Life-cycle analysis—a look into the key parameters affecting life-cycle CO_2 emissions of passenger cars

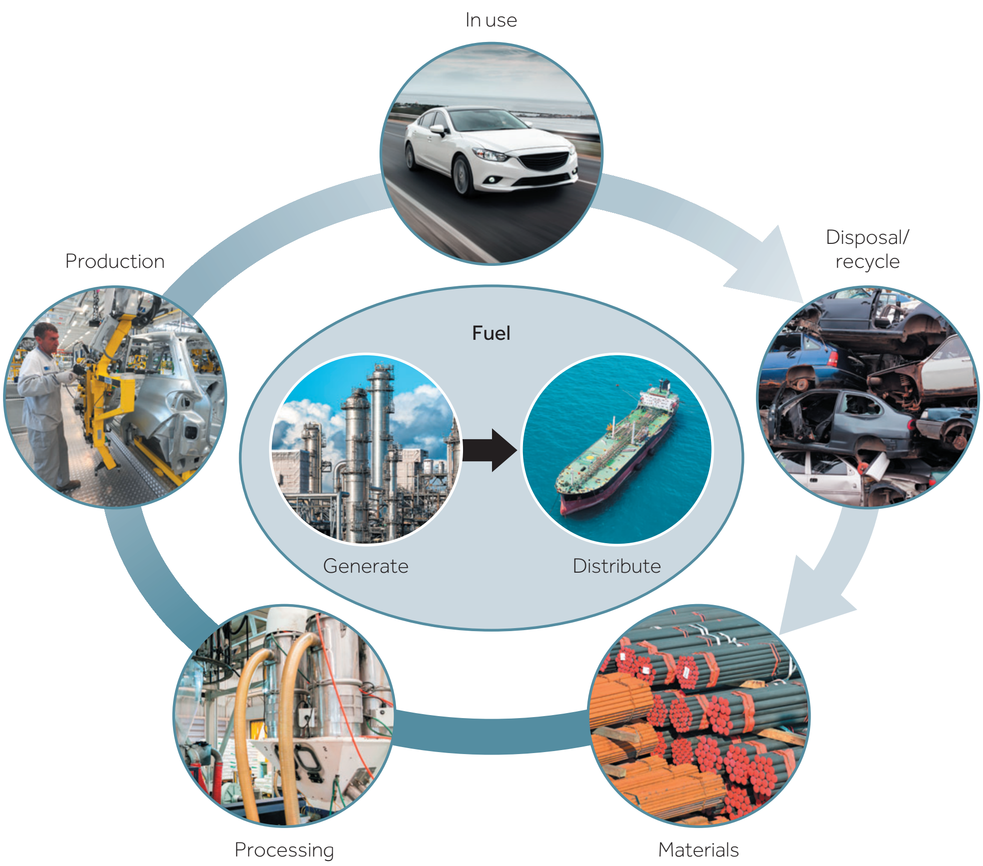
Introduction

The general framework and guidelines for a life-cycle assessment (LCA) are defined in ISO 14044:2006. This standard defines the general principles of a methodology used to assess the environmental impact of different products, from the extraction of the raw materials, through their use and finally recycling or disposal of the end-of-life and waste materials. Figure 1 shows how an LCA would apply to vehicles.

When applied to the CO_2 emissions associated with a vehicle, the LCA includes the well-to-wheels (WTW) emissions generated in the production and consumption of different fuels, as well as the CO_2 emissions associated with the production and disposal of the vehicle, including the batteries in the case of electric powertrains.

This article presents the basis of a Concawe analysis comparing the life-cycle CO_2 emissions of battery-electric vehicles (BEVs) and internal combustion engine (ICE) vehicles, and investigates the impact of a range of key parameters on total CO_2 emissions.

Figure 1: LCA applied to vehicles—a bigger picture



The aforementioned ISO 14044:2006 standard, despite providing general guidelines, is not specific enough to ensure a single and homogeneous methodology for conducting an LCA for fuels and powertrains. As an example, different methodologies to assess the energy consumption associated with battery manufacture can be found in recent literature, leading to very different results. Beyond the different approaches used, there is also a need to access more detailed and public data from manufacturers to ensure the robustness and representativeness of the final results. While these limitations prevent the LCA methodology from being used more widely, it is commonly agreed that such an analysis provides the key elements to perform a full technical comparison of the environmental impact of distinct energy/propulsion alternatives such as internal combustion engine (ICE) vehicles and battery electric vehicles (BEVs).

Concawe has used the LCA methodology to assess the CO_2 emissions associated with different fuel and powertrain combinations. This article presents the basis of that analysis, and investigates the impact that certain key parameters may have across the whole life cycle of a vehicle. The results and figures included are initial estimates based on relevant external publications and on Concawe's own internal research. Concawe is willing to engage with external stakeholders to assist in defining a standard LCA methodology to be applied to fuels and powertrains in the future.

Using LCA to assess CO_2 emissions from passenger cars

Basis

When comparing different electric vehicles with conventional powertrains, and the relative impacts associated with the energy or fuel generation, materials extraction, and manufacturing and production phases, the contributions to the total life-cycle emissions are distinct. The key parameters affecting the results are summarised in Table 1.

