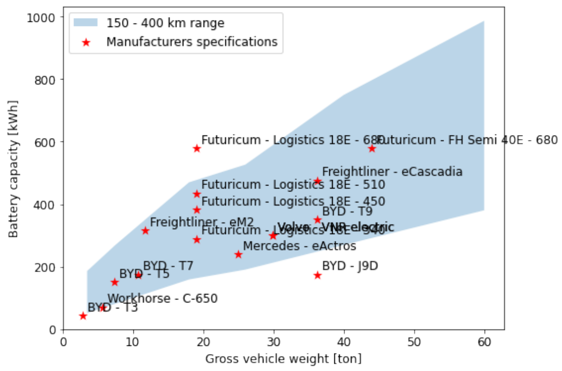
2. Battery electric trucks

Figure 44 compares some of the modeled parameters for battery electric trucks with the specifications of some commercial models disclosed by manufacturers. These manufacturers’ specifications can also be found in Annex D.

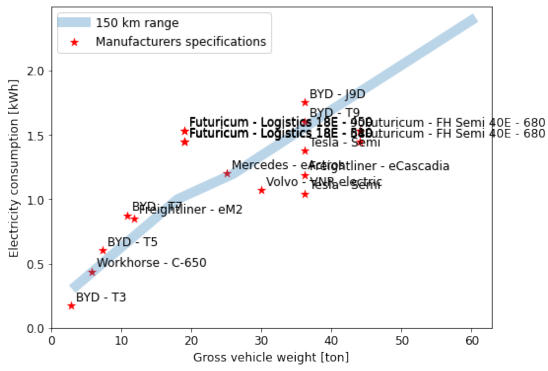


a) Maximum payload modeled (shaded line) versus commercial models, function of gross weight

b) Engine peak power output modeled (shaded line) versus commercial models, function of gross weight



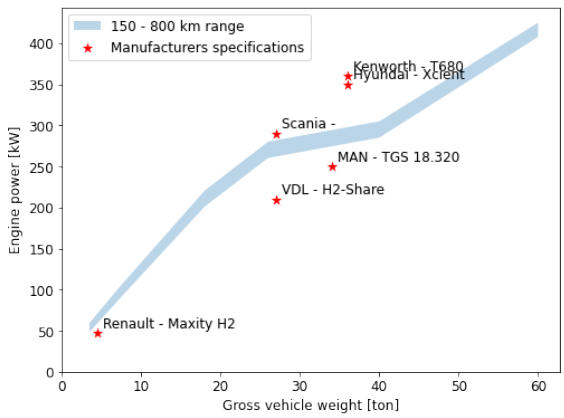
c) Battery capacity modeled (shared area) versus commercial models, function of gross weight. The lower bound of the shaded area represents a vehicle with a range autonomy of 150 km. The upper bound of the shaded area represents a vehicle with a range autonomy of 400 km.



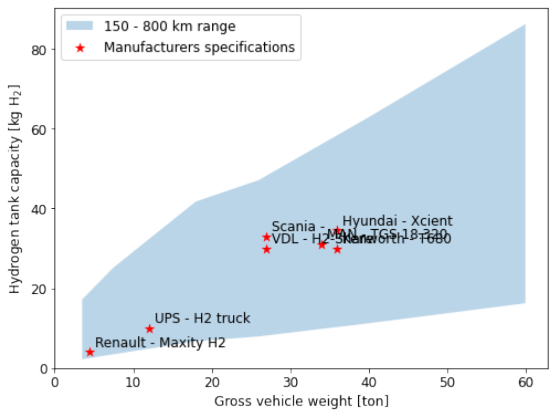
d) Tank-to-wheel energy consumption modeled (shaded line) versus commercial models, function of gross weight

Figure 44 Comparison of modeled maximum payload, engine peak power, battery capacity, and tank-to-wheel fuel consumption with the specification of commercial models.

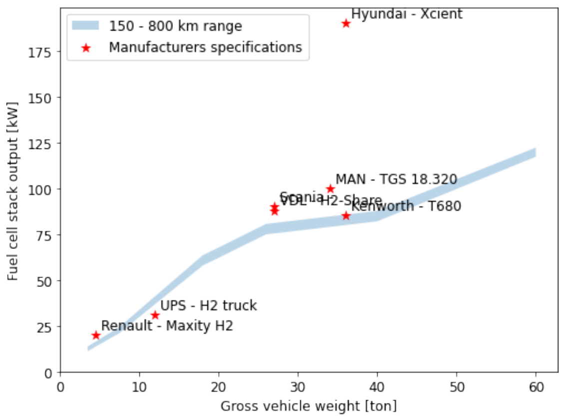
3. Fuel cell electric trucks



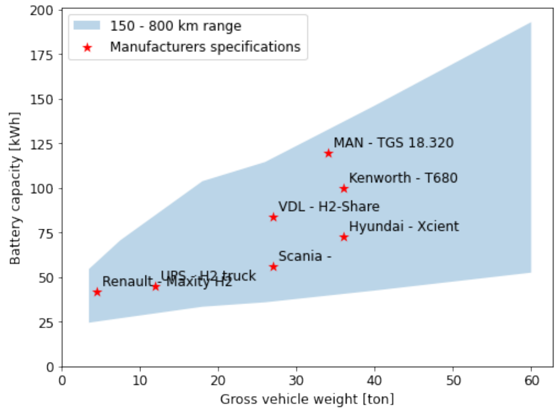
a) Engine peak power output modeled (shaded line) versus commercial models, function of gross weight.



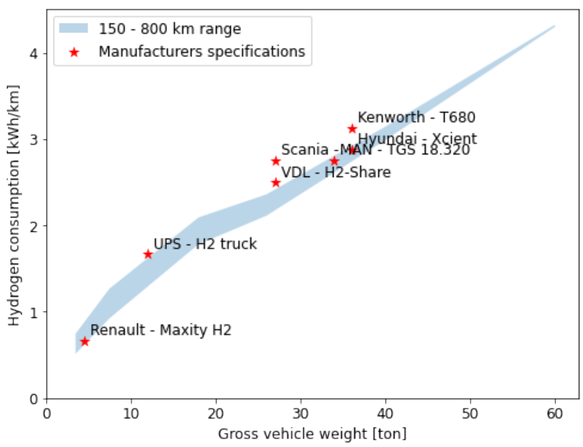
b) Hydrogen tank capacity modeled (shaded line) versus commercial models, function of gross weight. The lower bound of the shaded area represents a vehicle with a range autonomy of 150 km. The upper bound of the shaded area represents a vehicle with a range autonomy of 800 km.



c) Fuel cell stack power output modeled (shaded line) versus commercial models, function of gross weight.



d) Battery capacity modeled (shaded line) versus commercial models, function of gross weight. The lower bound of the shaded area represents a vehicle with a range autonomy of 150 km. The upper bound of the shaded area represents a vehicle with a range autonomy of 800 km.



e) Tank-to-wheel energy consumption modeled (shaded line) versus commercial models, function of gross weight.

VI. Conclusion

Modeling considerations and assumptions for generating life cycle inventories for road transportation of passengers and goods have been presented. These inventories link to ecoinvent v.3.6 (cut-off), 3.7.1 (cut-off), 3.8 (cut-off), as well as UVEK:2018 in a format that brightway2 and Simapro 9.1/9.2 can consume.

All vehicle specifications, life cycle inventories, and environmental indicator results (i.e., Global Warming and Ecological Scarcity 2013) are available via the following Data Object Identifier (DOI): https://doi.org/10.5281/zenodo.5156043. The inventories will also be made available via the UVEK:2018 database.

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Annex A

A. Correspondence between ecoinvent 3.7 and UVEK:2018 datasets.

Important remark: some datasets in UVEK:2018 have a different reference unit from their counterpart found in ecoinvent v.3.7. Such examples are listed in table below.

UVEK:2018 dataset	Unit	Ecoinvent v.3.7 dataset	Unit	Multiplication factor
Steam, for chemical processes, at plant/RER U	kilogram	market for heat, from steam, in chemical industry	megajoule	1 / 2.257
Steam, for chemical processes, at plant/RER U	kilogram	steam production, as energy carrier, in chemical industry	megajoule	1 / 2.257
Natural gas, from high pressure network (1-5 bar), at service station/CH U	kilogram	market group for natural gas, high pressure	cubic meter	0.842
Natural gas, from medium pressure network (0.1-1 bar), at service station/CH U	kilogram	market for natural gas, high pressure	cubic meter	0.842
Natural gas, from medium pressure network (0.1-1 bar), at service station/CH U	kilogram	market for natural gas, high pressure, vehicle grade	kilogram	0.842
Chemical plant, organics/RER/I U	Unit	market for chemical factory	kilogram	1 / 12.6e6

Important remark: some datasets describing treatment activities have a negative reference flow in ecoinvent v.3.7, while they do not in UVEK:2018.

UVEK:2018 dataset	Unit	Ecoinvent v.3.7 dataset	Unit	Multiplication factor
disposal, powertrain, for electric passenger car/RER/I U	kilogram	market for used powertrain from electric passenger car, manual dismantling	kilogram	-1
disposal, powertrain, for electric scooter/RER/I U	kilogram	market for used powertrain from electric scooter	Kilogram	-1

Important remark: not all dataset locations in ecoinvent are available in UVEK:2018. For example, several processes with a global or European geographical scope in ecoinvent v.3.7 can only be found with a Swiss geographical scope in UVEK:2018. Instances where the geographical scope of ecoinvent v.3.7 datasets do not match those of UVEK:2018 are listed in the table below.

Ecoinvent v.3.7 geographical scope	UVEK:2018 geographical scope
GLO	DE
RoW	RER
CN	RER
GLO	RER

Ecoinvent v.3.7 geographical scope	UVEK:2018 geographical scope
IAI Area, Asia, without China and GCC	RER
IAI Area, EU27 & EFTA	RER
RoW	CN
GLO	CH
DE	CH
DE	UCTE
DE	RER
RoW	CH
Europe without Switzerland	RER
RER	CH
GLO	CN
GLO	RLA
Europe, without Russia and Turkey	WEU
Europe without Switzerland	CH
RER w/o RU	RER
GLO	US
GLO	SE
GLO	OCE
CH	RER
RoW	GLO
RER	GLO
ENTSO	E-ENTSO
CN	GLO
Europe without Austria	RER
RoW	RLA
Europe without Switzerland and Austria	RER
RoW	DE
Europe without Switzerland	ENTSO

Also, some datasets can simply not be found at all in UVEK:2018.

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product
market for activated carbon, granular	GLO	Kilogram	activated carbon, granular
market for iodine			Iodine
market for manganese sulfate	GLO	Kilogram	Manganese sulfate
market for molybdenum trioxide			molybdenum trioxide
market for nickel sulfate	GLO	Kilogram	nickel sulfate
market for fly ash and scrubber sludge	Europe without Switzerland	Kilogram	fly ash and scrubber sludge

Important remark: Inputs of *manganese sulfate* and *nickel sulfate* being important for the battery cell manufacture but missing in the UVEK:2018 database, their environmental burdens are approximated by inputs of refined ore, to the extent that it matches their respective GWP100a score, as shown in the table below.

Ecoinvent v.3.7	UVEK:2018

Input quantity [kg]	Name	GWP100a [kg CO2-eq./kg]	Input quantity [kg]	Name	GWP100a [kg CO2-eq./kg]
1	Market for manganese sulfate	0.83	0.34	Manganese, at regional storage/RER	0.83
1	Market for nickel sulfate	4.76	0.445	Nickel, 99.5%, at plant/GLO	4.76

Important remark: there is a factor 5 in difference for the GWP 100a score for cobalt supply between the ecoinvent v.3.7.1 and UVEK:2018 databases ("market for cobalt" and "Cobalt, at plant/GLO", respectively). This indirectly leads to different results for battery-equipped vehicles, as cobalt is an important metal entering the composition of NMC and NCA batteries.

Ecoinvent v.3.7			UVEK:2018		
Input quantity [kg]	Name	GWP100a [kg CO2-eq./kg]	Input quantity [kg]	Name	GWP100a [kg CO2-eq./kg]
1	Market for cobalt	15	1	Cobalt, at plant/GLO	2.61

The table below lists the correspondence between ecoinvent v.3.7 and UVEK:2018 exchanges used in this study.

