Preparing for a Life Cycle CO_2 Measure

A report to inform the debate by identifying and establishing the viability of assessing a vehicle's life cycle CO_2e footprint

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LowCVP commissioned a study to identify and establish the viability of assessing a vehicle's life cycle CO_2 footprint

Background

- The current metric for comparing the GHG emissions of European passenger cars is based on measuring the tailpipe CO_2 emissions over the New European Drive Cycle (NEDC)
- Legislative targets for reducing corporate fleet average CO_2 are driving the development of low carbon technologies and alternative fuels
- The tailpipe CO_2 metric is insufficient for comparing the environmental impact of zero and ultra-low emission vehicles, such as electric (EV) and fuel cell vehicles (FCV), since it does not consider CO_2 emissions resulting from the generation of the fuel, or those embedded within the vehicle production
- There is growing demand from consumers for information on the carbon footprint of the goods and services they purchase

Life cycle thinking is required to develop new measures for comparing the environmental impact of passenger cars

- The purpose of this report is inform the debate by examining the feasibility of considering a vehicle's whole life cycle, exploring the options for developing new metrics, and explaining how this could be taken forward

This report endeavours to answer a series of questions related to developing new CO_2 metrics

Report Objectives

1. What are the strengths and limitations of the current gCO_2/km metric for comparing the GHG-emissions of European passenger cars?
2. What elements contribute to a vehicle's life cycle CO_2 emissions?
3. What is an appropriate boundary for the evaluation of a vehicle's life cycle CO_2 emissions?
4. This question is in four parts:
   a. What international regulations apply to light duty vehicles in Europe? How might these regulations impact the vehicle's life cycle CO_2 emissions?
   b. What CO_2 emissions typically arise during the production, use and disposal of European passenger cars? How will evolving technologies, such as vehicle electrification, alter the balance of life cycle emissions between production, in-use and disposal?
   c. What is an appropriate balance of focus between the production, in-use and disposal phases for relevant combinations of new technologies?
   d. To what degree can the contributing elements currently be assessed?
5. What are the current gaps in understanding surrounding LCA of passenger cars? What is the present status of accuracy for assessing the elements contributing to a vehicle's life cycle emissions? What further work is required to achieve a fair life cycle CO_2 measure for vehicles?
6. In Ricardo's opinion, what are the most appropriate forms for a new measure of CO_2 emissions for European passenger vehicles? What timescales are desirable and practicable for transitioning to a new CO_2 emission measure?

Exclusions

- In accordance with the LowCVP's tender document, this study has not:
  - Assessed the suitability of existing drive cycles, but has reviewed the limitations already identified
  - Sought to define an improved test-cycle for determination of emissions arising from the in-use phase, but has identified and assessed the viability for measuring contributing elements for vehicle production, in-use and disposal
  - Considered metrics for different vehicle classes at this stage, but has focused on light duty vehicles
  - Considered individual components unless significantly relevant to life cycle emissions
  - Considered individual components unless causing a significant variation to life cycle emissions
  - Defined a metric to replace tailpipe CO_2, but has recommend elements of a life cycle CO_2 analysis for inclusion in a metric and define principles for determining which elements should be included and a gap analysis for determining them

Source: LowCVP document "For Tender – Preparing for a lifecycle CO2 measure.doc"

Abbreviations

Abbr.	Explanation	Abbr.	Explanation	Abbr.	Explanation
AMT	Automated Manual Transmission	EREV	Extended Range Electric Vehicle	MPI	Multi-Point (fuel) Injection
Auto	Automatic Transmission	EV	Electric Vehicle	NEDC	New European Drive Cycle
B7	Diesel with up to 7%vol FAME	FAME	Fatty Acid Methyl Ester	NiMH	Nickel Metal Hydride
B10	Diesel with up to 10%vol FAME	FCV	Fuel Cell Vehicle	OEM	Original Equipment Manufacturer
B100	100% biodiesel	FQD	Fuel Quality Directive	PAS	Power Assisted Steering
BoM	Bill of materials	GDI	Gasoline Direct Injection	PEM	Proton Exchange Membrane
CO_2	Carbon Dioxide	GHG	Greenhouse Gas	PFI	Port Fuel Injection
CO_2e	Carbon Dioxide equivalent	GWP	Greenhouse Gas Warming Potential	PHEV	Plug-In Hybrid Electric Vehicle
CVT	Continuously Variable Transmission	H&S	Health and Safety	TTW	Tank-to-Wheels
DCT	Dual Clutch Transmission	HC	Hydrocarbons	R&D	Research and Development
DECC	Department for Energy and Climate Change	HCCI	Homogeneous Charge Compression Ignition	RED	Renewable Energy Directive
DI	Direct Injection	HEV	Hybrid Electric Vehicle	UN ECE	United Nations Economic Commission for Europe
E10	Gasoline with up to 10%vol ethanol	HVAC	Heating Ventilation and Air Conditioning	V6	V 6-cylinder engine
E20	Gasoline with up to 20%vol ethanol	I4	In-line 4-cylinder engine	VCA	Executive Agency of the United Kingdom Department for Transport
E85	Gasoline with up to 85%vol ethanol	ICE	Internal Combustion Engine	VGT	Variable Geometry Turbocharger
EC	European Commission	ISO	International Organisation for Standardization	VVA	Variable Valve Actuation
ECU	Engine Control Unit	LCA	Life Cycle Assessment	VVT	Variable Valve Timing
EoL	End-of-Life	LCI	Life Cycle Inventory	WTT	Well-to-Tank
EPAS	Electric Power Assisted Steering	Li-Ion	Lithium Ion	WTW	Well-to-Wheels
				ZEV	Zero Emission Vehicle

Source: Ricardo

Carbon dioxide, greenhouse gases and Global Warming Potential

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Explanation of definitions

- Greenhouse gas (GHG) is the collective term for the gases which are considered to contribute to global warming
- Carbon dioxide (CO_2) is considered to be one of the main contributors to global warming
- However GHG also includes gases, such as methane (CH_4) and nitrous oxide (N_2O)
- Life cycle assessment studies frequently refer to carbon dioxide equivalent (CO_2e or CO_2eq), which is a metric for comparing the emissions from various greenhouse gases depending on their Global Warming Potential (GWP) for a specified time horizon. The quantity of the gas is multiplied by its GWP to obtain its CO_2e value
- Examples of GWP for common GHGs is provided in the table below

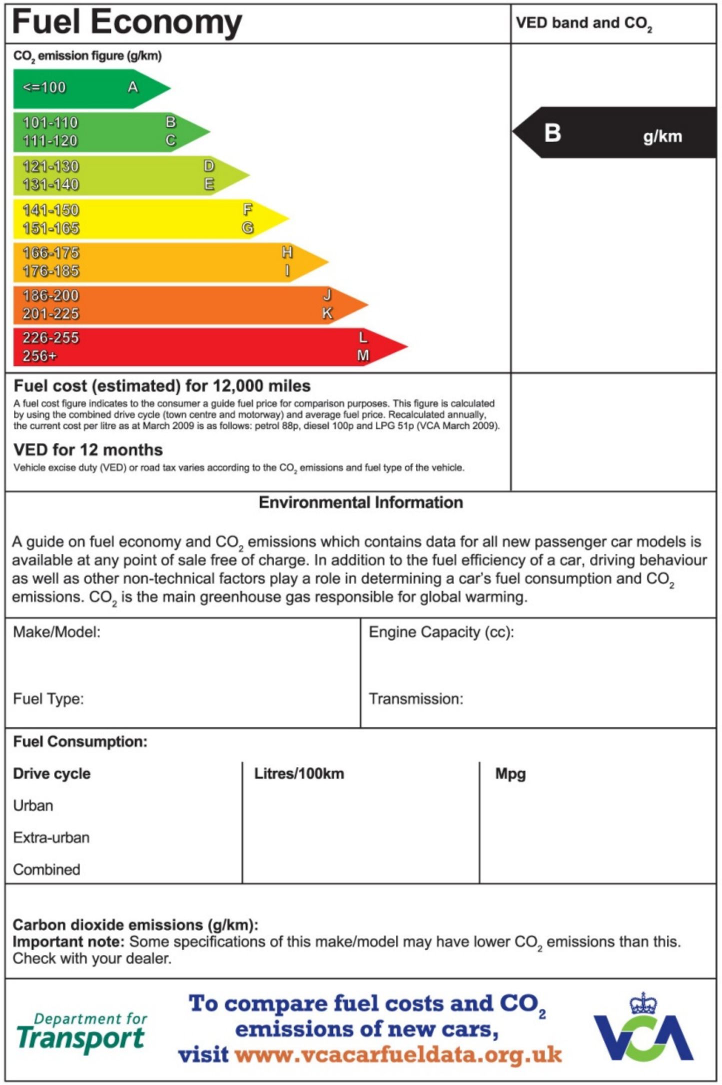
Greenhouse Gas	Global Warming Potential (100 years time horizon)
CO_2	1
CH_4	21
N_2O	310

- GWP is sometimes refered to as Climate Change Potential (CCP)
- This study has focused on the vehicle's life cycle impact in terms of CO_2 and GHG emissions. However a vehicle can also impact the environment in other ways, such as air acidification (SO_2 and NOx), water footprint, depletion of resources, human toxicity and air quality

Source: IPCC (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html [last accessed 15 April 2011]); http://lct.jrc.ec.europa.eu/glossary

Contents

The current CO_2 metric for comparing passenger cars is based on measuring tailpipe CO_2 emissions over the NEDC



Source: Ricardo EMLEG, InterRegs; LowCVP

- The current CO_2 metric for comparing passenger cars in Europe is based on measuring the tailpipe CO_2 emissions [gCO_2/km] (EU Directive 2003/76)
  - The tailpipe CO_2 test is based on the New European Drive Cycle (NEDC), which comprised of four ECE phases (urban driving) and one EUDC phase (extra-urban)
  - The test occurs in a controlled laboratory environment, using rolling road dynamometers for repeatability
  - The vehicle has to be 'cold' at the start of the test, requiring a soak period of at least 6 hours before the test. The ambient temperature during testing has to be within 20°C and 30°C
  - For validation purposes, the test is overseen by an authorised person from the Type Approval Agency (e.g. VCA)
- The EU is adopting a fleet average tailpipe CO_2 target for new passenger cars (M1), with non-compliance penalties and super-credits for low emission vehicles (EU Regulation No 443/2009)
  - The requirement for fleet average 130 gCO_2/km will phase in from 2012 to 2015
  - A further 10 gCO_2/km reduction is to come from additional measures such as gear shift indicators, more efficient air conditioning, low rolling resistance tyres, aerodynamics and biofuels
  - The long term target is fleet average 95 gCO_2/km by 2020

Strengths of the current CO_2 measure include the used of a defined drive cycle, test procedures and reference fuel

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Strengths of the existing tailpipe CO_2 measure

Strengths	Comments
Fixed drive cycle	• The same drive cycle is used for all light duty vehicles, providing a common reference • Historic data set exists from 1995 to present day – enabling tracking of overall reduction
Defined reference fuels	• Prevents differences in results due to different fuels
Defined test procedure	• Clearly defined and understood • Covers all necessary requirements for a variety of vehicles • Ensures each vehicle is tested using the same procedure
'Cold' start emissions included	• Covers the warm-up period of vehicle
Level playing field	• All OEMs abide by same set of rules • The results acquired are consistent and, therefore, create meaningful historical emissions trends

- These strengths conversely can be seen as limitations …

Limitations of the existing tailpipe CO_2 measure revolve around the laboratory conditions not representing the real world conditions

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Limitations of the existing tailpipe CO_2 measure

Limitations	Comments
Tailpipe only	• No consideration of well-to-tank CO_2 emissions, just tank-to-wheels • Under this condition, EVs have zero tailpipe emissions at point of use
Constrained drive cycle	• The current modal cycle (NEDC) is not representative of the range of real-world driving conditions • Focuses on lower speeds (urban and extra urban), without considering higher speeds • It does not consider gradients, does not account for cornering, or how driver behaviour effects driving performance
Unrepresentative environment	• The test ambient temperature (~25°C) is higher than average ambient temperature across Europe • There is no allowance for climatic variation between regional markets
No ancillaries	• Effect of ancillaries is not considered – No HVAC loading – No electrical loads (e.g. lights) – No PAS/EPAS loads from steering inputs
Road load factors	• Data is not publicly available • Scope for differing interpretation of rules when defining road load factors
Powertrain	• Little knowledge on effect of hybrids and electric vehicles • Range provided for EV not representative

Comparing the current tailpipe CO_2 measure with the real world experience suggests real world typically exceeds NEDC results

- In 2009 TNO analysed records of fuel-card usage in the Netherlands to understand the differences between real world driving and the test-based, published fuel consumption and tailpipe CO_2 data
  - In general, fuel consumption and tailpipe CO_2 was higher than the official, published fuel consumption from the NEDC test
  - Real world tailpipe CO_2 could be 15-40% higher, depending of fuel type, technology and usage pattern
  - In the Netherlands, the real world use is approximately 20% urban, 35% extra-urban and 40% motorway driving. The NEDC is split 35% urban and 65% extra-urban driving (by distance travelled)
  - Therefore, the differences between published and real world CO_2 can be attributed, in part, to the greater share of motorway driving in the real world experience

- AutoCar regularly review new passenger cars for the benefit of their readers. The vehicles are assessed by experienced drivers, who perform a similar set of driveability tests for each vehicle. AutoCar publish the average fuel consumption of the vehicle experienced during the test drive, along side the fuel consumption stated by the vehicle manufacturer. This data provides an indication of the difference between the published fuel consumption values and the “real world” experience. Tailpipe CO_2 can be calculated from the fuel consumption, depending on the fuel type
  - A comparison of NEDC results with AutoCar experience is provided in the next slide
  - For the selected examples, real-world vehicle CO_2 emissions appear to be ~20% worse than the certified figures

