Understanding the life cycle GHG emissions for different vehicle types and powertrain technologies

Final Report for LowCVP

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Confidential	LowCVP and Project Steering Group
Report by	Jane Patterson
Approved	A. Johnson
	Angela Johnson Head of Knowledge & Technology Strategy

Version History & Disclaimer

Reference Number	Issued Date	Revision
RD18-001581-1	31 May 2018	Draft Report – issues for discussion with LowCVP and Project Steering Group
RD18-001581-2	1 August 2018	Final Report

Contents

This report, commissioned by LowCVP, seeks to continue informing the debate on future metrics for comparing low emission vehicles

Introduction

- In 2011 LowCVP commissioned "Preparing for a life cycle CO_2 measure", a report from Ricardo. The purpose was to inform the debate regarding future metrics for comparing low carbon vehicles by assessing a vehicle's life cycle CO_2e footprint
- A follow-up project in 2013, completed by PE International for LowCVP, assessed the life cycle CO_2e emissions for a range of low carbon passenger cars in the time frame 2020 to 2030
- This report provides the next level of understanding by examining how life cycle CO_2e emissions vary by vehicle type, powertrain architecture and fuel
  - Results are primarily based on a broad literature review and critique of existing automotive LCA material to provide insight into current industry understanding of life cycle CO_2e emissions for low carbon vehicles. LowCVP members contributed to this literature review by providing recommended LCA papers and reports
  - A "guidance framework" to interpreting LCA studies has also be developed, at the request of LowCVP, to help the wider automotive community and policy makers understand the reasons for variations between published LCA studies

This study focused on providing insight into how life cycle CO_2e emissions vary by vehicle segment and powertrain technology

Study Objectives

- The purpose of this study was to provide LowCVP with a high-level understanding of how life cycle CO_2e emissions vary for different vehicle segments and technology architectures, based on public domain data
  - The study focused on **L-category vehicles**, **passenger cars**, **heavy duty trucks** and **buses**
  - Technology architectures of interest include **conventional internal combustion engine, battery electric, hybrid** and **plug-in hybrid vehicles**
  - Regarding fuels and energy vectors, this study primarily focused on **gasoline, diesel** and **electricity**
- The study endeavoured to answer these questions:
  - What is the relative contribution of each life cycle stage (vehicle production, fuel production, vehicle use and vehicle disposal) to life cycle CO_2e emissions?
  - How do the relative contributions of life cycle stages vary by vehicle type?
  - Do the relative contributions change significantly for different powertrain types?
  - What are sensible assumptions for key analysis inputs, such as life time mileage?
- The study also highlighted areas requiring future study, based on gaps in the available public domain literature

Abbreviations

Abbr.	Explanation	Abbr.	Explanation	Abbr.	Explanation
AP	Acidification Potential	**eLCAr**	E-Mobility Life Cycle Assessment Recommendations	**ICE**	Internal Combustion Engine
B7	7%vol biofuel blend in diesel	**EPD**	Environmental Product Declaration	**ICEV**	Internal Combustion Engine Vehicle
BAU	Business As Usual	**EoL**	End-of-Life	**ICEV-D**	Diesel ICE Vehicle
BEV	Battery Electric Vehicle	**EP**	Eutrophication Potential	**ISO**	International Organisation for Standardisation
BSi	British Standards Institute	**EV**	Electric Vehicle	**L-cat**	L-category Vehicle
CH_4	Methane	**FCEV**	Fuel Cell Electric Vehicle	**LCA**	Life Cycle Assessment
CNG	Compressed Natural Gas	**FP7**	Framework Programme 7	**LCI**	Life Cycle Inventory
CO	Carbon Monoxide	**GHG**	Greenhouse Gases	**Li-ion**	Lithium Ion
CO_2	Carbon Dioxide	**GWP**	Global Warming Potential	**LR**	Long Range
CO_2e	Carbon Dioxide equivalent	**H_2**	Hydrogen	**MD**	Medium Duty
DB	Database	**HD**	Heavy Duty	**N_2O**	Nitrous Oxide
EC	European Commission	**HEV**	Hybrid Electric Vehicle	**NEDC**	New European Drive Cycle

Abbreviations

Abbr.	Explanation	Abbr.	Explanation	Abbr.	Explanation
NH_3	Ammonia	**PHEV**	Plug-in Hybrid Vehicle	**SR**	Short Range
NGO	Non-Government Organisation	**PIV**	Plug-in Vehicle *	**TTW**	Tank-to-Wheel
NOx	Nitrogen Oxides	**PO_4**	Phosphate	**VOC**	Volatile Organic Compound
OEM	Original Equipment Manufacturer	**PO_4e**	Phosphate equivalent	**WHVC**	World Harmonised Vehicle Cycle (for heavy duty vehicles)
Q&A	Question & Answer	**POCP**	Photochemical Ozone Creation Potential	**WLTC**	World harmonised Light duty vehicle Test Cycle
PAN	Peroxyacyl Nitrates	**SETAC**	Society of Environmental Toxicology and Chemistry	**WLTP**	World harmonised Light duty vehicle Test Procedure
PCR	Product Category Rules	**SMR**	Steam Methane Reforming	**WMTC**	World Motorcycle Test Cycle
PEF	Product Environmental Footprints	**SO_2**	Sulphur Dioxide	**WTT**	Well-to-Tank
PEM	Proton Exchange Membrane	**SO_2e**	Sulphur Dioxide equivalent	**WTW**	Well-to-Wheel

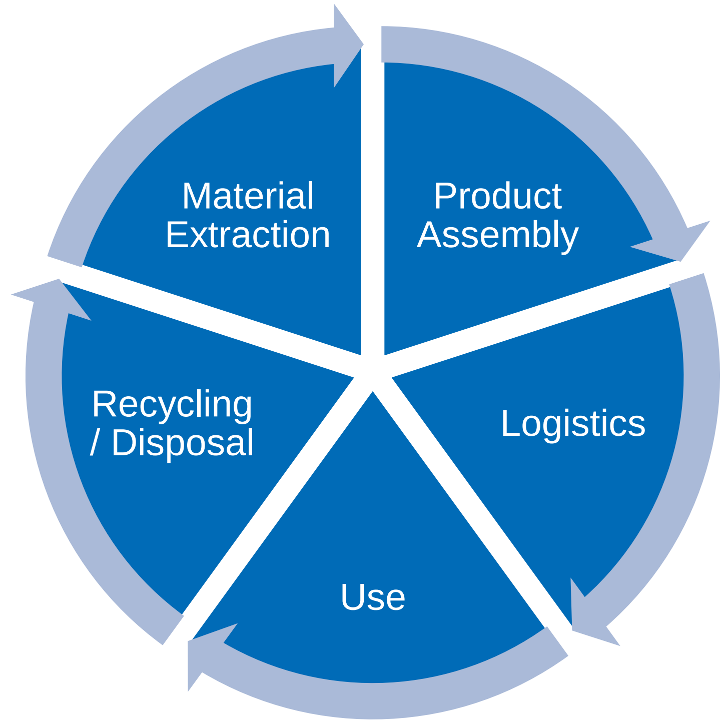
* A Plug-in Vehicle (PIV) includes all powertrain architecture options that can plug into the electricity network, such as Battery Electric (BEV) and Plug-in Hybrid (PHEV)

Contents

Life Cycle Assessment (LCA) is about taking a holistic approach to the analysis of a product's environmental impact

What is Life Cycle Assessment?

- All things have a **life cycle** of "birth", "use/service" and "death" in which they impact on their environment
- **Life Cycle Assessment (LCA)** is a technique for quantifying the environmental and human health impacts of a product over its life cycle
  - Other names include "life cycle analysis", "life cycle approach", "cradle-to-grave analysis", "ecobalance" or "environmental footprinting"
- **Life Cycle Thinking** is a way of thinking that includes the economic, environmental and social consequences of a product or process over its entire life cycle



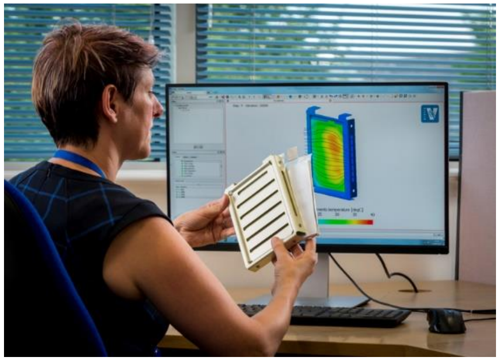
Formal Definition of Life Cycle Assessment

"It is a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment. The assessment includes the entire life cycle of product, process or activity, encompassing extracting and processing raw materials, manufacturing, transport and distribution; use, re-use, maintenance; recycling, and final disposal"

SETAC, 1991

LCA can be used to support decision making (micro and macro), or to support environmental accounting and reporting

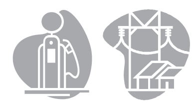
What is LCA used for?



- A life cycle assessment may be used to support decision making, or used for environmental accounting
  - **Micro-level decision support** covers product-related questions, such as design and development decisions (e.g. identification of key environmental parameters and eco-design to reduce environmental impact), or consumer choice (e.g. eco-labelling)
  - **Macro-level decision support** covers informing and developing policy, such as identifying technologies with the largest environmental improvement potential, and understanding the wider implications of changes to infrastructure
  - **Environmental accounting**, such as company social responsibility reporting, or monitoring the environmental impacts of a nation, industry sector, product group, or specific product
- Stakeholders include OEMs, suppliers, marketing & branding teams, product development teams, policy makers, and researchers

As discussed in the 2011 report, a vehicle's life cycle consists of four stages – vehicle production, fuel production, use and end of life

Vehicle Life Cycle



Fuel Production

Assessment of environmental impact of producing the energy vector(s) from primary energy source to point of distribution (e.g. refuelling station)

Vehicle Production

Assessment of environmental impact of producing the vehicle including extract of raw materials, processing, component manufacture, logistics, vehicle assembly and painting

Use

- Environmental impact of driving
- Impact from maintenance and servicing

End-of-Life

Assessment of environmental impact of "end of life" scenario, including re-using components, recycling materials, energy recovery, and disposal to landfill

A vehicle LCA study may consider the whole life of the vehicle, or just part of it, such as Well-to-Wheel or "cradle-to-gate"

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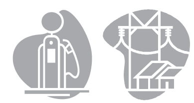
Vehicle Life Cycle

Well-to-Wheel (WTW) Analysis is Life Cycle Assessment of the fuel (energy) used to power the vehicle

"Embedded" emissions result from from vehicle production; fluid, filter and component replacement during life; and end-of-life activities. A **"cradle-to-gate"** LCA study may only consider vehicle or component production



Fuel Production

Assessment of environmental impact of producing the energy vector(s) from primary energy source to point of distribution (e.g. refuelling station)

Analysis of the **whole vehicle life cycle** will include embedded emissions from vehicle production, maintenance and servicing, and end-of-life activities, and WTW emissions from production and use of the fuel / energy

Vehicle Production

Assessment of environmental impact of producing the vehicle including extract of raw materials, processing, component manufacture, logistics, vehicle assembly and painting

Use

- Environmental impact of driving
- Impact from maintenance and servicing

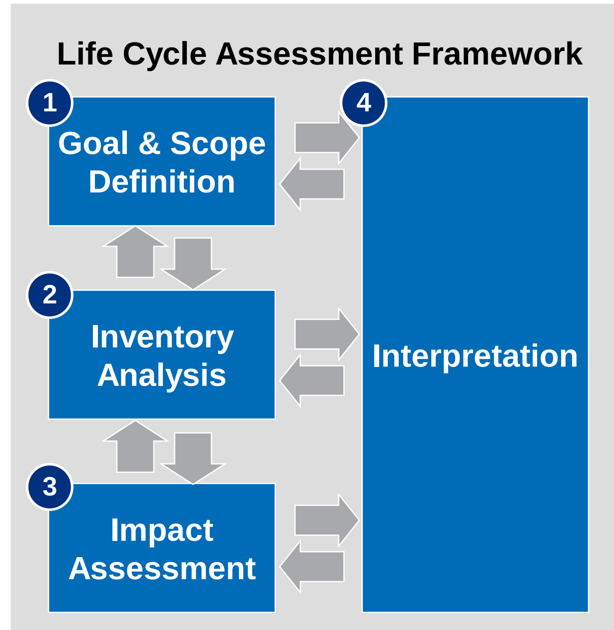
End-of-Life

Assessment of environmental impact of "end of life" scenario, including re-using components, recycling materials, energy recovery, and disposal to landfill

There are existing international standards and published guidelines relevant for conducting LCA studies in the automotive sector, …

Standards & Guidelines

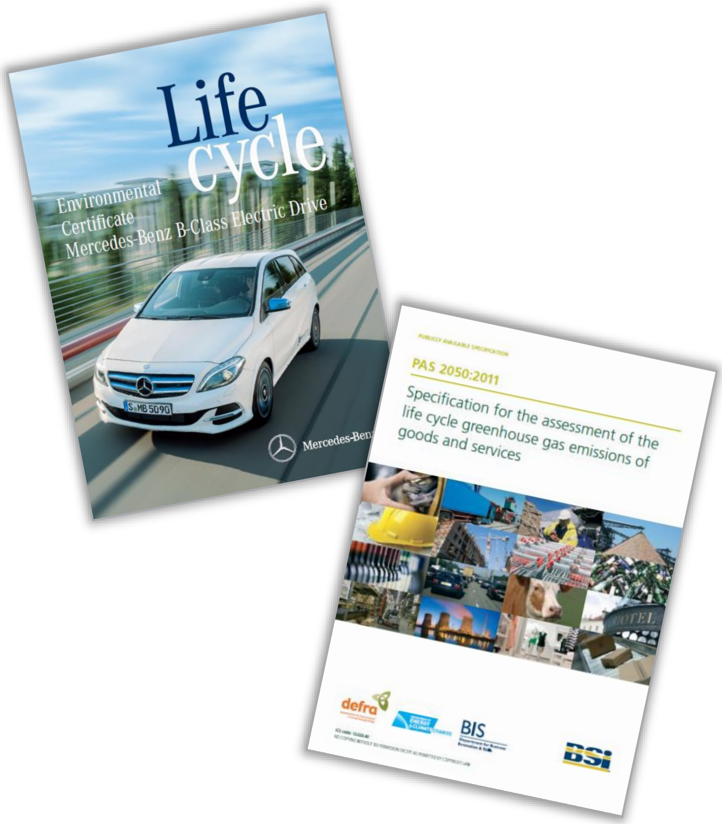
- The methodological framework for conducting a **Life Cycle Assessment (LCA)** is described in ISO 14040 and ISO 14044. The main phases are:
  - Defining **Goal & Scope**, including the functional unit (the unit on which the study is performed) and analysis system boundary
  - **Inventory Analysis**, creating a list of required materials and energy for each part of the life cycle considered (i.e. creating the life cycle model), and the resulting emissions to air, water and soil
  - **Impact Assessment** to group emissions into impact categories (e.g. Global Warming Potential (GWP) from GHG emission)
  - **Interpretation** to check results, refine analysis and identify key messages for the intended audience