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
activated bentonite production	DE	kilogram	activated bentonite	DE	kilogram	Bentonite, at processing/DE U
activated silica production	GLO	kilogram	activated silica	DE	kilogram	Silica sand, at plant/DE U
air separation, cryogenic	RoW	kilogram	oxygen, liquid	RER	kilogram	Oxygen, liquid, at plant/RER U
air separation, cryogenic	RER	kilogram	oxygen, liquid	RER	kilogram	Oxygen, liquid, at plant/RER U
aluminium hydroxide production	CN	kilogram	aluminium hydroxide	RER	kilogram	Aluminium hydroxide, at plant/RER U
aluminium ingot, primary, to aluminium, wrought alloy market	GLO	kilogram	aluminium, wrought alloy	RER	kilogram	aluminium, production mix, wrought alloy, at plant/kg/RER U
aluminium production, primary, ingot	IAI Area, Asia, without China and GCC	kilogram	aluminium, primary, ingot	RER	kilogram	aluminium, production mix, at plant/kg/RER U
aluminium production, primary, ingot	IAI Area, EU27 & EFTA	kilogram	aluminium, primary, ingot	RER	kilogram	aluminium, production mix, at plant/kg/RER U
anode production, graphite, for lithium-ion battery	RoW	kilogram	anode, graphite, for lithium-ion battery	CN	kilogram	Anode, lithium-ion battery, graphite, at plant/CN U
argon production, liquid	RoW	kilogram	argon, liquid	RER	kilogram	Argon, liquid, at plant/RER U
arsine production	GLO	kilogram	arsine	GLO	kilogram	Arsine, at plant/GLO U
barite production	RER	kilogram	barite	RER	kilogram	Barite, at plant/RER U
carbon black production	GLO	kilogram	carbon black	GLO	kilogram	Carbon black, at plant/GLO U
cast iron production	RoW	kilogram	cast iron	RER	kilogram	Cast iron, at plant/RER U
casting, brass	CH	kilogram	casting, brass	CH	kilogram	Casting, brass/CH U
cement production, Portland	CH	kilogram	cement, Portland	CH	kilogram	Portland cement, strength class Z 42.5, at plant/CH U
chemical factory construction, organics	RER	unit	chemical factory, organics	RER	unit	Chemical plant, organics/RER/I U
chemical factory construction, organics	RoW	unit	chemical factory, organics	RER	unit	Chemical plant, organics/RER/I U
cobalt production	GLO	kilogram	cobalt	GLO	kilogram	Cobalt, at plant/GLO U
computer production, desktop, without screen	GLO	unit	computer, desktop, without screen	GLO	unit	Desktop computer, without screen, at plant/GLO U
copper production, blister-copper	RER	kilogram	copper, blister-copper	RER	kilogram	Copper, blister-copper, at primary smelter/RER U
delimbing, with excavator-based processor	RER	hour	delimbing/sorting, excavator-based processor	RER	hour	delimbing/sorting, excavator-based processor/hr/RER
diesel, burned in building machine	GLO	megajoule	diesel, burned in building machine	CH	megajoule	diesel, burned in building machine, average/MJ/CH U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
diesel, burned in diesel-electric generating set, 18.5kW	GLO	megajoule	diesel, burned in diesel-electric generating set, 18.5kW	GLO	megajoule	Diesel, burned in diesel-electric generating set/GLO U
distribution network construction, electricity, low voltage	CH	kilometer	distribution network, electricity, low voltage	CH	kilometer	distribution network, electricity, low voltage/km/CH/I U
drawing of pipe, steel	RER	kilogram	drawing of pipe, steel	RER	kilogram	Drawing of pipes, steel/RER U
electricity production, hard coal	DE	kilowatt hour	electricity, high voltage	DE	kilowatt hour	Electricity, hard coal, at power plant/DE U
electricity production, hydro, run-of-river	DE	kilowatt hour	electricity, high voltage	CH	kilowatt hour	electricity, high voltage, production from hydro power, at grid/CH U
electricity production, natural gas, conventional power plant	DE	kilowatt hour	electricity, high voltage	DE	kilowatt hour	Electricity, natural gas, at power plant/DE U
electricity production, nuclear, pressure water reactor	DE	kilowatt hour	electricity, high voltage	DE	kilowatt hour	Electricity, nuclear, at power plant pressure water reactor/DE U
electricity production, oil	DE	kilowatt hour	electricity, high voltage	UCTE	kilowatt hour	Electricity, oil, at power plant/UCTE U
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	DE	kilowatt hour	electricity, low voltage	CH	kilowatt hour	electricity, PV, at 3kWp facade installation, multi-Si, panel, mounted/kWh/CH U
electricity production, wind, 1-3MW turbine, onshore	DE	kilowatt hour	electricity, high voltage	RER	kilowatt hour	Electricity, at wind power plant/RER U
electronics production, for control units	RoW	kilogram	electronics, for control units	RER	kilogram	Electronics for control units/RER U
electronics production, for control units	RER	kilogram	electronics, for control units	RER	kilogram	Electronics for control units/RER U
epichlorohydrin production from allyl chloride	RoW	kilogram	epichlorohydrin	RER	kilogram	Epichlorohydrin, from hypochlorination of allyl chloride, at plant/RER U
epoxy resin production, liquid	RER	kilogram	epoxy resin, liquid	RER	kilogram	Epoxy resin, liquid, at plant/RER U
epoxy resin production, liquid	RoW	kilogram	epoxy resin, liquid	RER	kilogram	Epoxy resin, liquid, at plant/RER U
ethylene glycol production	RER	kilogram	ethylene glycol	RER	kilogram	Ethylene glycol, at plant/RER U
ethylene glycol production	RoW	kilogram	ethylene glycol	RER	kilogram	Ethylene glycol, at plant/RER U
forwarding, forwarder	RER	hour	forwarding, forwarder	RER	hour	forwarding, forwarder/hr/RER
gas motor production, 206kW	RER	unit	gas motor, 206kW	RER	unit	Gas motor 206kW/RER/I U
glass fibre reinforced plastic production, polyamide, injection moulded	RoW	kilogram	glass fibre reinforced plastic, polyamide, injection moulded	RER	kilogram	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U
glass fibre reinforced plastic production, polyamide, injection moulded	RER	kilogram	glass fibre reinforced plastic, polyamide, injection moulded	RER	kilogram	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U
glass fibre reinforced plastic production, polyester resin, hand lay-up	RER	kilogram	glass fibre reinforced plastic, polyester resin, hand lay-up	RER	kilogram	Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER U
graphite production	RoW	kilogram	graphite	RER	kilogram	Graphite, at plant/RER U
gravel and sand quarry operation	CH	kilogram	sand	CH	kilogram	Sand, at mine/CH U
gravel production, crushed	RoW	kilogram	gravel, crushed	CH	kilogram	Gravel, crushed, at mine/CH U
harvesting, forestry harvester	RER	hour	harvesting, forestry harvester	RER	hour	harvesting, forestry harvester/hr/RER
heat and power co-generation, natural gas, 1MW electrical, lean burn	Europe without Switzerland	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, at cogen 1MWe lean burn, allocation heat/RER U
heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	DE	kilowatt hour	electricity, high voltage	CH	kilowatt hour	Electricity, at cogen 6400kWth, wood, allocation heat/CH U
heat production, heavy fuel oil, at industrial furnace 1MW	RoW	megajoule	heat, district or industrial, other than natural gas	RER	megajoule	Heat, heavy fuel oil, at industrial furnace 1MW/RER U
heat production, natural gas, at boiler condensing modulating >100kW	Europe without Switzerland	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, natural gas, at boiler condensing modulating >100kW/RER U
heat production, natural gas, at industrial furnace >100kW	RoW	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, natural gas, at industrial furnace >100kW/RER U
heat production, natural gas, at industrial furnace low-NOx >100kW	Europe without Switzerland	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, natural gas, at industrial furnace low-NOx >100kW/RER U
heat production, natural gas, at industrial furnace low-NOx >100kW	RoW	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, natural gas, at industrial furnace low-NOx >100kW/RER U
heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	CH	megajoule	heat, district or industrial, other than natural gas	CH	megajoule	Heat from waste, at municipal waste incineration plant/CH U
hydrogen peroxide production, product in 50% solution state	RER	kilogram	hydrogen peroxide, without water, in 50% solution state	RER	kilogram	Hydrogen peroxide, 50% in H2O, at plant/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
infrastructure construction, for regional distribution of oil product	RER	unit	infrastructure, for regional distribution of oil product	RER	unit	Regional distribution, oil products/RER/I U
injection moulding	RoW	kilogram	injection moulding	RER	kilogram	Injection moulding/RER U
kraft paper production	RER	kilogram	kraft paper	RER	kilogram	Kraft paper, unbleached, at plant/RER U
kraft paper production, bleached	RoW	kilogram	kraft paper, bleached	RER	kilogram	Kraft paper, bleached, at plant/RER U
laminating service, foil, with acrylic binder	RER	square meter	laminating service, foil, with acrylic binder	RER	square meter	Laminating, foil, with acrylic binder/RER U
lignite mine operation	RER	kilogram	lignite	RER	kilogram	Lignite, at mine/RER U
lime production, milled, packed	CH	kilogram	lime, packed	CH	kilogram	Lime, hydrated, packed, at plant/CH U
liquid storage tank production, chemicals, organics	CH	unit	liquid storage tank, chemicals, organics	CH	unit	Liquid storage tank, chemicals, organics/CH/I U
lithium hydroxide production	GLO	kilogram	lithium hydroxide	GLO	kilogram	Lithium hydroxide, at plant/GLO U
lubricating oil production	RoW	kilogram	lubricating oil	RER	kilogram	Lubricating oil, at plant/RER U
magnesium production, electrolysis	RoW	kilogram	magnesium	RER	kilogram	Magnesium, at plant/RER U
maintenance, lorry 16 metric ton	CH	unit	maintenance, lorry 16 metric ton	CH	unit	Maintenance, lorry 16t/CH/I U
maintenance, lorry 28 metric ton	CH	unit	maintenance, lorry 28 metric ton	CH	unit	Maintenance, lorry 28t/CH/I U
maintenance, lorry 40 metric ton	CH	unit	maintenance, lorry 40 metric ton	CH	unit	Maintenance, lorry 40t/CH/I U
maintenance, passenger car	RER	unit	passenger car maintenance	RER	unit	Maintenance, passenger car/RER/I U
market for acetylene	RER	kilogram	acetylene	CH	kilogram	Acetylene, at regional storehouse/CH U
market for acrylic acid	RoW	kilogram	acrylic acid	RER	kilogram	Acrylic acid, at plant/RER U
market for acrylonitrile	GLO	kilogram	acrylonitrile	RER	kilogram	Acrylonitrile from Sohio process, at plant/RER U
market for acrylonitrile-butadiene-styrene copolymer	GLO	kilogram	acrylonitrile-butadiene-styrene copolymer	RER	kilogram	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U
market for air compressor, screw-type compressor, 300kW	GLO	unit	air compressor, screw-type compressor, 300kW	RER	unit	Air compressor, screw-type compressor, 300 kW, at plant/RER/I U
market for aluminium alloy, AlLi	GLO	kilogram	aluminium alloy, AlLi	RER	kilogram	Aluminium alloy, AlMg3, at plant/RER U
market for aluminium alloy, AlMg3	GLO	kilogram	aluminium alloy, AlMg3	RER	kilogram	Aluminium alloy, AlMg3, at plant/RER U
market for aluminium casting facility	GLO	unit	aluminium casting facility	RER	unit	Aluminium casting, plant/RER/I U
market for aluminium oxide, metallurgical	IAI Area, EU27 & EFTA	kilogram	aluminium oxide, metallurgical	RER	kilogram	aluminium oxide, at plant/kg/RER U
market for aluminium scrap, new	RER	kilogram	aluminium scrap, new	RER	kilogram	Aluminium scrap, new, at plant/RER U
market for aluminium, cast alloy	GLO	kilogram	aluminium, cast alloy	RER	kilogram	aluminium, production mix, cast alloy, at plant/kg/RER U
market for aluminium, wrought alloy	GLO	kilogram	aluminium, wrought alloy	RER	kilogram	aluminium, production mix, wrought alloy, at plant/kg/RER U
market for ammonia, anhydrous, liquid	RER	kilogram	ammonia, anhydrous, liquid	CH	kilogram	Ammonia, liquid, at regional storehouse/CH U
market for ammonia, liquid	RER	kilogram	ammonia, liquid	CH	kilogram	Ammonia, liquid, at regional storehouse/CH U
market for ammonium sulfate	RER	kilogram	ammonium sulfate	RER	kilogram	Ammonium sulphate, as N, at regional storehouse/RER U
market for ammonium sulfate, as N	GLO	kilogram	ammonium sulfate, as N	RER	kilogram	Ammonium sulphate, as N, at regional storehouse/RER U
market for anode, graphite, for lithium-ion battery	GLO	kilogram	anode, graphite, for lithium-ion battery	CN	kilogram	Anode, lithium-ion battery, graphite, at plant/CN U
market for anodising, aluminium sheet	GLO	square meter	anodising, aluminium sheet	RER	square meter	Anodising, aluminium sheet/RER U
market for antimony	GLO	kilogram	antimony	CN	kilogram	Antimony, at refinery/CN U
market for blasting	GLO	kilogram	blasting	RER	kilogram	Blasting/RER U
market for blow moulding	GLO	kilogram	blow moulding	RER	kilogram	Blow moulding/RER U
market for brake wear emissions, passenger car	GLO	kilogram	brake wear emissions, passenger car	RER	kilogram	brake wear emissions, passenger car/RER U
market for brass	CH	kilogram	brass	CH	kilogram	Brass, at plant/CH U
market for butadiene	RER	kilogram	butadiene	RER	kilogram	Butadiene, at plant/RER U
market for butyl acrylate	RoW	kilogram	butyl acrylate	RER	kilogram	Butyl acrylate, at plant/RER U
market for cable, ribbon cable, 20-pin, with plugs	GLO	kilogram	cable, ribbon cable, 20-pin, with plugs	GLO	kilogram	Cable, ribbon cable, 20-pin, with plugs, at plant/GLO U
market for calcium chloride	RER	kilogram	calcium chloride	RER	kilogram	Calcium chloride, CaCl2, at plant/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for carbon black	GLO	kilogram	carbon black	GLO	kilogram	Carbon black, at plant/GLO U
market for carbon dioxide, liquid	RER	kilogram	carbon dioxide, liquid	RER	kilogram	Carbon dioxide liquid, at plant/RER U
market for carbon monoxide	RER	kilogram	carbon monoxide	RER	kilogram	Carbon monoxide, CO, at plant/RER U
market for carboxymethyl cellulose, powder	GLO	kilogram	carboxymethyl cellulose, powder	RER	kilogram	Carboxymethyl cellulose, powder, at plant/RER S
market for cast iron	GLO	kilogram	cast iron	RER	kilogram	Cast iron, at plant/RER U
market for casting, brass	GLO	kilogram	casting, brass	CH	kilogram	Casting, brass/CH U
market for ceramic tile	GLO	kilogram	ceramic tile	CH	kilogram	Ceramic tiles, at regional storage/CH U
market for charger, electric passenger car	GLO	kilogram	charger, electric passenger car	RER	kilogram	charger, for electric passenger car/RER/I U
market for chemical factory	GLO	kilogram	chemical factory	RER	unit	Chemical plant, organics/RER/I U
market for chemical factory, organics	GLO	unit	chemical factory, organics	RER	unit	Chemical plant, organics/RER/I U
market for chemical, organic	GLO	kilogram	chemical, organic	GLO	kilogram	Chemicals organic, at plant/GLO U
market for chemicals, inorganic	GLO	kilogram	chemical, inorganic	GLO	kilogram	Chemicals inorganic, at plant/GLO U
market for chromium oxide, flakes	GLO	kilogram	chromium oxide, flakes	RER	kilogram	Chromium oxide, flakes, at plant/RER U
market for cobalt	GLO	kilogram	cobalt	GLO	kilogram	Cobalt, at plant/GLO U
market for compost	GLO	kilogram	compost	CH	kilogram	Compost, at plant/CH U
market for concrete block	DE	kilogram	concrete block	DE	kilogram	Concrete block, at plant/DE U
market for concrete, high exacting requirements	CH	cubic meter	concrete, high exacting requirements	CH	cubic meter	Concrete, exacting, at plant/CH U
market for concrete, normal	RoW	cubic meter	concrete, normal	CH	cubic meter	Concrete, normal, at plant/CH U
market for concrete, normal	CH	cubic meter	concrete, normal	CH	cubic meter	Concrete, normal, at plant/CH U
