Preparing for a Life Cycle CO₂ Measure

A report to inform the debate by identifying and establishing the viability of assessing a vehicle’s life cycle CO₂e footprint

Date 20 May 2011
Report RD.11/124801.4
Project Q57627
Confidential Low Carbon Vehicle Partnership

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Approved Dave Greenwood
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  - Gaps, Accuracy and Further Work
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LowCVP commissioned a study to identify and establish the viability of assessing a vehicle’s life cycle CO₂ footprint

Background

- The current metric for comparing the GHG emissions of European passenger cars is based on measuring the tailpipe CO₂ emissions over the New European Drive Cycle (NEDC).
- Legislative targets for reducing corporate fleet average CO₂ are driving the development of low carbon technologies and alternative fuels.
- The tailpipe CO₂ 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 CO₂ 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 to 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?
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
<table>
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<tbody>
<tr>
<td>AMT</td>
<td>Automated Manual Transmission</td>
<td>EREV</td>
<td>Extended Range Electric Vehicle</td>
<td>MPI</td>
<td>Multi-Point (fuel) Injection</td>
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<td>Auto</td>
<td>Automatic Transmission</td>
<td>EV</td>
<td>Electric Vehicle</td>
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<td>New European Drive Cycle</td>
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<td>FAME</td>
<td>Fatty Acid Methyl Ester</td>
<td>NiMH</td>
<td>Nickel Metal Hydride</td>
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<td>Diesel with up to 10%vol FAME</td>
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<td>Fuel Cell Vehicle</td>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>100% biodiesel</td>
<td>FQD</td>
<td>Fuel Quality Directive</td>
<td>PAS</td>
<td>Power Assisted Steering</td>
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<td>BoM</td>
<td>Bill of materials</td>
<td>GDI</td>
<td>Gasoline Direct Injection</td>
<td>PEM</td>
<td>Proton Exchange Membrane</td>
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<td>CO₂</td>
<td>Carbon Dioxide</td>
<td>GHG</td>
<td>Greenhouse Gas</td>
<td>PFI</td>
<td>Port Fuel Injection</td>
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<td>CO₂e</td>
<td>Carbon Dioxide equivalent</td>
<td>GWP</td>
<td>Greenhouse Gas Warming Potential</td>
<td>PHEV</td>
<td>Plug-In Hybrid Electric Vehicle</td>
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<td>CVT</td>
<td>Continuously Variable Transmission</td>
<td>H&amp;S</td>
<td>Health and Safety</td>
<td>TTW</td>
<td>Tank-to-Wheels</td>
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<td>Dual Clutch Transmission</td>
<td>HC</td>
<td>Hydrocarbons</td>
<td>R&amp;D</td>
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<td>HCCI</td>
<td>Homogeneous Charge Compression Ignition</td>
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<td>DI</td>
<td>Direct Injection</td>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
<td>UN ECE</td>
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<td>E10</td>
<td>Gasoline with up to 10%vol ethanol</td>
<td>HVAC</td>
<td>Heating Ventilation and Air Conditioning</td>
<td>V6</td>
<td>V 6-cylinder engine</td>
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<tr>
<td>E20</td>
<td>Gasoline with up to 20%vol ethanol</td>
<td>I4</td>
<td>In-line 4-cylinder engine</td>
<td>VCA</td>
<td>Executive Agency of the United Kingdom Department for Transport</td>
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<td>E85</td>
<td>Gasoline with up to 85%vol ethanol</td>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<td>Variable Geometry Turbocharger</td>
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<td>EC</td>
<td>European Commission</td>
<td>ISO</td>
<td>International Organisation for Standardization</td>
<td>VVA</td>
<td>Variable Valve Actuation</td>
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<td>ECU</td>
<td>Engine Control Unit</td>
<td>LCA</td>
<td>Life Cycle Assessment</td>
<td>VVT</td>
<td>Variable Valve Timing</td>
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<tr>
<td>EoL</td>
<td>End-of-Life</td>
<td>LCI</td>
<td>Life Cycle Inventory</td>
<td>WTT</td>
<td>Well-to-Tank</td>
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<td>EPAS</td>
<td>Electric Power Assisted Steering</td>
<td>Li-Ion</td>
<td>Lithium Ion</td>
<td>WTW</td>
<td>Well-to-Wheels</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>ZEV</td>
<td>Zero Emission Vehicle</td>
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</table>

Source: Ricardo
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$_2$O).
- Life cycle assessment studies frequently refer to carbon dioxide equivalent (CO$_2$e or CO$_2$eq), 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$_2$e value.
- Examples of GWP for common GHGs is provided in the table below.