Table 1: Key parameters affecting vehicle LCA

	INTERNAL COMBUSTION ENGINE (ICE)	BATTERY ELECTRIC VEHICLE (BEV)

Non-road factors *
 	
* The % of non-use emissions of different powertrains may vary from 20–30% for ICEs, and from 30–70% for BEVs depending on the key parameters identified.[1]
	• Vehicle class (e.g. A, B, C)
	• Drivetrain materials (steel, aluminium)
	• Production of the fuel
		• Vehicle class (e.g. A, B, C)
		• Drivetrain materials (copper)
		• Battery production
		  ◦ Type (materials)
		  ◦ Size / Range
		  ◦ Cell production country
		  ◦ Battery assembly area
		  ◦ CO_2 estimation model
		• Energy use for electrical generation (well-to-tank)
		• Carbon intensity of the electricity mix

Road factors	• Vehicle use
	  ◦ Lifetime (years)
	  ◦ Total kilometres driven
	  ◦ Use (urban, rural, etc.)
	• Type of fuel (e.g. petrol/diesel)
	• Fuel consumption
	  ◦ Quantity (l/100 km)
	  ◦ Drive cycle (NEDC, WLTP, RDE)
		• Vehicle use
		  ◦ Lifetime (years)
		  ◦ Total kilometres driven
		  ◦ Use (urban, rural, etc.)
		• Unit consumption
		  ◦ Quantity (kWh/100 km)
		  ◦ Drive cycle

Table 2: Concawe LCA simple modelling tool—main inputs

PARAMETER	VALUE	COMMENT	SOURCE
Driving distance	150,000 km	To ensure that no battery replacement is required.	Concawe estimate.
Embedded emissions (battery manufacturing)	150 kg CO_2/kWh	Lithium ion battery (NMC). Top-to-bottom approach. Default value assumed constant regardless of the battery size (simplification). Energy use for battery manufacturing: 350–650 MJ/ KWh.	Average value from IVL report.
Embedded emissions, vehicle manufacturing	4 t CO_2/vehicle (Class B) 5 t CO_2/vehicle (Class C) 7 t CO_2/vehicle (Class D)	Generic values (lack of data per individual vehicle).	Based on NTNU.
EU electricity mix (low voltage, including losses)	350 g CO_2/kWh low voltage (2016). Preliminary estimate (see comments and sources).	2016 EU LV electricity mix (EU-28) **preliminary estimate** based on adjusted IEA data (WEO 2017 + JRC/JEC methodology including upstream emissions and losses). Reference: 2013: 447 g CO_2/kWh (JRC detailed analysis). 2016: 300 g CO_2/kWh (IEA WEO) EU electricity generation mix (HV without upstream emissions).	2016: Concawe preliminary estimate (subject to change once the updated JRC work is public).* 2013 value: JRC detailed analysis.[2] IEA WEO 2017.
Electricity/fuel consumption	Variable	Specific for each model considered.	OEM brochures.
Real-driving emissions (RDE) adjustment factor	1.4	Correction factor used to uplift fuel consumption from NEDC (New European Driving Cycle) to RDE values.	Concawe estimate. Conservative value aligned with other sources (EU Commission modelling).
Charging losses	10%	Default value aligned with 90% on-board battery charger efficiency (Conservative value. Fast charging not included).	Based on NTNU, Ricardo data.
End-of-life (EOL) emissions	0.5 t CO_2/vehicle (BEVs) 0.4 t CO_2/vehicle (ICEs)	Battery ≈ 20% of total EOL emissions for BEVs.	Based on NTNU data.

* JRC is currently working on a paper calculating the 2015 LV CO_2 intensity value using the most recent IEA statistic data issued with 2 years of delay (detailed methodology).[2]

The influence of some of these parameters have been explored by Concawe, and the initial results are presented below based on information currently available in external sources such as NTNU,[3] IVL,[4] European Commission data adapted from BMVI[5] as well as different OEMs' brochures for individual vehicles. Based on these sources, Concawe has developed an LCA model to explore different country-specific scenarios and run a sensitivity analysis on the key parameters across all vehicle segments. This model is intended to be a live tool to conduct periodic assessments as new data become publicly available. The main inputs used are summarised in Table 2 on page 19.

Sensitivity analysis

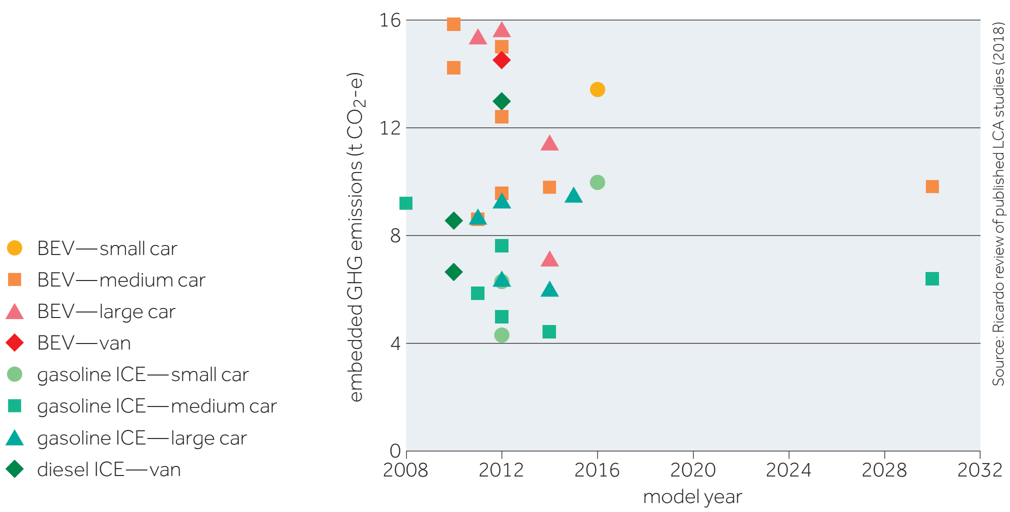
Manufacturing stage: battery type and size, and electricity mix used