market for concrete, sole plate and foundation	CH	cubic meter	concrete, sole plate and foundation	CH	cubic meter	Concrete, sole plate and foundation, at plant/CH U
market for converter, for electric passenger car	GLO	kilogram	converter, for electric passenger car	RER	kilogram	converter, for electric passenger car/RER/I U
market for copper	GLO	kilogram	copper	RLA	kilogram	Copper, primary, at refinery/RLA U
market for copper oxide	GLO	kilogram	copper oxide	RER	kilogram	Copper oxide, at plant/RER U
market for copper, anode	GLO	kilogram	copper, anode	RLA	kilogram	Copper, primary, at refinery/RLA U
market for corrugated board box	RoW	kilogram	corrugated board box	RER	kilogram	Corrugated board base paper, kraftliner, at plant/RER U
market for cyclohexane	GLO	kilogram	cyclohexane	RER	kilogram	Cyclohexane, at plant/RER U
market for diesel	Europe without Switzerland	kilogram	diesel	RER	kilogram	Diesel, at regional storage/RER U
market for diesel, burned in building machine	GLO	megajoule	diesel, burned in building machine	CH	megajoule	diesel, burned in building machine, average/MJ/CH U
market for diethanolamine	GLO	kilogram	diethanolamine	RER	kilogram	Diethanolamine, at plant/RER U
market for display, liquid crystal, 17 inches	GLO	unit	display, liquid crystal, 17 inches	GLO	unit	LCD flat screen, 17 inches, at plant/GLO U
market for dolomite	RER	kilogram	dolomite	RER	kilogram	Dolomite, at plant/RER U
market for electric connector, wire clamp	GLO	kilogram	electric connector, wire clamp	GLO	kilogram	Connector, clamp connection, at plant/GLO U
market for electric motor, electric passenger car	GLO	kilogram	electric motor, electric passenger car	RER	kilogram	electric motor, for electric passenger car/RER/I U
market for electricity, medium voltage	JP	kilowatt hour	electricity, medium voltage	JP	kilowatt hour	electricity, medium voltage, production JP, at grid/kWh/JP U
market for electronic component factory	GLO	unit	electronic component factory	GLO	unit	Electronic component production plant/GLO/I U
market for electronic component, passive, unspecified	GLO	kilogram	electronic component, passive, unspecified	GLO	kilogram	Electronic component, passive, unspecified, at plant/GLO U
market for electrostatic paint	GLO	kilogram	electrostatic paint	RER	kilogram	Alkyd paint, white, 60% in H2O, at plant/RER U
market for ethanol, without water, in 99.7% solution state, from ethylene	RER	kilogram	ethanol, without water, in 99.7% solution state, from ethylene	RER	kilogram	Ethanol, 99.7% in H2O, from biomass, at distillation/RER U
market for ethylene carbonate	GLO	kilogram	ethylene carbonate	CN	kilogram	Ethylene carbonate, at plant/CN U
market for ethylene glycol	GLO	kilogram	ethylene glycol	RER	kilogram	Ethylene glycol, at plant/RER U
market for extrusion, plastic film	GLO	kilogram	extrusion, plastic film	RER	kilogram	Extrusion, plastic film/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for flat glass, coated	RER	kilogram	flat glass, coated	RER	kilogram	Flat glass, coated, at plant/RER U
market for flat glass, uncoated	RER	kilogram	flat glass, uncoated	RER	kilogram	Flat glass, uncoated, at plant/RER U
market for gas turbine, 10MW electrical	GLO	unit	gas turbine, 10MW electrical	RER	unit	Gas turbine, 10MWe, at production plant/RER/I U
market for glass fibre	GLO	kilogram	glass fibre	RER	kilogram	Glass fibre, at plant/RER U
market for glider, passenger car	GLO	kilogram	glider, passenger car	RER	kilogram	glider, for passenger car/RER/I U
market for gold	GLO	kilogram	gold	RER	kilogram	Gold, at regional storage/RER U
market for graphite	GLO	kilogram	graphite	RER	kilogram	Graphite, at plant/RER U
market for gravel, crushed	CH	kilogram	gravel, crushed	CH	kilogram	Gravel, crushed, at mine/CH U
market for gravel, crushed	RoW	kilogram	gravel, crushed	CH	kilogram	Gravel, crushed, at mine/CH U
market for gypsum fibreboard	GLO	kilogram	gypsum fibreboard	CH	kilogram	Gypsum fibre board, at plant/CH U
market for hard coal	Europe, without Russia and Turkey	kilogram	hard coal	WEU	kilogram	Hard coal, at regional storage/WEU U
market for heat, district or industrial, natural gas	RoW	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, natural gas, at industrial furnace >100kW/RER U
market for heat, district or industrial, natural gas	Europe without Switzerland	megajoule	heat, district or industrial, natural gas	RER	megajoule	Heat, natural gas, at industrial furnace >100kW/RER U
market for heat, district or industrial, other than natural gas	Europe without Switzerland	megajoule	heat, district or industrial, other than natural gas	RER	megajoule	Heat, heavy fuel oil, at industrial furnace 1MW/RER U
market for heat, central or small-scale, biomethane	Europe without Switzerland	megajoule	heat, central or small-scale, biomethane	CH	megajoule	heat, biogas from sugar beet, at cogen/CH U
market for heat, central or small-scale, other than natural gas	CH	megajoule	heat, central or small-scale, other than natural gas	CH	megajoule	Heat, heavy fuel oil, at industrial furnace 1MW/CH U
market for heat, from steam, in chemical industry	RER	megajoule	heat, from steam, in chemical industry	RER	kilogram	Steam, for chemical processes, at plant/RER U
market for heat, from steam, in chemical industry	RoW	megajoule	heat, from steam, in chemical industry	RER	kilogram	Steam, for chemical processes, at plant/RER U
market for heat, central or small-scale, biomethane	RoW	megajoule	heat, central or small-scale, biomethane	CH	megajoule	heat, biogas from sugar beet, at cogen/CH U
market for heat, future	GLO	megajoule	heat, future	CH	megajoule	Heat, natural gas, allocation exergy, at PEM fuel cell 2kWe, future/CH U
market for hexane	GLO	kilogram	hexane	RER	kilogram	Hexane, at plant/RER U
market for hydrochloric acid, without water, in 30% solution state	RER	kilogram	hydrochloric acid, without water, in 30% solution state	RER	kilogram	Hydrochloric acid, 30% in H2O, at plant/RER U
market for hydrogen, liquid	RER	kilogram	hydrogen, liquid	RER	kilogram	Hydrogen, liquid, at plant/RER U
market for injection moulding	GLO	kilogram	injection moulding	RER	kilogram	Injection moulding/RER U
market for integrated circuit, logic type	GLO	kilogram	integrated circuit, logic type	GLO	kilogram	Integrated circuit, IC, logic type, at plant/GLO U
market for internal combustion engine, passenger car	GLO	kilogram	internal combustion engine, for passenger car	RER	kilogram	internal combustion engine, for passenger car/RER/I U
market for inverter, for electric passenger car	GLO	kilogram	inverter, for electric passenger car	RER	kilogram	inverter, for electric passenger car/RER/I U
market for iron sulfate	RoW	kilogram	iron sulfate	RER	kilogram	Iron sulphate, at plant/RER U
market for isopropanol	RER	kilogram	isopropanol	RER	kilogram	Isopropanol, at plant/RER U
market for lead	GLO	kilogram	lead	RER	kilogram	Lead, at regional storage/RER U
market for light fuel oil	RoW	kilogram	light fuel oil	RER	kilogram	Light fuel oil, at regional storage/RER U
market for liquefied petroleum gas	Europe without Switzerland	kilogram	liquefied petroleum gas	CH	kilogram	Liquefied petroleum gas, at service station/CH U
market for liquid storage tank, chemicals, organics	GLO	unit	liquid storage tank, chemicals, organics	CH	unit	Liquid storage tank, chemicals, organics/CH/I U
market for lithium hexafluorophosphate	GLO	kilogram	lithium hexafluorophosphate	CN	kilogram	Lithium hexafluorophosphate, at plant/CN U
market for lithium hydroxide	GLO	kilogram	lithium hydroxide	GLO	kilogram	Lithium hydroxide, at plant/GLO U
market for lubricating oil	RER	kilogram	lubricating oil	RER	kilogram	Lubricating oil, at plant/RER U
market for lubricating oil	RoW	kilogram	lubricating oil	RER	kilogram	Lubricating oil, at plant/RER U
market for magnesium oxide	GLO	kilogram	magnesium oxide	RER	kilogram	Magnesium oxide, at plant/RER U
market for magnesium sulfate	GLO	kilogram	magnesium sulfate	RER	kilogram	Magnesium sulphate, at plant/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for maize seed, for sowing	GLO	kilogram	maize seed, for sowing	CH	kilogram	maize seed organic, at regional storehouse/kg/CH U
market for manual dismantling of used electric passenger car	GLO	unit	manual dismantling of used electric passenger car	RER	kilogram	Disposal, passenger car, electric, city car, without battery/RER/I U
market for manual dismantling of used passenger car with internal combustion engine	GLO	unit	manual dismantling of used passenger car with internal combustion engine	RER	unit	Disposal, passenger car/RER/I U
market for metal working factory	GLO	unit	metal working factory	RER	unit	Metal working factory/RER/I U
market for metal working, average for aluminium product manufacturing	GLO	kilogram	metal working, average for aluminium product manufacturing	RER	kilogram	Aluminium product manufacturing, average metal working/RER U
market for metal working, average for copper product manufacturing	GLO	kilogram	metal working, average for copper product manufacturing	RER	kilogram	Copper product manufacturing, average metal working/RER U
market for metal working, average for metal product manufacturing	GLO	kilogram	metal working, average for metal product manufacturing	RER	kilogram	Metal product manufacturing, average metal working/RER U
market for metal working, average for steel product manufacturing	GLO	kilogram	metal working, average for steel product manufacturing	RER	kilogram	Steel product manufacturing, average metal working/RER U
market for methanol	GLO	kilogram	methanol	CH	kilogram	Methanol, at regional storage/CH U
market for monoethanolamine	GLO	kilogram	monoethanolamine	RER	kilogram	Monoethanolamine, at plant/RER U
market for municipal solid waste	RoW	kilogram	municipal solid waste	CH	kilogram	disposal, municipal solid waste, 22.9% water, to municipal incineration/kg/CH U
market for municipal solid waste	CH	kilogram	municipal solid waste	CH	kilogram	disposal, municipal solid waste, 22.9% water, to municipal incineration/kg/CH U
market for natural gas, from high pressure network (1-5 bar), at service station	GLO	kilogram	natural gas, from high pressure network (1-5 bar), at service station	CH	kilogram	Natural gas, from high pressure network (1-5 bar), at service station/CH U
market for natural gas, from medium pressure network (0.1-1 bar), at service station	GLO	kilogram	natural gas, from medium pressure network (0.1-1 bar), at service station	CH	kilogram	Natural gas, from medium pressure network (0.1-1 bar), at service station/CH U
market for natural gas, high pressure	CH	cubic meter	natural gas, high pressure	CH	kilogram	Natural gas, from high pressure network (1-5 bar), at service station/CH U
market for natural gas, high pressure, vehicle grade	GLO	kilogram	natural gas, high pressure, vehicle grade	RER	megajoule	natural gas, high pressure, at consumer/MJ/RER U
market for natural gas, medium pressure, vehicle grade	GLO	kilogram	natural gas, medium pressure, vehicle grade	CH	kilogram	Natural gas, from medium pressure network (0.1-1 bar), at service station/CH U
market for natural gas service station	GLO	unit	natural gas service station	CH	unit	Natural gas service station/CH/I U
market for nickel sulfate	GLO	kilogram	nickel sulfate	GLO	kilogram	Nickel, 99.5%, at plant/GLO U
market for nickel, 99.5%	GLO	kilogram	nickel, 99.5%	GLO	kilogram	Nickel, 99.5%, at plant/GLO U
market for nickel, class 1	GLO	kilogram	nickel, class 1	GLO	kilogram	Nickel, 99.5%, at plant/GLO U
market for nitric acid, without water, in 50% solution state	RER w/o RU	kilogram	nitric acid, without water, in 50% solution state	RER	kilogram	Nitric acid, 50% in H2O, at plant/RER U
market for nitrogen fertiliser, as N	GLO	kilogram	nitrogen fertiliser, as N	RER	kilogram	nitro-compounds, at regional storehouse/kg/RER U
market for nitrogen, liquid	RoW	kilogram	nitrogen, liquid	RER	kilogram	Nitrogen, liquid, at plant/RER U
market for nitrogen, liquid	RER	kilogram	nitrogen, liquid	RER	kilogram	Nitrogen, liquid, at plant/RER U
market for nitrogen, liquid	RER	kilogram	nitrogen, liquid	RER	kilogram	Nitrogen, liquid, at plant/RER U
market for N-methyl-2-pyrrolidone	GLO	kilogram	N-methyl-2-pyrrolidone	RER	kilogram	N-methyl-2-pyrrolidone, at plant/RER U
market for nylon 6	RoW	kilogram	nylon 6	RER	kilogram	Nylon 6, at plant/RER U
market for nylon 6-6, glass-filled	RoW	kilogram	nylon 6-6, glass-filled	RER	kilogram	Nylon 66, glass-filled, at plant/RER U
market for nylon 6-6, glass-filled	RER	kilogram	nylon 6-6, glass-filled	RER	kilogram	Nylon 66, glass-filled, at plant/RER U
market for packaging film, low density polyethylene	GLO	kilogram	packaging film, low density polyethylene	RER	kilogram	Packaging film, LDPE, at plant/RER U
market for pesticide, unspecified	GLO	kilogram	pesticide, unspecified	CH	kilogram	pesticide unspecified, at regional storehouse/kg/CH U
market for petrol, low-sulfur	Europe without Switzerland	kilogram	petrol, low-sulfur	CH	kilogram	Petrol, low-sulphur, at refinery/CH U
market for phenolic resin	RER	kilogram	phenolic resin	RER	kilogram	Phenolic resin, at plant/RER U
market for phosphate fertiliser, as P2O5	GLO	kilogram	phosphate fertiliser, as P2O5	RER	kilogram	Ammonium nitrate phosphate, as P2O5, at regional storehouse/RER U
market for phosphoric acid, industrial grade, without water, in 85% solution state	GLO	kilogram	phosphoric acid, industrial grade, without water, in 85% solution state	RER	kilogram	Phosphoric acid, industrial grade, 85% in H2O, at plant/RER U
market for plastic processing factory	GLO	unit	plastic processing factory	RER	unit	Plastics processing factory/RER/I U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for platinum	GLO	kilogram	platinum	RER	kilogram	Platinum, at regional storage/RER U
market for polycarbonate	GLO	kilogram	polycarbonate	RER	kilogram	Polycarbonate, at plant/RER U
market for polyethylene terephthalate, granulate, amorphous	GLO	kilogram	polyethylene terephthalate, granulate, amorphous	RER	kilogram	Polyethylene terephthalate, granulate, amorphous, at plant/RER U
market for polyethylene, high density, granulate	GLO	kilogram	polyethylene, high density, granulate	RER	kilogram	Polyethylene, HDPE, granulate, at plant/RER U
market for polyethylene, high density, granulate, recycled	Europe without Switzerland	kilogram	polyethylene, high density, granulate, recycled	RER	kilogram	Polyethylene, HDPE, granulate, at plant/RER U
market for polyethylene, low density, granulate	GLO	kilogram	polyethylene, low density, granulate	RER	kilogram	Polyethylene, LDPE, granulate, at plant/RER U
market for polyphenylene sulfide	GLO	kilogram	polyphenylene sulfide	GLO	kilogram	Polyphenylene sulfide, at plant/GLO U
market for polypropylene, granulate	GLO	kilogram	polypropylene, granulate	RER	kilogram	Polypropylene, granulate, at plant/RER U
market for polyurethane, flexible foam	RER	kilogram	polyurethane, flexible foam	RER	kilogram	Polyurethane, flexible foam, at plant/RER U
market for polyurethane, rigid foam	RER	kilogram	polyurethane, rigid foam	RER	kilogram	Polyurethane, rigid foam, at plant/RER U
market for polyvinylchloride, suspension polymerised	GLO	kilogram	polyvinylchloride, suspension polymerised	RER	kilogram	Polyvinylchloride, suspension polymerised, at plant/RER U
market for polyvinylfluoride	GLO	kilogram	polyvinylfluoride	US	kilogram	polyvinylfluoride, at plant/kg/US U
market for portafer	GLO	kilogram	portafer	RER	kilogram	Portafer, at plant/RER U