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Global Warming Potential (100 years time horizon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>1</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>21</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>310</td>
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</tbody>
</table>

- GWP is sometimes referred 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.

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The current CO$_2$ metric for comparing passenger cars is based on measuring tailpipe CO$_2$ emissions over the NEDC

- 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\textsubscript{2} measure include the used of a defined drive cycle, test procedures and reference fuel

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

- These strengths conversely can be seen as limitations …
Limitations of the existing tailpipe CO\textsubscript{2} measure revolve around the laboratory conditions not representing the real world conditions

<table>
<thead>
<tr>
<th>Limitations</th>
<th>Comments</th>
</tr>
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</table>
| Tailpipe only              | ● No consideration of well-to-tank CO\textsubscript{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\textsubscript{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\textsubscript{2} data
  - In general, fuel consumption and tailpipe CO\textsubscript{2} was higher than the official, published fuel consumption from the NEDC test
  - Real world tailpipe CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} emissions appear to be ~20\% worse than the certified figures
Real world tailpipe CO\textsubscript{2} could be 5-40% higher than the NEDC CO\textsubscript{2} measure for conventional passenger cars …

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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>NEDC [L/100km]</td>
<td>AutoCar Test [L/100km]</td>
<td>NEDC [gCO\textsubscript{2}/km]</td>
<td>AutoCar Test [gCO\textsubscript{2}/km]</td>
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<tr>
<td>A: Mini</td>
<td>Hyundai I10</td>
<td>Gasoline</td>
<td>5</td>
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<td>5.5</td>
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<td>B: Small</td>
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<td>158.4</td>
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<td>189.6</td>
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<td>Ford Fiesta</td>
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<td>8.3</td>
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<td>199.2</td>
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<tr>
<td>C: Lower Medium</td>
<td>Audi A3</td>
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<td>9.1</td>
<td>12.2</td>
<td>218.4</td>
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<td>D: Upper Medium</td>
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<td>10.7</td>
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<td>10.8</td>
<td>175.2</td>
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Source: AutoCar; Ricardo Analysis
Strengths and Limitations of the existing tailpipe CO₂ measure

... and for hybrids

<table>
<thead>
<tr>
<th>Segment</th>
<th>Vehicle</th>
<th>Fuel</th>
<th>Fuel Consumption</th>
<th>Tailpipe CO₂</th>
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<tbody>
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<td></td>
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<td></td>
<td>NEDC [L/100km]</td>
<td>AutoCar Test [L/100km]</td>
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<td>Gasoline Hybrid</td>
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<td>Lexus RX450h</td>
<td>Gasoline Hybrid</td>
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<thead>
<tr>
<th>Segment</th>
<th>Vehicle</th>
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<th>Consumption</th>
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<td>NEDC [Wh/100km]</td>
<td>AutoCar Test [Wh/100km]</td>
<td>NEDC [gCO₂/km]</td>
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<td>G: Sports</td>
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<td>Electricity</td>
<td>1.74</td>
<td>2.67</td>
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</table>
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A vehicle’s life cycle can be divided into four “blocks” – production of the vehicle, production of the fuel, “in-use”, and disposal.

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

**“Fuel”**
- Fossil fuel production
- Electricity generation
- Hydrogen production
- ...

**Distribute**
Distribution network efficiency
- Power lines
- Pipelines
- Tankers
- ...

**“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

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>R&amp;D / prototypes</td>
<td>Vehicle size / segment</td>
<td>Material selection</td>
<td>Manufacturing processes</td>
<td>Supply chain</td>
<td>Number of workers</td>
</tr>
<tr>
<td>Test rigs</td>
<td>Vehicle mass</td>
<td>Geographic source of material</td>
<td>Manufacturing / factory efficiency</td>
<td>Types of transport</td>
<td>Daily commute</td>
</tr>
<tr>
<td>Design process</td>
<td>Powertrain technology</td>
<td>Extraction process</td>
<td>Location</td>
<td>Distance travelled</td>
<td>Heat and light for offices / factory</td>
</tr>
<tr>
<td>Supplier selection</td>
<td>Technology options</td>
<td>Recycled content (primary vs. secondary)</td>
<td>Waste produced</td>
<td>Packaging</td>
<td></td>
</tr>
<tr>
<td>Homologation testing</td>
<td>E.g. Choice of battery, electric motor, etc.</td>
<td>Material availability</td>
<td>Re-use of waste material</td>
<td>Geography</td>
<td></td>
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<tr>
<td></td>
<td>Number of components</td>
<td>Energy mix</td>
<td></td>
<td></td>
<td>H&amp;S considerations</td>
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<tr>
<td></td>
<td>Model variant</td>
<td></td>
<td></td>
<td></td>
<td>Environmental legislation considerations</td>
</tr>
</tbody>
</table>