- Since 2011, more guidelines have been published to support conducting LCA studies of automotive products
  - For example, the European FP7 project **eLCAr** wrote extensive guidelines and training material for conducting LCA studies of electric vehicles (2013, www.elcar-project.eu)

… including standards for product environmental footprinting and how results should be communicated the public

Product Environmental Footprints



- **Environmental Product Declarations (EPDs)** are defined by ISO 14025, building on ISO 14040 and ISO 14044. An EPD must be based on a product LCA, use **Product Category Rules (PCR)** for the relevant product type, and be verified by a third party
- Other standards for environmental footprinting include:
  - Carbon Footprint - ISO/TS 14067 or BSi PAS 2050
  - Water Footprint - ISO 14046
  - Footprint Reporting - ISO 14026

Source: International Standards Organisation; https://www.environdec.com/What-is-an-EPD/; British Standards Institute

Although useful for making strategic decisions, a critical eye should be aware of LCA's limitations when interpreting the results

Benefits of LCA

- **Structured method** for managing a large amount of complex data
  - Life cycle inventory data includes product bill of materials, energy consumption, and associated environmental impacts
- Facilitates **holistic comparison** of the options
  - Helps ensure that a company's decisions are environmentally sound, whether in the design, manufacture, use or disposal of a product
- Highlights **environmental "hot spots"** along the life cycle chain
- **Avoids shifting the problem** from one life cycle stage to another, or from one environmental impact medium to another
- **Useful for communicating** the system wide consequences of the product or technology options to the stakeholders

Limitations of LCA

- Performing a Life Cycle Assessment study can be **resource and time intensive**
- The accuracy of LCA studies may be **limited by accessibility, availability or quality of relevant data**
  - Assumptions have to be made when data is inaccessible or unavailable
- The nature of choices made in **LCA may be subjective**
  - For example, selecting what to include and what to exclude from the system boundary
  - Assumptions are likely to be subjective
- Results of LCA studies focused on global and regional issues **may not be appropriate for local applications**
  - E.g. City air quality issues, or noise pollution

Generally the results of an LCA should be used as part of a much more comprehensive decision making process. Comparing results of different LCAs is only possible if the assumptions and context of each study are the same. **Assumptions should be explicitly stated**

Source: Various

Contents

Ricardo employed a literature search, scan and prioritisation approach to select the "Top 50" papers to review

Study Methodology – Literature Review

Literature Searches

Searches of relevant LCA and related literature using a range of tools such as Ricardo Powerlink, Science Direct and Google. Also includes input from LowCVP members and Ricardo background information

Literature Scan & Categorisation

Identified documents entered into LCA Literature Database. Initial high-level review of all documents to categorise by vehicle type, powertrain technology, fuel / energy vector, vehicle components, life cycle stages, environmental impacts and LCA tools used

Prioritisation

Papers ranked according to relevance to this study (more recent papers and European context considered most relevant), and usefulness of data recorded. Highly ranked papers selected for next-level Literature Review

Literature Review of "Top 50"

Review of papers by vehicle type (and batteries) to extract relevant information such as application, key assumptions, life cycle impact results

L-Category | **Passenger Car** | **Trucks** | **Buses** | **Batteries**

Discussion & Critique

Recording of Literature Review outputs to provide understanding of life cycle GHG emissions for different vehicle types and powertrain technologies. Also, highlighting areas of commonality or convergence, and reasons for variation

Ricardo, with input from LowCVP members, identified >150 relevant documents, the top 50 were included in the Literature Review

Literature Review Dashboard – Status Update 23 May 2018 (1/2)

136 papers & reports identified

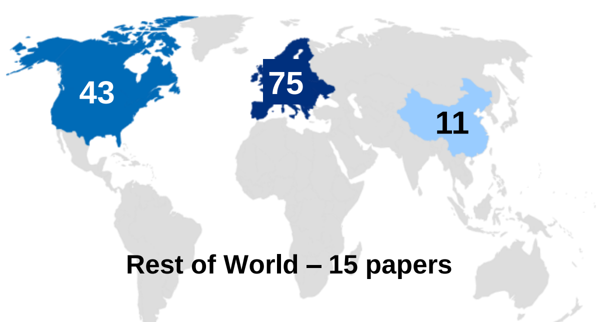
15+ Literature Searches completed

Including c.25 documents submitted by LowCVP members

>100
papers scan read or reviewed

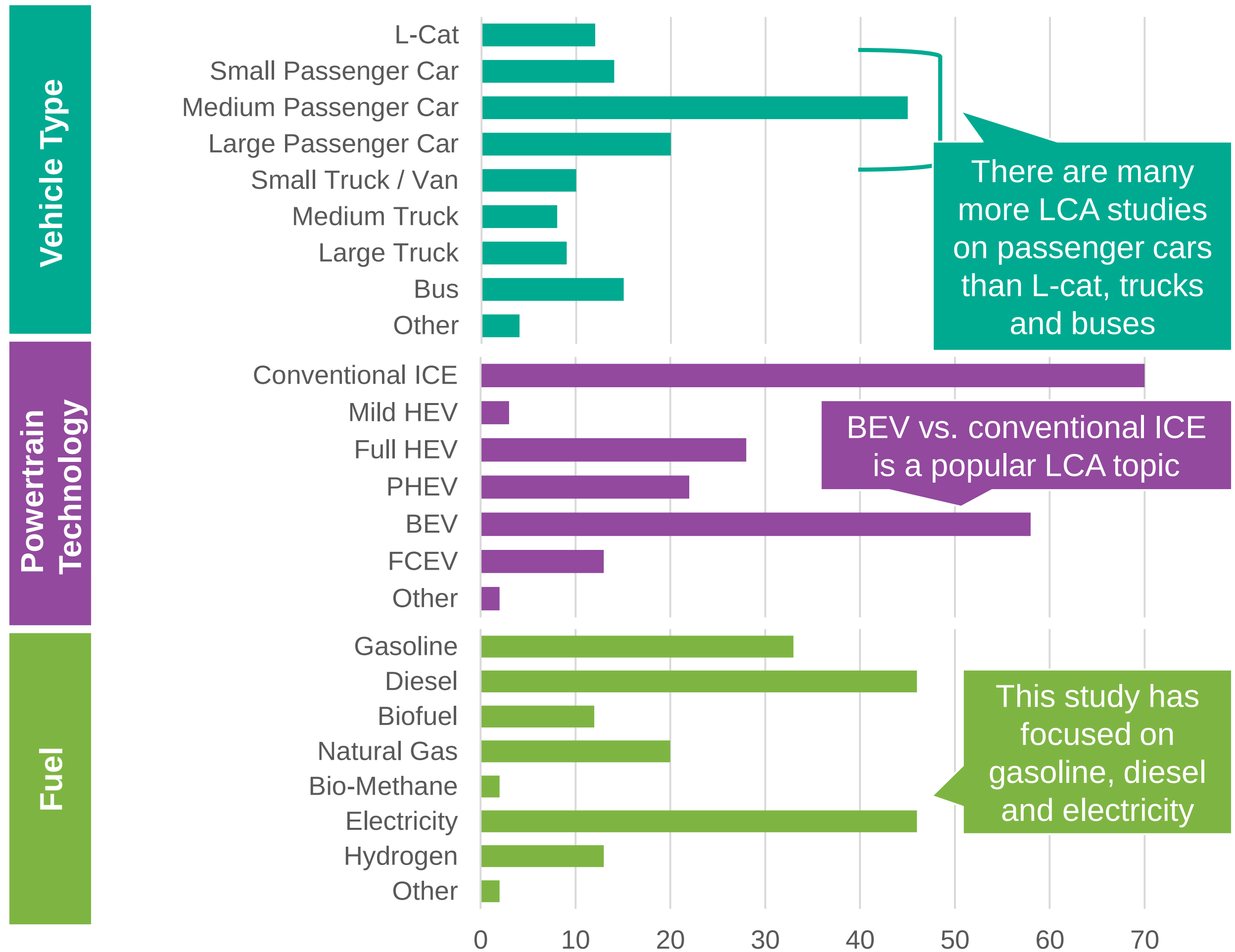
In addition **30** News Articles and **c.20** OEM and Supplier Sustainability & Environmental reports also considered

Geography



Some papers considered >1 geographical region

Interest by Topic Area

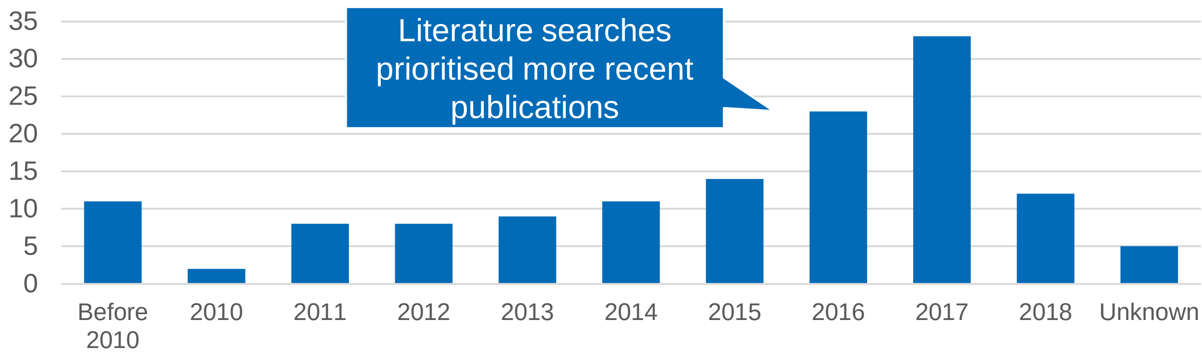


Source: Full list of literature provided to LowCVP in the LCA Literature Database (RD18-001155)

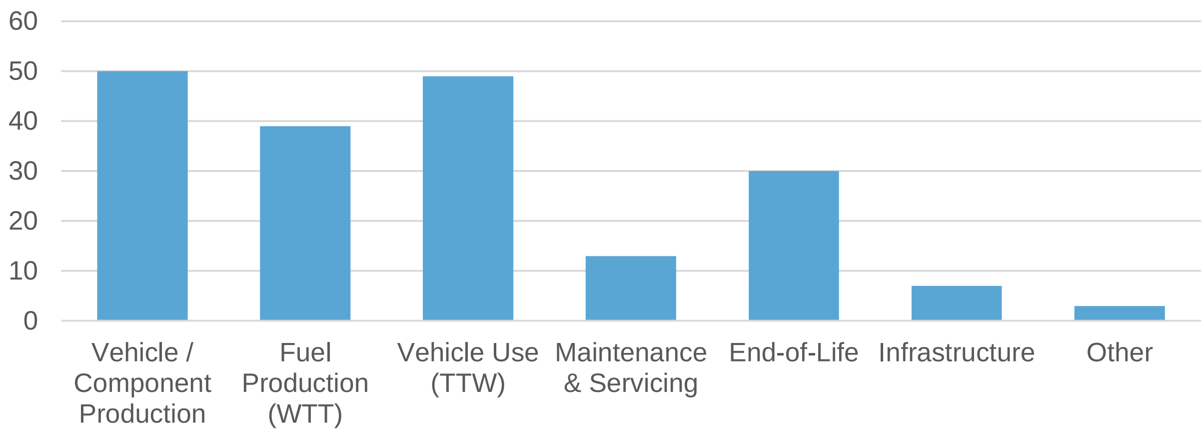
The collected literature covers all vehicle life cycle stages, with a focus on more recent publications

Literature Review Dashboard – Status Update 23 May 2018 (2/2)

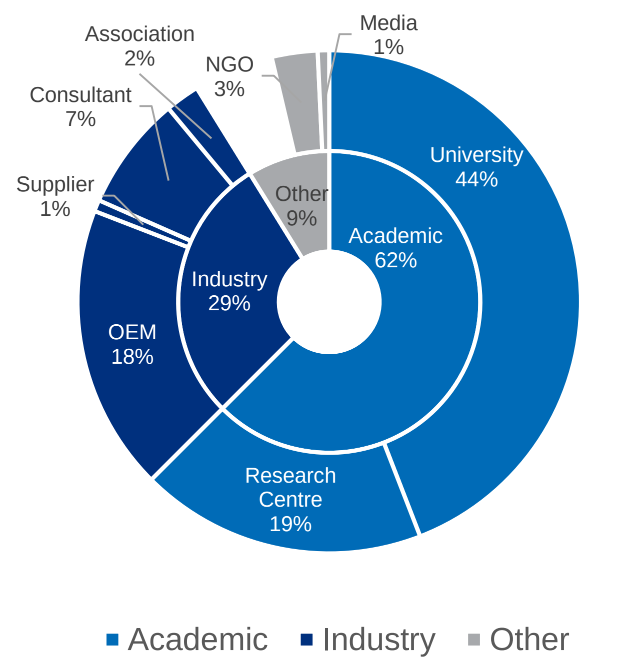
Interest by Study Geographical Location



Interest by Life Cycle Stage



Publications by Organisation Type



The chart above shows publications by organisation type of the main author. It does not include analysis of press releases or OEM Environmental and Sustainability reports.