Source: Ligterink and Bos (2010); AutoCar

Real world tailpipe CO_2 could be 5-40% higher than the NEDC CO_2 measure for conventional passenger cars …

SELECTED EXAMPLES

Segment	Vehicle	Fuel	Fuel Consumption NEDC [L/100km]	Fuel Consumption AutoCar Test [L/100km]	Tailpipe CO_2 NEDC [gCO_2/km]	Tailpipe CO_2 AutoCar Test [gCO_2/km]	Difference [%]
A: Mini	Hyundai I10	Gasoline	5	7.5	120	180	33%
	Fiat Panda	Gasoline	4.3	5.5	103.2	132	22%
	Mini	Gasoline	6.9	9.5	165.6	228	27%
B: Small	Renault Clio	Gasoline	6.6	8	158.4	192	18%
	Seat Ibiza	Gasoline	6.2	7.9	148.8	189.6	22%
	Ford Fiesta	Gasoline	6.5	8.3	156	199.2	22%
C: Lower Medium	Audi A3	Gasoline	9.1	12.2	218.4	292.8	25%
	Ford Focus	Gasoline	6.4	8.4	153.6	201.6	24%
D: Upper Medium	BMW 3-series	Diesel	5.7	7.1	151.1	188.2	20%
	Ford Mondeo	Diesel	6.1	7.2	161.7	190.8	15%
E: Executive	BMW 5-series	Diesel	6.2	7.8	164.3	206.7	21%
	Mercedes C-class	Gasoline	6.1	8	146.4	192	24%
F: Luxury	Bentley Continental	Gasoline	17.1	20.3	410.4	487.2	16%
	Jaguar XJ	Gasoline	7.2	10.2	172.8	244.8	29%
	BMW 7-series	Gasoline	7.2	9.7	172.8	232.8	26%
G: Sports	Nissan 370Z	Gasoline	10.4	10.9	249.6	261.6	5%
	Mazda MX-5	Gasoline	8.2	11.8	196.8	283.2	31%
	Audi TT	Gasoline	10.3	12.6	247.2	302.4	18%
SUV	Land Rover Freelander	Diesel	7.5	10.1	198.8	267.7	26%
	BMW X5	Diesel	8.7	10.7	230.6	283.6	19%
	Suzuki Grand Vitara	Diesel	9.1	11.3	241.2	299.5	19%
MPV	Ford S-max	Diesel	6.4	9.1	169.6	241.2	30%
	Mazda 5	Diesel	5.2	8.1	137.8	214.7	36%
	Vauxhall Zafira	Gasoline	7.3	10.8	175.2	259.2	32%

Source: AutoCar; Ricardo Analysis

… and for hybrids

SELECTED EXAMPLES

Segment	Vehicle	Fuel	Fuel Consumption NEDC [L/100km]	Fuel Consumption AutoCar Test [L/100km]	Tailpipe CO_2 NEDC [gCO_2/km]	Tailpipe CO_2 AutoCar Test [gCO_2/km]	Tailpipe CO_2 Difference [%]
D: Upper Medium	Honda Insight	Gasoline Hybrid	4.6	7.1	110.4	170.4	35%
	Toyota Prius	Gasoline Hybrid	4	5.9	96	141.6	32%
SUV	Lexus RX450h	Gasoline Hybrid	6.3	9.7	151.2	232.8	35%

Segment	Vehicle	Fuel	Fuel Consumption NEDC [Wh/100km]	Fuel Consumption AutoCar Test [Wh/100km]	Tailpipe CO_2 NEDC [gCO_2/km]	Tailpipe CO_2 AutoCar Test [gCO_2/km]	Consumption Difference [%]
D: Upper Medium	Nissan Leaf	Electricity	1.73	1.99	0	0	15%
G: Sports	Tesla Roadster	Electricity	1.74	2.67	0	0	54%

Source: AutoCar; Ricardo Analysis

Contents

A vehicle's life cycle can be divided into four "blocks" – production of the vehicle, production of the fuel, "in-use", and disposal

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"Fuel"

Generate

- Fossil fuel production
- Electricity generation
- Hydrogen production
- …

Distribute

Distribution network efficiency

- Power lines
- Pipelines
- Tankers
- …

Production

Assessment of environmental impact of producing the vehicle from raw materials to complete product

"In-Use"

- Tailpipe CO_2 from driving
- Impact from maintenance and servicing

Disposal

Assessment of environmental impact of "end of life" scenario, including re-use of components, recycle of materials and landfill

Source: Ricardo

Material selection, energy use, production processes and supply chain logistics all contribute to the CO_2 emissions from production

Elements from vehicle production contributing to life cycle CO_2 emissions

Design & Development
- R&D / prototypes
- Test rigs
- Design process
- Supplier selection
- Homologation testing

Vehicle Specification
- Vehicle size / segment
- Vehicle mass
- Powertrain technology
- Technology options
  - E.g. Choice of battery, electric motor, etc.
- Number of components
- Model variant

Materials & Energy
- Material selection
- Geographic source of material
- Extraction process
- Recycled content (primary vs. secondary)
- Material availability
- Energy mix

Production Processes
- Manufacturing processes
- Manufacturing / factory efficiency
- Location
- Waste produced
- Re-use of waste material

Logistics
- Supply chain
- Types of transport
- Distance travelled
- Packaging
- Geography

People
- Number of workers
- Daily commute
- Heat and light for offices / factory
- H&S considerations
- Environmental legislation considerations
- Advertising and sales marketing
- Business trips to visit suppliers, etc.

Production

Source: Ricardo

The vehicle specification determines the design of the vehicle, and its resulting embedded emissions

Elements from vehicle production contributing to life cycle CO_2 emissions

Design & Development

- R&D / prototypes
- Test rigs
- Design process
- Supplier selection
- Homologation testing

These elements are generally considered to be outside the LCA boundary for a typical passenger car

Production

Vehicle Specification

- Vehicle size / segment
- Vehicle mass
- Powertrain technology
- Technology options
  - E.g. Choice of battery, electric motor, etc.
- Number of components
- Model variant

Vehicle size / segment:
- Luxury segments tend to use more expensive materials, and have more equipment onboard the vehicle, which may contribute to raising the embedded emissions from vehicle production

Vehicle mass:
- The greater the mass, the more material (and energy) required to make the vehicle, implying higher embedded emissions
- Size and mass of vehicle (and its components) known to OEM (e.g. BoM)
- Some data may be available within public domain

Powertrain technology:
- This influences the components on the vehicle
- The powertrain technology, and its associated components, is known by the OEM

Technology options:
- Again, this is known by the OEM, who controls the supply chain
- Detail of the components (e.g. battery cell chemistry) may be known only by the Tier 1 supplier. This may mean the Tier 1 supplier has to complete a cradle-to-gate LCA study for the OEM

Model variant:
- The base model tends to have basic features and fittings
- While the premium version has more gadgets, plush interior (e.g. leather), and alloy wheels

Source: Ricardo

Selection of materials, production processes and location have a strong impact on the embedded CO_2 from vehicle production

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Elements from vehicle production contributing to life cycle CO_2 emissions

- Strong influence on embedded emissions
- Usually decided by OEM or supplier

- May (or may not) be known by material supplier
- Some geographic / region specific LCI data available

- Extraction process dependent on geographical source, and cost

- Strong influence on carbon intensity of material
- Information may, or may not, be available from material / Tier 1 supplier

- Data available, although national, or regional averaging may be required
- Some LCI databases contain generic carbon intensity data for different types of energy

Materials & Energy

- Material selection
- Geographic source of material
- Extraction process
- Recycled content (primary vs. secondary)
- Material availability
- Energy mix

Production Processes

- Manufacturing processes
- Manufacturing / factory efficiency
- Location
- Waste produced
- Re-use of waste material

- Most of the data for these elements would be available to OEM / Tier 1, although some investigative work may be required
- Some LCI databases include emission factors for different production processes

- LCA tools allow for the user to include the re-use of waste material within the LCA model of the vehicle

- Emission factors on the carbon intensity of most common automotive materials are readily available in Life Cycle Inventory (LCI) databases
- These factors take into consideration the emissions resulting from the extraction process, and may average variations due to the geographical source of the raw material
- Some proprietary LCI databases require users to purchase a licence, while others are freely available within the public domain
- However emission factor values vary between LCI databases

Source: Ricardo

The logistics of the supply chain can impact the embedded CO_2 emissions from vehicle production

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Elements from vehicle production contributing to life cycle CO_2 emissions

Design &

Vehicle

Materials &

Production

Logistics

- Supply chain
- Types of transport
- Distance travelled
- Packaging
- Geography

People

- Number of workers
- Daily commute
- Heat and light for offices / factory
- H&S considerations
- Environmental legislation considerations
- Advertising and sales marketing
- Business trips to visit suppliers, etc.

- LCA studies suggest transport of parts along the supply chain has a relatively small contribution to life cycle CO_2 emissions
- Data on the logistics of the supply chain would be known by the OEM / Tier 1 supplier
- Several LCI databases contain data on CO_2 emissions resulting from transport of goods. Again, values can vary between databases, depending on information source, global region and year

- Homologation testing

- Technology options
  - E.g. Choice of battery, electric motor, etc.
- Number of components
- Model variant

- process
- Recycled content (primary vs. secondary)
- Material availability
- Energy mix

- Waste produced
- Re-use of waste material

These elements are generally considered to be outside the LCA boundary for a typical passenger car

Production

Source: Ricardo

The proposed element boundary for production includes vehicle specification, materials, energy, production processes and logistics

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Elements from vehicle production contributing to life cycle CO_2 emissions

Design & Development
- R&D / prototypes
- Test rigs
- Design process
- Supplier selection
- Homologation testing

Vehicle Specification
- ● Vehicle size / segment
- ● Vehicle mass
- ● Powertrain technology
- ● Technology options
  - E.g. Choice of battery, electric motor, etc.
- ● Number of components
- ● Model variant

Materials & Energy
- ● Material selection
- ▲ Geographic source of material
- ▲ Extraction process
- ■ Recycled content (primary vs. secondary)
- ■ Material availability
- ■ Energy mix

Production Processes
- ● Manufacturing processes
- ■ Manufacturing / factory efficiency
- ● Location
- ● Waste produced
- ● Re-use of waste material

Logistics
- ● Supply chain
- ● Types of transport
- ● Distance travelled
- ● Packaging
- ● Geography

People
- Number of workers
- Daily commute
- Heat and light for offices / factory
- H&S considerations
- Environmental legislation considerations
- Advertising and sales marketing
- Business trips to visit suppliers, etc.

Proposed Element Boundary


Production

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

Source: Ricardo

Well-to-tank CO_2 emissions from the fuel depend on the primary energy source, production process and the refuelling infrastructure

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Elements from fuel well-to-tank contributing to life cycle CO_2 emissions

Primary Energy

- Primary energy of fuel
- Primary energy source / location
- Energy extraction process (e.g. mining, farming, etc.)
- Embedded emissions associated with mining / extraction facilities
- Embedded emissions associated with electricity generation
- Feedstock availability for renewable fuels

Processing

- Type of fuel / energy vector
- Selected production process(es)
- Process efficiency
- Waste
- Production of by-products along with fuel
- Fuel quality requirements
- Embedded emissions associated with production facilities
- Energy mix used during processing
- Electricity mix available (e.g. Fossil vs. Renewable)

Distribution & Infrastructure

- Method of distribution / transportation
  - Pipelines, tankers, road, etc.
- Infrastructure chain
- Embedded emissions associated with refuelling stations
- Fuel additive packs
- Fuel supplier
- Fuel distributer
- Restrictions on fuel transportation

People

- Employees
- H&S considerations
- Environmental legislation considerations

Fuel

Source: Ricardo

The choice of primary energy source has a strong influence on the fuel production process and associated WTW CO_2 emissions

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Elements from fuel well-to-tank contributing to life cycle CO_2 emissions

Primary Energy

- Primary energy of fuel
- Primary energy source / location
- Energy extraction process (e.g. mining, farming, etc.)
- Embedded emissions associated with mining / extraction facilities
- Embedded emissions associated with electricity generation
- Feedstock availability for renewable fuels

- Gasoline and diesel are produced from crude oil
- However alternative energy vectors, such as biofuels, electricity and hydrogen, can be produced from a range of different energy sources. The choice of primary energy will impact the fuel's CO_2 emission factor (e.g. wind vs. coal for electricity generation)

- This can influence the processes required to extract the raw energy, and how it is processed into the required fuel / energy vector

- This is generally accounted for in the available LCI databases and WTW pathways (e.g. CONCAWE)

- This may be accounted for in the publically available carbon intensity data for the national electricity grid

- E.g. CO_2 emission factors for biofuels depend on the mix of feedstocks used to make the fuel
- The Renewable Fuels Agency publish data on the feedstock mixes used to produce biofuels consumed in UK

Fuel

- The impact of direct change in land use is already accounted for in several LCI datasets for biofuels
- However discussions are on-going nationally and internationally regarding how the impact of indirect land use change (iLUC) should be accounted for

Source: Ricardo

Different processes can be used to make the fuel / energy vector, which will impact the WTW CO_2 emissions

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Elements from fuel well-to-tank contributing to life cycle CO_2 emissions

Primary Energy

- This is assumed and accounted for in the existing LCI databases and WTW pathways
- Embedded emissions associated with mining / extraction facilities
- It is unclear how much of the embedded emissions of the production facilities are accounted for in the LCI databases and WTW analysis of fuels
- The impact of this depends on the amount of fuel produced over the lifetime of the facility

Processing

- Type of fuel / energy vector
- Selected production process(es)
- Process efficiency
- Waste
- Production of by-products along with fuel
- Fuel quality requirements
- Embedded emissions associated with production facilities
- Energy mix used during processing
- Electricity mix available (e.g. Fossil vs. Renewable)