**Source**: Ricardo
The vehicle specification determines the design of the vehicle, and its resulting embedded emissions

Elements from vehicle production contributing to life cycle CO₂ emissions

- **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

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

- **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**

- **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**

- **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**

- **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**

- **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 CO₂ from vehicle production

Elements from vehicle production contributing to life cycle CO₂ emissions

- 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

- Extraction process dependent on geographical source, and cost

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

- Homologation / Technology

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

- 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

- 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

- Extraction process dependent on geographical source, and cost

- 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 CO₂ emissions from vehicle production

Elements from vehicle production contributing to life cycle CO₂ emissions

<table>
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<tr>
<td>- LCA studies suggest transport of parts along the supply chain has a relatively small contribution to life cycle CO₂ emissions</td>
<td>- Data on the logistics of the supply chain would be known by the OEM / Tier 1 supplier</td>
<td>- Several LCI databases contain data on CO₂ emissions resulting from transport of goods. Again, values can vary between databases, depending on information source, global region and year</td>
<td>- Supply chain</td>
<td>- Number of workers</td>
<td></td>
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<tr>
<td>- Technology options</td>
<td>- E.g. Choice of battery, electric motor, etc.</td>
<td>- Number of components</td>
<td>- Types of transport</td>
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<td>- Supplier selection</td>
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<td>- Business trips to visit suppliers, etc.</td>
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</table>

These elements are generally considered to be outside the LCA boundary for a typical passenger car.
The proposed element boundary for production includes vehicle specification, materials, energy, production processes and logistics.

Elements from vehicle production contributing to life cycle CO₂ 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**
  - Can be measured / known
  - Could be measured / known
  - Difficult to measure / has to be assumed

Source: Ricardo
Well-to-tank CO₂ emissions from the fuel depend on the primary energy source, production process and the refuelling infrastructure.

Elements from fuel well-to-tank contributing to life cycle CO₂ 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 distributor
  - Restrictions on fuel transportation

- **People**
  - Employees
  - H&S considerations
  - Environmental legislation considerations

Source: Ricardo
The choice of primary energy source has a strong influence on the fuel production process and associated WTW CO₂ emissions

Elements from fuel well-to-tank contributing to life cycle CO₂ emissions

**Primary Energy**
- 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 CO₂ 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

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

**Embedded emissions**
- E.g. CO₂ 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

**Distribution & Infrastructure**
- 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

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)

**Distribution & Infrastructure**
- This will determine the fuel processing options
- There are different methods for allocating the CO$_2$ emissions by by-product
- This can impact the carbon intensity of the fuel

**People**
- 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

**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 CO₂ 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 distributors.
  - 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.

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

### Elements from fuel well-to-tank contributing to life cycle CO₂ 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
- Employees
  - H&S considerations
  - Environmental legislation considerations

#### People
- Employees
- H&S considerations
- Environmental legislation considerations
Elements and Boundaries for evaluating life cycle CO\textsubscript{2} emissions

**CO\textsubscript{2} emissions from the “in-use” phase depend on the vehicle technology, fuel, and how the vehicle is driven**