The LCA literature database is non-exhaustive and does not contain a complete list of all automotive LCA studies

Source: Full list of literature provided to LowCVP in the LCA Literature Database (RD18-001155)

Contents

LowCVP propose a "guidance framework" to help the wider automotive community and policy makers understand LCA studies

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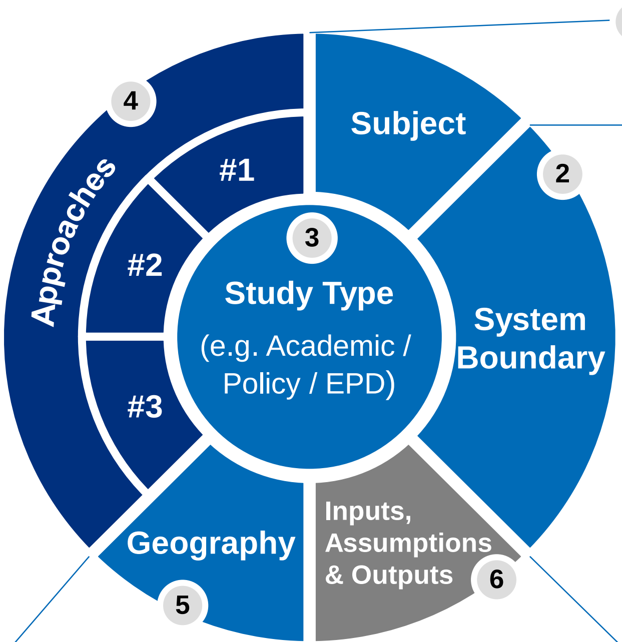
Understanding LCA Studies – "Guidance Framework" Overview

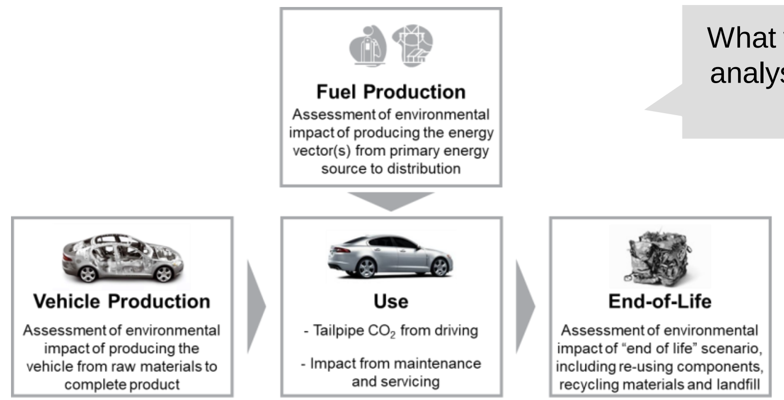


Study Subject & Functional Unit

What product system was studied? What was the functional unit?

System Boundary

What was included in the analysis? And what was excluded?



Geography	Input Data	Key Assumptions	LCI Datasets	Environmental Impact Factors	Time Horizon
 What is the location of use? What is the location(s) of production?	Primary vs. Secondary data Who provided the input data? What was provided?	• Vehicle duty cycle • Lifetime Mileage [km] • Electricity carbon intensity [$kgCO_2e/kWh$] • Battery embedded carbon factor [$kgCO_2e/kWh$ or $kgCO_2e/kg$] , etc.	E.g. EcoInvent How old is this data?	E.g. • Global Warming Potential (GWP) [tCO2e] • Human Toxicity, etc.	Model Year (current / historic / future) Vehicle Lifetime Allowance for temporal effects, etc.

The first step to understanding LCA studies is identifying the study subject (application) and functional unit

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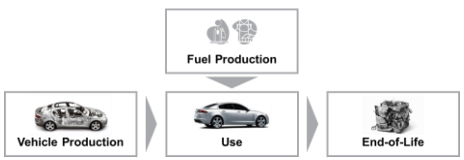
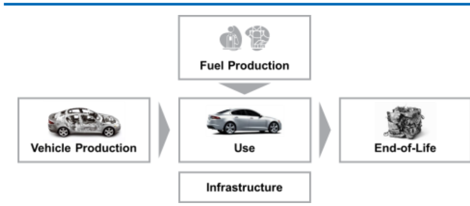
1 LCA Study Subject and Functional Unit

Study Subject	• **What product system was studied?** – The study subject could be a specific vehicle make and model, or a hypothetical situation (e.g. generic mid-size European passenger car) – The study may focus on a component or sub-system (e.g. battery pack), rather than the whole vehicle. Or it could consider a whole vehicle fleet or vehicle parc, rather than a single vehicle – It may focus on the energy vectors only (e.g. Well-to-Wheel analysis) – Or, it may consider the transportation of X passengers / cargo over a specified distance • If the study has considered more than one subject (e.g. comparison of different powertrain technologies), the subjects should have a common purpose and function
Functional Unit	• The scope of an LCA study should clearly specify the functions (performance characteristics) of the system studied (see ISO 14040 and ISO 14044) • The **functional unit** provides the reference for normalising input and output data. It should be clearly defined, measurable and technology-neutral • The units of the results usually provides an indication of the study's functional unit – For example, are the results presented as total emissions (e.g. tCO_2e), or per vehicle kilometre travelled (e.g. gCO_2e/km)?

The analysis may have considered the whole vehicle life cycle or part of it – common system boundaries are listed below

2 LCA Study Categorisation – Life Cycle System Boundary

Level A **Tailpipe only**		• Considers vehicle point-of-use only
Level B **Well-to-Wheel (WTW)**		• Considers the fuel or energy vector life cycle, from primary energy (e.g. drilling for oil) through to use in the vehicle • Frequently split into “Well-to-Tank” (fuel production and distribution) and “Tank-to-Wheels” (vehicle consumption during use)
Level C **Vehicle Life Cycle**		• Considers the whole vehicle life cycle (cradle-to-grave) from material extraction, through production to use and end-of-life processes
Level D **Whole mobility system life cycle**		• Considers impact of subject within the wider techno-, socio- and eco-spheres, such as including changes to infrastructure or analysing externalities
Cradle-to-gate		• Considers production phase of the vehicle or component, including material extraction • Analysis stops at end of production. Use and end-of-life phases not included in analysis

What has been excluded?

- Take note of what has not been included in the analysis system boundary
- (This is not clear for all studies)

Knowing who commissioned the study, who conducted it and the intended audience helps to categorise the type of LCA study

3 LCA Study Categorisation – Study Type

Academic	• The LCA study may be **commissioned by** an OEM, supplier or a public research fund • The study may be **conducted by** a researcher, consultant or manufacturer • The **intended audience** is the wider academic and research community. The primary interest is the creation of knowledge. Results may be published in technical journals • Subject may be real (e.g. specified vehicle make and model) or hypothetical (e.g. generic European mid-size passenger car)
Policy	• **Commissioned by** a government agency, NGO or research fund • **Conducted by** a researcher or consultant • The **intended audience** is policy makers and academics. The purpose is to provide understanding of the potential implications of policy changes • Usually considers the environmental impact of a product or service within a wider social system (e.g. externalities)
Environmental Reporting	• **Commissioned by** a manufacturer (e.g. OEM marketing department) • **Conducted by** manufacturer or consultant • The **intended audience** is customers and the general public • The purpose is to quantify the life cycle environmental impacts of the manufacturer's products • Studies usually conform to ISO 14025 or equivalent standard, with certification by an independent 3rd party (e.g. national certification authority). Results may be published in Environmental Product Declarations (EPDs) or Corporate Responsibility Reports

LCA studies can also by categorised by approach – bottom-up or top-down? Attributional or consequential? …

4 LCA Study Categorisation – Study Approaches (1/2)

#1 Study Approach – Bottom-Up or Top-Down?	
Bottom-Up	• Starts with each production step, mapping input and output flows, to build up to the final product
Top-Down	• Starts from known macro parameters describing the overall system • Gradually unravels the macro information into data describing the sub-processes of the production system
Combination	• Uses a combination of bottom-up and top-down approaches to understand the life cycle system

#2 Modelling Approach – Attributional or Consequential?	
Attributional	• Answers the question "what are the environmental impacts resulting from **activities that have contributed to** the production, use and disposal of the product?" • Attributional modelling is accounting based. It depicts the potential environmental impacts that can be attributed to a system along its supply chain, use and end-of-life. The system is modelled as it is, was or is forecast to be. It makes use of historical, fact-based, measurable data. It includes the processes that contributed to the system being studied. It uses cut-off rules and allocation to isolate the product system
Consequential	• Answers the question "what are the environmental impacts resulting from **activities that change due to** the production, use and disposal of the product?" • Consequential modelling is science based. It focuses on the physical and social unit processes that change as a consequence of a decision. Its purpose is decision support. Results do not represent the environmental impacts of the functional unit in itself, but the environmental exchanges resulting from adding or subtracting one functional unit compared to doing nothing

Source: ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance (2010); Meyer (2014) [#137]

… And, what accounting approach has been used for modelling reuse, recycling and energy recovery of waste and end-of-life?

4 LCA Study Categorisation – Study Approaches (2/2)

#3 Accounting Approach for modelling reuse, recycling and energy recovery

Processing waste and end-of-life products produces secondary (recycled) materials, energy resources (e.g. heat), and reconditioned parts for re-use. These outputs are used in subsequent products, where they replace primary production of material and/or change the energy mix. So, the process is multifunctional. The product being recycled has its primary function (what it was made for), and a secondary function of providing resources for the subsequent life cycle of another product.

In **closed-loop recycling**, the life cycle model loops the secondary material or energy back to an earlier process where it replaces primary input (e.g. using recycled rather than primary material). In **open-loop recycling**, all or part of the secondary material is used in another product system. The recycled material may have the same inherent properties as the primary material (open-loop same primary route). Or the material may undergo changes to its inherent properties during recycling (open-loop different primary route).

There are different methods that can be used to account for burdens and benefits of reuse, recycling and energy recovery

Simple Cut-Off	• All waste management burdens and benefits with value to a secondary product are assigned to the life cycle of that secondary product. Therefore, end-of-life analysis generally stops after vehicle dismantling, since the recycling of material will be counted in the new product that uses this recycled material • No credits are applied for recycling
Environmental Burden	• Recycling of a material avoids extraction and processing of primary materials (e.g. aluminium) • All avoided expenses and emissions are completely attributed to the product that delivers the material scrap after its service life (common practice) • Therefore credits are applied for recycling
Shared Benefits & Burden	• Benefits and burden of recycling are shared between the product recycled, and the new product using the recycled material

Common Errors: Omission or double counting / modelling or recycling – Inconsistency in modelling and use of background data can result in omitting or double counting the environmental impacts of recycling waste and end-of-life products

Source: ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance (2010);

Geographical location of the study subject (application) will define the subject specification and many key input assumptions

5 LCA Study Categorisation – Geography

- Geographical location of the product will define many of the key inputs and assumptions used in the life cycle model, such as:
  - Vehicle specification (affecting all life cycle stages)
  - Vehicle in-use duty cycle, and associated vehicle fuel / energy consumption (e.g. L/100km)
  - Expected lifetime (years) and lifetime mileage (km)
  - Electricity mix and associated carbon intensity [gCO_2e/kWh]
  - Fuel specification and associated environmental impacts (e.g. Well-to-Tank factors for fossil and biofuel, biofuel mix, and biofuel blend levels in conventional fuels)

- Note – The production locations of the vehicle and its many components may not be the same as its geographical region of use. Therefore, the environmental impacts of the energy used during production and assembly may be different to the energy used during vehicle use
  - Also, many vehicle OEMs are exploring opportunities for reducing the environmental footprint of their production facilities and supply chain, such as installing wind turbines or solar panels at factory sites. So the energy mix used in the factory may be different to the national average of the factory location

Finally, check what input data and assumptions have been applied, and …

6 LCA Study Data, Assumptions, and Environmental Impacts (1/2)

Input Data (Primary vs. secondary data)	• Does the study include **new data** collected from the manufacturer or through research in the field (primary data)? (e.g. factory energy consumption, bill of materials, etc.) • Or, does the study rely on **previous publications**? If so, how old is this secondary data?
Key Assumptions	**What key assumptions have been made in the life cycle model?** For example: • Vehicle lifetime mileage [km] • Vehicle fuel consumption [L/100km or kWh/100km] – is this based on simulation, a laboratory test (e.g. WLTP), or “real world” results? What duty cycle has been considered? • Electricity carbon intensity [gCO_2e/kWh] • For hybrid and electric vehicles – battery capacity [kWh], EV range [km], and assumed “embedded GHG emissions” factor for battery production (e.g. $kgCO_2e/kWh$ or $kgCO_2e/kg$ of battery pack), etc.
LCI Dataset	**What generic life cycle inventory (LCI) data was used for materials, manufacturing processes and other life cycle stages?** • Commonly used LCI datasets include EcoInvent, and thinkstep (GaBi)

… what environmental impact factors have been considered

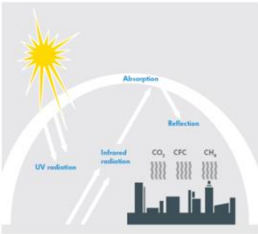
6 LCA Study Data, Assumptions, and Environmental Impacts (2/2)

Environmental Impact Factors	**What environmental impact factors have been considered?** • See next slide for examples
Time Horizon	• Is the study subject based on **current model year, historic model, or hypothetical future product** (prospective LCA)? • What has been assumed about the **vehicle lifetime** [years]? And what scenario has been presented about the vehicle's future end-of-life? • Are the **environmental impact factors for in-use fuel and energy consumption** based on current energy mix, historic energy mix, or projected future energy mix? **Has allowance been made for temporal effects?** (e.g. electricity decarbonisation with time)

There are many different types of environmental impact resulting from emissions to water, air and soil, resource use and depletion

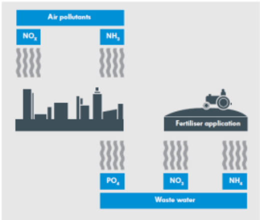
Typical Environmental Impact Categories

SELECTED EXAMPLES

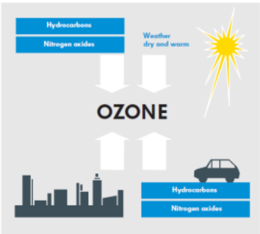


Global Warming Potential (GWP) describes GHG emissions that increase the absorption of heat from solar radiation in the atmosphere and therefore increase the average global temperature. The reference substance is CO_2, and all other substances that impact on this process (e.g. CH_4, N_2O) are measured in CO_2 equivalents (CO_2e)