- This will determine the fuel processing options
- Existing LCI databases and WTW pathways (e.g. CONCAWE) contain emission factor data for a range of different fuels and their associated production processes

- There are different methods for allocating the CO_2 emissions by by-product
- This can impact the carbon intensity of the fuel

- This will influence the amount for processing needed to produce the fuel
- It is unclear if existing LCI databases and WTW pathways consider the impact of fuel quality requirements on the WTT CO_2 emissions of the fuel

- The energy mix and electricity mix can be accounted for in the LCI databases and WTW pathways
- Data is available from a variety of sources (e.g. LCI databases, government agencies, etc.), but values can vary
- The carbon intensity of the electricity grid varies throughout the day, depending on electricity demand and the supply strategy. Therefore, annual averages tend to be used
- Marginal plant or mean CO_2 intensity could arguably be used

Source: Ricardo

There are different methods for transporting the fuel from source of primary energy, through production, to the refuelling station

Elements from fuel well-to-tank contributing to life cycle CO_2 emissions

- The LCI databases and WTW analysis pathways do account for distribution and transportation methods
- E.g. CONCAWE pathways contain a range of options for transporting fuel products

- This is known by the fuel suppliers

- Less data is available for embedded emissions associated with the refuelling stations

- Additive packs differ by fuel supplier. These are generally not considered in the standard WTW pathways

- Existing LCI databases and WTW pathways do not distinguish between fuel suppliers and distributers
- Also, it is likely that a vehicle will used fuels from a variety of different fuel suppliers over its lifetime. Therefore an "average" is required

Fuel

Distribution & Infrastructure

- Method of distribution / transportation
  - Pipelines, tankers, road, etc.
- Infrastructure chain
- Embedded emissions associated with refuelling stations
- Fuel additive packs
- Fuel supplier
- Fuel distributer
- Restrictions on fuel transportation

People

- Employees
- H&S considerations
- Environmental legislation considerations

These elements are generally considered to be outside the LCA boundary for assessing the well-to-tank emissions

Source: Ricardo

The proposed boundary for the fuel well-to-tank pathway includes elements regarding primary energy, processing and infrastructure

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Elements from fuel well-to-tank contributing to life cycle CO_2 emissions

Primary Energy

- ■ Primary energy of fuel
- ■ Primary energy source / location
- ■ Energy extraction process (e.g. mining, farming, etc.)
- ■ Embedded emissions associated with mining / extraction facilities
- ■ Embedded emissions associated with electricity generation
- ▲ Feedstock availability for renewable fuels

Processing

- ● Type of fuel / energy vector
- ■ Selected production process(es)
- ■ Process efficiency
- ■ Waste
- ■ Production of by-products along with fuel
- ● Fuel quality requirements
- ■ Embedded emissions associated with production facilities
- ■ Energy mix used during processing
- ● Electricity mix available (e.g. Fossil vs. Renewable)

Distribution & Infrastructure

- ● Method of distribution / transportation
  - – Pipelines, tankers, road, etc.
- ● Infrastructure chain
- ● Embedded emissions associated with refuelling stations
- ● Fuel additive packs
- ● Fuel supplier
- ● Fuel distributer
- ● Restrictions on fuel transportation

People

- ● Employees
- ● H&S considerations
- ● Environmental legislation considerations

Proposed Element Boundary

Fuel

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

Source: Ricardo

CO_2 emissions from the "in-use" phase depend on the vehicle technology, fuel, and how the vehicle is driven

RICARDO

Elements from use phase contributing to life cycle CO_2 emissions

Vehicle Specification

- Vehicle size / type
- Kerb weight
- Powertrain architecture and technology
- Tailpipe emissions and aftertreatment
- Vehicle performance
- Model variant
- Load capacity
- Target price
- Fuel consumption [L/100km]
- Tailpipe CO_2 emissions [g/km]

Fuel

- Fuel type / energy vector(s)
- Fuel specification
- Fuel quality
- Fuel supplier
- Fuel additive packs
- Standard grade vs. Premium product
- Fuel availablity
- Fuel price
- Fuel taxation
- Actual, real-world fuel consumption

Driver

- Ownership model
- Owner affluence
- Driving habits
- Duty cycle(s)
- Length of journeys
- Number of journeys per day
- Annual mileage [km]
- Vehicle loading (e.g. passenger mass, luggage mass)
- Care of vehicle (e.g. regular checking of fluid levels and tyre pressure, etc.)
- Use of onboard gadgets (e.g. GPS)
- Use of air conditioning

Geography

- Location
- Terrain (e.g. hills vs. flat)
- Climate and weather conditions
- Types of road (e.g. motorway vs. urban)
- Traffic management
  - Roundabouts, traffic lights and junctions
  - Speed bumps
  - Speed limit changes
- Road congestion

Maintenance & Servicing

- Service interval
- Oil and coolant changes
- Replacement parts
  - Tyres, brake discs
- Component durability / failure
- Service personnel
- Heat and light for garage facilities
- Vehicle life time [years]

In-Use

Source: Ricardo

The manufacturer's vehicle specification has a strong influence on the published fuel consumption and tailpipe CO_2 data

Elements from use phase contributing to life cycle CO_2 emissions

Vehicle Specification

- Vehicle specification is determined by the vehicle manufacturer
- Much of this information is available within the public domain, usually in marketing brochures or technical specification documents for the vehicles

Maintenance & Servicing

- Vehicle size / type
- Kerb weight
- Powertrain architecture and technology
- Tailpipe emissions and aftertreatment
- Vehicle performance
- Model variant
- Load capacity
- Target price
- Fuel consumption [L/100km]
- Tailpipe CO_2 emissions [g/km]

- These elements strongly influence the vehicle's NEDC based fuel consumption and tailpipe CO_2 emissions

- Fuel consumption data is published, for the reference fuel and legislation drive cycle (NEDC)
- Some fuel economy improvements may be possible through improvements in the fuel (e.g. higher RON)

- Tailpipe CO_2 emissions [g/km] multiplied by assumed life time mileage provided an indication of vehicle's in-use tank-to-wheel CO_2 emissions

- Fuel type / energy vector(s)
- Fuel specification
- Standard grade vs. Premium product
- Fuel availablity

- Ownership model
- Owner affluence
- Driving habits
- per day
- Annual mileage [km]
- Vehicle loading (e.g.
- Use of air conditioning

- Location
- Terrain (e.g. hills vs. flat)
- motorway vs. urban)
- Traffic management
  - Roundabouts, traffic lights and

- Service interval
- Oil and coolant changes
- Service personnel
- Heat and light for garage facilities

In-Use

Source: Ricardo

Variations in the fuel / energy vectors used by the vehicle may impact the real world results

Elements from use phase contributing to life cycle CO_2 emissions

Vehicle Specification

- Vehicle size / type
- Kerb weight
- Powertrain architecture and technology
- Tailpipe emissions and aftertreatment
- Vehicle performance
- Model variant
- Load capacity
- Target price
- Fuel consumption [L/100km]
- Tailpipe CO_2 emissions [g/km]

Fuel

- Fuel type / energy vector(s)
- Fuel specification
- Fuel quality
- Fuel supplier
- Fuel additive packs
- Standard grade vs. Premium product
- Fuel availablity
- Fuel price
- Fuel taxation
- Actual, real-world fuel consumption

- The vehicle will be designed, and optimised, for a specified fuel(s), e.g. gasoline or diesel
- However the fuel specification may change during the vehicle's lifetime (e.g. allowable biofuel content), which will impact the WTT CO_2 factor

- In Europe, the current fuel specifications for diesel and gasoline are defined in EN 590:2009 and EN 228:2008

- Some fuel suppliers claim their fuel will improve fuel consumption
- This is often due to the fuel supplier's additive pack, which is added to the fuel

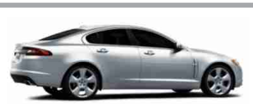
- In advance, it is difficult to know exactly what fuel blends will be available during the vehicle's life, and what fuel supplier the owner(s) will prefer

Maintenance &

- Driving habits
- Number of journeys
- passenger mass,
- fluid levels and tyre pressure, etc.)
- Use of onboard gadgets (e.g. GPS)
- Use of air conditioning

- flat)
- Types of road (e.g.
- junctions
- changes
- Road congestion

- changes
- Component durability



In-Use

Source: Ricardo

Driver behaviour adds variability into the in-use CO_2 results

Elements from use phase contributing to life cycle CO_2 emissions

- The vehicle manufacturer has little or no control over what happens to the vehicle after it is sold

- Kerb weight
- Powertrain architecture and

- vector(s)
- Fuel specification
- Fuel quality

- Distanced travelled over the lifetime of the vehicle has a strong influence over the lifetime CO_2 emissions from the in-use phase of the vehicles life
- The lifetime mileage of a vehicle depends on a large number of factors (as listed in the elements)
- Therefore average or assumed data is used in LCA studies

- Tailpipe CO_2 emissions [g/km]

In-Use

Source: Ricardo

Driver

- Ownership model
- Owner affluence
- Driving habits
- Duty cycle(s)
- Length of journeys
- Number of journeys per day
- Annual mileage [km]
- Vehicle loading (e.g. passenger mass, luggage mass)
- Care of vehicle (e.g. regular checking of fluid levels and tyre pressure, etc.)
- Use of onboard gadgets (e.g. GPS)
- Use of air conditioning

Geography

conditions

– Speed limit

Maintenance & Servicing

– Tyres, brake discs

- Driving habits and patterns can have a strong influence on the real-world fuel economy achieved by the driver
- All drivers are different, which adds variability into the data

- The greater the mass, the higher the fuel consumption and CO_2 emissions
- Vehicle loading will vary for each journey over the lifetime of the vehicle, making it difficult to measure accurately
- Assumptions could be made to compare usage scenarios

- This can impact the vehicle's fuel economy
- But it is difficult to quantify the impact

- These require energy, and therefore increase the fuel consumption of the vehicle

Gradients, weather conditions, road layout and traffic congestion can all impact in-use fuel consumption

RICARDO

Elements from use phase contributing to life cycle CO_2 emissions

- Local geography of a vehicle's use is highly variable and virtually impossible to accurately quantify
- During design and development, vehicle manufacturers usually assume an average, then consider worst case scenarios such as mountainous regions or Autobahn style driving

- Powertrain architecture and technology
- Tailpipe emissions and aftertreatment
- Vehicle performance

- Fuel specification
- Fuel quality
- Fuel supplier
- Fuel additive packs
- Standard grade vs. Premium product

- Driving habits
- Duty cycle(s)
- Length of journeys
- Number of journeys per day
- Annual mileage [km]

- Traffic management systems which require the vehicle to brake can contribute to higher fuel consumption and CO_2 emissions
- Across the UK, there is great variability between the use of roundabouts, traffic lights and filter junctions, making it difficult to quantify and account for the impact

- Tailpipe CO_2 emissions [g/km]

- fluid levels and tyre pressure, etc.)
- Use of onboard gadgets (e.g. GPS)
- Use of air conditioning

Geography

- Location
- Terrain (e.g. hills vs. flat)
- Climate and weather conditions
- Types of road (e.g. motorway vs. urban)
- Traffic management
  - Roundabouts, traffic lights and junctions
  - Speed bumps
  - Speed limit changes
- Road congestion

Maintenance & Servicing

- Service interval
- Oil and coolant
- garage facilities
- Vehicle life time [years]

- Climate varies by region and season
- The ambient conditions can impact on the vehicle's fuel consumption

In-Use

Source: Ricardo

Maintenance and servicing could increase the embedded emissions of the vehicle, depending on what components are replaced

RICARDO

Elements from use phase contributing to life cycle CO_2 emissions

- The vehicle manufacturer can specify the service interval and maintenance schedule for the vehicle, but they cannot make the vehicle owner comply with this schedule
- The MOT ensures older vehicles remain road worthy

- Wear and tear of components depends on many factors, such as on driving style, distance travelled, and the weather

- The environmental impact of workers is not usually included within LCA studies

- The actual lifetime of the vehicle has a strong influence on the in-use CO_2 emissions
- It is difficult to foretell the length of vehicle life
- This is usually assumed to be 10 years in LCA studies

Maintenance & Servicing

- Service interval
- Oil and coolant changes
- Replacement parts
  - Tyres, brake discs
- Component durability / failure
- Service personnel
- Heat and light for garage facilities
- Vehicle life time [years]

- Kerb weight
- technology
- Tailpipe emissions and aftertreatment
- Model variant
- Load capacity
- Target price
- Fuel consumption [L/100
- Tailpip emiss

- vector(s)
- Fuel supplier
- Fuel additive packs
- Fuel availablity
- Fuel price
- Fuel taxation
- Actual, real-world

- Owner affluence
- Length of journeys
- Number of journeys
- Vehicle loading (e.g. passenger mass, luggage mass)
- Care of vehicle (e.g.
- gadgets (e.g. GPS)
- Use of air conditioning

- Terrain (e.g. hills vs.
- ther conditions
- Types of road (e.g. motorway vs. urban)
- ent
  - Roundabouts, traffic lights and junctions
  - Speed bumps

In-Use

Source: Ricardo

The proposed boundary for assessing in-use CO_2 could include all these elements, or …

RICARDO

Elements from use phase contributing to life cycle CO_2 emissions

Vehicle Specification

- ● Vehicle size / type
- ● Kerb weight
- ● Powertrain architecture and technology
- ● Tailpipe emissions and aftertreatment
- ● Vehicle performance
- ● Model variant
- ● Load capacity
- ● Target price
- ● Fuel consumption [L/100km]
- ● Tailpipe CO_2 emissions [g/km]

Fuel

- ● Fuel type / energy vector(s)
- ● Fuel specification
- ▲ Fuel quality
- ▲ Fuel supplier
- ▲ Fuel additive packs
- ▲ Standard grade vs. Premium product
- ▲ Fuel availablity
- ▲ Fuel price
- ▲ Fuel taxation
- ▲ Actual, real-world fuel consumption