Elements from use phase contributing to life cycle CO\textsubscript{2} emissions

<table>
<thead>
<tr>
<th>Vehicle Specification</th>
<th>Fuel</th>
<th>Driver</th>
<th>Geography</th>
<th>Maintenance &amp; Servicing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle size / type</td>
<td>Fuel type / energy vector(s)</td>
<td>Ownership model</td>
<td>Location</td>
<td></td>
</tr>
<tr>
<td>Kerb weight</td>
<td>Fuel specification</td>
<td>Owner affluence</td>
<td>Terrain (e.g. hills vs. flat)</td>
<td></td>
</tr>
<tr>
<td>Powertrain architecture and technology</td>
<td>Fuel quality</td>
<td>Driving habits</td>
<td>Climate and weather conditions</td>
<td></td>
</tr>
<tr>
<td>Tailpipe emissions and aftertreatment</td>
<td>Fuel supplier</td>
<td>Duty cycle(s)</td>
<td>Types of road (e.g. motorway vs. urban)</td>
<td></td>
</tr>
<tr>
<td>Vehicle performance</td>
<td>Fuel additive packs</td>
<td>Length of journeys</td>
<td>Traffic management</td>
<td></td>
</tr>
<tr>
<td>Model variant</td>
<td>Standard grade vs. Premium product</td>
<td>Number of journeys per day</td>
<td>- Roundabouts, traffic lights and junctions</td>
<td></td>
</tr>
<tr>
<td>Load capacity</td>
<td>Fuel availability</td>
<td>Annual mileage [km]</td>
<td>- Speed bumps</td>
<td></td>
</tr>
<tr>
<td>Target price</td>
<td>Fuel price</td>
<td>Vehicle loading (e.g. passenger mass, luggage mass)</td>
<td>- Speed limit changes</td>
<td></td>
</tr>
<tr>
<td>Fuel consumption [L/100km]</td>
<td>Fuel taxation</td>
<td>Care of vehicle (e.g. regular checking of fluid levels and tyre pressure, etc.)</td>
<td>Road congestion</td>
<td></td>
</tr>
<tr>
<td>Tailpipe CO\textsubscript{2} emissions [g/km]</td>
<td>Actual, real-world fuel consumption</td>
<td>Use of onboard gadgets (e.g. GPS)</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Use of air conditioning</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Ricardo

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In-Use
The manufacturer’s vehicle specification has a strong influence on the published fuel consumption and tailpipe CO₂ data

Elements from use phase contributing to life cycle CO₂ emissions

- 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

- These elements strongly influence the vehicle’s NEDC based fuel consumption and tailpipe CO₂ 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 CO₂ emissions [g/km] multiplied by assumed life time mileage provided an indication of vehicle’s in-use tank-to-wheel CO₂ emissions

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

Elements and Boundaries for evaluating life cycle CO₂ emissions

### Elements from use phase contributing to life cycle CO₂ emissions

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<tr>
<td>- Vehicle size / type</td>
<td>- 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 CO₂ factor.</td>
<td>- 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.</td>
</tr>
<tr>
<td>- Kerb weight</td>
<td>- In Europe, the current fuel specifications for diesel and gasoline are defined in EN 590:2009 and EN 228:2008.</td>
<td></td>
</tr>
<tr>
<td>- Powertrain</td>
<td>- 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.</td>
<td></td>
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<tr>
<td>architecture and technology</td>
<td>- In Europe, the current fuel specifications for diesel and gasoline are defined in EN 590:2009 and EN 228:2008.</td>
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<td>- Vehicle performance</td>
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<td>- Load capacity</td>
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</table>

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

Source: Ricardo
Driver behaviour adds variability into the in-use CO₂ results

Elements from use phase contributing to life cycle CO₂ emissions

- The vehicle manufacturer has little or no control over what happens to the vehicle after it is sold
- Distanced travelled over the lifetime of the vehicle has a strong influence over the lifetime CO₂ 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 CO₂ emissions [g/km]

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
- 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 CO₂ 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

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

Source: Ricardo
Elements from use phase contributing to life cycle CO\textsubscript{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
- Traffic management systems which require the vehicle to brake can contribute to higher fuel consumption and CO\textsubscript{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

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

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

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.

In-Use

Source: Ricardo
The proposed boundary for assessing in-use CO₂ could include all these elements, or ...

### Elements from use phase contributing to life cycle CO₂ emissions

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

### Proposed Element Boundary

- 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
- 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
- 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]
... focus on the NEDC results and Product Categorisation Rules for a common comparison

Elements from use phase contributing to life cycle CO\textsubscript{2} emissions

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<td>Fuel specification</td>
<td>Owner affluence</td>
<td>Terrain (e.g. hills vs. flat)</td>
<td></td>
</tr>
<tr>
<td>Powertrain architecture and technology</td>
<td>Fuel quality</td>
<td>Driving habits</td>
<td>Climate and weather conditions</td>
<td></td>
</tr>
<tr>
<td>Tailpipe emissions and aftertreatment</td>
<td>Oil and coolant changes</td>
<td>Duty cycle(s)</td>
<td>Types of road (e.g. motorway vs. urban)</td>
<td></td>
</tr>
<tr>
<td>Vehicle performance</td>
<td>Fuel supplier</td>
<td>Length of journeys</td>
<td>Traffic management</td>
<td></td>
</tr>
<tr>
<td>Model variant</td>
<td>Fuel additive packs</td>
<td>Number of journeys</td>
<td>– Roundabouts, traffic lights and junctions</td>
<td></td>
</tr>
<tr>
<td>Load capacity</td>
<td>Standard grade vs. Premium product</td>
<td>per day</td>
<td>– Speed bumps</td>
<td></td>
</tr>
<tr>
<td>Target price</td>
<td>Fuel availability</td>
<td></td>
<td>– Speed limit changes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel taxation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Actual, real-world fuel consumption</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel consumption [L/100km]</td>
<td>Can be measured / known</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailpipe CO\textsubscript{2} emissions [g/km]</td>
<td>Could be measured / known</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