Acidification Potential (AP) describes the emissions of acidifying substances such as SO_2 and NOx, which have diverse impacts on soil, water, ecosystems, biological organisms and material (e.g. buildings). "Acid rain" and fish mortality in lakes are examples of such negative effects. The reference substance is SO_2, and all other substances that impact on this process (e.g. NOx and NH_3) are measured in SO_2 equivalents (SO_2e)



Eutrophication Potential (EP) describes excessive input of nutrients into water [or soil] that can lead to an undesirable change in the composition of flora and fauna. A secondary effect of the over-fertilisation of water is oxygen consumption and therefore oxygen deficiency. The reference substance is phosphate (PO_4), and all other substances that impact on this process (e.g. NOx, NH_3) are measured in phosphate equivalents (PO_4e)



Photochemical Ozone Creation Potential (POCP) describes the formation of photooxidants, such as ozone and peroxyacetyl nitrate (PAN), which can be formed from hydrocarbons, carbon monoxide (CO) and nitrogen oxides (NOx), in conjunction with sunlight. Photooxidants can impair human health and the functioning of ecosystems and damage plants. The reference substance is ethene, and all other substances that impact on this process (e.g. VOC, NOx and CO) are measured in ethene equivalents

Source: VW (2010) The New Transporter Environmental Commendation Background Report

Contents

During the literature search, c.10 papers were identified that assessed the life cycle, or part life cycle, emissions of L-cat vehicles

RICARDO

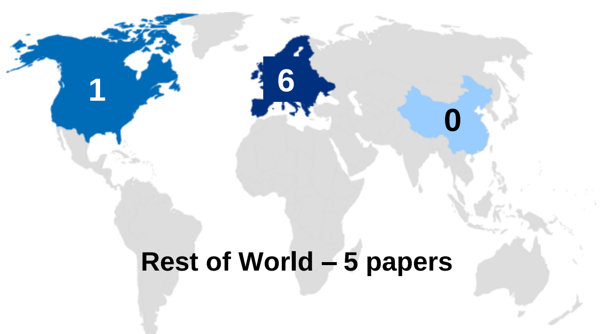
L-Category Vehicle – Literature Review Dashboard

12
papers & reports identified

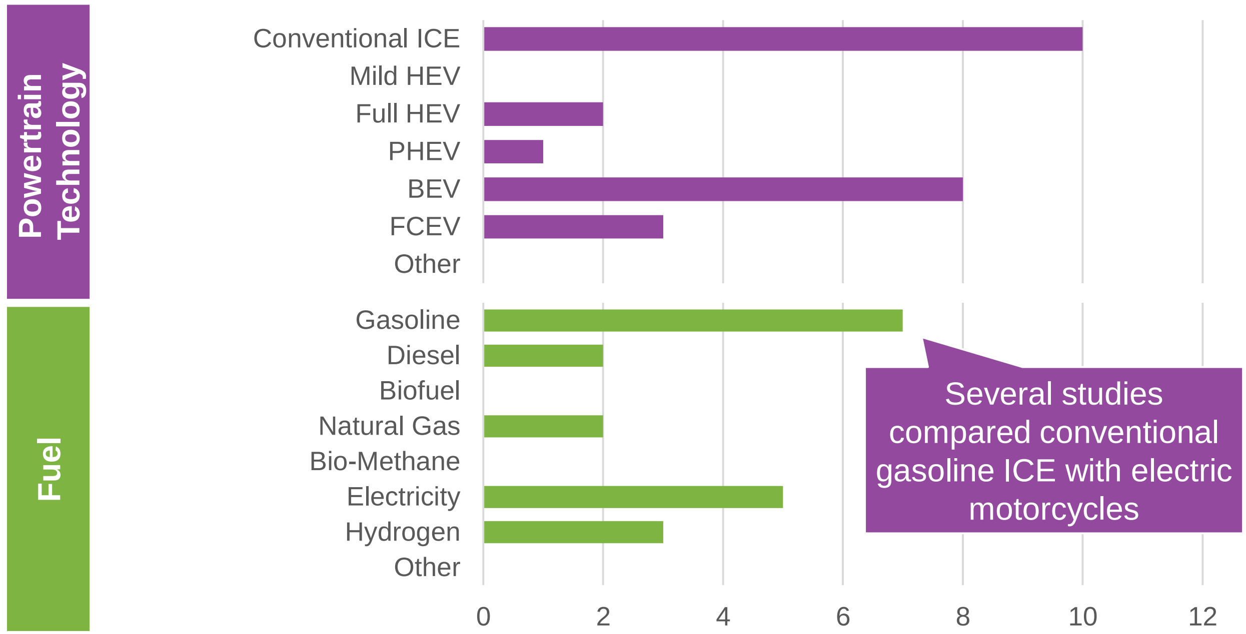
5
Papers reviewed

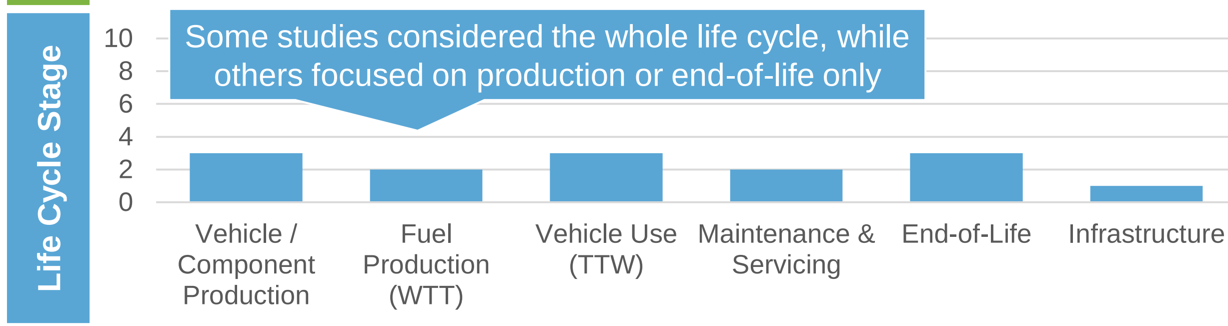
Most considered the environmental impacts of motorcycles, scooters or bicycles. A few considered L-category bicycles. A few considered L-category 4-wheel vehicles

Geography



Interest by Topic Area





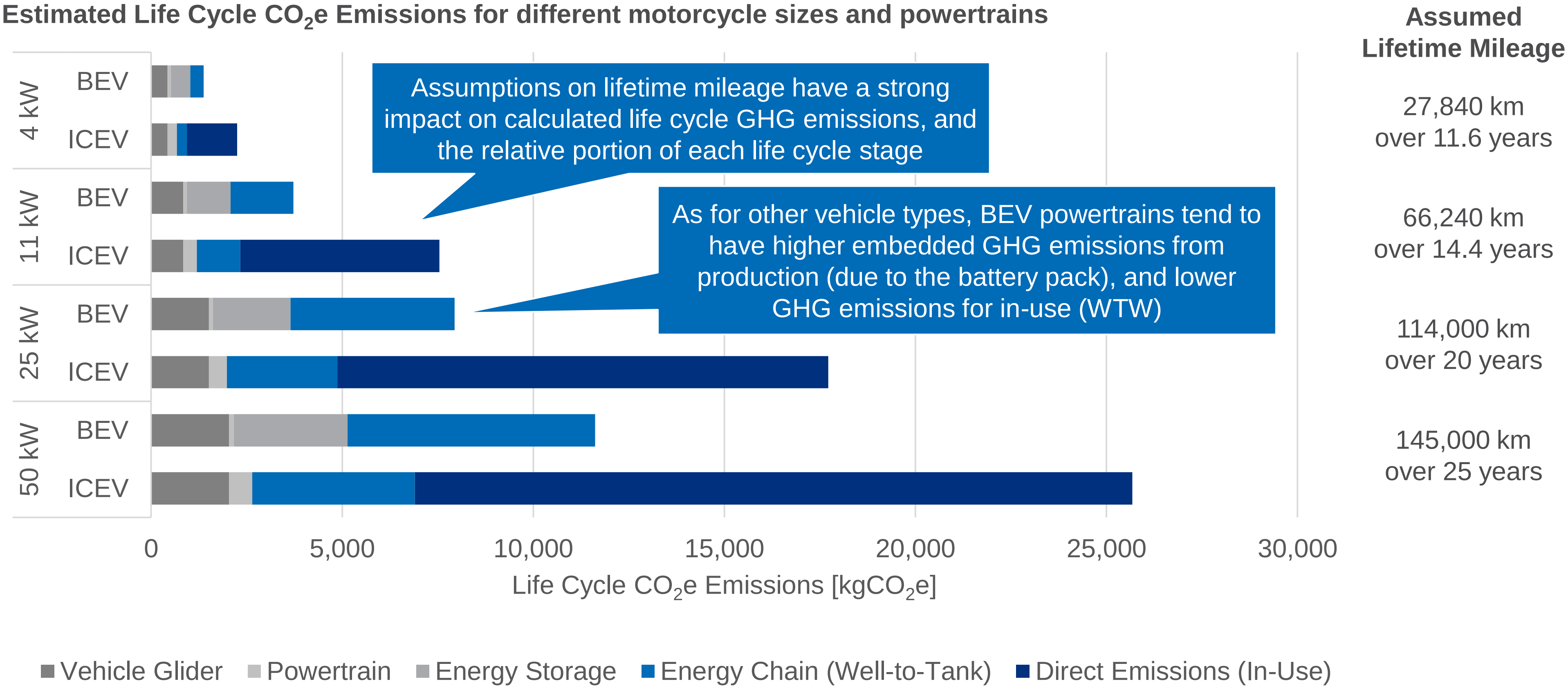
Source: Full list of literature provided to LowCVP in the LCA Literature Database (RD18-001155)

One LCA study on motorcycles suggested life cycle GHG emissions vary from 1.4 – 26 tCO_2e depending on size, technology and mileage

L-Category (Motorcycles) – Example Results (1/2)

SELECTED EXAMPLE

Estimated Life Cycle CO_2e Emissions for different motorcycle sizes and powertrains



Motorcycle assumed to operate in Europe, with average European electricity carbon intensity taken from EcoInvent 3.2 (other energy mixes also considered – see paper and support information for further details). Lifetime mileage assumed to vary by motorcycle size. Selected lifetime mileages based on Swiss travel statistics (1990 – 2014). In-use vehicle energy consumption based on WMTC. Vehicle end-of-life not included in analysis. The original analysis also included impact on infrastructure (e.g. road wear), however results for infrastructure have not been included in the selected results shown above

Source: Adapted from [#036] Cox, B. L, and Mutel, C. L. (2018). The environmental and cost performance of current and future motorcycles. Applied Energy Volume 212, 15 February 2018, Pages 1013-1024Available at: https://www.sciencedirect.com/science/article/pii/S0306261917318238 [Accessed 26 March 2018]

Vehicle production could contribute c.10-75% of life cycle CO_2e emissions, again depending on technology and lifetime mileage

RICARDO

L-Category (Motorcycles) – Example Results (2/2)

SELECTED EXAMPLE

Motorcycle Power [kW]	Powertrain	Lifetime Mileage	Relative Contribution of each Life Cycle Stage [%]					Climate Change Impact [gCO2e/km]
			Vehicle Production			Fuel Production (WTT)	Vehicle Use (TTW)	
			Glider	Powertrain	Energy Storage			
4 kW	**BEV**	27,840 km	31.1%	6.4%	36.7%	25.8%	0.0%	**49.4 gCO_2e/km**
	ICEV		19.0%	10.9%	0.1%	11.5%	58.4%	**80.8 gCO_2e/km**
11 kW	**BEV**	66,240 km	22.6%	2.6%	30.7%	44.2%	0.0%	**56.2 gCO_2e/km**
	ICEV		11.1%	4.6%	0.1%	15.1%	69.1%	**113.9 gCO_2e/km**
25 kW	**BEV**	114,000 km	19.0%	1.4%	25.5%	54.1%	0.0%	**69.7 gCO_2e/km**
	ICEV		8.5%	2.6%	0.1%	16.3%	72.5%	**155.4 gCO_2e/km**
50 kW	**BEV**	145,000 km	17.5%	1.1%	25.6%	55.8%	0.0%	**80.1 gCO_2e/km**
	ICEV		7.9%	2.3%	0.0%	16.6%	73.1%	**177.1 gCO_2e/km**

This study suggests Vehicle Production contributes c.10-30% for ICEV and c.45-75% BEV depending on size of motorcycle, lifetime mileage and battery capacity

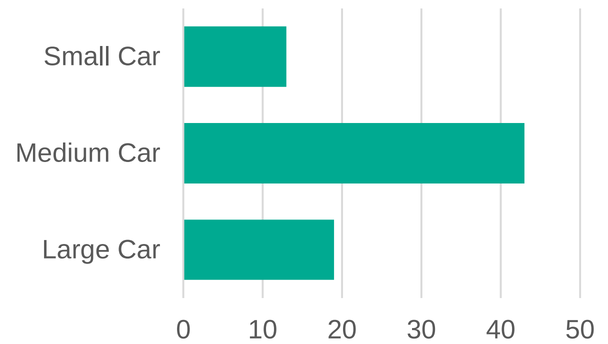
Source: Adapted from [#036] Cox, B. L, and Mutel, C. L. (2018). The environmental and cost performance of current and future motorcycles. Applied Energy Volume 212, 15 February 2018, Pages 1013-1024Available at: https://www.sciencedirect.com/science/article/pii/S0306261917318238 [Accessed 26 March 2018]

There are many LCA publications covering life cycle emissions of passenger cars – Ricardo focused on ICE, hybrid and EV technology

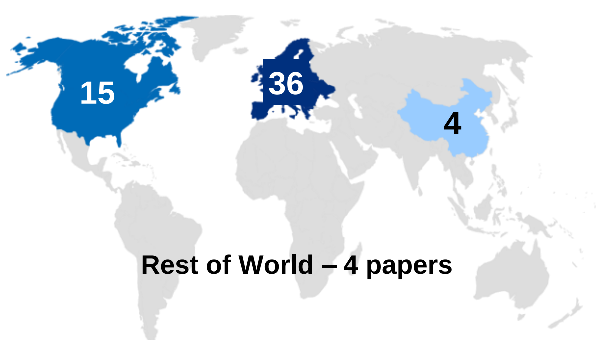
Passenger Cars – Literature Review Dashboard