market for potassium carbonate	GLO	kilogram	potassium carbonate	GLO	kilogram	Potassium carbonate, at plant/GLO U
market for potassium fertiliser, as K2O	GLO	kilogram	potassium fertiliser, as K2O	RER	kilogram	Potassium nitrate, as K2O, at regional storehouse/RER U
market for potassium hydroxide	GLO	kilogram	potassium hydroxide	RER	kilogram	Potassium hydroxide, at regional storage/RER U
market for potassium sulfate	RER	kilogram	potassium sulfate	RER	kilogram	Potassium sulphate, as K2O, at regional storehouse/RER U
market for potassium sulfate, as K2O	GLO	kilogram	potassium sulfate, as K2O	RER	kilogram	Potassium sulphate, as K2O, at regional storehouse/RER U
market for power distribution unit, for electric passenger car	GLO	kilogram	power distribution unit, for electric passenger car	RER	kilogram	power distribution unit, for electric passenger car/RER/I U
market for precious metal refinery	GLO	unit	precious metal refinery	SE	unit	Facilities precious metal refinery/SE/I U
market for printed wiring board, through-hole mounted, unspecified, Pb free	GLO	kilogram	printed wiring board, through-hole mounted, unspecified, Pb free	GLO	kilogram	Printed wiring board, through-hole mounted, unspec., Pb free, at plant/GLO U
market for pump, 40W	GLO	unit	pump, 40W	CH	unit	Pump 40W, at plant/CH/I U
market for quicklime, milled, packed	RER	kilogram	quicklime, milled, packed	CH	kilogram	Quicklime, milled, packed, at plant/CH U
market for rainwater mineral oil storage	Europe without Switzerland	cubic meter	rainwater mineral oil storage	CH	cubic meter	Treatment, rainwater mineral oil storage, to wastewater treatment, class 2/CH U
market for rape seed	GLO	kilogram	rape seed	DE	kilogram	rape seed conventional, at farm/kg/DE U
market for refrigerant R134a	GLO	kilogram	refrigerant R134a	RER	kilogram	Refrigerant R134a, at plant/RER U
market for reinforcing steel	GLO	kilogram	reinforcing steel	RER	kilogram	Reinforcing steel, at plant/RER U
market for road	GLO	meter-year	road	CH	meter-year	Road/CH/I U
market for road maintenance	RER	meter-year	road maintenance	CH	meter-year	Operation, maintenance, road/CH/I U
market for road wear emissions, passenger car	GLO	kilogram	road wear emissions, passenger car	RER	kilogram	road wear emissions, passenger car/RER U
market for sheet rolling, aluminium	GLO	kilogram	sheet rolling, aluminium	RER	kilogram	Sheet rolling, aluminium/RER U
market for sheet rolling, chromium steel	GLO	kilogram	sheet rolling, chromium steel	RER	kilogram	Sheet rolling, chromium steel/RER U
market for sheet rolling, copper	GLO	kilogram	sheet rolling, copper	RER	kilogram	Sheet rolling, chromium steel/RER U
market for sheet rolling, steel	GLO	kilogram	sheet rolling, steel	RER	kilogram	Sheet rolling, copper/RER U
market for silica sand	GLO	kilogram	silica sand	RER	kilogram	Sheet rolling, steel/RER U
market for silicon, electronics grade	GLO	kilogram	silicon, electronics grade	DE	kilogram	silicon, electronic grade, at plant/kg/DE U
market for silicone product	RER	kilogram	silicone product	RER	kilogram	Silicone product, at plant/RER U
market for soap	GLO	kilogram	soap	RER	kilogram	Soap, at plant/RER U
market for soda ash, light, crystalline, heptahydrate	GLO	kilogram	soda ash, light, crystalline, heptahydrate	GLO	kilogram	Sodium carbonate from ammonium chloride production, at plant/GLO U
market for sodium chloride, powder	GLO	kilogram	sodium chloride, powder	RER	kilogram	Sodium chloride, powder, at plant/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for sodium hydroxide, without water, in 50% solution state	GLO	kilogram	sodium hydroxide, without water, in 50% solution state	RER	kilogram	Sodium hydroxide, 50% in H2O, production mix, at plant/RER U
market for sodium methoxide	GLO	kilogram	sodium methoxide	GLO	kilogram	Sodium methoxide, at plant/GLO U
market for sodium persulfate	GLO	kilogram	sodium persulfate	GLO	kilogram	Sodium persulfate, at plant/GLO U
market for soft solder, Sn97Cu3	RER	kilogram	soft solder, Sn97Cu3	RER	kilogram	soft solder, Sn97Cu3, at plant/RER U
market for soil pH raising agent, as CaCO3	GLO	kilogram	soil pH raising agent, as CaCO3	CH	kilogram	Limestone, at mine/CH U
market for steel, chromium steel 18/8	GLO	kilogram	steel, chromium steel 18/8	RER	kilogram	Chromium steel 18/8, at plant/RER U
market for steel, chromium steel 18/8, hot rolled	GLO	kilogram	steel, chromium steel 18/8, hot rolled	RER	kilogram	Sheet rolling, chromium steel/RER U
market for steel, low-alloyed	GLO	kilogram	steel, low-alloyed	RER	kilogram	Steel, low-alloyed, at plant/RER U
market for steel, low-alloyed, hot rolled	GLO	kilogram	steel, low-alloyed, hot rolled	RER	kilogram	Steel, low-alloyed, at plant/RER U
market for steel, unalloyed	GLO	kilogram	steel, unalloyed	RER	kilogram	Steel, converter, unalloyed, at plant/RER U
market for stone wool, packed	GLO	kilogram	stone wool, packed	CH	kilogram	Glass wool mat, at plant/CH U
market for styrene	GLO	kilogram	styrene	RER	kilogram	Styrene, at plant/RER U
market for sugar beet seed, for sowing	GLO	kilogram	sugar beet seed, for sowing	CH	kilogram	Sugar beet seed IP, at regional storehouse/CH U
market for sulfur dioxide, liquid	RER	kilogram	sulfur dioxide, liquid	RER	kilogram	Sulphur dioxide, liquid, at plant/RER U
market for sulfur hexafluoride, liquid	RER	kilogram	sulfur hexafluoride, liquid	RER	kilogram	Sulphur hexafluoride, liquid, at plant/RER U
market for sulfuric acid	RER	kilogram	sulfuric acid	RER	kilogram	Sulphuric acid, liquid, at plant/RER U
market for synthetic rubber	GLO	kilogram	synthetic rubber	RER	kilogram	Synthetic rubber, at plant/RER U
market for tap water	Europe without Switzerland	kilogram	tap water	RER	kilogram	tap water, at user/kg/RER U
market for tap water	CH	kilogram	tap water	CH	kilogram	tap water, at user/kg/CH U
market for tap water	RoW	kilogram	tap water	RER	kilogram	tap water, at user/kg/RER U
market for thermoforming, with calendering	GLO	kilogram	thermoforming, with calendering	RER	kilogram	Thermoforming, with calendering/RER U
market for tin	GLO	kilogram	tin	RER	kilogram	Tin, at regional storage/RER U
market for titanium dioxide	RoW	kilogram	titanium dioxide	RER	kilogram	Titanium dioxide, production mix, at plant/RER U
market for transformer, high voltage use	GLO	kilogram	transformer, high voltage use	GLO	kilogram	Transformer, high voltage use, at plant/GLO U
market for transport, freight train	Europe without Switzerland	ton kilometer	transport, freight train	RER	ton kilometer	transport, freight, rail/tkm/RER U
market for transport, freight train	CH	ton kilometer	transport, freight train	CH	ton kilometer	transport, freight, rail, electricity with shunting/tkm/CH U
market for transport, freight, inland waterways, barge	RER	ton kilometer	transport, freight, inland waterways, barge	RER	ton kilometer	transport, barge tanker/tkm/RER U
market for transport, freight, lorry >32 metric ton, EURO3	RoW	ton kilometer	transport, freight, lorry >32 metric ton, EURO3	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 3/tkm/RER U
market for transport, freight, lorry >32 metric ton, EURO4	RER	ton kilometer	transport, freight, lorry >32 metric ton, EURO4	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 4/tkm/RER U
market for transport, freight, lorry >32 metric ton, EURO5	RER	ton kilometer	transport, freight, lorry >32 metric ton, EURO5	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 5/tkm/RER U
market for transport, freight, lorry >32 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry >32 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 6/tkm/RER U
market for transport, freight, lorry 16-32 metric ton, EURO3	RoW	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO3	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 3/tkm/RER U
market for transport, freight, lorry 16-32 metric ton, EURO5	RoW	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO5	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 5/tkm/RER U
market for transport, freight, lorry 7.5-16 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 7.5-16 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 7.5-16 metric ton, EURO 6/tkm/RER U
market for transport, freight, lorry, unspecified	RER	ton kilometer	transport, freight, lorry, unspecified	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 5/tkm/RER U
market for transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas	GLO	ton kilometer	transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas	OCE	ton kilometer	transport, transoceanic tanker/tkm/OCE U
market for transport, freight, sea, tanker for petroleum	GLO	ton kilometer	transport, freight, sea, tanker for petroleum	OCE	ton kilometer	transport, transoceanic tanker/tkm/OCE U
market for transport, helicopter	GLO	hour	transport, helicopter	CH	hour	transport, freight helicopter, single-engine/hr/CH U
market for transport, pipeline, onshore, petroleum	RER	ton kilometer	transport, pipeline, onshore, petroleum	RER	kilometer	Pipeline, crude oil, onshore/RER/I U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for tyre wear emissions, passenger car	GLO	kilogram	tyre wear emissions, passenger car	RER	kilogram	tyre wear emissions, passenger car/RER U
market for urea	RER	kilogram	urea	RER	kilogram	Urea, as N, at regional storehouse/RER U
market for urea, as N	GLO	kilogram	urea, as N	RER	kilogram	Urea, as N, at regional storehouse/RER U
market for used powertrain from electric passenger car, manual dismantling	GLO	kilogram	used powertrain from electric passenger car, manual dismantling	RER	kilogram	disposal, powertrain, for electric passenger car/RER/I U
market for used vegetable cooking oil	GLO	kilogram	used vegetable cooking oil	CH	kilogram	Vegetable oil, from waste cooking oil, at plant/CH U
market for waste plastic, industrial electronics	RoW	kilogram	waste plastic, industrial electronics	CH	kilogram	disposal, plastic, industr. electronics, 15.3% water, to municipal incineration/kg/CH U
market for waste rubber, unspecified	RoW	kilogram	waste rubber, unspecified	CH	kilogram	disposal, rubber, unspecified, 0% water, to municipal incineration/kg/CH U
market for water, completely softened	RER	kilogram	water, completely softened	RER	kilogram	Water, completely softened, at plant/RER U
market for water, decarbonised	DE	kilogram	water, decarbonised	RER	kilogram	Water, decarbonised, at plant/RER U
market for water, decarbonised	RoW	kilogram	water, decarbonised	RER	kilogram	Water, decarbonised, at plant/RER U
market for water, decarbonised	CH	kilogram	water, decarbonised	RER	kilogram	Water, decarbonised, at plant/RER U
market for water, deionised	Europe without Switzerland	kilogram	water, deionised	CH	kilogram	Water, deionised, at plant/CH U
market for water, deionised	CH	kilogram	water, deionised	CH	kilogram	Water, deionised, at plant/CH U
market for water, deionised	RoW	kilogram	water, deionised	CH	kilogram	Water, deionised, at plant/CH U
market for water, ultrapure	RoW	kilogram	water, ultrapure	GLO	kilogram	Water, ultrapure, at plant/GLO U
market for water, ultrapure	RER	kilogram	water, ultrapure	GLO	kilogram	Water, ultrapure, at plant/GLO U
market for welding, arc, steel	GLO	meter	welding, arc, steel	RER	meter	Welding, arc, steel/RER U
market for wheat seed, for sowing	GLO	kilogram	wheat seed, for sowing	CH	kilogram	wheat seed organic, at regional storehouse/kg/CH U
market for zeolite, powder	GLO	kilogram	zeolite, powder	RER	kilogram	Zeolite, powder, at plant/RER S
market for zinc	GLO	kilogram	zinc	GLO	kilogram	Zinc concentrate, at beneficiation/GLO U
market for zinc	GLO	kilogram	zinc	GLO	kilogram	Zinc concentrate, at beneficiation/GLO U
market for zinc oxide	GLO	kilogram	zinc oxide	RER	kilogram	Zinc oxide, at plant/RER U
market group for diesel	RER	kilogram	diesel	RER	kilogram	Diesel, at regional storage/RER U
market group for diesel, low-sulfur	RER	kilogram	diesel, low-sulfur	RER	kilogram	Diesel, at regional storage/RER U
market group for electricity, high voltage	ENTSO-E	kilowatt hour	electricity, high voltage	ENTSO	kilowatt hour	electricity, high voltage, production ENTSO, at grid/kWh/ENTSO U
market group for electricity, low voltage	ENTSO-E	kilowatt hour	electricity, low voltage	ENTSO	kilowatt hour	electricity, low voltage, production ENTSO, at grid/kWh/ENTSO U
market group for electricity, low voltage	GLO	kilowatt hour	electricity, low voltage	GLO	kilowatt hour	electricity, low voltage, production GLO, at grid/kWh/GLO U
market group for electricity, medium voltage	ENTSO-E	kilowatt hour	electricity, medium voltage	ENTSO	kilowatt hour	electricity, medium voltage, production ENTSO, at grid/kWh/ENTSO U
market group for electricity, medium voltage	GLO	kilowatt hour	electricity, medium voltage	GLO	kilowatt hour	electricity, medium voltage, production GLO, at grid/kWh/GLO U
market group for heat, central or small-scale, natural gas	RER	megajoule	heat, central or small-scale, natural gas	RER	megajoule	Heat, natural gas, at boiler condensing modulating >100kW/RER U
market group for inorganic nitrogen fertiliser, as N	RER	kilogram	inorganic nitrogen fertiliser, as N	RER	kilogram	nitro-compounds, at regional storehouse/kg/RER U
market group for inorganic phosphorus fertiliser, as P2O5	RER	kilogram	inorganic phosphorus fertiliser, as P2O5	RER	kilogram	Ammonium nitrate phosphate, as P2O5, at regional storehouse/RER U
market group for inorganic potassium fertiliser, as K2O	RER	kilogram	inorganic potassium fertiliser, as K2O	RER	kilogram	Potassium nitrate, as K2O, at regional storehouse/RER U
market group for light fuel oil	RER	kilogram	light fuel oil	RER	kilogram	Light fuel oil, at regional storage/RER U
market group for natural gas, high pressure	Europe without Switzerland	cubic meter	natural gas, high pressure	CH	kilogram	Natural gas, from high pressure network (1-5 bar), at service station/CH U
metal coating facility construction	RoW	unit	metal coating facility	RER	unit	Metal coating plant/RER/I U
metal working, average for aluminium product manufacturing	RoW	kilogram	metal working, average for aluminium product manufacturing	RER	kilogram	Aluminium product manufacturing, average metal working/RER U
metal working, average for aluminium product manufacturing	RER	kilogram	metal working, average for aluminium product manufacturing	RER	kilogram	Aluminium product manufacturing, average metal working/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
metal working, average for chromium steel product manufacturing	RER	kilogram	metal working, average for chromium steel product manufacturing	RER	kilogram	Chromium steel product manufacturing, average metal working/RER U
metal working, average for chromium steel product manufacturing	RoW	kilogram	metal working, average for chromium steel product manufacturing	RER	kilogram	Chromium steel product manufacturing, average metal working/RER U
metal working, average for copper product manufacturing	RER	kilogram	metal working, average for copper product manufacturing	RER	kilogram	Copper product manufacturing, average metal working/RER U
metal working, average for steel product manufacturing	RER	kilogram	metal working, average for steel product manufacturing	RER	kilogram	Steel product manufacturing, average metal working/RER U
nickel mine operation and benefication to nickel concentrate, 7% Ni	CN	kilogram	nickel concentrate, 7% Ni	GLO	kilogram	Nickel, 99.5%, at plant/GLO U