▲ Annual mileage [km]

▲ Vehicle life time [years]

Source: Ricardo
Emissions from vehicle end-of-life largely depend on what happens to the vehicle and its components.
Elements related to the vehicle specification determine what could happen during the EoL phase

Elements from vehicle end-of-life contributing to life cycle CO\textsubscript{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
  - 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

- **People**
  - 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

Source: Ricardo
Geographical location and the processes used to dismantle and recycle the vehicle could have a large impact on EoL CO₂ emissions

Elements from vehicle end-of-life contributing to life cycle CO₂ emissions:

- **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

- **Disposal**
  - Waste disposal method (e.g. Landfill vs. energy recovery)
  - Components suitable for re-use or re-manufacturing
  - Allocation of credit for recycling / re-use
  - Waste disposal method (e.g. Landfill vs. energy recovery)
  - Hazardous substances

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 CO₂ emissions

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 [link](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.

Re-Use & Recycling:

- Recycability of vehicle components.
- Actual quantity 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.

<table>
<thead>
<tr>
<th>Vehicle Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Vehicle size / segment</td>
</tr>
<tr>
<td>• Vehicle mass</td>
</tr>
<tr>
<td>• Powertrain technology</td>
</tr>
<tr>
<td>• Technology options (e.g. battery type)</td>
</tr>
<tr>
<td>• Number of components</td>
</tr>
<tr>
<td>• Model variant</td>
</tr>
<tr>
<td>• Materials</td>
</tr>
<tr>
<td>• Methods for joining parts together</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Logistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Vehicle collection</td>
</tr>
<tr>
<td>• Transport of vehicle / components to EoL facility</td>
</tr>
<tr>
<td>• Distributions of recycled materials / components</td>
</tr>
<tr>
<td>• Geographical location of EoL facility (e.g. Europe vs BRIC)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Process for vehicle disassembly</td>
</tr>
<tr>
<td>• Crushing</td>
</tr>
<tr>
<td>• Process for sorting materials / components</td>
</tr>
<tr>
<td>• Processing efficiency</td>
</tr>
<tr>
<td>• EoL process effectiveness</td>
</tr>
<tr>
<td>• Cleaning</td>
</tr>
<tr>
<td>• Energy required</td>
</tr>
<tr>
<td>• Available energy mix used</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Re-Use &amp; Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Recyclability of vehicle components</td>
</tr>
<tr>
<td>• Actual quantity of material / components recycled</td>
</tr>
<tr>
<td>• Components suitable for re-use or re-manufacturing</td>
</tr>
<tr>
<td>• EoL process effectiveness</td>
</tr>
<tr>
<td>• Cleaning</td>
</tr>
<tr>
<td>• Energy required</td>
</tr>
<tr>
<td>• Available energy mix used</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Quantity of waste material</td>
</tr>
<tr>
<td>• Waste disposal method (e.g. Landfill vs. energy recovery)</td>
</tr>
<tr>
<td>• Disposal of waste fluids</td>
</tr>
<tr>
<td>• Disposal of electrical and battery components</td>
</tr>
<tr>
<td>• Hazardous substances</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>People</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Employees in logistics chain</td>
</tr>
<tr>
<td>• Employees of waste disposal facilities</td>
</tr>
<tr>
<td>• People vs machines for sorting materials</td>
</tr>
<tr>
<td>• H&amp;S considerations</td>
</tr>
<tr>
<td>• Environmental considerations</td>
</tr>
</tbody>
</table>

Source: Ricardo

Proposed Element Boundary

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.
Contents

- Introduction
- Strengths and Limitations of the existing tailpipe CO\textsubscript{2} measure
- Elements and Boundaries for evaluating life cycle CO\textsubscript{2} emissions
- Impact of Regulations on life cycle CO\textsubscript{2} emissions
- Consequences of Technology Evolution on life cycle CO\textsubscript{2} emissions
- Gaps, Accuracy and Further Work
- Recommendations
- Conclusions
- Appendices
Some legislation is directly designed to reduce a passenger car’s environmental impact but with unintended consequences …