Driver

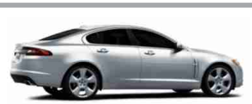
- ▲ Ownership model
- ▲ Owner affluence
- ▲ Driving habits
- ▲ Duty cycle(s)
- ▲ Length of journeys
- ▲ Number of journeys per day
- ▲ Annual mileage [km]
- ▲ Vehicle loading (e.g. passenger mass, luggage mass)
- ▲ Care of vehicle (e.g. regular checking of fluid levels and tyre pressure, etc.)
- ▲ Use of onboard gadgets (e.g. GPS)
- ▲ Use of air conditioning

Geography

- ▲ Location
- ▲ Terrain (e.g. hills vs. flat)
- ▲ Climate and weather conditions
- ▲ Types of road (e.g. motorway vs. urban)
- ▲ Traffic management
  - – Roundabouts, traffic lights and junctions
  - – Speed bumps
  - – Speed limit changes
- ▲ Road congestion

Maintenance & Servicing

- ● Service interval
- ● Oil and coolant changes
- ■ Replacement parts
  - – Tyres, brake discs
- ■ Component durability / failure
- ● Service personnel
- ● Heat and light for garage facilities
- ▲ Vehicle life time [years]



In-Use

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

Proposed Element Boundary

Source: Ricardo

… focus on the NEDC results and Product Categorisation Rules for a common comparison

RICARDO

Elements from use phase contributing to life cycle CO_2 emissions

Vehicle Specification
- Vehicle size / type
- Kerb weight
- Powertrain architecture and technology
- Tailpipe emissions and aftertreatment
- Vehicle performance
- Model variant
- Load capacity
- Target price
- Fuel consumption [L/100km] (can be measured / known)
- Tailpipe CO_2 emissions [g/km] (can be measured / known)

Fuel
- Fuel type / energy vector(s)
- Fuel specification
- Fuel quality
- Fuel supplier
- Fuel additive packs
- Standard grade vs. Premium product
- Fuel availablity
- Fuel price
- Fuel taxation
- Actual, real-world fuel consumption

Driver
- Ownership model
- Owner affluence
- Driving habits
- Duty cycle(s)
- Length of journeys
- Number of journeys per day
- Annual mileage [km] (difficult to measure / has to be assumed)
- Vehicle loading (e.g. passenger mass, luggage mass)
- Care of vehicle (e.g. regular checking of fluid levels and tyre pressure, etc.)
- Use of onboard gadgets (e.g. GPS)
- Use of air conditioning

Geography
- Location
- Terrain (e.g. hills vs. flat)
- Climate and weather conditions
- Types of road (e.g. motorway vs. urban)
- Traffic management
  - Roundabouts, traffic lights and junctions
  - Speed bumps
  - Speed limit changes
- Road congestion

Maintenance & Servicing
- Service interval (can be measured / known)
- Oil and coolant changes (can be measured / known)
- Replacement parts (could be measured / known)
  - Tyres, brake discs
- Component durability / failure
- Service personnel
- Heat and light for garage facilities
- Vehicle life time [years] (difficult to measure / has to be assumed)


In-Use

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

Proposed Element Boundary

Source: Ricardo

Emissions from vehicle end-of-life largely depend on what happens to the vehicle and its components

Elements from vehicle end-of-life contributing to life cycle CO_2 emissions

Vehicle Specification

- Vehicle size / segment
- Vehicle mass
- Powertrain technology
- Technology options (e.g. battery type)
- Number of components
- Model variant
- Materials
- Methods for joining parts together

Logistics

- Vehicle collection
- Transport of vehicle / components to EoL facility
- Distributions of recycled materials / components
- Geographical location of EoL facility (e.g. Europe vs BRIC)

Processing

- Process for vehicle disassembly
- Crushing
- Process for sorting materials / components
- Processing efficiency
- EoL process effectiveness
- Cleaning
- Energy required
- Available energy mix used

Re-Use & Recycling

- Recycability of vehicle components
- Actual quantiy of material / components recycled
- Components suitable for re-use or re-manufacturing
- Allocation of credit for recycling / re-use

Waste

- Quantity of waste material
- Waste disposal method (e.g. Landfill vs. energy recovery)
- Disposal of waste fluids
- Disposal of electrical and battery components
- Hazardous substances

People

- Employees in logistics chain
- Employees of waste disposal facilities
- People vs machines for sorting materials
- H&S considerations
- Environmental considerations

RIP

Disposal

Source: Ricardo

Elements related to the vehicle specification determine what could happen during the EoL phase

RICARDO

Elements from vehicle end-of-life contributing to life cycle CO_2 emissions

Vehicle Specification

- Vehicle specification is determined by the vehicle manufacturer
- Much of this information is available within the public domain, usually in marketing brochures or technical specification documents for the vehicles

People

- Vehicle size / segment
- Vehicle mass
- Powertrain technology
- Technology options (e.g. battery type)
- Number of components
- Model variant
- Materials
- Methods for joining parts together

- Vehicle collection
- Transport of
- EoL facility
- Distributions of recycled materials / components
- Geographical
- Europe vs BRIC)

- Process for vehicle
- Process for sorting materials / components
- Processing efficiency
- Cleaning
- Energy required

- Recycability of vehicle
- material / components recycled
- Components suitable for re-use or re-
- credit for recycling / re-use

- Quantity of waste material
- Landfill vs. energy recovery)
- Disposal of waste fluids
- Disposal of electrical and
- Hazardous substances

- Choice of technology may influence disposal process
- Some materials will be easier to re-use or recycle than others
- The vehicle may or may not be designed for easy disassembly
- This will influence the quantity of parts that could be re-manufactured

- Employees in logistics chain
- Employees of waste disposal facilities
- People vs machines for sorting materials
- H&S considerations
- Environmental considerations

These elements are generally considered to be outside the LCA boundary for a typical passenger car

RIP

Disposal

Source: Ricardo

Geographical location and the processes used to dismantle and recycle the vehicle could have a large impact on EoL CO_2 emissions

RICARDO

Elements from vehicle end-of-life contributing to life cycle CO_2 emissions

- As for production, it is likely that the transport logistics associated with vehicle end-of-life will have a small contribution to the life cycle CO_2 emissions

components

- Model variant
- Materials
- Methods for joining parts together

Logistics

- Vehicle collection
- Transport of vehicle / components to EoL facility
- Distribution of recycled materials / components
- Geographical location of EoL facility (e.g. Europe vs BRIC)

Processing

- Process for vehicle disassembly
- Crushing
- Process for sorting materials / components
- Processing efficiency
- EoL process effectiveness
- Cleaning
- Energy required
- Available energy mix used

- These processes will require energy, which will result in CO_2 emissions
- Little data is currently available on the energy required to dismantle a vehicle and process its materials

components

- Actual quantiy of material / components recycled
- Components suitable for re-use or re-manufacturing
- Allocation of credit for recycling / re-use

- Waste disposal method (e.g. Landfill vs. energy recovery)
- Disposal of waste fluids
- Disposal of electrical and battery components
- Hazardous substances

- Employees of waste disposal facilities
- People vs machines for sorting materials
- H&S considerations
- Environmental considerations

RIP

Disposal

- This could have a large impact on the processes used to dismantle and sort materials (e.g. machine vs. by hand)
- It will also impact on the energy mix available for processing the vehicle and its components

Source: Ricardo

It is likely that most of the vehicle will be re-used or recycled, with a small quantity of waste material for landfill

Elements from vehicle end-of-life contributing to life cycle CO_2 emissions

- Under the End-of-Life Directive, >85% of the vehicle (by mass) should be re-used or recycled
- But this does not mean that 85% of the vehicle is re-used or recycled at the end of its life
- Some national statistics are available on vehicle re-use and recovery rates across Europe (http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/elvs)

- Currently there is much debate within the automotive community regarding what could happen to the battery pack at the EoL of a plug-in vehicle

- Should the credit for re-use or recycling be assigned to the old product, or to the new product using the materials?

- Methods for joining parts together

- Energy required
- Available energy mix used

RIP

Disposal

Re-Use & Recycling

- Recycability of vehicle components
- Actual quantiy of material / components recycled
- Components suitable for re-use or re-manufacturing
- Allocation of credit for recycling / re-use

Waste

- Quantity of waste material
- Waste disposal method (e.g. landfill vs. energy recovery)
- Disposal of waste fluids
- Disposal of electrical and battery components
- Hazardous substances

- Under the ELD, <15% of the vehicle should go to landfill or energy recovery

- logistics chain
- Employees of waste disposal facilities

- Some LCI databases contain default values for the CO_2 emissions associated with landfill or energy recovery systems

- Standards and legislation is available on how hazardous materials and electrical components should be treated in a waste disposal facility

Source: Ricardo

Ideally, LCA of the vehicle end-of-life should consider the logistics, energy and processes required to dispose of the vehicle

RICARDO

Elements from vehicle end-of-life contributing to life cycle CO_2 emissions

Vehicle Specification
- ● Vehicle size / segment
- ● Vehicle mass
- ● Powertrain technology
- ● Technology options (e.g. battery type)
- ● Number of components
- ● Model variant
- ● Materials
- ■ Methods for joining parts together

Logistics
- ▲ Vehicle collection
- ▲ Transport of vehicle / components to EoL facility
- ▲ Distributions of recycled materials / components
- ▲ Geographical location of EoL facility (e.g. Europe vs BRIC)

Processing
- ▲ Process for vehicle disassembly
- ▲ Crushing
- ▲ Process for sorting materials / components
- ▲ Processing efficiency
- ▲ EoL process effectiveness
- ▲ Cleaning
- ▲ Energy required
- ▲ Available energy mix used

Re-Use & Recycling
- ● Recycability of vehicle components
- ▲ Actual quantiy of material / components recycled
- ● Components suitable for re-use or re-manufacturing
- ▲ Allocation of credit for recycling / re-use

Waste
- ▲ Quantity of waste material
- ▲ Waste disposal method (e.g. Landfill vs. energy recovery)
- ▲ Disposal of waste fluids
- ▲ Disposal of electrical and battery components
- ▲ Hazardous substances

Proposed Element Boundary

People
- ● Employees in logistics chain
- ● Employees of waste disposal facilities
- ● People vs machines for sorting materials
- ● H&S considerations
- ● Environmental considerations

RIP

Disposal

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

A vehicle LCA study is likely to be conducted during the pre-production or launch phase of a new vehicle model. There is some uncertainty regarding how well these EoL elements can be quantified ~10 years in advance

Source: Ricardo

Contents

Some legislation is directly designed to reduce a passenger car's environmental impact but with unintended consequences …

RICARDO

Legislation	Relative effect on life cycle CO_2 emissions				Commentary
	Production	In-use		Disposal	
		WTT	TTW		
Renewable Energy Directive (Directive 2009/28/EC) / Fuel Quality Directive (Directive 2009/30/EC)	-	↓↓ ★	?	-	• Set European targets for increasing use of renewable energy in transport fuel, and for decreasing GHG emissions of fuels
Tailpipe CO_2 (Regulation No 443/2009)	↑↑	-	↓↓↓ ★	↑	• Driver for uptake of new "low carbon" technologies, e.g. hybridisation and electrification • Many of these technologies increase the embedded emissions of the vehicle, while significantly decreasing tailpipe CO_2
Tailpipe Emissions (Directive 2003/76/EC)	↑	-	↑	↑	• Driver for aftertreatment and advanced combustion technologies • Often strategies compromise on fuel consumption to reduce tailpipe emissions of CO, HC, NOx and particulate
Other Type Approval legislation* (as defined by Directive 2007/46/EC)	↑	-	↑	↑	• The objective of most Type Approval legislation is to improve safety • This legislation can lead to increasing the number of components within the vehicle, which increases vehicle mass and embedded CO_2 emissions
End-of-Life Directive (Directive 2000/53/EC)	?	-	-	↓↓ ★	• Driver for improving the re-usability and recyclability of automotive components

Legend: ↑ Increases CO_2 emissions ↓ Decreases CO_2 emissions - No significant impact on CO_2 emissions ? Unknown impact ★ Intended impact

* A list of Type Approval legislation is supplied in the Appendices

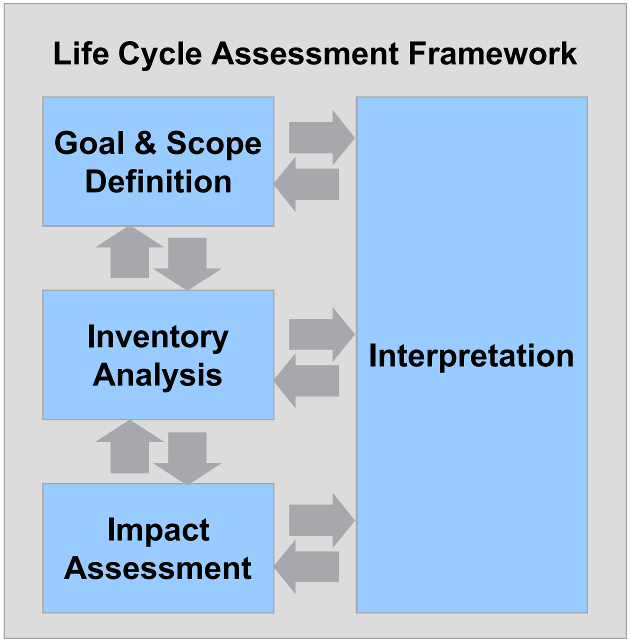
Source: European Commission, IFQC, Ricardo analysis

… while other legislation, not aimed at vehicle CO_2, has an indirect effect on vehicle life cycle CO_2 emissions