nickel mine operation, sulfidic ore	GLO	kilogram	nickel, 99.5%	GLO	kilogram	Nickel, 99.5%, at plant/GLO U
nitric acid production, product in 50% solution state	RER	kilogram	nitric acid, without water, in 50% solution state	RER	kilogram	Nitric acid, 50% in H2O, at plant/RER U
nitric acid production, product in 50% solution state	RER w/o RU	kilogram	nitric acid, without water, in 50% solution state	RER	kilogram	Nitric acid, 50% in H2O, at plant/RER U
operation, computer, desktop, with liquid crystal display, active mode	CH	hour	operation, computer, desktop, with liquid crystal display, active mode	RER	hour	Use, computer, desktop with LCD monitor, active mode/RER U
packaging box factory construction	RoW	unit	packaging box factory	RER	unit	Packaging box production unit/RER/I U
phenolic resin production	RoW	kilogram	phenolic resin	RER	kilogram	Phenolic resin, at plant/RER U
pipeline construction, natural gas, high pressure distribution network	RoW	kilometer	pipeline, natural gas, high pressure distribution network	RER	kilometer	Pipeline, natural gas, high pressure distribution network/RER/I U
pipeline construction, natural gas, high pressure distribution network	Europe without Switzerland	kilometer	pipeline, natural gas, high pressure distribution network	RER	kilometer	Pipeline, natural gas, high pressure distribution network/RER/I U
polyethylene production, high density, granulate	RER	kilogram	polyethylene, high density, granulate	RER	kilogram	Polyethylene, HDPE, granulate, at plant/RER U
polyethylene production, low density, granulate	RoW	kilogram	polyethylene, low density, granulate	RER	kilogram	Polyethylene, LDPE, granulate, at plant/RER U
polyvinylchloride production, bulk polymerisation	RER	kilogram	polyvinylchloride, bulk polymerised	RER	kilogram	Polyvinylchloride, bulk polymerised, at plant/RER U
power sawing, without catalytic converter	RER	hour	power sawing, without catalytic converter	RER	hour	power sawing, without catalytic converter/hr/RER
pump production, 40W	CH	unit	pump, 40W	CH	unit	Pump 40W, at plant/CH/I U
reinforcing steel production	RoW	kilogram	reinforcing steel	RER	kilogram	Reinforcing steel, at plant/RER U
reinforcing steel production	RER	kilogram	reinforcing steel	RER	kilogram	Reinforcing steel, at plant/RER U
reinforcing steel production	Europe without Austria	kilogram	reinforcing steel	RER	kilogram	Reinforcing steel, at plant/RER U
router, internet	CH	unit	router, internet	CH	unit	Router, IP network, at server/CH/I U
sheet rolling, aluminium	RoW	kilogram	sheet rolling, aluminium	RER	kilogram	Sheet rolling, aluminium/RER U
sheet rolling, chromium steel	RoW	kilogram	sheet rolling, chromium steel	RER	kilogram	Sheet rolling, chromium steel/RER U
sheet rolling, steel	RoW	kilogram	sheet rolling, steel	RER	kilogram	Sheet rolling, steel/RER U
skidding, skidder	RER	hour	skidding, skidder	RER	hour	skidding/hr/RER
smelting of copper concentrate, sulfide ore	RoW	kilogram	copper, anode	RLA	kilogram	Copper, primary, at refinery/RLA U
Sohio process	RoW	kilogram	acrylonitrile	RER	kilogram	Acrylonitrile from Sohio process, at plant/RER U
steam production, as energy carrier, in chemical industry	RoW	megajoule	heat, from steam, in chemical industry	RER	kilogram	Steam, for chemical processes, at plant/RER U
steel production, chromium steel 18/8, hot rolled	RoW	kilogram	steel, chromium steel 18/8, hot rolled	RER	kilogram	Sheet rolling, chromium steel/RER U
steel production, converter, low-alloyed	RER	kilogram	steel, low-alloyed	RER	kilogram	Steel, low-alloyed, at plant/RER U
steel production, electric, low-alloyed	RER	kilogram	steel, low-alloyed	RER	kilogram	Steel, low-alloyed, at plant/RER U
steel production, electric, low-alloyed	Europe without Switzerland and Austria	kilogram	steel, low-alloyed	RER	kilogram	Steel, low-alloyed, at plant/RER U
sulfuric acid production	RoW	kilogram	sulfuric acid	RER	kilogram	Sulphuric acid, liquid, at plant/RER U
synthetic gas factory construction	CH	unit	synthetic gas factory	CH	unit	Synthetic gas plant/CH/I U
synthetic rubber production	RER	kilogram	synthetic rubber	RER	kilogram	Synthetic rubber, at plant/RER U
tetrafluoroethylene production	RoW	kilogram	tetrafluoroethylene	RER	kilogram	tetrafluoroethylene, at plant/kg/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
tin production	RoW	kilogram	tin	RER	kilogram	Tin, at regional storage/RER U
transmission network construction, electricity, high voltage	CH	kilometer	transmission network, electricity, high voltage	CH	kilometer	transmission network, electricity, high voltage/km/CH/I U
transmission network construction, electricity, medium voltage	CH	kilometer	transmission network, electricity, medium voltage	CH	kilometer	transmission network, electricity, medium voltage/km/CH/I U
transmission network construction, long-distance	UCTE	kilometer	transmission network, long-distance	UCTE	kilometer	transmission network, long-distance/km/UCTE/I U
transport, freight train, diesel, with particle filter	CH	ton kilometer	transport, freight train	RER	ton kilometer	transport, freight, rail/tkm/RER U
transport, freight, inland waterways, barge	RER	ton kilometer	transport, freight, inland waterways, barge	RER	ton kilometer	transport, barge tanker/tkm/RER U
transport, freight, lorry >32 metric ton, EURO6	RoW	ton kilometer	transport, freight, lorry >32 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 6/tkm/RER U
transport, freight, lorry 16-32 metric ton, EURO5	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO5	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 5/tkm/RER U
transport, freight, lorry 16-32 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 16-32 metric ton, EURO 6/tkm/RER U
transport, helicopter	GLO	hour	transport, helicopter	CH	hour	transport, freight helicopter, single-engine/hr/CH U
transport, helicopter, LTO cycle	GLO	unit	transport, helicopter, LTO cycle	CH	unit	transport, helicopter, single-engine, LTO cycle/p/CH U
treatment of brake wear emissions, lorry	RER	kilogram	brake wear emissions, lorry	RER	kilogram	brake wear emissions, lorry/RER U
treatment of drilling waste, landfarming	CH	kilogram	drilling waste	CH	kilogram	Disposal, drilling waste, 71.5% water, to landfarming/CH U
treatment of drilling waste, residual material landfill	CH	kilogram	drilling waste	CH	kilogram	Disposal, drilling waste, 71.5% water, to residual material landfill/CH U
treatment of hard coal ash, residual material landfill	DE	kilogram	hard coal ash	CH	kilogram	Disposal, hard coal ash from stove, 0% water, to sanitary landfill/CH U
treatment of hazardous waste, hazardous waste incineration	RoW	kilogram	hazardous waste, for incineration	CH	kilogram	Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U
treatment of hazardous waste, hazardous waste incineration	CH	kilogram	hazardous waste, for incineration	CH	kilogram	Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH U
treatment of inert waste, inert material landfill	CH	kilogram	inert waste, for final disposal	CH	kilogram	Disposal, inert waste, 5% water, to inert material landfill/CH U
treatment of municipal solid waste, incineration	DE	kilowatt hour	electricity, for reuse in municipal waste incineration only	CH	kilowatt hour	Electricity from waste, at municipal waste incineration plant/CH U
treatment of road wear emissions, lorry	RER	kilogram	road wear emissions, lorry	RER	kilogram	road wear emissions, lorry/RER U
treatment of scrap steel, inert material landfill	CH	kilogram	scrap steel	CH	kilogram	Disposal, steel, 0% water, to inert material landfill/CH U
treatment of sewage sludge by anaerobic digestion	CH	cubic meter	biogas	CH	cubic meter	Biogas, from sewage sludge, at storage/CH U
treatment of spent anion exchange resin from potable water production, municipal incineration	RoW	kilogram	spent anion exchange resin from potable water production	CH	kilogram	disposal, anion exchange resin f. water, 50% water, to municipal incineration/kg/CH U
treatment of tyre wear emissions, lorry	RER	kilogram	tyre wear emissions, lorry	RER	kilogram	tyre wear emissions, lorry/RER U
treatment of used lorry, 16 metric ton	CH	unit	used lorry, 16 metric ton	CH	unit	Disposal, lorry 16t/CH/I U
treatment of used lorry, 28 metric ton	CH	unit	used lorry, 28 metric ton	CH	unit	Disposal, lorry 28t/CH/I U
treatment of used lorry, 40 metric ton	CH	unit	used lorry, 40 metric ton	CH	unit	Disposal, lorry 40t/CH/I U
treatment of waste asphalt, sanitary landfill	RoW	kilogram	waste asphalt	CH	kilogram	Disposal, asphalt, 0.1% water, to sanitary landfill/CH U
treatment of waste bulk iron, excluding reinforcement, sorting plant	Europe without Switzerland	kilogram	waste bulk iron, excluding reinforcement	CH	kilogram	Disposal, building, bulk iron (excluding reinforcement), to sorting plant/CH U
treatment of waste gypsum, inert material landfill	Europe without Switzerland	kilogram	waste gypsum	CH	kilogram	Disposal, gypsum, 19.4% water, to inert material landfill/CH U
treatment of waste mineral oil, hazardous waste incineration	RoW	kilogram	waste mineral oil	CH	kilogram	Disposal, bilge oil, 90% water, to hazardous waste incineration/CH U
treatment of waste mineral wool, inert material landfill	CH	kilogram	waste mineral wool, for final disposal	CH	kilogram	Disposal, building, mineral wool, to final disposal/CH U
treatment of waste plastic, mixture, sanitary landfill	RoW	kilogram	waste plastic, mixture	CH	kilogram	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U
treatment of waste reinforced concrete, collection for final disposal	Europe without Switzerland	kilogram	waste reinforced concrete	CH	kilogram	Disposal, building, reinforced concrete, to final disposal/CH U
treatment of wastewater from lorry production, capacity 4.7E10l/year	CH	cubic meter	wastewater from lorry production	CH	cubic meter	Treatment, sewage, from residence, to wastewater treatment, class 2/CH U
treatment of wastewater, average, capacity 1.1E10l/year	CH	cubic meter	wastewater, average	CH	cubic meter	Treatment, sewage, from residence, to wastewater treatment, class 2/CH U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
treatment of wastewater, average, capacity 1E9l/year	CH	cubic meter	wastewater, average	CH	cubic meter	Treatment, sewage, from residence, to wastewater treatment, class 2/CH U
treatment of wastewater, average, capacity 1E9l/year	Europe without Switzerland	cubic meter	wastewater, average	CH	cubic meter	Treatment, sewage, from residence, to wastewater treatment, class 2/CH U
treatment of wastewater, from residence, capacity 1.1E10l/year	RoW	cubic meter	wastewater, from residence	CH	cubic meter	Treatment, sewage, from residence, to wastewater treatment, class 2/CH U
treatment of wastewater, unpolluted, capacity 5E9l/year	RoW	cubic meter	wastewater, unpolluted	CH	cubic meter	Treatment, sewage, unpolluted, from residence, to wastewater treatment, class 2/CH U
treatment of wood ash mixture, pure, municipal incineration with fly ash extraction	CH	kilogram	wood ash mixture, pure	CH	kilogram	disposal, wood ash mixture, pure, 0% water, to municipal incineration/kg/CH U
tree seedling production, in heated greenhouse	RER	unit	tree seedling, for planting	RER	unit	tree seedling, from heated greenhouse, 1000 units, at tree nursery/p/RER
tree seedling production, in heated greenhouse	RER	unit	tree seedling, for planting	RER	unit	tree seedling, from unheated greenhouse, 1000 units, at tree nursery/p/RER
tree seedling production, in unheated greenhouse	RER	unit	tree seedling, for planting	RER	unit	tree seedling, from unheated greenhouse, 1000 units, at tree nursery/p/RER
tube insulation production, elastomere	RoW	kilogram	tube insulation, elastomere	DE	kilogram	Tube insulation, elastomere, at plant/DE U
water production, deionised	Europe without Switzerland	kilogram	water, deionised	CH	kilogram	Water, deionised, at plant/CH U
welding, arc, aluminium	RER	meter	welding, arc, aluminium	RER	meter	Welding, arc, aluminium/RER U
welding, arc, steel	RoW	meter	welding, arc, steel	RER	meter	Welding, arc, steel/RER U
wire drawing, copper	RoW	kilogram	wire drawing, copper	RER	kilogram	Wire drawing, copper/RER U
wood chipping, mobile chipper, at forest road	RER	hour	wood chipping, chipper, mobile, diesel, at forest road	RER	hour	wood chipping, chipper, mobile, diesel, at forest road/hr/RER
wood chipping, terrain chipper, diesel	RER	hour	wood chipping, forwarder with terrain chipper, in forest	RER	hour	wood chipping, forwarder with terrain chipper, in forest/hr/RER
yarding and processing, mobile cable yarder on truck	RER	hour	cable yarding	RER	hour	cable yarding and processing, mobile cable yarder on truck/hr/RER
yarding, mobile cable yarder on trailer	RER	hour	cable yarding	RER	hour	cable yarding, mobile cable yarder on trailer/hr/RER
yarding, sled yarder	RER	hour	cable yarding	RER	hour	cable yarding, sled yarder/hr/RER
market for used Li-ion battery	GLO	kilogram	used Li-ion battery	GLO	kilogram	Disposal, Li-ions batteries, mixed technology/GLO U
market group for electricity, medium voltage	Europe without Switzerland	kilowatt hour	electricity, medium voltage	ENTSO	kilowatt hour	electricity, medium voltage, production ENTSO, at grid/kWh/ENTSO U
market group for electricity, low voltage	Europe without Switzerland	kilowatt hour	electricity, low voltage	ENTSO	kilowatt hour	electricity, low voltage, production ENTSO, at grid/kWh/ENTSO U
treatment of wood ash mixture, pure, municipal incineration	Europe without Switzerland	kilogram	wood ash mixture, pure	CH	kilogram	disposal, wood ash mixture, pure, 0% water, to municipal incineration/kg/CH U
treatment of wood ash mixture, pure, municipal incineration	CH	kilogram	wood ash mixture, pure	CH	kilogram	disposal, wood ash mixture, pure, 0% water, to municipal incineration/kg/CH U
synthetic gas factory construction	RoW	unit	synthetic gas factory	CH	unit	Synthetic gas plant/CH/I U
market for compressed air, 1000 kPa gauge	RER	cubic meter	compressed air, 1000 kPa gauge	RER	cubic meter	Compressed air, average generation, <30kW, 10 bar gauge, at compressor/RER U
transport, freight, lorry 7.5-16 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 7.5-16 metric ton, EURO6	RER	ton kilometer	transport, freight, lorry 7.5-16 metric ton, EURO 6/tkm/RER U
air separation, cryogenic	RER	kilogram	nitrogen, liquid	RER	kilogram	Nitrogen, liquid, at plant/RER U
market for dimethyl sulfoxide	GLO	kilogram	dimethyl sulfoxide	RER	kilogram	Dimethyl sulfoxide, at plant/RER U
market for steam, in chemical industry	RER	kilogram	steam, in chemical industry	RER	kilogram	Steam, for chemical processes, at plant/RER U
market for NOx retained, by selective catalytic reduction	GLO	kilogram	NOx retained, by selective catalytic reduction	GLO	kilogram	NOx retained, in SCR/GLO U
market for ammonium bicarbonate	RER	kilogram	ammonium bicarbonate	RER	kilogram	Ammonium bicarbonate, at plant/RER U
market for potassium permanganate	GLO	kilogram	potassium permanganate	RER	kilogram	Potassium permanganate, at plant/RER U
market for epoxy resin, liquid	RER	kilogram	epoxy resin, liquid	RER	kilogram	Epoxy resin, liquid, at plant/RER U
market for electronics, for control units	GLO	kilogram	electronics, for control units	RER	kilogram	Electronics for control units/RER U
market for metal working, average for chromium steel product manufacturing	GLO	kilogram	metal working, average for chromium steel product manufacturing	RER	kilogram	Steel product manufacturing, average metal working/RER U