51+ papers & reports identified

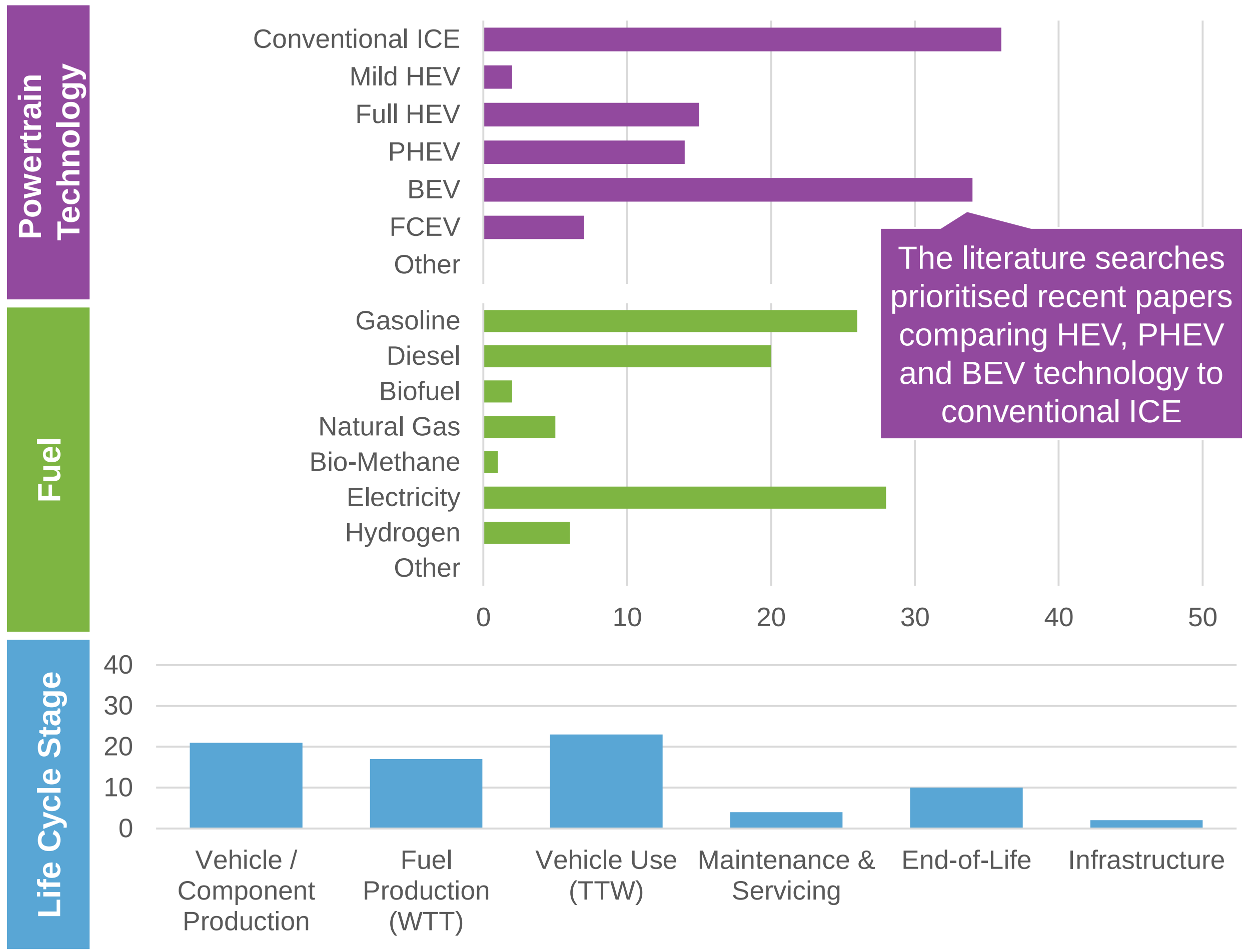
36 Papers, Reports & Press Releases reviewed



Geography



Interest by Topic Area



Source: Full list of literature provided to LowCVP in the LCA Literature Database (RD18-001155)

For Passenger Cars, OEM LCA studies suggest life cycle CO_2e is c.20-40 tonnes, depending on segment and lifetime mileage

Passenger Cars – Selected results from OEM literature

SELECTED EXAMPLES

Vehicle	Description	Lifetime Mileage [km]	Total Life Cycle CO_2e [tCO_2e]	Life Cycle [%]				Source
				Vehicle Production	Fuel & Electricity Production (WTT)	In-Use (TTW)	Disposal	
BMW i3 BEV (MY2014)	125 kW electric motor, 160 km EV range	150,000	-	57%	40%	0%	3%	#102
Renault Megane (MY2016)	C-segment, 1.46L diesel K9K engine, Euro 6	150,000	20.5	26.3%	72%		1.7%	#105
Mercedes-Benz B180	1.6L I4 90 kW gasoline engine, Euro 6	160,000	29.8	18.5%	12.8%	67.1%	1.7%	#093
Mercedes-Benz B-Class EV (MY2014)	132 kW electric motor,28 kWh Li-ion battery with 200 km EV range	160,000	22.6	44.7%	52.7%	0%	2.7%	#093
Mercedes-Benz C180 (MY2015)	C-Class saloon with 1.6L I4 115 kW gasoline engine, Euro 6	200,000	34.7	21.6%	10.7%	66.9%	0.9%	#103
Mercedes-Benz C-Class Plug-in Hybrid (MY2015)	C-Class saloon plug-in hybrid with 2.0L I4 155 kW gasoline engine and 60 kW electric motor, Euro 6	200,000	27.4	36.9%	26.7%	35%	1.5%	#103

Increasing vehicle size

Lifetime mileage has a strong influence on total life cycle CO_2e emissions

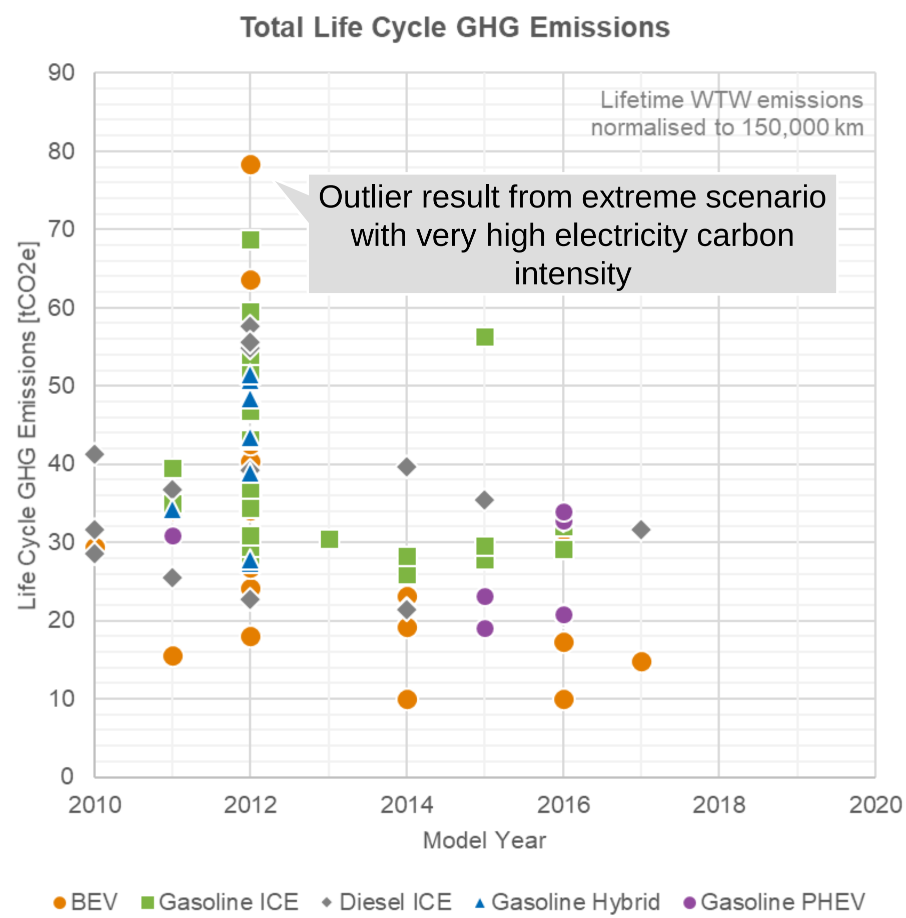
Sources: See LCA Literature Database - #102, #103, #093, #105

Recent academic LCA studies continue to show that overall life cycle GHG emissions for BEVs are generally lower than for ICEs

Passenger Cars – Review of Total Life Cycle GHG Emissions

SELECTED EXAMPLES

- Further review of OEM and academic published LCA studies on passenger cars shows a wide range of values for total life cycle GHG emissions, even if results are normalised to the same lifetime mileage
  - Reasons for variation include **differences in vehicle and powertrain specification**, **vehicle energy consumption, electricity and fuel carbon intensity**, and **study methodology** (e.g. credits for recycling)
- Generally, for most LCA studies and sensitivity scenarios, passenger car BEV and hybrid life cycle GHG emissions are lower than gasoline and diesel ICE equivalent vehicles. However, there are a few exceptions, usually related to sensitivity scenarios with high electricity carbon intensity
  - Since BEVs have higher embedded GHG emissions, if the electricity carbon intensity is as high as gasoline and diesel WTW emissions, then the BEV will have higher life cycle GHG emissions



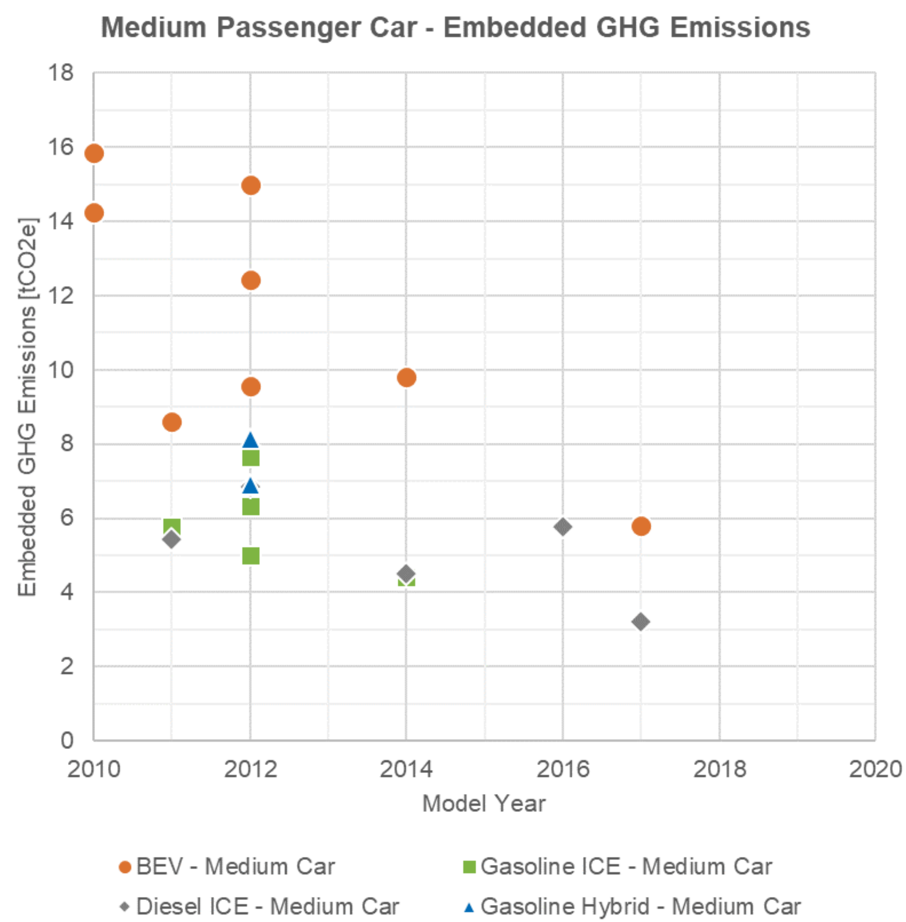
Passenger Car life cycle GHG emissions results from c.20 published studies, normalised to the same lifetime mileage (150,000 km)

Source: Ricardo analysis of selected published LCA studies on passenger cars and light commercial vehicles (vans)

Although embedded GHG emissions from BEV production could be 50-100% higher, depending of battery pack size and emissions factor

Passenger Cars – Review of Embedded GHG Emissions

- From published literature, embedded GHG emissions from vehicle production and end-of-life account for:
  - 10-30% of total life cycle GHG emissions for conventional ICEVs
  - 20-95% of total life cycle GHG emissions for BEVs (depending on electricity carbon intensity)
- Variation in embedded GHG emissions is due to modelling approach and fidelity, (e.g. top-down vs. bottom-up), vehicle specification, LCI datasets, and electricity carbon intensity
- For a medium-sized passenger car, embedded emissions are typically 5-8 tCO_2e for gasoline ICE, and 6-16 tCO_2e for BEV, depending on size of battery pack and assumed production emissions factor



Passenger Car life cycle GHG emissions results from c.10 published studies, focusing on embedded emissions from vehicle production and end-of-life

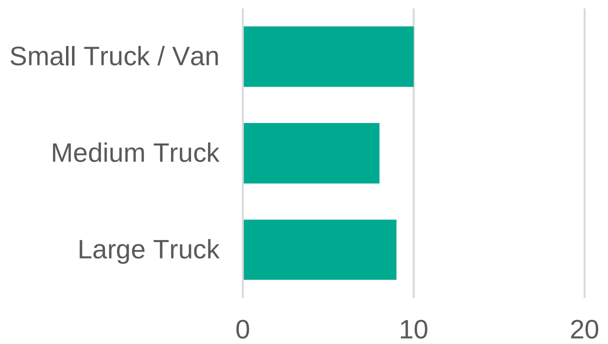
Source: Ricardo analysis of published LCA studies on passenger cars and light commercial vehicles (vans)

Although >20 documents related to commercial trucks were identified, only a few considered the whole vehicle life cycle