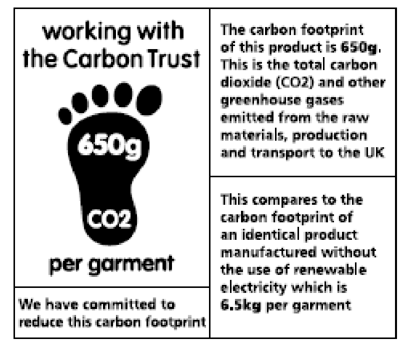
- Examples of legislation that may have a positive or negative effect on the life cycle CO_2 emissions of a passenger car:
  - Environmental Legislation applying to material extraction and processing, or manufacturing
    - Overall, likely to have a positive effect on environmental impact, but may compromise on CO_2 emissions to achieve targets
  - Health and Safety Legislation applying to material extract and processing, manufacturing, or handling and transport of materials and components
    - May restrict "best CO_2 reduction" option
  - Shipping restrictions on transport of potentially hazardous materials and components, such as battery cells
  - Emissions Trading Scheme (Directive 2009/29/EC)
  - State Aid Rules
    - May delay the market introduction of new and novel low CO_2 technologies due limited government capability to bridge the commercialisation valley of death / mountain of risk
  - Intellectual Property and Patents
    - May restrict the availability of good solutions depending on who owns the "rights"
  - Employment Law
  - Taxation and Incentives
  - Highway regulations, road restrictions and traffic management
    - E.g. Spain reducing national speed limit

Contents

International Standards already exist for defining the Life Cycle Assessment (LCA) process



- The Life Cycle Assessment (LCA) process is outlined ISO 14040:2006 (general principles) and 14044:2006 (guide for practitioners)
  - LCA considers the entire life cycle of a product or service, from cradle-to-grave
  - It is a relative approach, structured around a functional unit, which defines what is being studied
  - LCA studies are inherently complex. Therefore transparency is important to ensure proper interpretation of the results
  - LCA considers many types of environmental impact, not just CO_2 emissions
  - Several databases are available containing Life Cycle Inventory (LCI) data on the environmental impact of different materials, energy sources and manufacturing processes
- Environmental Product Declarations (EPDs) are defined by ISO 14025. 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
- In October 2008, BSI British Standards published PAS 2050, a Publicly Available Specification "for the assessment of life cycle greenhouse gas emissions of goods and services". This process for using LCA techniques to calculate the "carbon footprint" (CO_2 equivalent) of a product or service was co-sponsored by the Carbon Trust and UK Department for Environment, Food and Rural Affairs (DEFRA)
- An international standard for carbon footprinting is currently under discussion (ISO 14067)



Source: ISO 14040:2006, PAS 2050, "Product carbon footprinting: the new business opportunity" published by Carbon Trust www.carbontrust.co.uk; SPMJ Technology Consulting

Many OEMs are already conducting Life Cycle Assessment studies of their vehicles that comply with ISO 14040 and ISO 14044

- Many OEMs conduct Life Cycle Assessment studies of their vehicles as part of their Environmental Management strategies
  - VW began investigating LCA in the early 1990s
  - Toyota started using LCA in 1997. Since 2004, LCA has been implemented for all new passenger car models, as well as those undergoing a model change
  - PE International's published customer list for their GaBi LCA tool includes Audi, Daimler, Fiat, Ford, GM, Honda, Renault, Mitsubishi, Nissan, Toyota, VW, Volvo Bosch, Continental, Delphi, Siemens, Valeo, and Anglo Platinum
- Several OEMs have published the results from their LCA studies to inform customers, shareholders and other stakeholders
  - Although certificates of validity show the LCA is based on reliable data and conforms to ISO 14040, it is not clear if different OEMs use the same set of assumptions or input data sets


CERTIFICATE OF VALIDITY TÜV NORD

DIN EN ISO 14040 : 2006-10

Volkswagen AG
Berliner Ring 2
38346 Wolfsburg
Germany

Environmental Commendation Polo

- Standard methodologies
- Representative categories of balancing and effects
- General transparency and consistency


CERTIFICATE

COMPANY TOYOTA MOTOR CORPORATION

STANDARD ISO 14040 : 2006
ISO 14044 : 2006

SCOPE OF APPLICATION Toyota Prius (2009 model)

CERTIFICATE NUMBER

CRITICAL REVIEW DATE

Head of Critical Review Panel

Certificates from relevant technical inspection organisations show that the LCA has been based on reliable data, and conforms to the requirements of ISO standards 14040 and 14044

Sources: The Polo Environmental Commendation, VW, 2009 ; Prius Environmental Declaration, Toyota, 2009; www.gabi-software.com/uk-ireland/customers/

OEM LCA studies suggest passenger car life cycle CO_2 emissions are 20-80 tonnes, depending on segment and lifetime mileage

RICARDO

Life Cycle Assessment of Passenger Cars – Baseline Data from Literature

Vehicle	Description	Lifetime Mileage [km]	Life Cycle Total CO_2e [tonnes CO_2]	Life Cycle [%]			Source
				Production	In-Use	Disposal	
VW Polo	Diesel 1.6L TDI, 55 kW (un-laden weight 1157 kg)	150,000	23	20.6%	79%	0.4%	VW (2009)
VW Polo	Gasoline 1.4L MPI, 63 kW (un-laden weight 1104 kg)		29.5	~17%	~83%	<1%	VW (2009)
VW Passat Estate B6	Diesel 2.0L TDI, 103 kW (un-laden weight 1510kg)		32.4	19%	80%	1%	VW
VW Passat Estate B6	Gasoline 1.6L FSI, 85 kW (un-laden weight 1403kg)		38.2	18%	81%	1%	VW
Toyota Prius	Hatchback 1.8L VVTi V (un-laden weight 1420kg)	150,000	-	26%	71%	3%	Toyota
Mercedes-Benz A-Class	A150 Gasoline 1.5L, 70 kW, with ECO start-stop system	300,000	32	16%	83%	<1%	Mercedes-Benz (2008)
Mercedes-Benz E-Class	E 220 CDI BlueEFFICIENCY Diesel 2.1L, 125 kW		48	18%	82%	1%	Mercedes-Benz (2009a)
Mercedes-Benz S400 Hybrid	Gasoline 3.5L V6 205 kW 15 kW motor, Li-ion battery		78	14%	85%	<1%	Mercedes-Benz (2009b)

Sources: VW, Toyota, Mercedes-Benz – [See Appendices for further information on these sources]

Vehicle hybridisation and electrification can reduce life cycle CO_2 emissions, but this increases embedded emissions from production

RICARDO

- One of the main drivers for the development of automotive technology today is reducing the in-use CO_2 emissions. The trend is towards hybridisation and electrification
- The introduction of battery packs, electric motors and power electronics into a passenger car increases the embedded CO_2 emissions associated with the vehicle's production, while significantly reducing the tailpipe CO_2 emissions from the use phase
- This leads to a shift in the life cycle balance between production and use phases

SELECTED EXAMPLES

Vehicle	Description	Lifetime Mileage [km]	Life Cycle Total CO_2e [tonnes CO_2]	Life Cycle [%]			Source
				Production	In-Use	Disposal	
Conventional	Based on Toyota Corolla type vehicle Li-Ion battery technology	240,000	64.6	13%	87%	Not considered	Samaras and Meisterling (2008)
HEV			46.1	18.8%	81.3%		
PHEV 30			43.9	20.8%	79.2%		
PHEV 60			43.4	23.2%	76.8%		
PHEV 90			43.9	24.6%	74.9%		
Standard Car	C-segment vehicle (e.g. VW Golf)	150,000	40.3	12.9%	87.1%	Not considered	Gauch et al. (2009)
EV	C-segment vehicle (e.g. VW Golf), with 300 kg, 30 kWh Li-Ion battery pack	150,000	19.5	34.7%	65.3%		

Source: Samaras and Meisterling (2008); Gauch et al. (2009) – [See Appendices for further information on these sources]

To investigate further, Ricardo has compared estimates of life cycle CO_2 emissions for a range of vehicle technologies and fuels

- Comparing results from different LCA studies can be difficult if the assumptions and input data are not the same
- Therefore, in order to evaluate how evolving technologies will alter the balance of emissions between production, in-use and disposal phases, Ricardo has produced high level estimates of life cycle CO_2 emissions for different vehicle architectures. Information on the methodology used is provided in the Appendices
- Three comparison sets have been prepared. In each set, the options are compared to a mid-size gasoline passenger car

Comparing Technologies

- Mid-size gasoline
- Mid-size plug-in hybrid vehicle (PHEV)
- Mid-size extended range electric vehicle (EREV)
- Mid-size pure electric vehicle (EV)
- Mid-size fuel cell vehicle (FCV)

Comparing Vehicle Size

- Mid-size gasoline
- Small gasoline
- Mid-size diesel
- Large diesel
- Large diesel, with downsized ICE

Comparing Biofuels

- Mid-size gasoline with E10
- Mid-size gasoline with E20
- Mid-size gasoline with E85
- Mid-size diesel with B7 (FAME)
- Mid-size diesel with B10 (FAME)
- Mid-size diesel with B100 (FAME)

- Vehicle specifications based on Ricardo roadmap projections for 2015
- Assumed lifetime mileage 150,000 km
- Baseline gasoline assumed to be E10 (10%vol ethanol), in line with current fuel specifications
- Baseline diesel assumed to be B7 (7%vol FAME), in line with current fuel specifications
- Electricity grid mix assumed to be 500 gCO_2e/kWh (2010 values published by DECC)
- Further information about vehicle and fuel specifications is provided in the Appendix 2

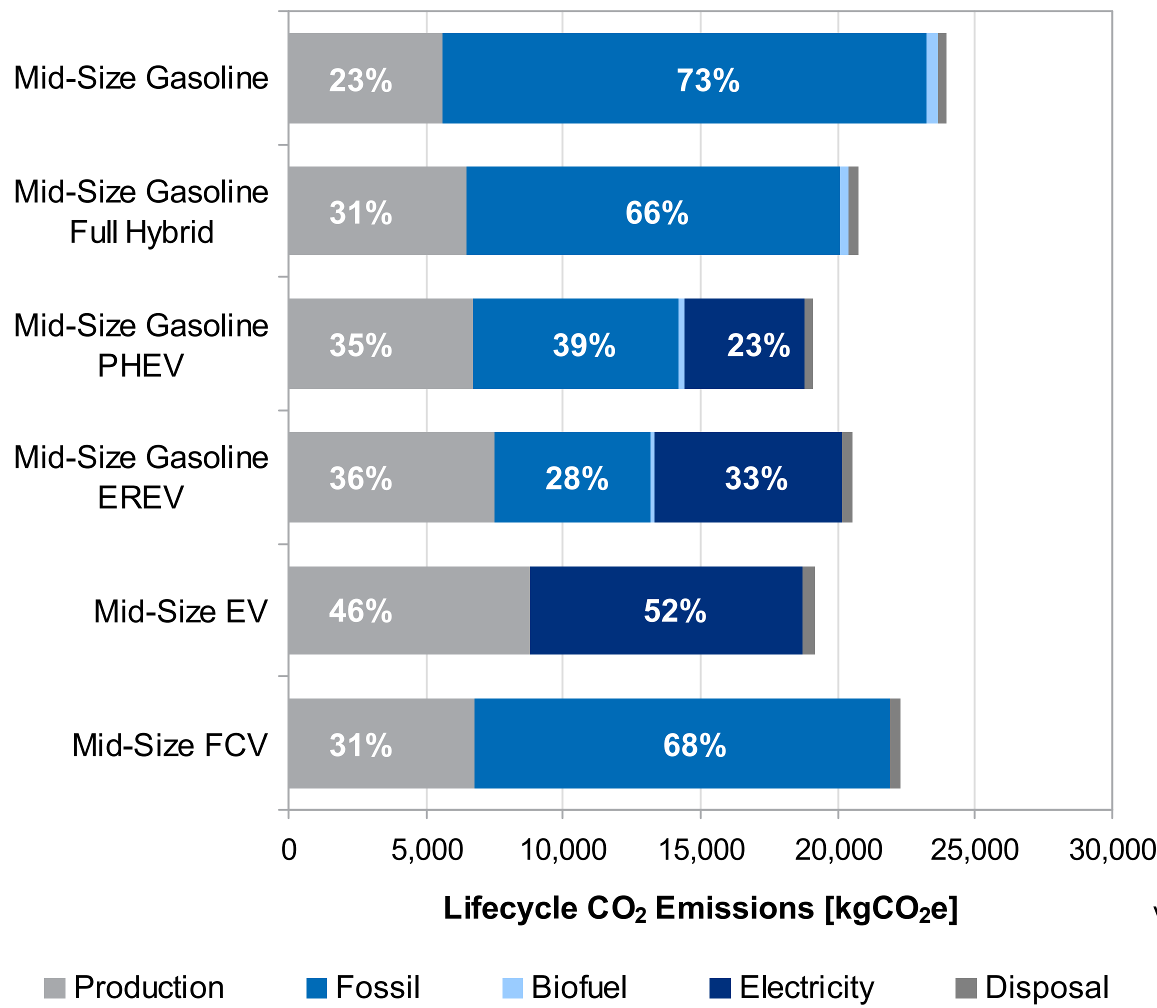
Health Warning

The charts on the following slides are based on high level estimates of life cycle CO_2, and provide an indication of expected future trends. The results do not come from detailed LCA studies conducted in accordance with ISO 14040

Source: Ricardo

Ricardo results show hybrids and EVs will have lower life cycle CO_2 emissions, but embedded emissions will be more significant