Different published LCA studies show a wide variability in the embedded CO_2 emissions of BEVs related to the battery manufacturing process. Generally, these show that BEVs have higher embedded greenhouse gas (GHG) emissions than equivalent gasoline and diesel ICEs primarily due to:

- **Methodological factors** such as the chosen life-cycle inventory (LCI) database or the LCA methodology used (top-down or bottom-up approach). The selection of the manufacturing calculation method is one of the main causes of the discrepancies in embedded emissions found in literature. While top-down studies allocate energy use based on information about the individual process, the bottom-up approach aggregates data from each individual activity including energy consumption from utilities and additional auxiliary processes. The top-down approach causes higher greenhouse gas emissions and cumulative energy demand.
- **Battery pack** size and chemistry/technology used; this also determines the energy density of the package.
- CO_2 intensity of the **energy mix used** during the manufacturing and assembly process, usually performed in different locations.

Figure 2 shows the results of an LCA comparison recently conducted by Ricardo.

Figure 2: Summary of embedded GHG emissions for light-duty vehicles



In terms of the BEV emissions, the LCA impact of the battery is mainly caused by the production chains of three components: the battery cells, the cathode and the anode, comprising together approximately 55% to 85% of the battery's total impact.[6] Table 3 summarises the contribution of different elements to the final embedded CO_2 emissions associated with the battery manufacturing (and recycling) process.

Table 3: Summary of the embedded CO_2 emissions in the battery manufacturing (and recycling) process

	kg CO_2-e/ kWh battery			
Component	**Raw material and refining** [a]	**Battery grade material production (including mining and refining)** [b]	**Manufacturing (component and cell + battery assembly)**	**Recycling**
Anode	2–11	7–25		
Cathode	7–18	13–20 (90[c])		
Electrolyte	4	4–13		
Separator	<0.5	Approx. 1		
Cell case	<0.1	Approx. 1		
Battery case	4–13	10–25		
Cooling	0–3	2–6		
Battery management system (est.)	<1	4–30		
TOTAL	18–50	48–121 (216)	20–110	Pyro: 15 Hydro: -12
Most likely value *(based on the assessment of transparency and scientific method done in the report)*		60–70	70–110	15

[a] Example based on material needed for a 253-kg battery. (Ref. Ellingsen *et al.* (2014),[6] and data from Table 14 of the IVL report[4] where the varied results from using different cradle to gate datasets for material extraction and production are illustrated.)

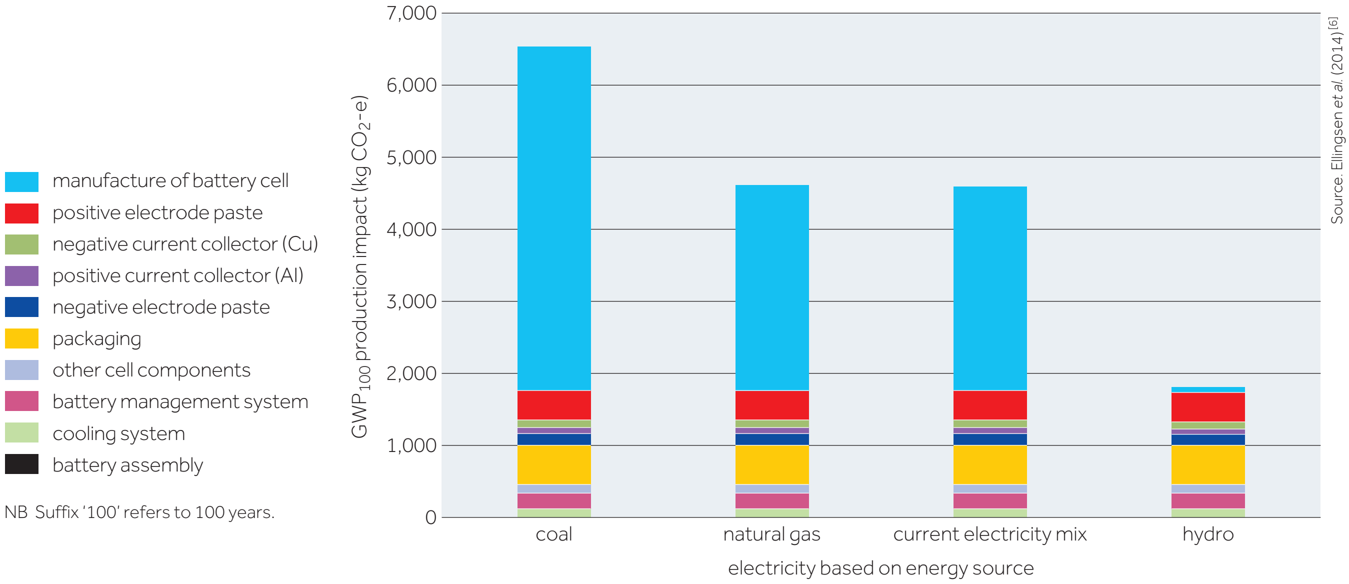
[b] Ranges based on a review of battery LCAs. (Ref. Table 15 in the IVL report.[4])

[c] Values in brackets are based on a report with approximate assumptions regarding processing materials.[7]

Source: IVL (2017)[4]

The electricity mix used during the manufacturing process of the different battery components has a significant impact and, as illustrated in Figure 3 on page 22, notable differences can be observed depending on the location (country) where both the manufacturing and assembly processes take place. As extreme cases, and as extreme references for individual countries, NTNU estimates that the potential impact of moving from a coal-based electricity mix to a purely hydro-based country can be up to 4 t CO_2-e, when an NMC lithium ion battery is considered (253 kg weight and 26.6 kWh energy capacity).