Commercial Trucks – Literature Review Dashboard

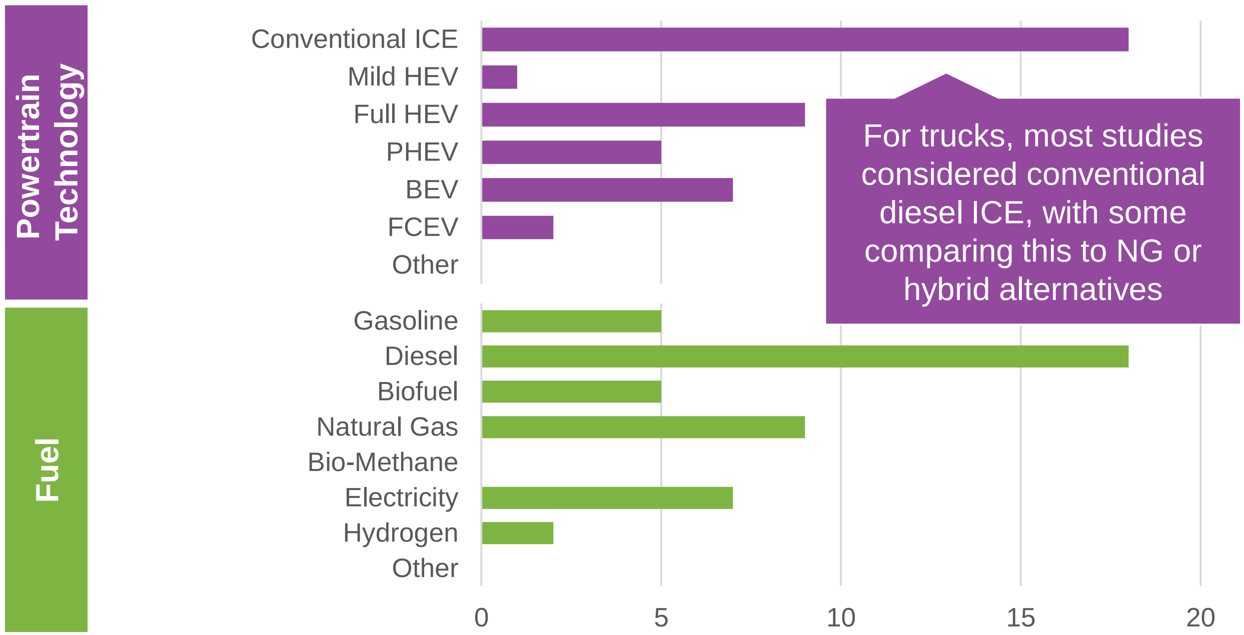
21+
papers & reports identified

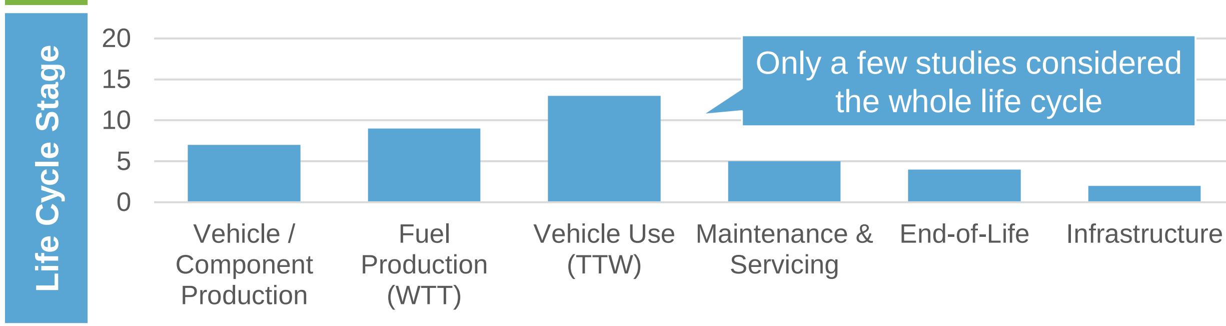
8
Papers, Reports & Press Releases reviewed



Geography

Interest by Topic Area





Source: Full list of literature provided to LowCVP in the LCA Literature Database (RD18-001155)

E.g. Volvo Trucks has produced a simple footprint calculator to help customers understand the potential life cycle environmental impacts

Commercial Medium & Heavy Duty Trucks

SELECTED EXAMPLE

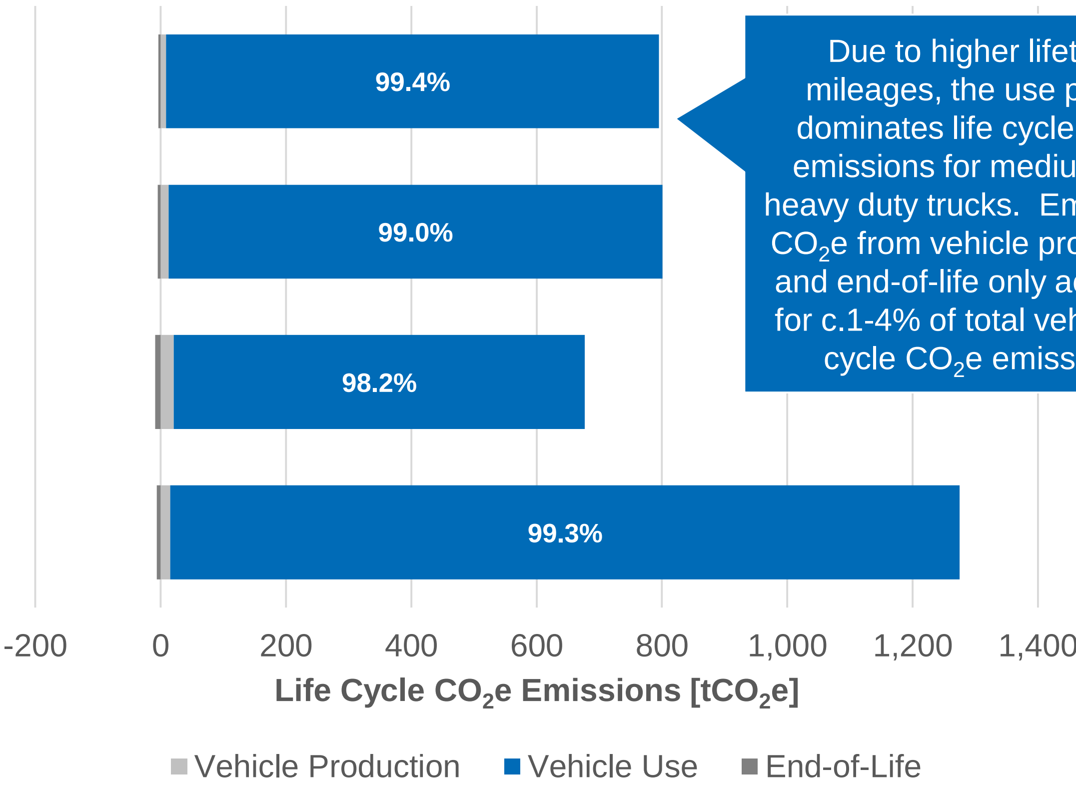
Estimated Life Cycle CO_2e Emissions for different medium and heavy duty trucks

Volvo FL medium duty rigid truck for city distribution, with 5L Euro VI diesel engine

Volvo FE medium duty rigid truck for regional distribution with 8L Euro VI diesel engine

Volvo FE hybrid MD rigid truck for regional distribution, with 7L Euro V diesel engine

Volvo FM heavy duty tractor for articulated truck for national and international distribution, with 11L Euro VI diesel engine



Due to higher lifetime mileages, the use phase dominates life cycle CO_2e emissions for medium and heavy duty trucks. Embedded CO_2e from vehicle production and end-of-life only accounts for c.1-4% of total vehicle life cycle CO_2e emissions

Assume lifetime mileage is **1,000,000 km**; B7 diesel fuel; fuel consumption 25 L/100 km for FL and FE ICEV, 20 L/100 km for FE hybrid, and 40 L/100km for FM.
Vehicle production does not include production of trailer or box.
Volvo applies a credit at vehicle end-of-life for recycling the vehicle

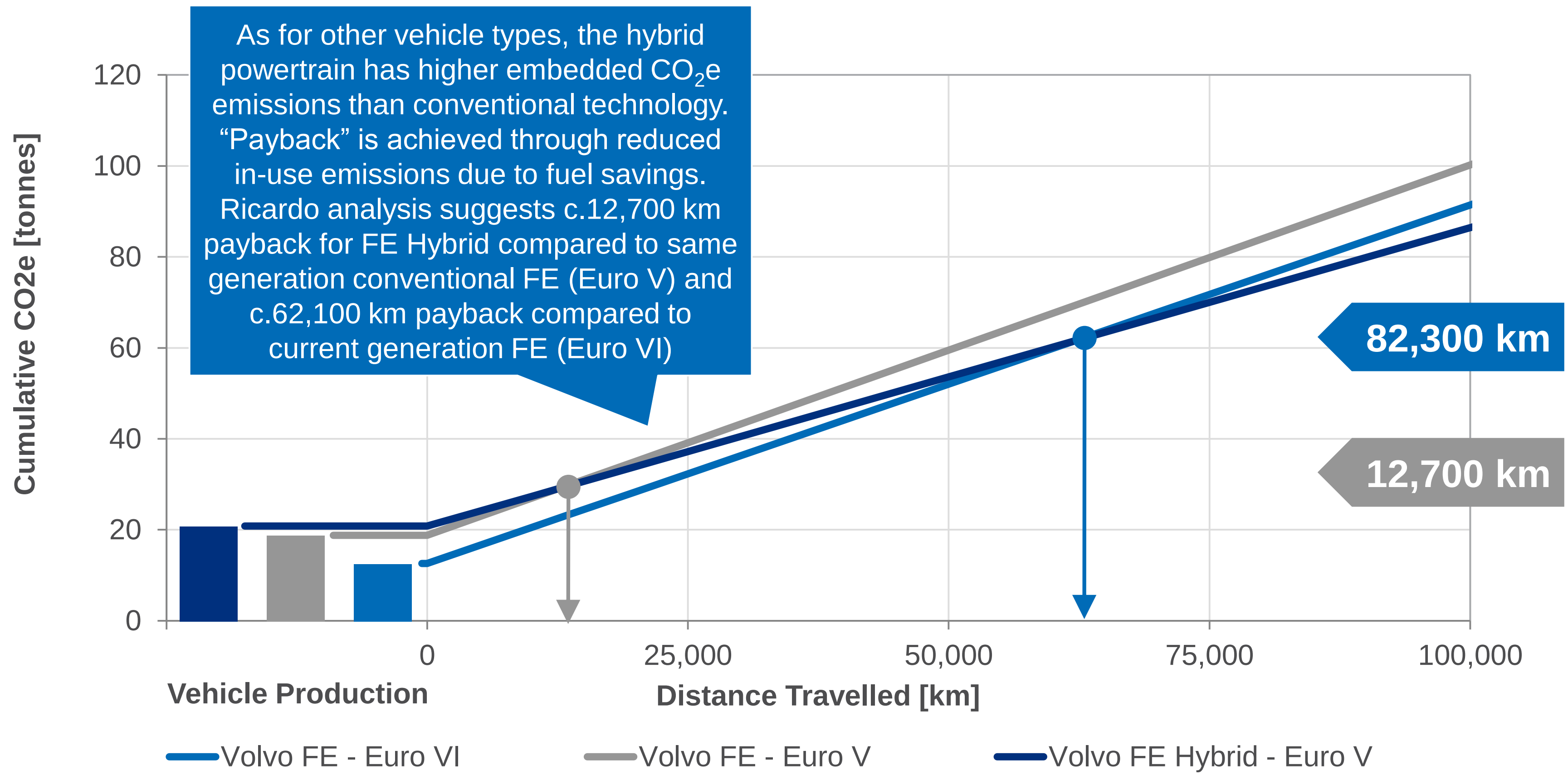
Feedback from LowCVP members suggests lifetime mileage for medium and heavy duty trucks is typically >1,000,000 km, which will further increase the portion of life cycle emissions from vehicle use

Source: Calculated using Volvo Trucks' Environment Footprint Calculator [#OEM22] - Available at: http://footprintcalculator.volvotrucks.com/ [Accessed 12 April 2018]

As for other vehicle types, hybridisation increases CO_2e emissions from truck production, with payback quickly achieved through use

Commercial Medium & Heavy Duty Trucks – Carbon Payback

SELECTED EXAMPLE



The current generation FE (Euro VI) has significantly lower embedded CO_2e emissions than the previous generation (Euro V), suggesting Volvo has taken measures to reduce GHG emissions from vehicle production, probably through design changes, material substitution, manufacturing improvements and decarbonising energy

Source: Ricardo analysis using data from Volvo Trucks' Environment Footprint Calculator [#OEM22] - Available at: http://footprintcalculator.volvotrucks.com/ [Accessed 12 April 2018]

For buses, 15 papers were identified during the literature search – many comparing a range of technologies in a specific context