Ecoinvent 3.x name	Ecoinvent 3.x location	Ecoinvent 3.x unit	Ecoinvent 3.x reference product	UVEK:2018 location	UVEK:2018 unit	UVEK:2018 (Simapro) name
market for waste concrete	RoW	kilogram	waste concrete	CH	kilogram	Disposal, building, concrete, not reinforced, to final disposal/CH U
market for lithium carbonate	GLO	kilogram	lithium carbonate	GLO	kilogram	Lithium carbonate, at plant/GLO U
market for titanium dioxide	RER	kilogram	titanium dioxide	RER	kilogram	Titanium dioxide, production mix, at plant/RER U
market for acrylic acid	RER	kilogram	acrylic acid	RER	kilogram	Acrylic acid, at plant/RER U
market for methyl acrylate	GLO	kilogram	methyl acrylate	GLO	kilogram	Methyl acrylate, at plant/GLO U

Annex B

B. Specifications for commercial electric kick-scooters

Model	Power [kW]	Curb mass [kg]	Battery cap. [kWh]	Range [km]
Unagi - Model One	0.5	12	0.3	24
Swagtron Swagger 5 Elite	0.25	12.5	0.16	18
Glion - Dolly	0.25	13	0.28	24
GoTrax - XR Ultra	0.3	12	0.25	26
Levy - Electric scooter	0.35	12	0.23	24
Slidgo - X8	0.35	13.6	0.3	26
Segway Ninebot - ES4	0.5	14	0.19	29
Xiaomi - Mi Electric Scooter	0.25	12.5	0.27	29

C. Specifications for commercial electric bicycles

Model	Type	Power [kW]	Curb mass [kg]	Battery cap. [kWh]	Range [km]
Tern GSD S00	Cargo	0.25	32.5	0.5/1	50
Prophete Cargo 2.0	Cargo	0.25	49	0.57	100
Babboe - Curve-E	Cargo	0.25	65	0.374	40-60
Bakfiets Troy E-Bike	Cargo	0.25	65	0.45	40-70
Bluelabel Cruiser HS	45 km/h	0.35	26	0.4	60
Haibike Xduro Race S	45 km/h	0.35	19	0.5	
Raleigh Dover 40	45 km/h	0.3	23	0.47	24-32
Bulls E45	45 km/h	0.5	30	0.67	210
Bulls Green Mover Mountain	45 km/h	0.25	24	0.45	130
Hercules - Futura 45	45 km/h	0.27	27	0.4	180