Figure 3: Sensitivity analysis with respect to the source of electricity for battery cell manufacture (results include production and manufacturing). Impact category: global warming potential (2013 data)



Impact of fuel consumption (ICEs) and electricity mix (BEVs)

Life-cycle phases — definition of terms

When an LCA is applied to a vehicle, it includes the CO_2 emissions from manufacturing and disposing of the vehicle itself, as well as the CO_2 emissions from producing and supplying the fuel to the vehicle and consuming the fuel in the vehicle.

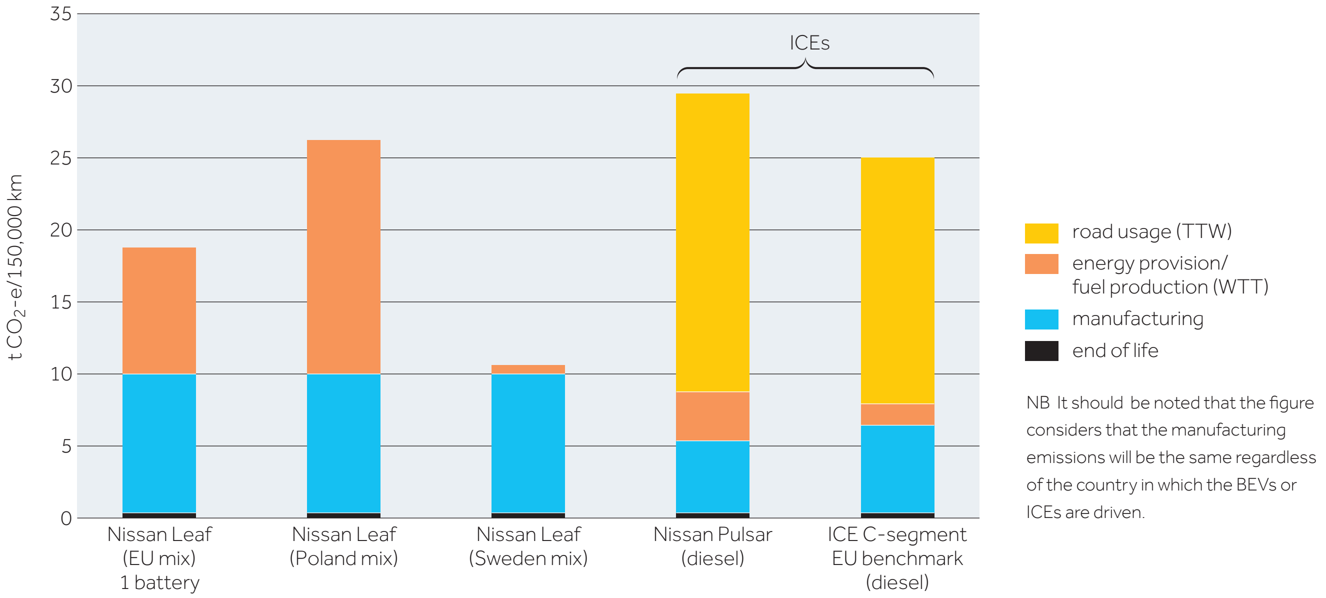
The CO_2 emissions from producing and supplying the fuel to the vehicle are referred to as well-to-tank (WTT) emissions, while the CO_2 emissions from consuming the fuel in the vehicle are referred to as tank-to-wheels (TTW) emissions. For BEVs, when only the TTW CO_2 emissions are accounted, the BEV is considered as a zero-CO_2 vehicle due to the absence of tail pipe emissions. However, the WTT approach brings additional CO_2 emissions into the whole picture, i.e. the emissions associated with the production of the electricity consumed and the energy losses from the electricity generation site to the recharging device. Besides this definition, there is currently an ongoing debate addressing how to consider the additional TTW-related losses associated with the battery recharging process, including the use of external charging devices.

Electricity mix

Currently, Europe has a wide range of electricity power generation technologies across different countries ranging from coal based national electricity mixes to mainly renewable ones. In this context, the EU electricity mix concept included in the study is considered as a reference point, while individual assessments at country level need to be conducted to produce specific scenarios that can be used to inform different stakeholders, including end users, about the LCA CO_2 performance of different alternatives.

Based on the assumptions mentioned in Table 2 (page 19), Concawe has conducted LCA-based comparisons of the CO_2 emissions of a compact class (C-segment) vehicle, for both BEV and ICE, where the impact of the national electricity mix on the use phase is explored (see Figure 4).

Figure 4: The impact of national electricity mix on the use phase of two C-segment vehicles: Nissan Leaf (BEV) vs Nissan Pulsar (diesel ICE)—1 battery/150,000 km



NB It should be noted that the figure considers that the manufacturing emissions will be the same regardless of the country in which the BEVs or ICEs are driven.