Urban Buses – Literature Review Dashboard

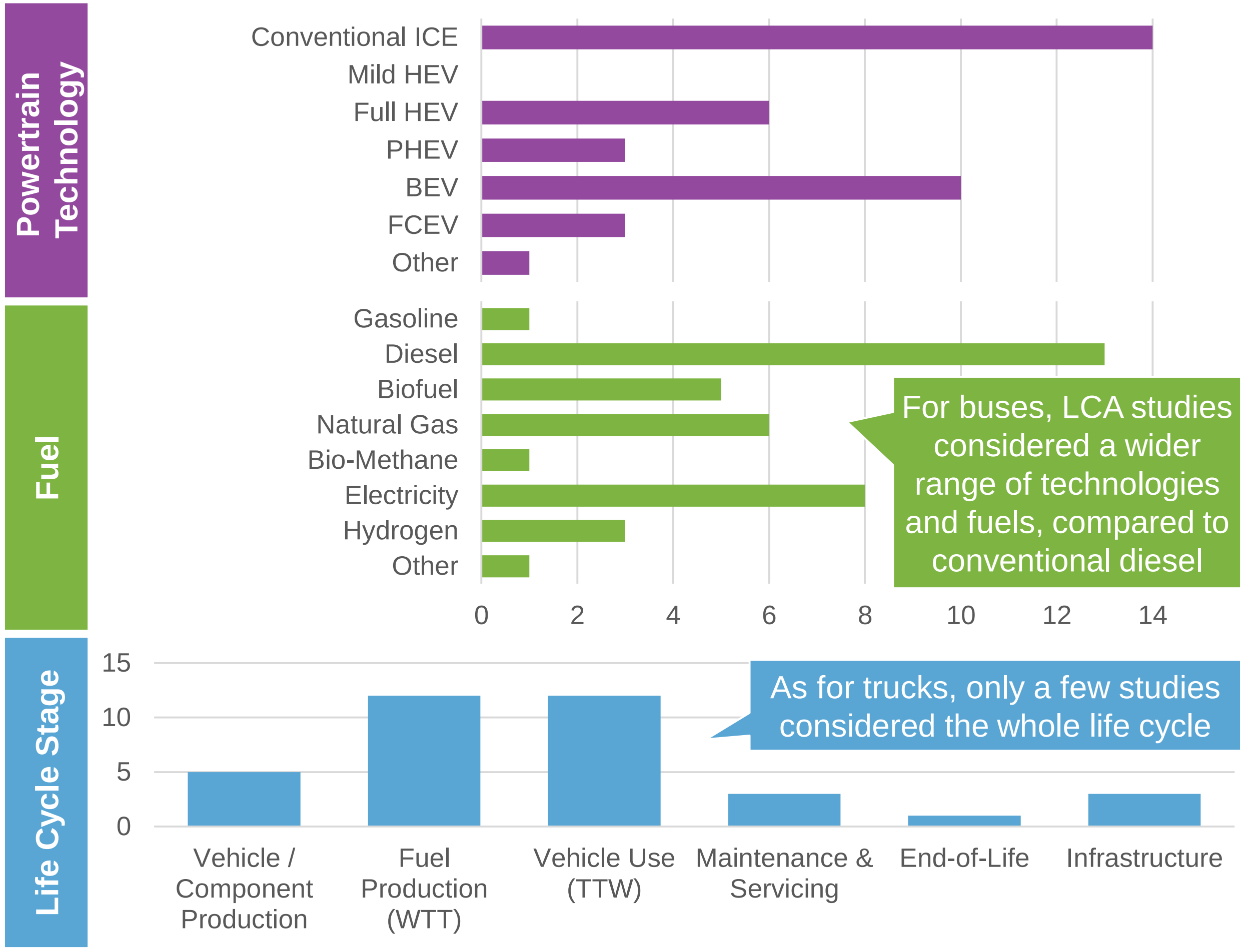
15
papers & reports identified

5
Papers reviewed

Many of the studies considered buses within a specific context, operating on specific routes in cities or transport corridors

Geography

Interest by Topic Area



For buses, LCA studies considered a wider range of technologies and fuels, compared to conventional diesel

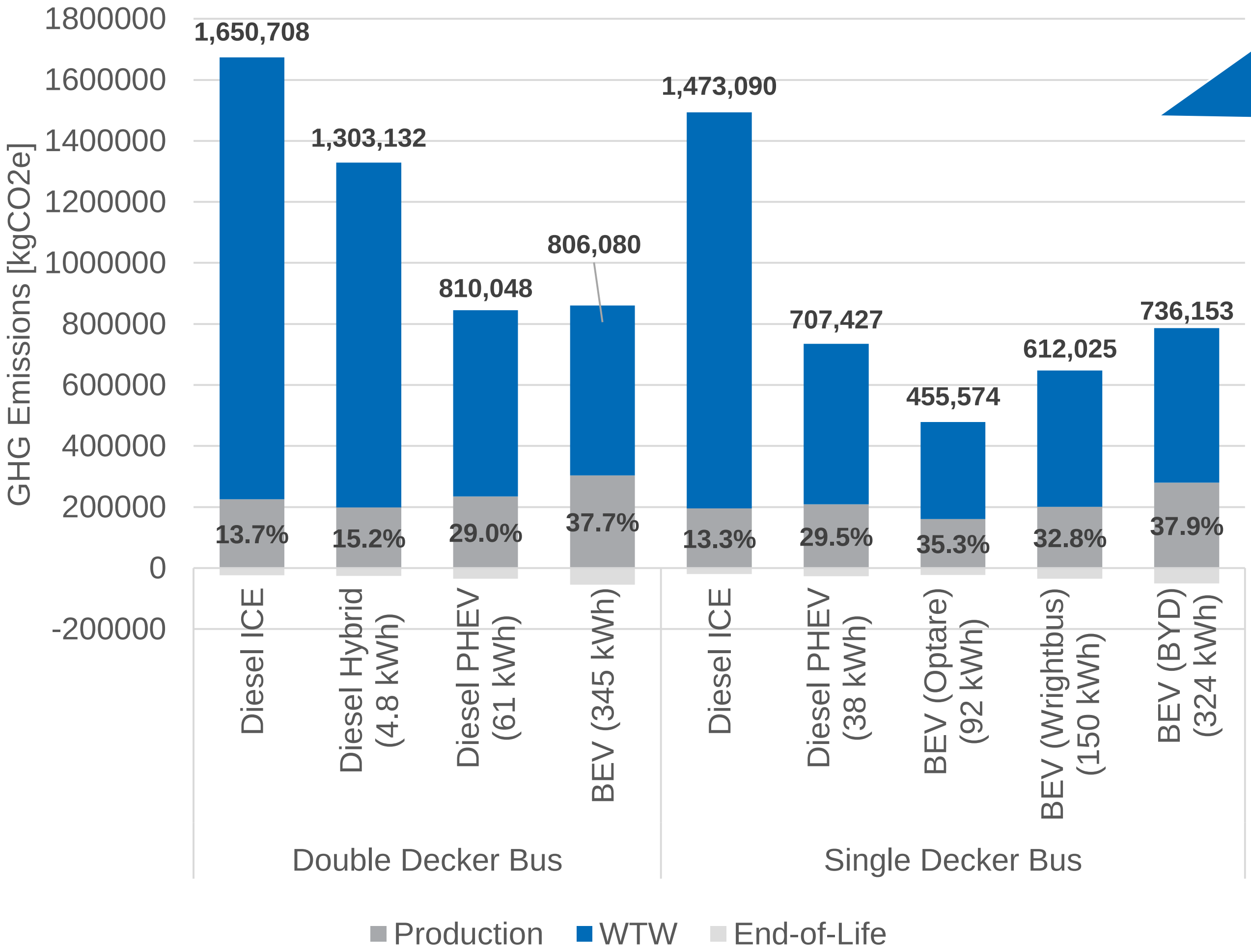
As for trucks, only a few studies considered the whole life cycle

Source: Full list of literature provided to LowCVP in the LCA Literature Database (RD18-001155)

For example, McCreadie (2016) considered the life cycle GHG emissions from UK buses during his MSc Sustainability dissertation

Urban Buses – McCreadie (2016)

SELECTED EXAMPLE



As for other commercial vehicles, life cycle GHG emissions for buses are dominated by the use (WTW) phase. However, vehicle production for plug-in vehicles is more significant due to battery pack production, size of battery pack, and assumed reductions in electricity carbon intensity

Feedback from LowCVP members confirmed that 50,000-80,000 km annual mileage over 12-15 years is a reasonable assumption for the lifetime of UK buses

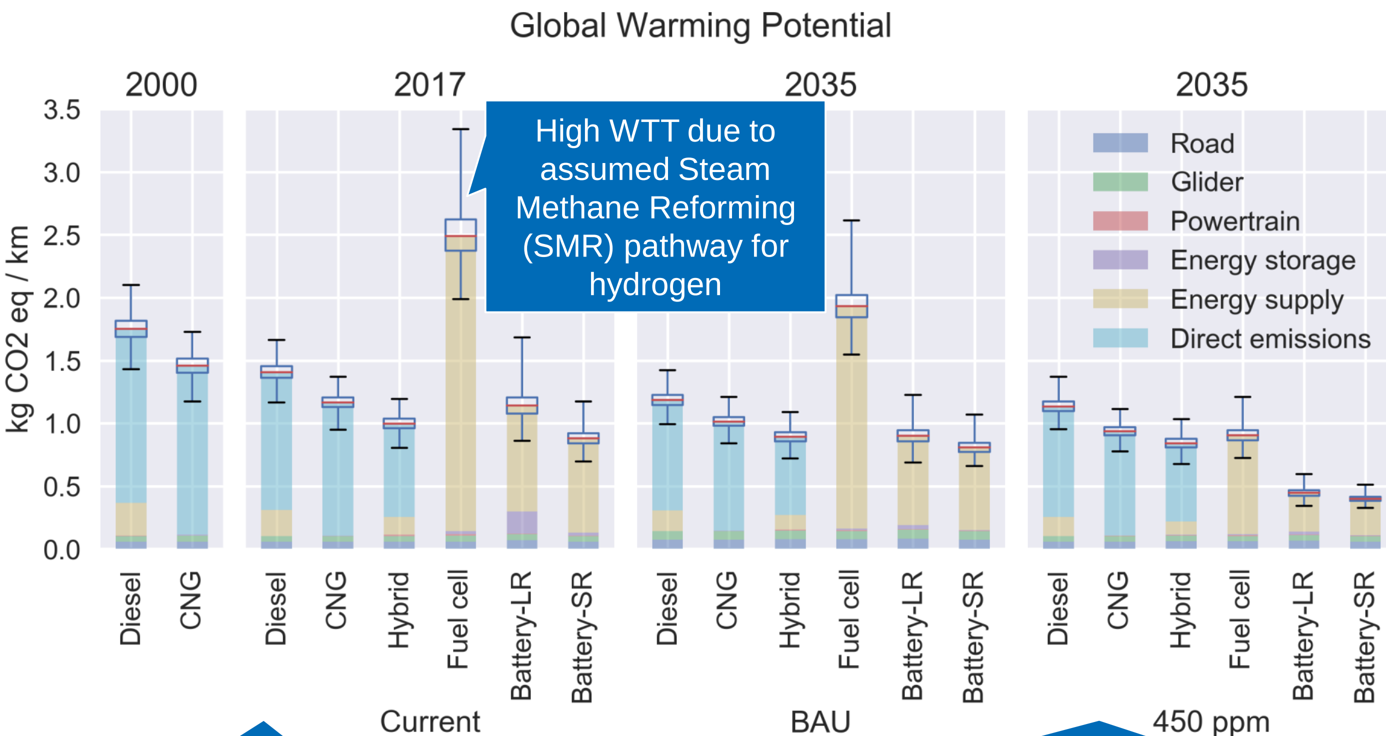
Function unit based on hypothetical bus used 59,000 km/year over 15 years (the typical life cycle for an urban bus in UK).
Production includes infrastructure changes (e.g. recharging stations) as well as vehicle production. Battery pack production assumed to produce 172 kgCO_2e/kWh, based on Ellingsen (2013).
Electricity scenario starts at 2015 baseline, and assumes 4% improvement each year (218gCO2e/kWh by 2029).
See Dissertation Report for a full list of vehicle specifications, assumptions and study methodology

Source: Results from [#013] McCreadie, D. (2016). Life Cycle Analysis of Hybrid, Plug-in Hybrid, Full-Electric and Trolley Buses. University of Leeds, MSc Sustainability (Transport) Dissertation Thesis, Project ID 187

While Cox et al. (2017) considered current and future scenarios for bus technologies in Europe

Urban Buses – Cox et al. (2017)

SELECTED EXAMPLE



Most life cycle GHG emissions result from vehicle use and fuel production

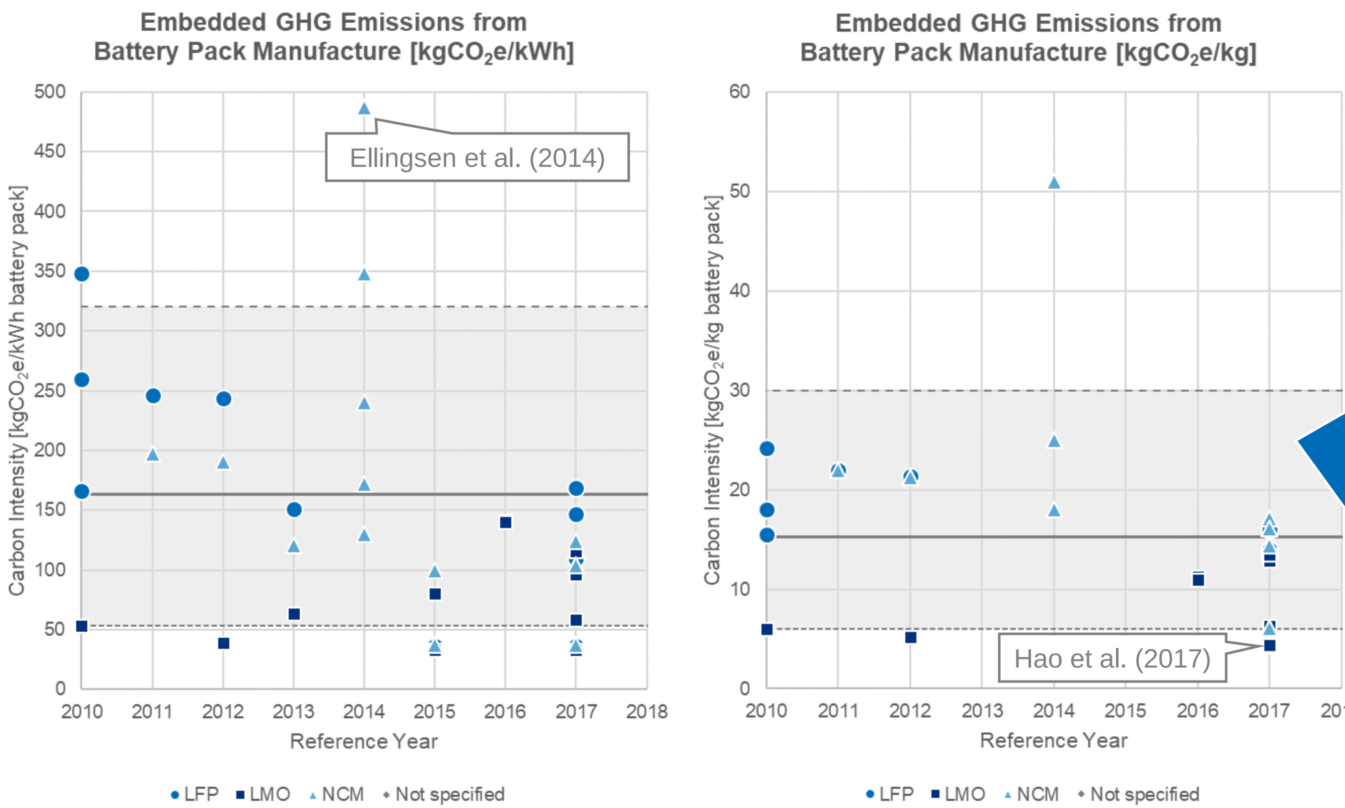
Prospective LCA shows potential to reduce life cycle GHG emissions through predicted vehicle efficiency improvements, and decarbonisation of fuel and energy pathways through greater use of renewables