Model	Type	Power [kW]	Curb mass [kg]	Battery cap. [kWh]	Range [km]
Stromer ST1	45 km/h	0.67	29	0.5	90
Haibike SDURO Trekking RC eBike 2015	25 km/h	0.25	23	0.4	130
Kalkhoff Endeavour 7.B	25 km/h	0.25	27	0.63	125
Cube Reaction Hybrid SLT 500	25 km/h	0.25	23	0.5	350
Bergamont E-Line C-N360 Harmony	25 km/h	0.25	25	0.4	190
E-Bike Victoria Mondeville	25 km/h	0.25	26	0.3	100
Fischer ETH 1822 Pedelec	25 km/h	0.25	33	0.56	160
KTM Macina Freeze	25 km/h	0.25	22	0.5	
Winora - Sinus 9	25 km/h	0.25		0.63	
Hercules - Robert R8	25 km/h	0.25		0.5/0.63	

D. Specifications for commercial electric scooters

Model	Power [kW]	Curb mass [kg]	Battery cap. [kWh]
NIU - M+ - m+sport	1.2	72	2
Sunra HAWK	1.8	83	3
Yadea G5	1.8	96	1.9
PGO eWave	2	115	
UNU Motors - UNU	2	82	1.7
Nova Motors - eGrace - eGrace	2	109	1.4
NIU - N1S - NIU N1S Civic 2016	2.4	92	1.7
Hiker Amaze 50	2.7	145	1.9
Super SOCO - CU - CU-x	2.8	70	1.8
NIU - Npro	3	109	4.2
Pink 2021	3	94	2.1
E-Vivacity	3	115	
UNU Motors - UNU - Unu 3kW	3	82	1.7
TRINITY 2017 L2-Akku	3	110	2.4
Trinity Romex 3.0	3	82	
NIU - NGT - NGT	3	115	2.1
Vespa Elettrica	3.5	130	4.2
E-Max - 90S - E-Max 90s	3.9	150	

Model	Power [kW]	Curb mass [kg]	Battery cap. [kWh]
Solarscooter Sport SCP 3540	4	71	
Thunder 4000Li	4	135	2.4
GOELIX E-BOX	4	130	3.6
Emax 120L	4	115	3.1
PCX	4.2	143	2
Thunder Sportivo S	5	135	
Innoscooter EM6000	5	165	3
Ekoway ML5000	5	133	2.9
Govecs GO 3,4	5	120	2.9
Emco Novum 77	5	130	1.9
SmartScooter 3	6	110	3
SmartScooter 3 Plus	6.2	110	3
E-Max - Puma	9	170	4.8
TRINITY - Jupiter 8.6	10	172	5.7
Vectrix Vx-1	11	120	3
Goelix Viva	11	114	4.3

E. Specifications for commercial electric motorbike models

1. 4-11 kW

Brand	Model	Power [kW]	Curb mass [kg]	Battery cap. [kWh]
Sodium Cycle	Xubaka	4.0	50	1.3
Brekr	B4000	4.0	90	4.0
Go Charged	Velociraptor	4.0	90	2.2
Cake	Ösa Lite	4.0	70	1.5
Ebroh	Bravo GLE	5.0	147	5.4
Rider	RS 5000	5.0	115	3.2
Ox Rider	Ox One S	5.0	140	1.4
Super Soco	TC Max 2020	5.0	115	3.2
Horwin	CR6	6.2	134	4.0

2. 11-35 kW

Brand	Model	Power [kW]	Curb mass [kg]	Battery cap. [kWh]
Horwin	CR6 Pro	11.0	140	4.0
Pursang	E-Track	11.0	147	7.2
RGNT Motorcycles	RGNT n1	11.0	165	7.7
Zero	Zero S	11.0	185	7.2
Zero	Zero FX	15.0	131	7.2
Evoke Motorcycles	Urban S	19.0	179	9.1
Evoke Motorcycles	Urban Classic	19.0	179	9.1
Zero	Zero DSR	22.0	190	14.4
Savic Motorcycles	Omega	25.0	170	7.0
Alta Motors	Redshift MXR	29.2	117	5.8
Tacita	T-Race	34.0	177	9.0
Fuell	Fllow	35.0	180	10.0

3. >35 kW

Brand	Model	Power [kW]	Curb mass [kg]	Battery cap. [kWh]
Victory	Empulse	39.4	213	10.4
Zero	SR	40.0	229	14.4
Savic Motorcycles	Delta	40.0	190	9.0
Tarform	Luna	41.0	200	10.0
Savic Motorcycles	Alpha	60.0	210	11.0
Curtiss	Curtiss 1	64.0	193	16.8
Brutus	V9	64.2	355	18.8
Harley Davidson	LiveWire	78.0	251	15.5
Lito	Sora	78.8	250	18.0
Energica	EVA EsseEsse9+	80.0	282	21.5
Lightning	Strike Carbon	90.0	206	20.0
Arc	Vector	95.0	220	16.8
Energica	Ego	107.0	265	13.4
Energica	Ego+	107.0	248	21.5
Energica	EVA Ribelle	107.0	267	21.5

Brand	**Model**	**Power [kW]**	**Curb mass [kg]**	**Battery cap. [kWh]**
Sarolea Motorcycles	MANX7	120.0	217	14.0
Sarolea Motorcycles	N60	120.0	215	22.0
Lightning	LS-218	146.0	225	12.0
Damon	Hypersport	160.0	200	21.5
Damon Motorcycles	Hypersport Premier	160.0	200	21.5

Annex C

A. Specifications for commercial diesel bus models

Powertrain	**Make**	**Model**	**Type**	**Deck number**	**Length**	**Height**	**Width**	**Fontal area**	**Pass. Capacity**	**Curb weight**	**Power [kW]**	**Energy storage [kWh]**	**Charging type**
Diesel	Mercedes-Benz	Citaro	City	Single	12135	3130	2550	7.98	105		220	2640	
Diesel	Setra	S 516+	Coach	Single	13115	3770	2550	9.61	55		335	4873	
Diesel	Mercedes-Benz	Connecto	City	Single	12134	3120	2550	7.96	101		220	2538	
Diesel	Setra	S 319	City	Single	14950	3200	2550	8.16	59				
Diesel	Neoplan	Cityliner	Coach	Single	14000	4000	2550	10.20	69				
Diesel	Setra	S 417	Coach	Single	14050	3860	2550	9.84	59		315		
Diesel	Setra	S 416	City	Single	13040	3240	2550	8.26	53		260	3553	
Diesel	Setra	S 417 UL	City	Single	14050	3175	2550	8.10	61		220		
Diesel	Setra	S 415 H	Coach	Single	12200	3175	2550	8.10	49	13025	260	3553	
Diesel	Setra	S 516 HD	Coach	Single	13115	3770	2550	9.61	55	13500	335	4873	
Diesel	Setra	S 431 DT	Coach	Double	13890	4000	2550	10.20	78	19000			
Diesel	Mercedes-Benz	Tourismo	Coach	Single	12925	3680	2550	9.38	51		265	4873	
Diesel	Setra	S 416 GT-HD	Coach	Single	13020	3620	2550	9.23	55		315	4975	
Diesel	Mercedes-Benz	Connecto-G	City	Artic.	18124	3120	2550	7.96	150	18000	265	2538	
Diesel	Bova	XHD 139 D430	Coach	Single	13900		2550	0.00	59	15487	315	4897	
Diesel	Van Hool	T916 Astron	Coach	Single	13200	3730	2550	9.51	51	14800	353	3703	
Diesel	Van Hool	927 SD3	Coach	Double	13070		2550	0.00	66	17132	338	4897	
Diesel	EVOBUS	Travego	City	Single	12180	3710	2550	9.46	51	13880	315	3106	
Diesel	Bova	FHD 15 430	Coach	Single	14990	3560	2550	9.08	70	15800	316	3703	
Diesel	Setra	S 328 DT	City	Double					73	16750	280	4897	
Diesel	Volvo	B12B	City	Single					44	15710	291	3703	
Diesel	DAF/Berkhof	SB 4000	City	Single					51	12920	283	3106	
Diesel	Bova	FHD 13.380	Coach	Single					51	13710	280	3106	
Diesel	VDL	Bus SB 4000	Coach	Single	12800	3500	2550	8.93	55	13380	300	3106	
Diesel	Van Hool	927 SD3	Coach	Double	13070		2550		66	17132	338	4897	
Diesel	Scania	K124 IB	Coach	Double					56	14600	268	4897	
Diesel	Bova	FHD 13.340	City	Single	12500		2550		55	13362	249	3106	
Diesel	Mercedes-Benz	Tourismo	Coach	Single	12925	3680	2550	9.38	51		265	4873	
Diesel	Neoplan	N316SHD	Coach	Single	12000	3730	2550	9.51	52	13850	300	4518	

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type
Diesel	Mercedes-Benz	O404 15R	City	Single					46	13350	280	5584	
Diesel	Mercedes-Benz	Tourismo O350	Coach	Single	12000	3650	2550	9.31	52	13900	200	3106	
Diesel	Neoplan	N1116	Coach	Single					54	13775	338	3106	
Diesel	Mercedes	O 350RHD	City	Single					49	13200	303	3106	
Diesel	Jonkheere/Volvo	B12 Mistral	City	Single					51	13130	313	3106	
Diesel	Neoplan	N122L	Coach	Double	13700	4000	2550	10.20	81	18745	338	4897	
Diesel	Volvo	Plaxton B12M	Coach	Single	12500				58	11134	246	3106	
Diesel	Neoplan	N122L	Coach	Double	13700	4000	2550	10.20	81	18745	338	4897	
Diesel	Volvo	Plaxton B12M	Coach	Single	12500				58	11134	246	3106	
Diesel	Scania	Irizar, i3LE	City	Single	12750	3399	2550	8.67	50		235	2741	
Diesel	Scania	Irizar, i3LE	City	Single	14000	3399	2550	8.67	50		235	2741	
Diesel	Scania	Irizar, i4	City	Single	12900	3405	2550	8.68	50		235	2741	
Diesel	Scania	Irizar, i4	City	Single	14000	3405	2550	8.68	50		235	2741	
Diesel	Leyland	Olympian	City	Double	12000	4400	2550	11.22	93	14520		4897	
Diesel	Volvo	B12B	City	Single					51	13340		3106	
Diesel	VDL	Bova	City	Double					67	18840		4897	
Diesel	Bova	XHD120.D340	City	Single					38	13370		4897	
Diesel	MAN	24.46	Coach	Double	13480		2550		71	18140	343	4897	
Diesel	Mercedes-Benz	Tourismo	Coach	Single	12925	3680	2550	9.38	51		265	4873	
Diesel	VDL Scania	Axial 100	City	Double					69	19260		4897	
Diesel	Van Hool	TD927 Astromega	Coach	Double					68	17000	338	4897	
Diesel	SETRA	Evobus D8553	City	Double					84	19200		4897	
Diesel	Scania	Irizar K124	Coach	Single					58	13752	309	4897	
Diesel	Van Hool	TD 927 Astromega	Coach	Double					68	17000	338	4897	
Diesel	Van Hool	T917	Coach	Single	13840		2550		52	16760	315	4897	
Diesel	Van Hool	TD 927 Astromega	Coach	Double					67	18370	338	4897	
Diesel	Van Hool	TD 927 Astromega	Coach	Double					69	18040	338	4897	
Diesel	Van Hool	A507	City	Midi	7680	2800	2250	6.30	48		110		
Diesel	Van Hool	A508	City	Midi	8940	2800	2250	6.30	48		110		
Diesel	Van Hool	A308	City	Midi	9495	2985	2350	7.01	22		162		
Diesel	Van Hool	A309	City	Midi	9990	3100	2350	7.29	23		165		
Diesel	Scania	OmniTown	City	Midi	9100	3000	2550	7.65	26				
Diesel	Optare	Versa	City	Midi	11785	2840	2510	7.13	54		130	2031	
Diesel	Optare	Solo, Slimline	City	Midi	7870	2885	2340	6.75	35		130	2031	
Diesel	Optare	Solo, Slimline	City	Midi	8570	2885	2340	6.75	41		130	2031	
Diesel	Optare	Metrocity	City	Midi	10130	2850	2470	7.04	60		130	2031	
Diesel	Optare	Metrocity	City	Midi	10820	2850	2470	7.04	60		130	2031	
Diesel	Optare	Metrocity	City	Midi	11520	2850	2470	7.04	60		130	2031	

B. Specifications for commercial hybrid diesel bus models

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type

Diesel hybrid	Scania	Irizar, i3LE	City	Single	12750	3399					235		
Diesel hybrid	Scania	Irizar, i3LE	City	Single	14000	3399					235		
Diesel hybrid	Scania	Irizar, i4	City	Single	12900	3405					235		
Diesel hybrid	Scania	Irizar, i4	City	Single	14000	3405					235		
Diesel hybrid	Solaris	Urbino 12 LE lite hybrid	City	Single	12000		2550		85	8885	169		
Diesel hybrid	Solaris	Urbine 18 hybrid	City	Single	18000	3500	2550	8.93	160	17500	253		
Diesel hybrid	New Flyer	Xcelsior DE	City	Single	12500	3380	2550	8.62	83	13200			

C. Specifications for commercial fuel cell electric bus models

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type
Fuel cell	Van Hool	A 330 FC	City	Single	11995	3420	2550	8.72	74	13630	210	1267	
Fuel cell	New Flyer	Xcelsior	City	Single						14000	170	1250	