Table 4: Specific inputs: C-segment

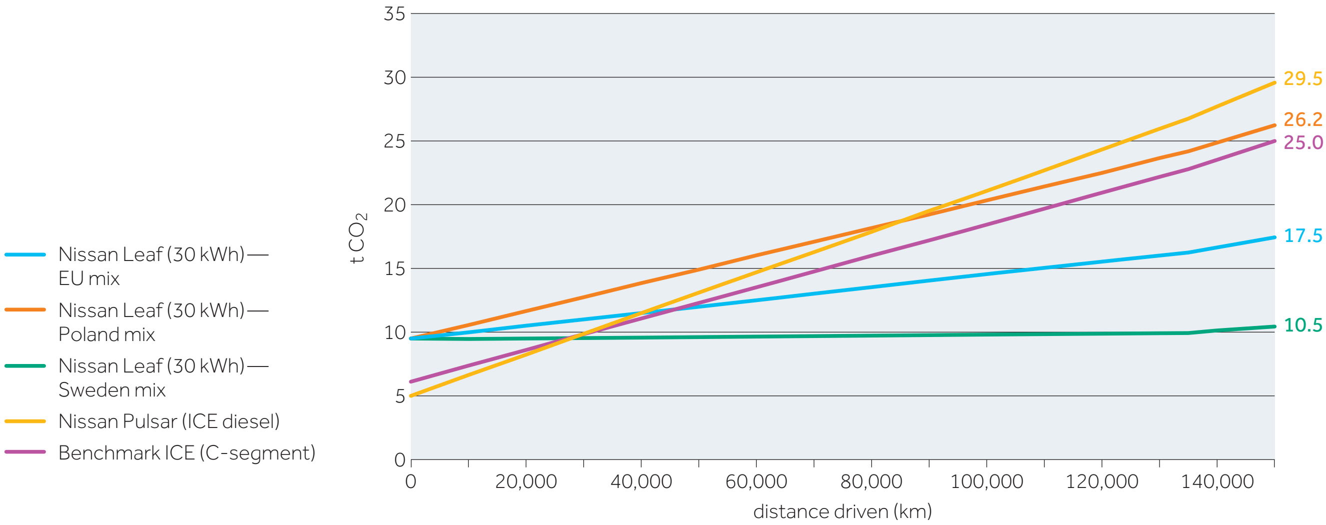
	CONSUMPTION AND WEIGHT*	BATTERY SIZE AND RANGE	CO_2 INTENSITY OF ELECTRICITY MIX
Nissan Leaf (BEV), 109 hp	150 Wh/km (without losses) Kerb weight: 1,570 kg	30 kWh battery 250 km driving range	EU mix (350 g CO_2/kWh) Higher range: Poland mix (750 g CO_2/kWh) Lower range: Sweden mix (20 g CO_2/kWh)
Nissan Pulsar (diesel ICE), 110 hp	3.8 l/100 km (NEDC) (Kerb weight: 1,352 kg)		

* Data from Nissan brochures

This comparison shows that the total amount of CO_2 emitted during the lifetime of a Nissan Pulsar (diesel) can be similar to the Nissan Leaf (BEV) when the electricity mix includes a large fraction of coal powered generating plants, as in Poland. When the Nissan Leaf is compared to the C-segment benchmark data published by the European Commission, the lifetime CO_2 emissions for the Nissan Leaf are greater than for the diesel vehicle for the stated electricity mix.

Although Figure 4 shows the contribution of each stage to the total CO_2 emissions, the evolution of the emissions along the driven distance during the whole lifetime of the vehicle leads to interesting conclusions (see Figure 5).

Figure 5: The impact of national electricity mix per distance driven for two C-segment vehicles: Nissan Leaf (BEV) vs Nissan Pulsar (diesel ICE)



At the beginning of the life of the vehicles, the BEVs have embedded emissions that are double those of the equivalent ICE powertrains, due to the battery manufacturing process. Once in use, and during the first 50,000 km driven, the emissions from the diesel fuelled vehicle (based on the C-segment benchmark vehicle) would remain lower than the overall emissions from a BEV when the anticipated 2030 EU average electricity mix is considered. The CO_2 emissions for the diesel vehicle can remain lower than for the Nissan Leaf from 30,000 to greater than 150,000 km, depending on the electricity mix used.

Over the full life cycle of the vehicle, the emissions from the use of an electric vehicle are eventually lower than those from an equivalent ICE powertrain vehicle, except in countries with a high reliance on coal. However, it is clear that on such an LCA basis, there are CO_2 emissions from the production and use of electric vehicles which should be taken into account in any assessment of the potential for electric vehicles to contribute to global GHG emission targets.

Size of the vehicle

The LCA methodology allows the comparison of different powertrains across different vehicle segments, from a small B-class vehicle to a larger D-class or a luxury one. In 2016, NTNU presented the concept of the 'fossil envelope' [8] which shows that the total CO_2 emissions are heavily dependent on the size of the vehicle/battery chosen. Therefore, a comparison between individual vehicles belonging to the same segment is crucial to conduct a comprehensive LCA.

a) Small vehicles (B-segment)

The category of 'subcompact' vehicles comprises a wide range of vehicles with power and weights similar to some of those considered as 'compact' vehicles. In this analysis, a Mercedes Benz B-Class and BMW i3 were initially chosen as representatives of this BEVs 'B' classification. However, the weight of the Mercedes Benz B-Class (1,700 kg) was more similar to a 'C' classification vehicle and, therefore, the comparison is focused on the BMW i3 (1,300 kg) with a 33 kW battery package. All these vehicles have higher power than equivalent ICE B-segment vehicles where consumers may opt for better fuel efficiency (smaller size) in less powerful vehicles than in other segments. Actually, this customer choice between more powerful vs more efficient vehicles is a constant across all the passenger car classes but it is especially important in the B-segment where higher fuel efficiencies can be achieved. Figure 6 compares the BMW i3 (one of the smaller BEVs in the market) with the Mercedes B-Class and a Renault Clio IV B-segment ICE vehicles.