Comparing Technologies



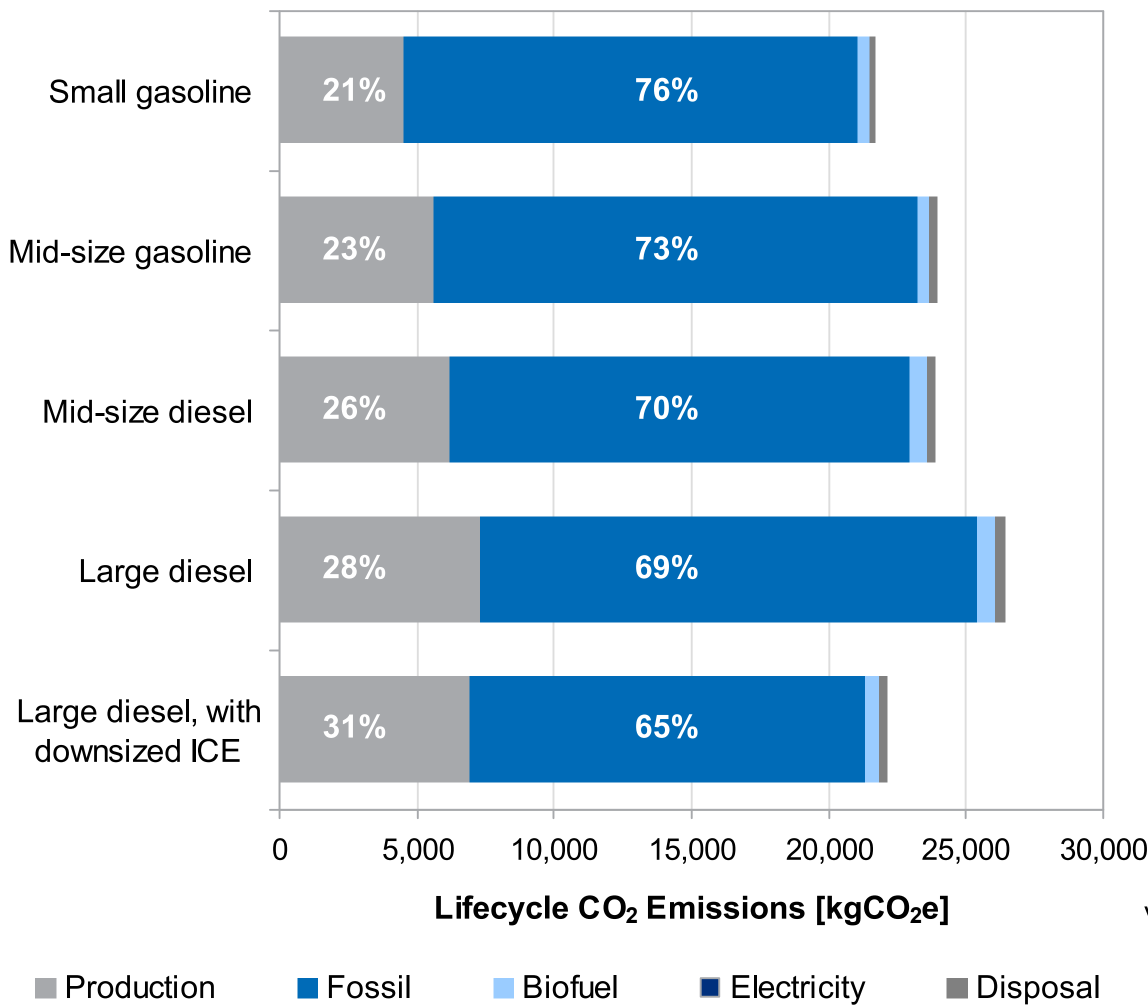
- Predicted improvements in the conventional ICE powertrain designed to reduce in-use tailpipe CO_2, will naturally help to lower the life cycle CO_2 emissions compared to current values
- Life cycle CO_2 reductions for hybridisation and electrification could be 10-20% (compared to a mid-size gasoline passenger car in 2015)
- However, embedded CO_2 from production will increase, due to the addition of components such as advanced battery packs, electronic motors and power electronics
  - For an EV, nearly half the life cycle CO_2 could result from production

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

Diesel and gasoline passenger cars have similar life cycle CO_2 emissions, which generally increase with vehicle size

Comparing Vehicle Size



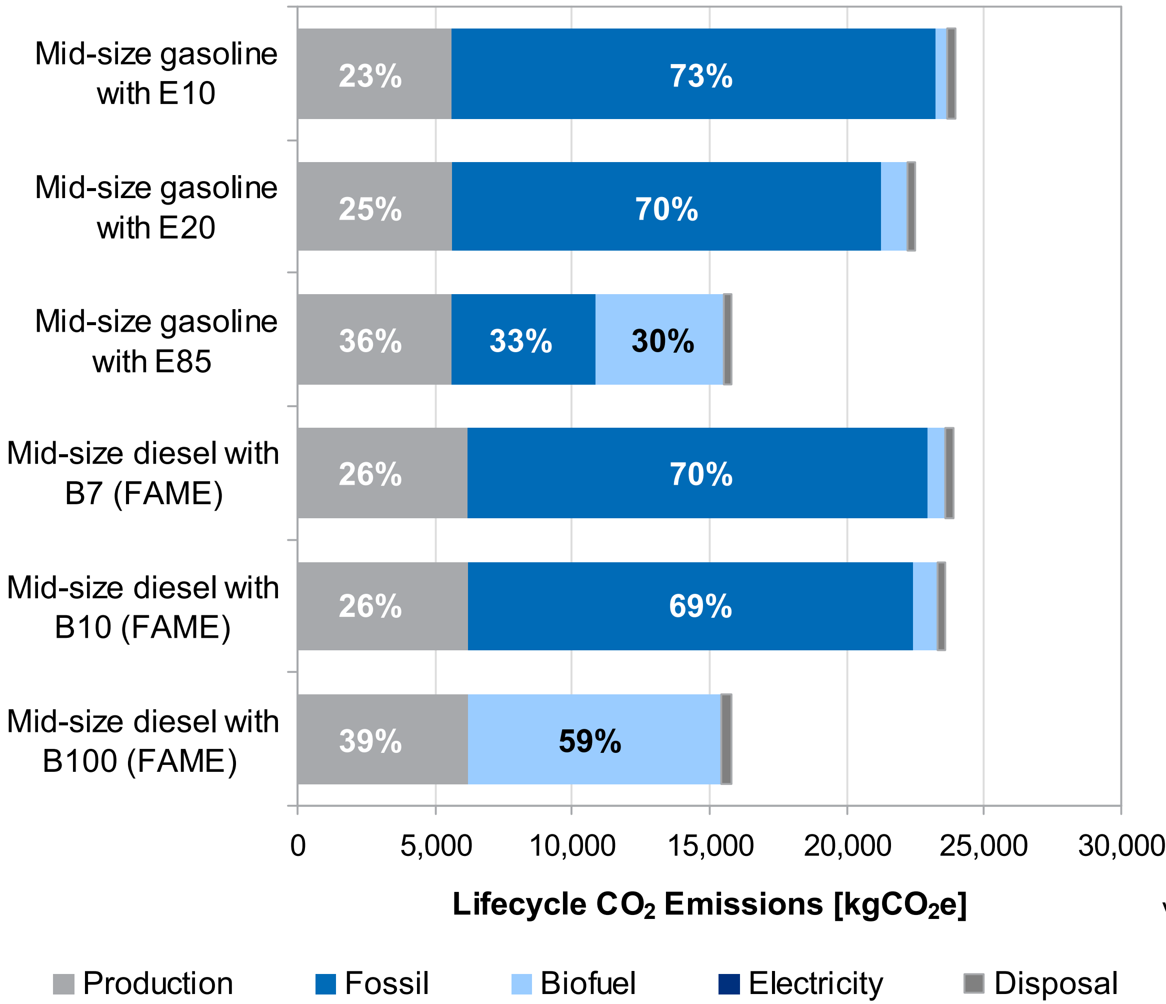
- As expected, larger cars have higher life cycle CO_2 emissions
- The embedded CO_2 for diesel vehicles is higher than the embedded CO_2 for gasoline vehicles. However, since tailpipe CO_2 emissions are generally lower, the life cycle CO_2 emissions for gasoline and diesel passenger cars are very similar (assuming lifetime mileage is 150,000 km)
- Adopting downsizing ICE technology will help to reduce life cycle CO_2 emissions, although this is mainly due to improvements in fuel economy leading to lower tailpipe CO_2

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

Increasing the biofuel content helps to reduce Well-to-Wheel CO_2 emissions …

Comparing Alternative Fuels



- The higher the biofuel content, the lower the WTW CO_2 emissions resulting from the use of fuel
- The actual level of saving is dependent on the feedstock and production processes used to make the biofuel
- As WTW CO_2 emissions reduce, the embedded CO_2 emissions from production and disposal become a more significant part of the whole life cycle CO_2 metric

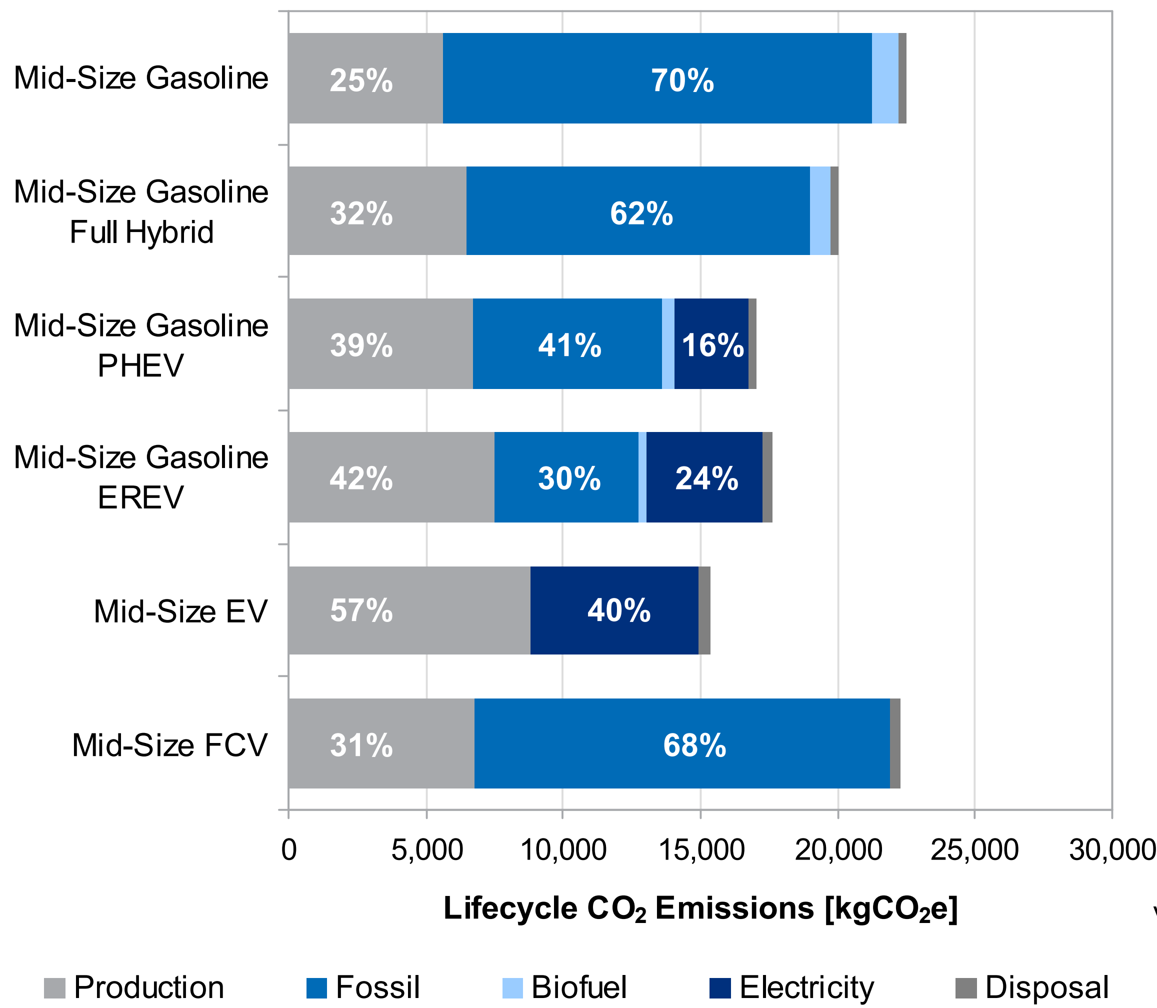
Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

… for conventional and alternative powertrain technologies

RICARDO

Comparing Technologies with Alternative Fuels



- The WTW CO_2 reductions achieved through increasing the use of biofuels also applies to other powertrain technologies
- Reducing the carbon intensity of the UK electricity mix also helps to reduce the WTW CO_2 emissions for plug-in vehicles
- But, as a consequence, CO_2 emissions from production become more significant
  - For an EV, >50% of life cycle CO_2 could result from production
- Note: In this study it has been assumed that hydrogen is produced by steam methane reforming of natural gas. If produced from renewable sources, its carbon intensity would be significant reduced by ~90%