D. Specifications for commercial battery electric bus models

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type
Electric	Hess	SwissTrolley BGT-N2D	City	Artic.	18740		2550		147	18800	320	66	In motion
Electric	Hess	Light Tram BG-GT-N2D	City	Artic.	24720		2550		221			23	In motion
Electric	Skoda	Perun HP	City	Single	12000		2550		82		160	80	In motion
Electric	Skoda	26 Tr	City	Single	12000		2550		94	11800	160	45	In motion
Electric	Skoda	26Tr	City	Single	12000		2550		85		160	50	In motion
Electric	Skoda	27Tr	City	Artic.	18000		2550		125	17500	250	80	In motion
Electric	Skoda	Tr187.2	City	Artic.	18720		2550		125			81	In motion
Electric	Solaris	Trollino 12	City	Single	12000		2550		83	12700	160	69	In motion
Electric	Solaris	Trollino 12	City	Single	12000		2550		83	12700	160	37	In motion
Electric	Solaris	Trollino 18	City	Artic.	18000		2550		123		250	90	In motion
Electric	Solaris	Trollino 18	City	Artic.	18000		2550		139		250	69	In motion
Electric	Solaris	Trollino 18	City	Artic.	18000		2550		139		250	72	In motion
Electric	Solaris	Trollino 18	City	Artic.	18000		2550		125		250	38	In motion
Electric	SOR	EBN 11	City	Single	11100		2550		90		120	172	In motion
Electric	Temsa	Avenue EV	City	Single	12000		2550		90		270	75	In motion
Electric	Ursus Bus	City Smile	City	Single	12000		2550		62		226	105	In motion
Electric	Ursus Bus	City Smile	City	Artic.	18000		2550		104		452	105	In motion
Electric	Ursus Bus	T70116	City	Single	12000		2550		75			14	In motion
Electric	Van Hool	Exqui.City	City	Artic.	18610		2550		131	18500	120	35	In motion
Electric	Van Hool	Exqui.City	City	Artic.	18610		2550		131	18500	120	28	In motion
Electric	Van Hool	Exqui.City	City	Artic.	23820		2550		149	24000	320	20	In motion
Electric	Van Hool	A 330T	City	Single	12000		2550		86			23	In motion
Electric	Volvo	7900 Electric	City	Single	12000		2550		105		155	76	In motion
Electric	New Flyer	Xcelsior Trolley	City	Artic.	18540	3380	2550	8.62	123	21112	246	26	In motion

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type
Electric	ADL	Enviro400 VE	City	Midi	10300		2340		83		175	61	Opportunity
Electric	Göppel	G58	City	Single	12000		2550		58			86	Opportunity
Electric	HAW	12 LE	City	Single	12000		2550		65			80	Opportunity
Electric	HAW	18 LE	City	Artic.	18000		2550		100			80	Opportunity
Electric	Hess	Swiss Primove	City	Single	12000		2550		80			60	Opportunity
Electric	Linkker	12+ LE	City	Single	12000		2550		80	10500		55	Opportunity
Electric	Optare	Solo EV	City	Midi	10000		2340		55			86	Opportunity
Electric	Optare	Solo EV	City	Midi	9200		2340		42			150	Opportunity
Electric	Optare	Solo EV	City	Midi	9200		2340		42			95	Opportunity
Electric	Optare	Versa EV	City	Midi	10500		2340		65			95	Opportunity
Electric	Scania	Citywide LE4	City	Single	12000		2550		75			56	Opportunity
Electric	Skoda	Perun HP	City	Single	12000		2550		82		160	75	Opportunity
Electric	Solaris	Urbino 8.9 LE	City	Midi	8950		2550		49		160	80	Opportunity
Electric	Solaris	Urbino 12	City	Single	12000		2550		78			60	Opportunity
Electric	Solaris	Urbino 12	City	Single	12000		2550		70			70	Opportunity
Electric	Solaris	Urbino 12	City	Single	12000		2550		87			90	Opportunity
Electric	Solaris	Urbino 12	City	Single	12000		2550		71			100	Opportunity
Electric	Solaris	Urbino 12	City	Single	12000		2550		73			120	Opportunity
Electric	Solaris	Urbino 12	City	Single	12000		2550		80			160	Opportunity
Electric	Solaris	Urbino 18	City	Artic.	18000		2550		115		240	125	Opportunity
Electric	Van Hool	A 308 citybus	City	Midi	9650		2550		55			37	Opportunity
Electric	Volvo	7900 Electric hybrid	City	Single	12000		2550		94			19	Opportunity
Electric	VDL	Citea LLE-99	City	Midi	9950		2550		60		153	80	Opportunity
Electric	VDL	Citea SLF-120	City	Single	12000		2550		92		153	62.5	Opportunity
Electric	VDL	Citea SLFA-180	City	Artic.	18000		2550		145		210	180	Opportunity
Electric	VDL	Citea SLFA-180	City	Artic.	18000		2550		139		210	123	Opportunity
Electric	Higer	Chariot e-Bus	City	Single	12000		2550		91			32	Opportunity
Electric	SOR	EBN 9.5	City	Midi	9700		2550		69	7600		72	Opportunity
Electric	SOR	EBN 11	City	Single	11100		2550		93	10100		172	Opportunity
Electric	SOR	NS 12	City	Single	12000		2550		102			225	Opportunity
Electric	TOSA	Articulated Bus	City	Artic.	18750		2550		133			40	Opportunity
Electric	Alstom	Aptis	City	Single	12000		2550		77		180	330	Plug-in
Electric	Bluebus	12m	City	Single	12000		2550		92		160	240	Plug-in
Electric	BYD	E12	City	Single	12000		2550		78	14300	180	324	Plug-in
Electric	BYD	K9	City	Single	12000		2550		61	13800	180	324	Plug-in
Electric	BYD	K9-13C	City	Single	12000		2550		70	13800	180	292	Plug-in
Electric	Ebusco	2.0	City	Single	12000		2550		80	13800		150	Plug-in
Electric	Ebusco	2.1 HV	City	Single	12000		2550		95			311	Plug-in
Electric	Ebusco	2.2	City	Single	12000		2550		90	12850	270	363	Plug-in
Electric	Ebusco	2.2	City	Artic.	18000		2550		130	19000	250	525	Plug-in
Electric	evopro	Modulo C68e	City	Midi	7980		2350		68	6700	160	144	Plug-in
Electric	Heuliez	GX 337 Elec	City	Single	12000		2550		92			199	Plug-in
Electric	Irizar	i2e	City	Single	12000		2550		66			376	Plug-in
Electric	Irizar	i2e	City	Single	12000		2550		64			339	Plug-in
Electric	Optare	Solo, Slimline	City	Midi	7870	2885	2340	6.75	35		150	138	Plug-in

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type
Electric	Optare	Solo, Slimline	City	Midi	8570	2885	2340	6.75	41		150	138	Plug-in
Electric	Optare	Metrocity	City	Midi	10800				58		150	138	Plug-in
Electric	Optare	Metrocity	City	Midi	10800				60		150	92	Plug-in
Electric	Otokar	Elektra	City	Midi	9000				55		103	170	Plug-in
Electric	Rampini	E12	City	Single	12000		2550		70		160	180	Plug-in
Electric	Safra	Businova	City	Midi	10500				70		200	135	Plug-in
Electric	Sileo	S10	City	Midi	10700		2550		66		240	230	Plug-in
Electric	Sileo	S12	City	Single	12000		2550		76		240	230	Plug-in
Electric	Sileo	S12	City	Single	12000		2550		76		240	260	Plug-in
Electric	Sileo	S18	City	Artic.	18000		2550		137		480	300	Plug-in
Electric	Skoda	Perun HE	City	Single	12000		2550		82		160	230	Plug-in
Electric	Skoda	Perun HE	City	Single	12000		2550		82		160	222	Plug-in
Electric	Solaris	Urbino 8.9 LE	City	Midi	8950		2550		65		160	120	Plug-in
Electric	Solaris	Urbino 12	City	Single	12000		2550		90	12500	120	230	Plug-in
Electric	Solaris	Urbino 12	City	Single	12000		2550		90	12500	120	210	Plug-in
Electric	Solaris	Urbino 12	City	Single	12000		2550		70	12500	120	200	Plug-in
Electric	Solaris	Urbino 18	City	Artic.	18000		2550		129	16000	240	240	Plug-in
Electric	SOR	EBN 10.5	City	Midi	10370		2550		82		120	172	Plug-in
Electric	Temsa	MD9 electriCITY	City	Midi	9300		2550		65	9670	200	200	Plug-in
Electric	Hyundai		City	Double	13000	3395	2550	8.66	70			384	Plug-in
Electric	Ursus Bus	Ekovolt	City	Midi	11960		2550		81		170	120	Plug-in
Electric	Ursus Bus	City Smile	City	Midi	8500		2550		61	12400	170	175	Plug-in
Electric	Ursus Bus	City Smile	City	Midi	9950		2550		84	12400	120	210	Plug-in
Electric	Ursus Bus	City Smile	City	Single	12000		2550		82	12400	170	175	Plug-in
Electric	VDL	Citea SLF-120	City	Single	12000		2550		92		153	240	Plug-in
Electric	SOR	EBN 10.5	City	Midi	10300		2550		69			172	Plug-in
Electric	Yutong	E12LF	City	Single	12000		2550		92			230	Plug-in
Electric	Yutong	E12LF	City	Single	12000		2550		77			295	Plug-in
Electric	New Flyer	Xcelsior Charge NG	City	Midi	10800	3300	2550	8.42	67	12519	160	350	Plug-in
Electric	New Flyer	Xcelsior Charge NG	City	Single	12240	3300	2550	8.42	88	13086	160	350	Plug-in
Electric	New Flyer	Xcelsior Charge NG	City	Artic.	18290	3300	2550	8.42	123	20276	320	525	Plug-in

E. Specifications for commercial compressed gas bus models

Powertrain	Make	Model	Type	Deck number	Length	Height	Width	Fontal area	Pass. Capacity	Curb weight	Power [kW]	Energy storage [kWh]	Charging type
CNG	Karsan	Avancity	City	Single	12000	3373	2550	8.60	88		205		
CNG	NABI	BRT-07	City	Single					48	15370	208		
CNG	New Flyer	Xcelsoir CNG	City	Single	12500	3380	2550	8.62	83	13426	200		
CNG	New Flyer	Xcelsoir CNG	City	Artic.	18540	3380	2550	8.62	123	19640	300		

Annex D

A. Specifications for commercial battery electric truck models

Brand	Model	GVW [ton]	Max. Payload [ton]	Engine power [kW]	Battery capacity [kWh]	Range [km]	TtW energy [kWh/km]
Freightliner	eCascadia	36.2		391	475	400	1.19
Freightliner	eM2	11.8		224	315	370	0.85
Volvo	VNR electric	29.9	19.2	400	300	120	
Volvo	VNR electric	29.9	19.2	400	300	281	1.07
Workhorse	C-650	5.7			70	160	0.44
Tesla	Semi	36.2	22	745	500	480	1.04
Tesla	Semi	36.2	12	745	1100	800	1.38
BYD	T3	2.8	0.8		43	250	0.17
BYD	T5	7.3	2.6		150	250	0.60
BYD	T7	10.8	5		175	200	0.88
BYD	J9D	36.2			175	100	1.75
BYD	T9	36.2			350	200	1.60
Mercedes	eActros	25	5	250	240	200	1.20
Futuricum	Logistics 18E - 340	19	11	500	289	200	1.45
Futuricum	Logistics 18E - 450	19	10.6	500	383	250	1.53
Futuricum	Logistics 18E - 510	19	9.8	500	434	300	1.45
Futuricum	Logistics 18E - 680	19	6.4	500	578	400	1.45
Futuricum	Logistics 18E - 900	19	5.6	500	765	500	1.53
Futuricum	FH Semi 40E - 680	44	32	500	578	400	1.45
Futuricum	FH Semi 40E - 680	44	31.2	500	765	500	1.53

B. Specifications for fuel cell electric truck models

Brand	Model	GVW [ton]	Engine power [kW]	Hydrogen tank capacity [kg H2]	Fuel cell stack output [kW]	Battery capacity [kWh]	Range [km]	TtW energy [kWh/km]
MAN	TGS 18.320	34	250	31	100	120	375	2.76
Hyundai	Xcient	36	350	34.5	190	73	400	2.88
Renault	Maxity H2	4.5	47	4	20	42	200	0.67
VDL	H2-Share	27	210	30	88	84	400	2.50
Scania		27	290	33	90	56	400	2.75
Kenworth	T680	36	360	30	85	100	320	3.13
UPS	H2 truck	12		10	31	45	200	1.67

C. Specifications for diesel plug-in and regular hybrid truck models

Brand	Model	Type	GVW [ton]	Electric motor power [kW]	Combustion engine power [kW]	Total power [kW]	Combustion power share	Battery capacity [kWh]	Range in batter-depleting mode [km]
Scania	PHEV-d	PHEV-d	29	130	280	410	68%	90	60
Class 2 Van	Light	HEV-d	3.5	50	130	180	72%		
Class 2 Van	Light	PHEV-d	4	180	100	280	36%		
Class 3 Van	Light	HEV-d	5	70	140	210	67%		
Class 3 Van	Light	PHEV-d	6	200	135	335	40%		
Class 5 Utility	Medium	HEV-d	8	105	230	335	69%		
Class 5 Utility	Medium	PHEV-d	8	280	105	385	27%		
Class 7 Tractor	DayCab	HEV-d	26	60	240	300	80%	5	
Class 7 Aero	DayCab	PHEV-d	26	480	260	480	54%		
Class 8 Tractor	DayCab	HEV-d	40	90	310	400	78%	8	
Class 8 Aero	DayCab	PHEV-d	40	510	280	510	55%		

Reviewer report