When the same approach described in Figure 5 is applied to these subcompact vehicles, the break-even points for a BEV are between 20,000 and 60,000 km, usually sooner than for the C-segment vehicle but depending heavily on the electricity mix and the power of the ICE vehicle chosen. In cases where a lower-HP ICE B-segment vehicle is chosen (e.g. the Renault Clio IV), the life-cycle emissions are less than those of a BEV with a Polish electricity mix.

Figure 6: The impact of national electricity mix per distance driven for three B-segment vehicles: BMW i3 (BEV) vs Mercedes Benz B-Class (diesel ICE) vs Renault Clio IV GrandTour (diesel ICE)

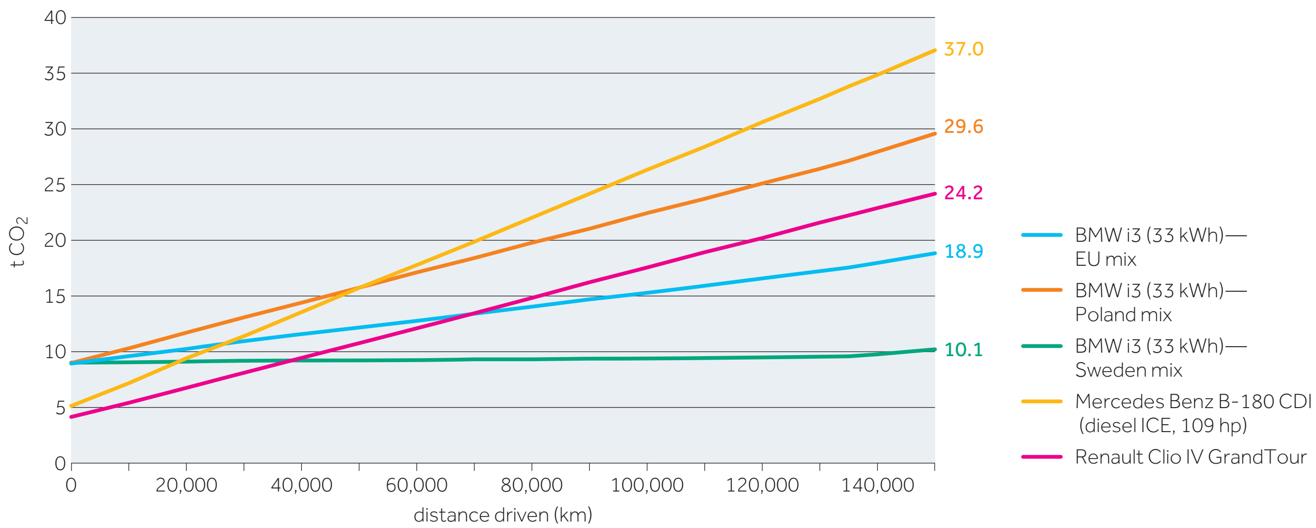


Table 5: Specific inputs: B-segment

	CONSUMPTION AND WEIGHT*	BATTERY SIZE AND RANGE	CO_2 INTENSITY OF ELECTRICITY MIX
BMW i3 (BEV)	161 Wh/km (without losses) Kerb weight: 1,300 kg	33 kWh battery 180 km driving range	EU mix (350 g CO_2/kWh) Higher range: Poland mix (750 g CO_2/kWh) Lower range: Sweden mix (20 g CO_2/kWh)
Renault Clio (diesel ICE)	3.2 l/100 km (NEDC) (Kerb weight: 1,200 kg)		
Mercedes Benz B-180 (diesel ICE), 109 hp	3.6 l/100 km (NEDC) (Kerb weight: 1,395 kg)		

* Data from Mercedes brochures

b) Large vehicles (D-segment/best-in-class)

In the case of large vehicles, the embedded emissions associated with the manufacturing stage increase significantly due to the combination of the larger sizes of both of the vehicle and the battery used to increase the driving range (representing ≈45% of the total CO_2 emissions in the selected BEV example). The location of the battery manufacturing and assembling facilities has a large impact on lifetime emissions in this vehicle segment. Also, due to the higher embedded CO_2 emissions for these D-segment BEVs, and as the vehicles in this segment are typically used to drive longer distances on more frequent journeys, ensuring that no battery replacement would be required along their lifetimes becomes the key factor in the comparison versus an equivalent ICE vehicle.

Assuming that only one battery is used, a BEV consuming an electricity mix close to the EU mix would need to be driven more than 100,000 km to reach the crossover point at which both powertrains reach parity in CO_2. When a Polish electricity mix is used, the analysis shows that an ICE diesel vehicle emits less CO_2 than a BEV during its whole lifetime.