Function unit based on hypothetical 12m bus used over 12 years, travelling 750,000 km during lifetime. All buses meet Euro VI emission standards.
ICEV-D and CNG have 230 kW engines.
HEV has 185 kW diesel engine, with two 75 kW electric motors and 150 kW Li-ion battery pack.
FCEV has 150 kW PEM fuel cell system, 8 kWh Li-ion battery, two 75 kW electric motors and Type 3 H_2 tanks.
BEV-SR has 12 km EV range, with regular recharging at bus stops
BEV-LR has 200 km EV range, with once-a-day recharging.
LCI data for battery pack taken from EcoInvent. Two scenarios for reduced embedded impact considered for 2035.
Duty cycle based on World Harmonised Vehicle Cycle (WHVC) for heavy duty vehicles.
Electricity carbon intensity taken from EcoInvent, based on natural gas combined cycle plants and onshore wind from Germany.
Hydrogen produced from electricity via electrolysis or steam reforming of methane. Hydrogen WTT values taken from Simons and Bauer (2011)

Source: Results from [#021] Brian Cox; Analy Castillo; Chris Mutel (2017). ENVIRONMENTAL ASSESSMENT OF CURRENT AND FUTURE URBAN BUSES WITH DIFFERENT ENERGY SOURCES. (The 30th International Electric Vehicle Symposium & Exhibition (EVS 30), Stuttgart, Germany, Oct 2017, Paper - 8pp, Slides - 23pp.)

Battery production has a strong influence on PIV LCA results – however values used in published studies show wide variation

Li-ion Battery Pack Cradle-to-Gate GHG Emissions



There is some evidence in literature that the embedded CO_2e emissions factors for Li-ion battery production are reducing as the technology improves, and better data becomes available. However, further research, based on state-of-the-art battery technology and manufacturing processes, is still required to deepen understanding, given the sensitivity of battery embedded factors of life cycle GHG emissions results for plug-in vehicles

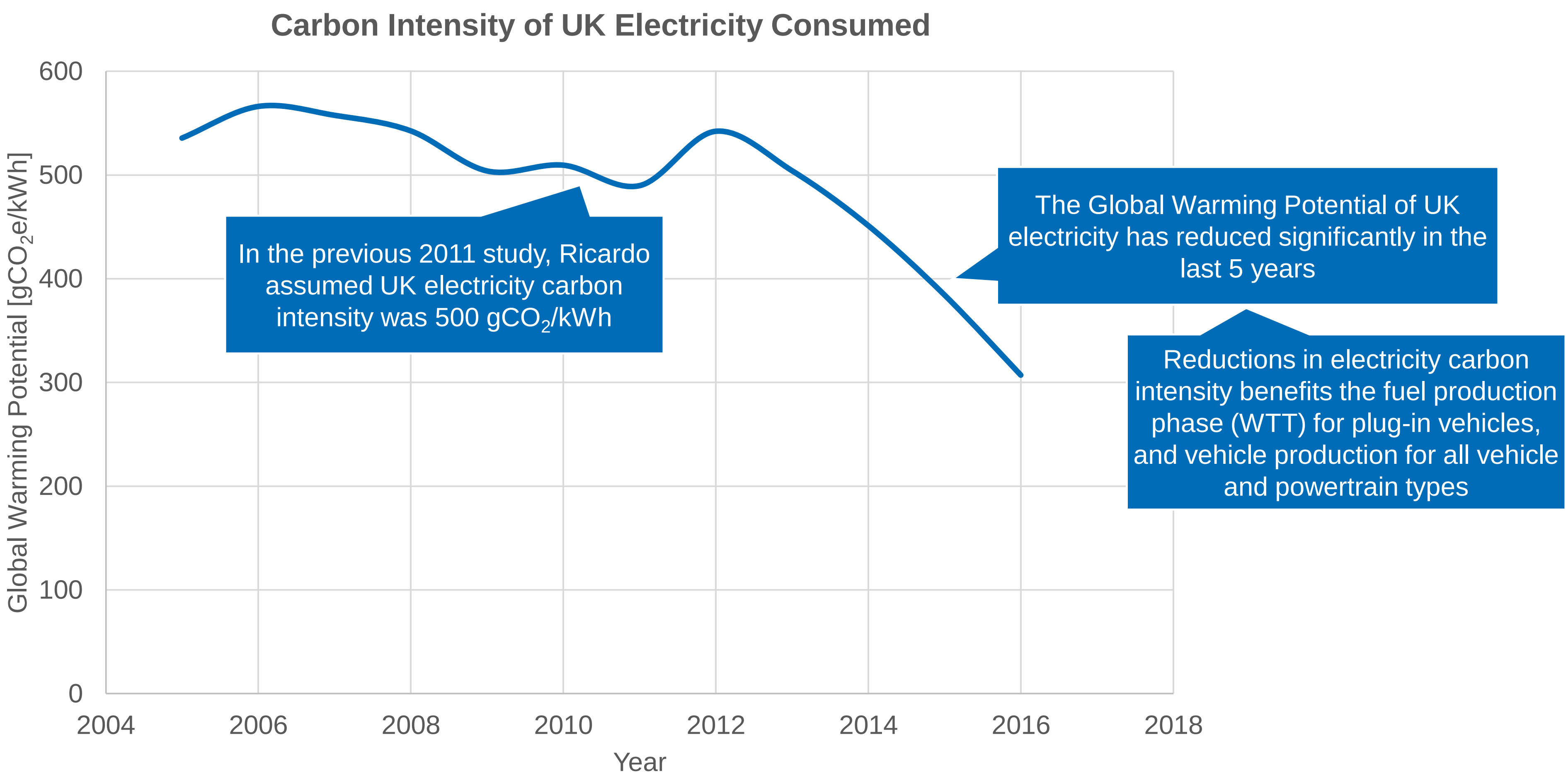
The charts above display embedded carbon intensity factors for Li-ion battery production (cradle-to-gate) from c.20 key papers published since 2010. The grey shading between the grey dashed lines represents a range of values used by Ricardo in a previous 2012 paper (Patterson et al, 2012 [#089])

Cradle-to-gate GHG emission from Li-ion battery production should be compared on per kWh and per kg basis, since studies have different assumptions regarding battery specific energy [kWh/kg]

Source: Ricardo analysis of published LCA studies

Carbon intensity of electricity is another key factor – according to UK government statistics, UK electricity is now ~300 gCO_2e/kWh (WTT)

UK Electricity Carbon Intensity



Source: 2017 Government GHG Conversion Factors for Company Reporting, Appendix 2, Table 48; 2018 Government GHG Conversion Factors for Company Reporting, Appendix 2, Table 48

Contents

To conclude, the relative contribution of each vehicle life cycle stage is highly dependent on the vehicle type and powertrain technology

RICARDO

Results Summary – Relative Contributions of each Life Cycle Stage by Vehicle Type and Powertrain Technology

Vehicle Type	Conventional ICE Powertrain Technology				BEV Powertrain Technology			
	Vehicle Production	WTT	TTW	EoL	Vehicle Production	WTT	TTW	EoL
L-Category	c.10-30%	c.10-15%	c.60-75%	<5%	c.45-75%	c.25-55%	-	<5%
Passenger Car	c.15-30%	c.10-15%	c.60-70%	<3%	c.20-60%	c.40-60%	-	<3%
Heavy Duty Truck	c.1-3%	>95%		<1%				
Bus	c.15%	>80%		<5%	c.30-40%	c.60-70%	-	<5%

The relative contribution of embedded emissions (from vehicle production and EoL) to in-use (WTW) is highly dependent on the vehicle type, lifetime mileage and duty cycle

The contribution of End-of-Life is difficult to quantify since most studies assume high recycle rates, and some apply "credits" for producing recycled material. However, the general consensus is that the portion to overall life cycle emissions is relatively low (<5%)

Carbon intensity for electricity could be nearly zero if renewable, sustainable electricity is used in the vehicle. This should shift all life cycle environmental burdens to vehicle production and end-of-life

Source: Review of published LCA literature, provided to LowCVP in LCA Literature Database (RD18-001155)

Therefore, LCA is particularly important for holistic understanding of the environmental impact of L-category, passenger cars and buses

RICARDO

Conclusions

- Life Cycle Assessment (LCA) is about taking a holistic approach to the analysis of a product's environmental impact. LCA can be used to support decision making (micro and macro level), or to support environmental accounting and reporting
- This study has focused on providing insight into how life cycle CO_2e emissions vary by vehicle segment and powertrain technology, considering L-category vehicles, passenger cars, heavy duty trucks and buses across four life cycle stages – vehicle production, fuel production, vehicle use and vehicle end-of-life
  - Insights have been drawn from published literature, prioritising recently published papers, with additional input from LowCVP members
- As shown in the previous slide, the relative contribution of each vehicle life cycle stage is highly dependent on the vehicle type, powertrain technology and key input parameters, such as assumptions regarding vehicle lifetime mileage and duty cycle. Electricity carbon intensity is also a key factor
  - For larger, heavy duty trucks, life cycle CO_2e emissions are overwhelmingly from vehicle use (>95%), which is unsurprising given the high utilisation and lifetime mileages of these types of vehicles
  - For smaller vehicles, such as passenger cars and L-category vehicles, there is greater sensitivity in each life cycle stage. Vehicle production does contribute to life cycle CO_2e emissions, and may be the dominant life cycle stage for BEV technology used with low carbon electricity
- LCA has an important role to play, along with other types of analysis, to inform discussions on the wider implications of adopting low and zero emissions technologies in road transport. Although, as discussed in the next section, on-going research is required to ensure up-to-date, quality LCA information is available on current products suitable for the UK market

Contents

UK strategic decision makers would benefit from future LCA studies that focus on vehicles available and used in UK

Recommendations (1/4)

UK Context

- Although Life Cycle Assessment is unable to answer every question related to the wider implications of adopting low emission vehicle technology, it does have a critical role to play in strategic decision making by providing holistic insight into life cycle environmental impacts
- Given the pace of technology change in the automotive sector, UK strategic decision makers would benefit from LCA studies that focus on current European vehicle specifications, with appropriate duty cycles and model inputs representing use in the UK

Alternative Fuels

- The next LowCVP LCA study should consider the life cycle impacts associated with using alternative fuels, such as natural gas, biofuels and hydrogen
  - This is likely to be particularly significant for medium and heavy duty trucks, and buses
- Also, alternative fuel Well-to-Tank pathways and associated emission factors should be developed that are appropriate to the production and use of alternative fuels in UK

Better Life Cycle Inventory data is urgently needed for key components and materials, such as Li-ion battery pack

Recommendations (2/4)

Li-ion Battery Packs

- Given the sensitivity of plug-in vehicle LCA studies to embedded emissions from battery production, and given that many academic studies are based on old data (>5 years), a detailed cradle-to-gate LCA study of current state-of-the-art Li-ion battery technology and manufacturing processes is urgently required to improve the reliability of vehicle LCA studies and Life Cycle Inventories
- Cradle-to-gate emissions for other electric vehicle components, such as the electric motor, power electronics, onboard charger, should also be considered

Life Cycle Inventories

- All LCA studies make use of Life Cycle Inventory datasets on the environmental impacts of common materials and processes
- The selected LCI datasets strongly influence the LCA results
- A future study reviewing available Life Cycle Inventories for automotive materials and production processes would be useful for understanding the current state-of-the-art of LCI data availability, and for highlighting areas requiring improvement

Continued research on LCA of L-category vehicles and passenger cars is critical for informing the transition to zero emission transport

Recommendations (3/4)

L-Category Vehicles

- L-category vehicles may offer an opportunity to reduce life cycle environmental impact compared to passenger cars. However, to date, relatively few LCA studies have been conducted on L-category vehicles
- Further LCA studies on L-category vehicles, including Kei-size* / sub-A segment cars, would help to quantify the environmental opportunity, and to deepen understanding on the life cycle implications of switching to alternative technologies such as BEV

* Kei-car is the Japanese vehicle category for smallest, most limited power, road-legal vehicle. Vehicle length and width are below 3.4 m and 1.48 m. Engine capacity is <660 cc. Maximum power is 47 kW

Passenger Cars

- Passenger cars represent a very important, high volume vehicle segment for the transition to low / zero emission transport
- LCA results for passenger cars are sensitive to multiple factors, such as lifetime mileage, vehicle specification, fuel economy and energy vector for in-use
- Therefore, it is critical to maintain up-to-date LCA research based on current products with a strong market context (e.g. UK specific)

Although LCA is less important for HD trucks, it could influence strategic decisions regarding choices for LD & MD trucks and buses

Recommendations (4/4)

Heavy Duty Commercial Trucks

- Since the vehicle use phase (WTW) contributes >95% of life cycle GHG emissions for heavy duty commercial trucks, opportunities to decarbonise fuel will have the greatest life cycle impact
- Although the relative contribution of embedded CO_2e emissions from vehicle production is less significant, it would be worth investigating the "payback period" for low emission technologies and fuels. This would inform strategic decisions, and encourage OEMs to continue improving the eco-design and manufacturing of their commercial vehicles

Light & Medium Duty Commercial Vans & Trucks

- Life cycle environmental impacts may be more significant for light duty vans and medium duty trucks used in urban and regional delivery
- Therefore, life cycle impacts should not be excluded from strategic decision making

Buses

- Changing to plug-in vehicle technologies has the potential to significantly reduce environmental impacts from buses. However, embedded emissions from production and end-of-life are likely to be higher
- LCA, along with other tools, should be used to inform decision making
  - LCA models should be tailored to the specific context of bus operation to ensure appropriate comparison