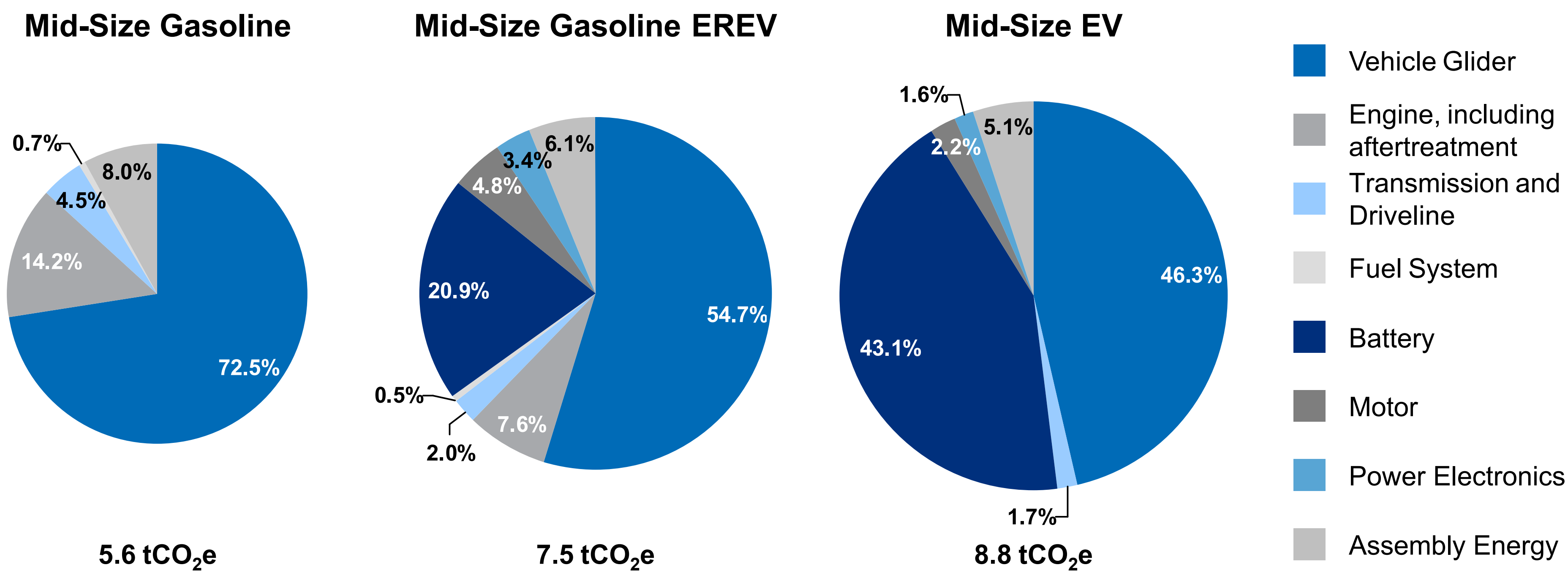
Vehicle specifications based on roadmap projections for 2015.
Assumed lifetime mileage 150,000 km. Fuels E20.
Electricity carbon intensity assumed to be 310 gCO_2/kWh.
Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

The technology evolution to plug-in vehicles will lead to higher embedded CO_2 emissions due to the addition of new components

RICARDO

Embedded CO_2 Emissions [$kgCO_2e$]



- For a standard family gasoline passenger car, >70% of the embedded CO_2 emissions result from the non-powertrain components (the vehicle glider)
- However this balance will change with the additional components required for hybridisation and electrification. For an extended range EV, the battery could account for >20% of the embedded CO_2 emissions. While for an EV, the battery could represent >40% of the embedded CO_2 emissions from production

Vehicle specifications based on roadmap projections for 2015. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

Contents

Current gaps in understanding surrounding LCA revolve around the LCI data for materials, processes, fuels and energy

Gaps in Understanding

Life Cycle Inventory (LCI)

- Quantifying the difference in results due to different LCI datasets and LCA tools
- Assessing environmental impacts of new automotive materials, such as composites
- Assessing environmental impacts of advanced production processes
- In addition to CO_2, what other environmental impacts should be considered?
  - E.g. water footprint, toxicity, etc.

Real World Use

- What is the extent of the variability introduced by a population of different users?
  - E.g. Impact of using air conditioning, impact of low tyre pressures, etc.
- What is the realistic lifetime for a future vehicle?
  - How far will it travel?

Vehicle End-of-Life

- What really happens at the end of a vehicle's life?
- What will happen to new technologies (e.g. EV)?
  - What disposal processes will be required?
  - How can these be modelled within an LCA study?
- How should the environmental impact be allocated between old and new products?

Future Fuels & Energy Vectors

- What will be the future biofuel content for gasoline and diesel?
  - What biofuel mix will be used?
    - What will be the feedstock mix?
  - What will be the carbon intensity of these fuels?
- What will be the future carbon intensity of the electricity grid?
  - Marginal vs. Mean?

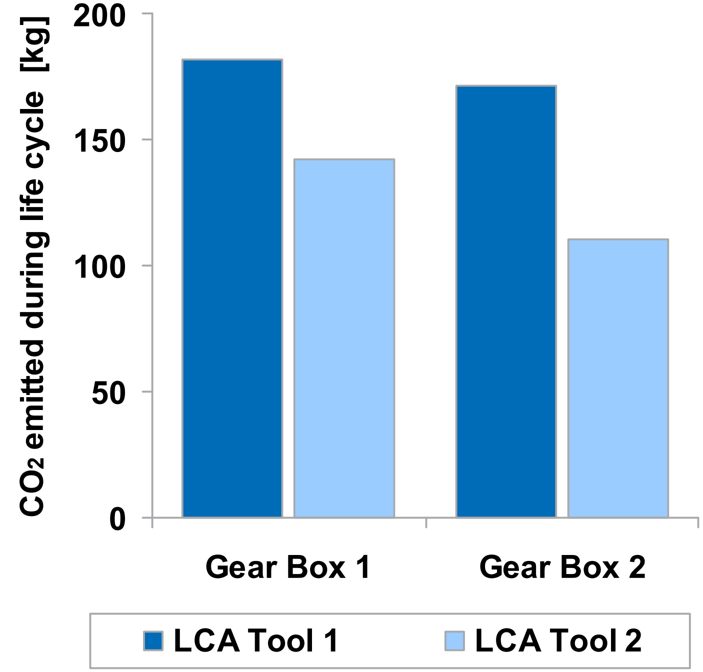
Source: Ricardo

The detail of the methodology employed by the LCA user can have a significant impact on the life cycle results

EXAMPLE

- It is possible to conduct two LCA studies of the same product, which both comply with the ISO 14040 standards, but have very different results
- Variability in LCA results can be a consequence of:
  - Functional unit definition (e.g. lifetime mileage)
  - LCA boundary, determining what has been included or excluded from the study
  - Assumptions employed
  - Life Cycle Inventory data set, and associated data quality
    - LCI databases define emission factors for materials, energy and processes
    - When selecting LCI data, the user should consider the geographical horizon, time horizon, precision, completeness and representativeness of the LCI data
  - Method for allocating environmental impact of co-products
    - If a process produces more than one product, the environmental impact can be split between the products produced
  - Choice of LCA software tool
    - Several commercial LCA tools available, in addition to in-house tools developed by vehicle manufacturers

Results from LCA study of two gear boxes, using two different LCA tools



In the above example, an LCA study was conducted of two gear boxes, one with an aluminium casing and the other with a steel casing. The study was repeated using two different LCA software tools, with the same bill of materials for the gear boxes. The differences in results is primarily due to the LCA tools using different LCI databases

Source: Ricardo (2008)

Peer review and sensitivity analysis are recommended to ensure use of a rigorous process and to quantify variability of results

- ISO 14040 recommends that LCA studies are peer reviewed to ensure an appropriate methodology has been used
- Conducting sensitivity analysis can help to identify which elements could contribute most to result variability, and to understand the range
- Some LCI databases have data quality indexes to help users identify if the selected data is suitable for the application being investigated

However even with peer review and sensitivity analysis LCA results from different studies can still be significantly different depending on input data sets and assumptions

The LCA community is already active in initiatives to improve accuracy, data quality and use of consist methodology

Existing LCA Initiatives

- There are several organisations engaged in activities to improve the accuracy of life cycle assessment and to establish common methodologies and data sets so products can be compared on a "like with like" basis

EXAMPLES

- **European Platform on Life Cycle Assessment** (http://lct.jrc.ec.europa.eu)
  - The aim is to support businesses and public authorities in the implementation of Sustainable Consumption and Production
  - In March 2010 the European Commission published their ILCD handbook
  - Their Life Cycle Thinking website and LCA Forum is hosted by the European Commission Joint Research Centre, Institute for the Environment and Sustainability (JRC-IES)
- **UNEP Life Cycle Initiative** (http://lcinitiative.unep.fr)
  - An international life cycle partnership set up by the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC)
  - Their main mission is to bring science-based Life Cycle approaches into practice worldwide
- **The Carbon Label Company** (www.carbon-label.com)
  - Set up by the Carbon Trust in 2007
  - Primary objective is to help businesses to measure, certify, reduce and communicate the lifecycle greenhouse gas (GHG) emissions of their products and services

Source: EC JRC-IES, UNEP Life cycle Initiative; The Carbon Trust and the Carbon Label Company

Further work is required, engaging with OEMs, LCA practitioners and vehicle drivers, to close the gaps in life cycle understanding

Suggestions to LowCVP for Future Work

- **Open the dialogue with vehicle manufacturers**
  - Encourage OEMs to publish the results (and their methodology/assumptions) from their LCA studies. This will provide a benchmark of the current life cycle CO_2 emissions of European passenger cars, split between production, in-use and disposal
- **Make contact with LCA networks and initiatives**
  - Many of these networks are already active in trying to improve the quality of life cycle inventory data
  - Work with the existing initatives to develop a standard / default LCI dataset for the automotive industry
- **Investigate the variability of vehicle use to understand the range between extremes**
  - E.g. Consumer surveys to understand travel patterns, driver styles, typical vehicle loading, use of on-board heating and air conditioning
  - Conduct sensitivity studies to appreciate the impact of different use patterns on life cycle emissions
- **Research vehicle end-of-life to understand what really happens during vehicle disposal**
  - What will be the impact of new technologies, such as advanced battery packs?
  - How will new materials impact re-use and recyclability?
- **Make LCA part of the process**
  - Get life cycle thinking embedded within the design process
  - Allow LCA results to drive reduction in both cost and CO_2 footprint (“Clean ‘n’ Lean”)

Contents

Europe currently has specific targets for reducing the environmental impact of a vehicle during the fuel, use and disposal phases, …

The Renewable Energy Directive and Fuel Quality Directive have set targets for increasing renewable energy in transport, and reducing GHG emissions from fuel

"Fuel"

Generate

- Fossil fuel production
- Electricity generation
- Hydrogen production
- …

Distribute

Distribution network efficiency

- Power lines
- Pipelines
- Tankers
- …

The fleet average tailpipe CO_2 target is encouraging vehicle manufacturers to develop low carbon technology

The End-of-Life Vehicle Directive is encouraging re-use and recycling of automotive components, which should help to reduce the environmental impact of disposal

Currently, there are no automotive targets specifically aimed at reducing CO_2 from production of the whole vehicle

Production

Assessment of environmental impact of producing the vehicle from raw materials to complete product

"In-Use"

- Tailpipe CO_2 from driving
- Impact from maintenance and servicing

Disposal

Assessment of environmental impact of "end of life" scenario, including re-use of components, recycle of materials and landfill

Source: Ricardo

… but there are no specific CO_2 targets for the production of the whole vehicle

Recommendations for a life cycle CO_2 measure

- Consider a new CO_2 metric based on the GHG emissions emitted during vehicle production [tCO_2e]
  - The vehicle's life cycle CO_2 can then be calculated for a defined use, fuel and disposal scenario
- Consider targets aimed at reducing the life cycle CO_2 [tCO_2e]. For example:
  - Cap on production CO_2, dependent on vehicle segment
  - Reduction target for production or life cycle CO_2, compared to an appropriate baseline
  - Maximum "pay back period" for trading increased embedded emissions against reductions in tailpipe / WTW CO_2 emissions
- Consider the fiscal and regulatory framework in which vehicles are sold, used and disposed
  - Allocation of incentives / regulation to best influence commercial and consumer behaviours for lowest life cycle CO_2

Contents

Future CO_2 metrics will need to consider a vehicle's whole life cycle, but work is required to obtain common methodologies and data sets

Conclusions

- The vehicle's embedded CO_2 from production and disposal is becoming a greater portion of the life cycle CO_2 emissions
- Current regulatory frameworks do not recognise this
- Standards, guidelines and manuals already exist for conducting Life Cycle Assessment and Environmental Product Declarations of products such as passenger cars
  - However input data, boundary conditions and assumption can vary between LCA studies
- Life Cycle Inventory databases exist containing information on the carbon intensity of materials, energy, production processes and fuels
  - Some databases are freely available within the public domain, while other proprietary databases require users to purchase a licence
  - Values can vary between databases depending on the geographical horizon, time horizon, data source, completeness and representativeness of the LCI data
- For a life cycle CO_2 measure to be regulated, work will be required to standardise the process detail, life cycle boundary, and input data, such that results from different manufacturers are directly comparable
- Key areas for further investigation include:
  - Development of a common LCI dataset to be used by the automotive industry
  - Impact of different in-use assumptions, especially around drive cycles and use of ancillary functions
  - Obtain a better understanding and modelling of the environmental impact of vehicle end of life, especially for new technologies such as electric vehicles

Contents

Appendix 1

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Appendix 2

Further information on Ricardo analysis of impact of technology evolution on life cycle CO_2 emissions

Ricardo derived a set of vehicle specifications designed to produce equivalent performance characteristics by vehicle size

Vehicle Specifications based on Technology Roadmap projections for 2015

Vehicle	Vehicle Description	Vehicle Mass [kg]	Tailpipe CO_2 [gCO_2/km]	EV Driving Range * [km]
Mid-Size Gasoline	1.4L 91kW I4 DI engine with VVT and FGT	1340 kg	109 gCO_2/km	-
Mid-Size Gasoline Full Hybrid	1.4L 91kW I4 DI engine with VVT, 1.8 kWh NiMH battery pack, 56 kW Motor	1430 kg	84 gCO_2/km	-
Mid-Size Gasoline PHEV	1.4L 91kW I4 DI engine with VVT, 4.8 kWh Li-ion battery back, 56 kW Motor	1460 kg	47 gCO_2/km	20 km
Mid-Size Gasoline EREV	1.0L 44kW I3 PFI engine, 13.4 kWh Li-ion battery back, 72 kW Motor	1510 kg	35 gCO_2/km	55 km
Mid-Size EV	32.2 kWh Li-ion battery back, 71 kW Motor	1480 kg	0 gCO_2/km	180 km
Mid-Size FCV	73 kW PEM fuel cell system, 1.8 kWh Li-ion battery back, 67 kW Motor	1410 kg	0 gCO_2/km	-
Small Gasoline	1.0L 59kW I3 PFI engine with VVT	1080 kg	103 gCO_2/km	-
Mid-Size Diesel	2.0L 101kW I4 engine with VGT Turbo	1420 kg	105 gCO_2/km	-
Large Diesel	3.0L 123kW V6 engine with VGT Turbo	1720 kg	113 gCO_2/km	-
Large Diesel, with downsized ICE and reduced vehicle weight	2.0L 123kW I4 engine with 2 stage turbocharging	1680 kg	90 gCO_2/km	-