Figure 7: The impact of national electricity mix and battery replacement on the use phase of two D-segment vehicles: Tesla Model S (BEV) vs Audi A4 (diesel ICE)—150,000 km

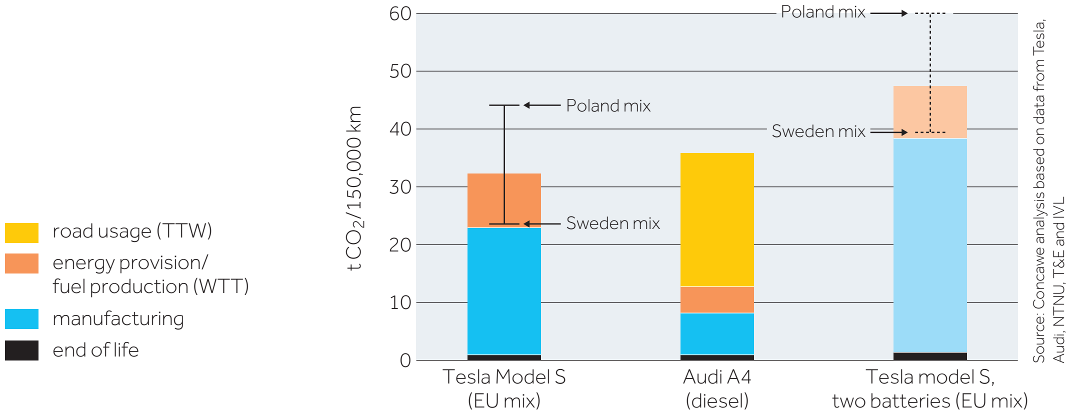


Figure 8: The impact of national electricity mix per distance driven for two D-segment vehicles: Tesla Model S (BEV) vs Audi A4 (diesel ICE)

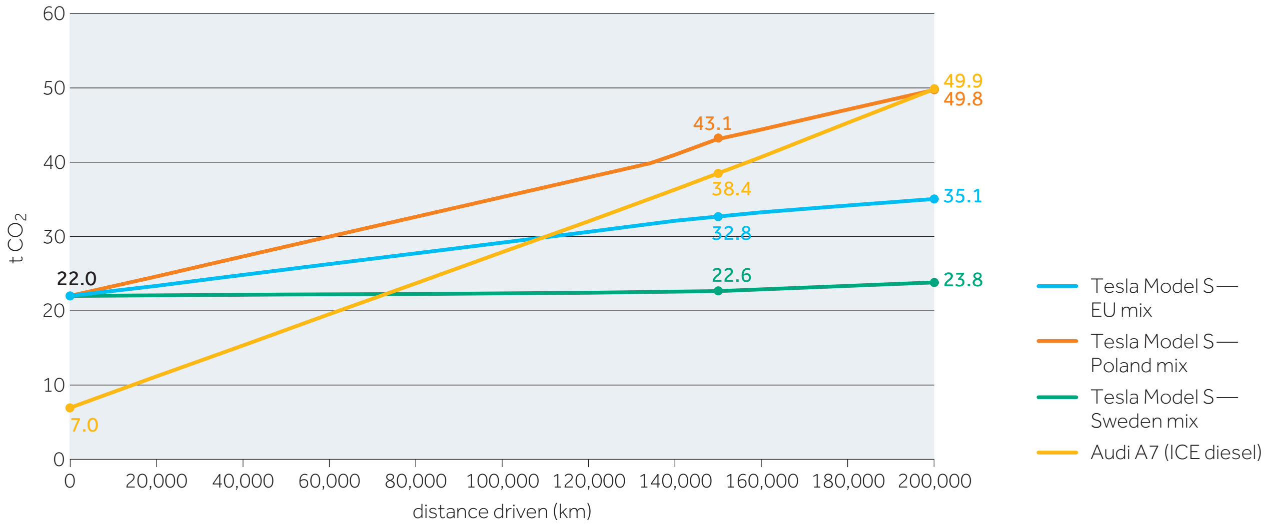


Table 6: Specific inputs: D-segment

	CONSUMPTION AND WEIGHT*	BATTERY SIZE AND RANGE	CO_2 INTENSITY OF ELECTRICITY MIX
Tesla Model S (BEV)	181 Wh/km (without losses) Kerb weight: 2,100 kg	100 kWh battery > 250 km driving range (NTNU value)	EU mix (350 g CO_2/kWh) Higher range: Poland mix (750 g CO_2/kWh) Lower range: Sweden mix (20 g CO_2/kWh)
Audi A7 3.0 TDI (diesel ICE)	4.7 l/100 km (NEDC) (Kerb weight: 1,800 kg)		

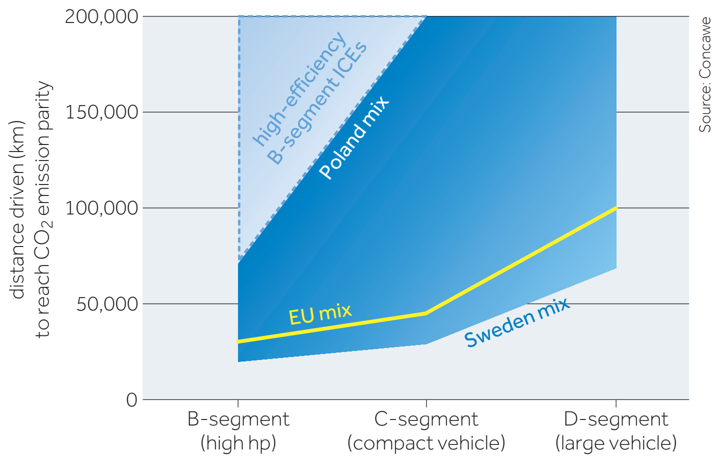
* Data from Tesla and Audi brochures, blogs and NTNU data

c) The electricity envelope

Figure 9 on page 28 shows the minimum distance that a vehicle would need to be driven to reach CO_2 emission parity between a BEV and an ICE powertrain for different electricity mixes, similar to the fossil fuel envelope developed by NTNU for ICE vehicles. The concept of an electricity mix envelope can be applied to explore the importance of the carbon intensity of the electricity mix consumed by BEVs.

This type of figure at a national level could help to inform different stakeholders, including consumers and policymakers, of the best available options, considering vehicle class, battery manufacturing locations and expected distance driven.

Figure 9: Example of an electricity mix envelope based on selected vehicles



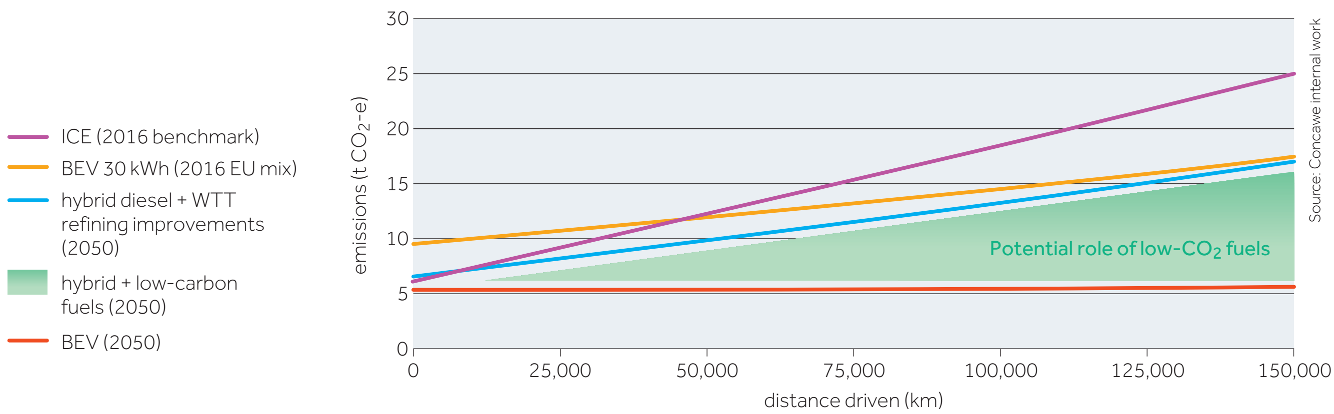
Fuel consumption: the role of low-carbon liquid fuels

Concawe is also exploring how future high efficiency internal combustion engine technologies, combined with low-carbon fuels, have the potential to deliver significant CO_2 savings.

To guide future research and policy, the same LCA analyses can be developed to assess the mitigation potential of different pathways. As shown by the green area in Figure 10, the combination of ICE and hybridisation has the potential to provide life-cycle CO_2 emission savings comparable with forecasted figures for future improved BEVs powered by electricity generated mainly using renewable sources (red line).

Ricardo is currently conducting an analysis assessing the LCA emissions associated with low-carbon fuels combusted in the most efficient internal combustion/hybrid vehicles.[1] The preliminary results confirm that, by 2050 for certain advanced biofuels and power-to-liquid technologies, the combination of highly efficient ICE powertrains and lower-carbon fuels are likely to give similar reductions in life-cycle CO_2 emissions when compared with BEV vehicles powered by a highly decarbonized electricity mix.

Figure 10: The potential role of low-carbon fuels in an LCA (conceptual approach)



Conclusions

This is the first published article associated with Concawe's ongoing research on life-cycle analysis and the potential role of low-carbon fuels that is being undertaken as part of the long-term strategy of the refining industry.[9,10] Several conclusions can be drawn from the results presented:

- Methodology:
  - LCA is a scientifically sound, well accepted methodology allowing the comparison of different powertrains on the same basis.
  - Currently, there is a need for more data from manufacturers, especially regarding batteries, to improve the accuracy of the LCAs conducted in the transport sector, and a recognised standardised basis for conducting LCAs.
  - Comparisons should be performed at the country level and by vehicle classification to provide meaningful results.

- Results:
  - When comparing electric vehicles with conventional powertrains, the relative contribution to the total life-cycle emissions associated with the different phases of energy or fuel generation, materials extraction, manufacturing and production all need to be included.
  - The energy mix used during the battery manufacturing process has a significant impact on the total CO_2 emitted during the life of the vehicle.
  - The carbon intensity of the electricity mix used to recharge the vehicles has a strong influence on the life-cycle emissions of electric vehicles.
  - The break-even distance for the life-cycle CO_2 emissions of electric vehicles compared to conventional vehicles is dependent on the vehicle size as well as the electricity mix. B-segment vehicles have the shortest break-even distance, while D-segment vehicles have the longest break-even distance. For an electricity mix that is heavily dependent on coal and heavier vehicles, the life-cycle CO_2 emissions of electric vehicles will be greater than for conventional vehicles.
  - Future high-efficiency ICE technologies, combined with low-carbon fuels, have the potential to deliver significant CO_2 savings across all segments, similar to BEVs using a largely renewable-based electricity mix.

Finally, the vehicles presented in this study are examples chosen to illustrate the main concepts of the LCA methodology, stressing the importance of different parameters in the final CO_2 emissions associated with each powertrain considered.

Concawe is willing to engage with external stakeholders to assist in developing a standard LCA methodology specifically for analysing future fuels and powertrains.

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