* Depth of battery discharge for calculating EV range assumed to be 50% for PHEV and EREV, and 70% for EV

Source: Ricardo

A variety of alternative fuels were considered …

RICARDO

Fuel Specifications, and assumptions regarding Well-to-Tank CO_2 emissions (1/2)

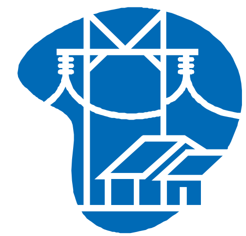
- The study has considered three grades of gasoline:
  - E10 containing $10\%_{vol}$, $7\%_{energy}$ ethanol
  - E20 containing $20\%_{vol}$, $14\%_{energy}$ ethanol
  - E85 containing $80\%_{vol}$, $73\%_{energy}$ ethanol, to allow for seasonal and regional variations
  - Ethanol is assumed to be from a range of feedstocks (70% sugar cane, 20% sugar beet, 8% wheat, 2% corn)
  - Carbon intensity of ethanol is assumed to be 28.7 gCO_2e/MJ_{fuel}, derived from RED typical values
  - Carbon intensity of gasoline is assumed to be 83.8 gCO_2e/MJ_{fuel}, RED default value

- The study has considered three grades of diesel:
  - B7 containing $7\%_{vol}$, $6\%_{energy}$ FAME
  - B10 containing $10\%_{vol}$, $9\%_{energy}$ FAME
  - B100 containing $100\%_{vol}$, $100\%_{energy}$ FAME
  - FAME is assumed to be from a range of feedstocks (40% soy, 25% oilseed rape, 15% tallow, 10% palm, 10% other)
  - Carbon intensity of FAME is assumed to be 43.4 gCO_2e/MJ_{fuel}, derived from RED typical values
  - Carbon intensity of diesel is assumed to be 83.8 gCO_2e/MJ_{fuel}, RED default value

Source: Ricardo, UK Renewable Fuels Agency, European Renewable Energy Directive

… including electricity and hydrogen

Fuel Specifications, and assumptions regarding Well-to-Tank CO_2 emissions (2/2)



- Electricity for plug-in vehicles assumed to be from UK National Grid
  - 2010 UK electricity carbon intensity assumed to be 500 gCO_2e/kWh, 139 gCO_2e/MJ (DECC)
  - 2020 UK electricity carbon intensity assumed to be 310 gCO_2e/kWh, 86 gCO_2e/MJ (CCC Scenario)

- Hydrogen was assumed to be from industrial sources, produced using steam methane reforming
  - Carbon intensity for hydrogen assumed to be 99.7 gCO_2e/MJ_{fuel}

Source: Ricardo, DECC, Committee on Climate Change (CCC), CONCAWE

Ricardo have developed a top-down methodology for estimating life cycle CO_2 emissions for a range of vehicle technologies

Ricardo's methodology for calculating high level estimates of life cycle CO_2 emissions

Vehicle Production

- Divide vehicle into key sub-systems
- For each system, determing the system mass and split by material
- Calculate embedded emissions associated with the materials used
- Estimate embedded emissions resulting from production processes (e.g. energy mix)
- Sum together to calculate embedded CO_2 emissions for vehicle production [kgCO_2e]

In-Use

- Build a vehicle simulation model to predict fuel consumption, energy requirements, and tailpipe CO_2 emissions [kgCO_2e]

Fuel Production

- Use energy consumption data, split by fuel type, from Use phase
- Identify carbon intensity for each fuel
  - Use RED/FQD typical values
- Calculate the Well-to-Wheels CO_2 emissions resulting for the use of each fuel [gCO_2e/km]
- Multiply by life time mileage to obtain total CO_2 emissions from Use and Fuel [kgCO_2e]

For this study, life time mileage assumed to be 150,000 km *

Disposal

- For this study, assume CO_2 emissions from Disposal is 5% of CO_2 emissions from production [kgCO_2e]

Total

- Sum together the CO_2 emissions from each phase to obtain the total life cycle CO_2 emissions of the vehicle [kgCO_2e]

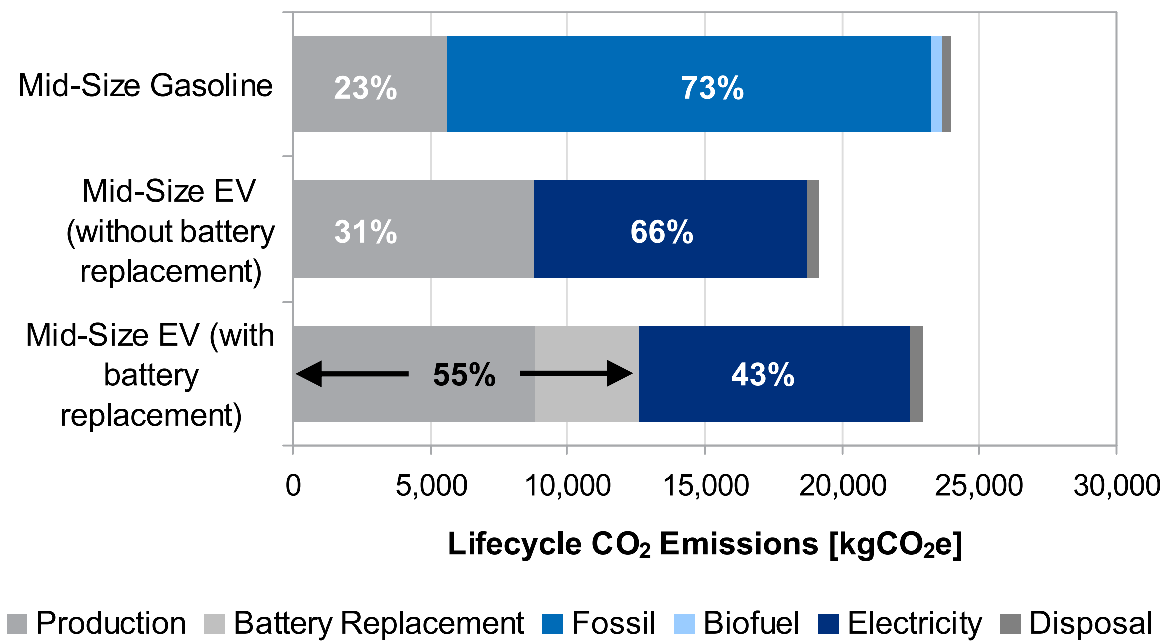
* The Product Category Rule for passenger cars currently states lifetime mileage as 150,000 km. This project has not assessed if this definition is appropriate for current and future passenger car technologies

Source: Ricardo

Other assumptions used in Ricardo's high level analysis of life cycle CO_2 emissions from passenger cars

Other assumptions

- Ricardo's top-down methodology provides a high level estimate of the production, in-use and disposal CO_2 emissions of a generic vehicle, useful for providing an indication of future trends in life cycle CO_2. This process does not currently confirm with ISO 14040
- Assume tailpipe CO_2 is equal to tailpipe CO_2e, since tailpipe emissions other GHGs will be very small
- For EVs, EREVs and PHEVs, assume the battery does not need to be replaced during the vehicle lifetime
  - This study has not investigated the likelihood of a Li-ion or NiMH battery pack lasting the lifetime of a plug-in vehicle



HIGH LEVEL ESTIMATE

- If the battery has to be replaced during the vehicle's life, then the embedded CO_2 emissions will increase, as illustrated in the chart left

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendices

Source: Ricardo

Appendix 3

Vehicle Type Approval

Regulations are enforceable by law, while codes and standards tend to be voluntary unless referred to in regulations

Definitions

Directives	• A directive is a legislative act of the European Union, which requires member states to transport it into national law, without dictating the means of achieving that result
Regulations	• A regulation is a legislative act which becomes immediately enforceable as law. It is a statutory document, legally binding and has to be adhered to • It is self-executing and do not require any implementing measures
Codes	• A code is a collection of laws or rules, specifying the minimum standard to adhere to • Usually voluntary, but depends on its jurisdiction
Standards	• A Technical Standard is an establish norm or requirement, usually defined in a formal document • Developed by Standards Organisations, with diverse input, usually voluntary, but might become mandatory if adopted by government • Standards are not legally binding unless refered to in a regulation

Source: Ricardo Legal Department; Wikipedia

Vehicle Type Approval is granted to a vehicle that meets a minimum set of regulatory, technical and safety requirements

What is European Vehicle Type Approval?

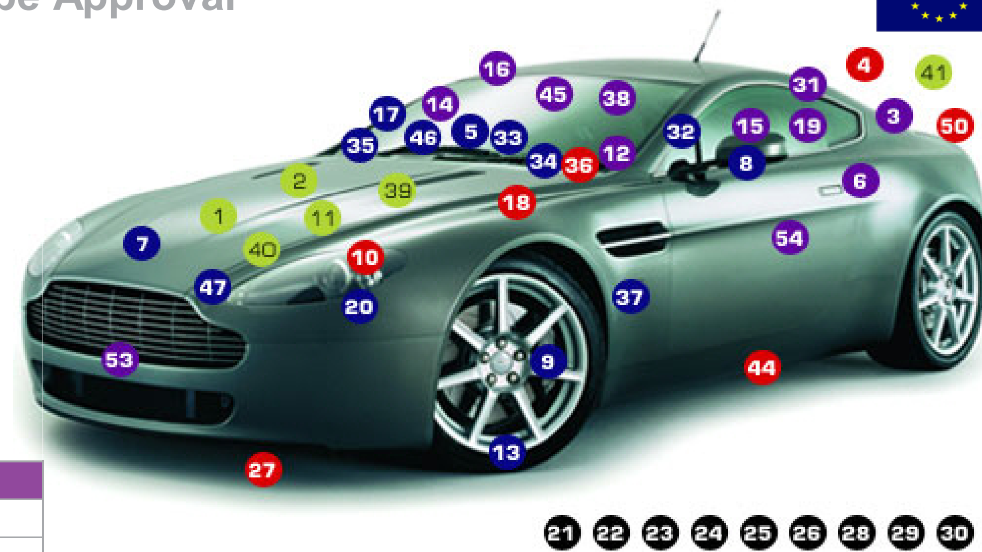
- Vehicle Type Approval is the procedure whereby a Member State certifies that a type of vehicle satisfies the relevant administrative provisions and technical requirements relating to:
  - Active and passive safety
  - Protection of the environment
  - Performance and other issues
- The objective of Vehicle Type Approval is:
  - To enable vehicles to be put on the market according to common requirements
  - To ensure the proper functioning of the internal market in the EU
- The concept is also applicable to components and systems
- Within the Europe Community, the framework for the type approval of motor vehicles is defined in **EC Directive 2007/46/EC**
- The **EC Whole Vehicle Type Approval** system **(ECWVTA)** means that if manufacturers can obtain approval for a vehicle type in one Member State, the vehicle can be marketed within the EU without further tests or checks, subject to presenting a **certificate of conformity**
- Automotive EC Directives and UN ECE Regulations require third party approval (e.g. UK VCA)

Source: European Commission

To obtain European Type Approval, a vehicle has to comply with ~50 EC Directives

Europe: Application Standards for Vehicle Type Approval

Environment
01. Sound Levels EC 2007/34
02. Emissions EC 2003/76
11. Diesel Smoke EC 2005/21
39. Fuel Consumption EC 2004/3
40. Engine Power EC 1999/99
41. Diesel Emissions EC 2008/74



Active Safety	Passive Safety
05. Steering Equipment EC 1999/7	19. Safety Belt Anchorage EC 2005/41
07. Audible Warning EC 70/388	16. Exterior Projections EC 2007/15
35. Wash / Wipe EC 94/68	15. Seat Strength EC 2005/39
13. Antitheft EC 95/56	14. Protective Steering EC 91/662
32. Forward Vision EC 90/630	03. Fuel Tank EC 2006/20
08. Rear Visibility EC 2005/27	12. Interior Fittings EC 2000/4
46. Tyres EC 2005/11	31. Safety Belts EC 2005/40
17. Speedometer and Reverse Gear EC 97/39	06. Door Latches and hinges EC 2001/31
34. Defrost / Demist EC 78/317	38. Head restraints EC 78/932
09. Braking EC 2002/78	45. Safety glazing EC 2001/92
20. Lighting Installation EC 2008/89	53. Frontal impact EC 1999/98
33. Identification of Controls EC 94/53	54. Side impact EC 96/27
37. Wheel Guards EC 94/78	

Lighting Equipment	Other Directives
21. Reflex Reflectors EC 97/29	27. Towing Hooks EC 96/64
22. Side, Rear and Stop lamps EC 97/30	04. Rear Registration Plate EC 70/222
23. Direction indicator lamps EC 1999/15	18. Statutory Plates EC 78/507
24. Rear registration plate lamp EC 97/31	36. Heating systems 2004/78
25. Headlamps (including bulbs) EC 1999/17	10. Radio Interference Suppression EC 2009/19
26. Front fog lamps EC 1999/18	44. Masses and Dimensions EC 95/48
28. Rear fog lamps EC 1999/14	50. Mechanical Couplings EC 94/20
29. Reversing Lamps EC 97/32	
30. Parking Lamps EC 1999/16	

Source: www.vca.gov.uk