<table>
<thead>
<tr>
<th>Legislation</th>
<th>Relative effect on life cycle CO₂ emissions</th>
<th>Commentary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production</td>
<td>In-use</td>
</tr>
<tr>
<td></td>
<td>WTT</td>
<td>TTW</td>
</tr>
<tr>
<td>Tailpipe CO₂ (Regulation No 443/2009)</td>
<td>✧</td>
<td>✧</td>
</tr>
<tr>
<td>Tailpipe Emissions (Directive 2003/76/EC)</td>
<td>✧</td>
<td>✧</td>
</tr>
<tr>
<td>Other Type Approval legislation* (as defined by Directive 2007/46/EC)</td>
<td>✧</td>
<td>✧</td>
</tr>
<tr>
<td>End-of-Life Directive (Directive 2000/53/EC)</td>
<td>✧</td>
<td>✧</td>
</tr>
</tbody>
</table>

Legend: ✧ Increases CO₂ emissions ✧ Decreases CO₂ emissions ✧ No significant impact on CO₂ emissions ✧ Unknown impact ✧ Intended impact

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

Source: European Commission, IFQC, Ricardo analysis
Examples of legislation that may have a positive or negative effect on the life cycle CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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

- Introduction
- Strengths and Limitations of the existing tailpipe CO\textsubscript{2} measure
- Elements and Boundaries for evaluating life cycle CO\textsubscript{2} emissions
- Impact of Regulations on life cycle CO\textsubscript{2} emissions
- Consequences of Technology Evolution on life cycle CO\textsubscript{2} emissions
- Gaps, Accuracy and Further Work
- Recommendations
- Conclusions
- Appendices
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 CO₂ 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” (CO₂ 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)
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

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/
Consequences of Technology Evolution on life cycle CO\textsubscript{2} emissions

OEM LCA studies suggest passenger car life cycle CO\textsubscript{2} emissions are 20-80 tonnes, depending on segment and lifetime mileage

Life Cycle Assessment of Passenger Cars – Baseline Data from Literature

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Description</th>
<th>Lifetime Mileage [km]</th>
<th>Life Cycle Total CO\textsubscript{2}e [tonnes CO\textsubscript{2}]</th>
<th>Life Cycle [%]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Production</td>
<td>In-Use</td>
</tr>
<tr>
<td>VW Polo</td>
<td>Diesel 1.6L TDI, 55 kW (un-laden weight 1157 kg)</td>
<td></td>
<td>23</td>
<td>20.6%</td>
<td>79%</td>
</tr>
<tr>
<td>VW Polo</td>
<td>Gasoline 1.4L MPI, 63 kW (un-laden weight 1104 kg)</td>
<td>150,000</td>
<td>29.5</td>
<td>~17%</td>
<td>~83%</td>
</tr>
<tr>
<td>VW Passat Estate B6</td>
<td>Diesel 2.0L TDI, 103 kW (un-laden weight 1510kg)</td>
<td></td>
<td>32.4</td>
<td>19%</td>
<td>80%</td>
</tr>
<tr>
<td>VW Passat Estate B6</td>
<td>Gasoline 1.6L FSI, 85 kW (un-laden weight 1403kg)</td>
<td></td>
<td>38.2</td>
<td>18%</td>
<td>81%</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>Hatchback 1.8L VVTi V (un-laden weight 1420kg)</td>
<td>150,000</td>
<td>-</td>
<td>26%</td>
<td>71%</td>
</tr>
<tr>
<td>Mercedes-Benz A-Class</td>
<td>A150 Gasoline 1.5L, 70 kW, with ECO start-stop system</td>
<td>300,000</td>
<td>32</td>
<td>16%</td>
<td>83%</td>
</tr>
<tr>
<td>Mercedes-Benz E-Class</td>
<td>E 220 CDI BlueEFFICIENCY Diesel 2.1L, 125 kW</td>
<td>300,000</td>
<td>48</td>
<td>18%</td>
<td>82%</td>
</tr>
<tr>
<td>Mercedes-Benz S400 Hybrid</td>
<td>Gasoline 3.5L V6 205 kW 15 kW motor, Li-ion battery</td>
<td>300,000</td>
<td>78</td>
<td>14%</td>
<td>85%</td>
</tr>
</tbody>
</table>

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

- 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

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Description</th>
<th>Lifetime Mileage [km]</th>
<th>Life Cycle Total CO(_2)e [tonnes CO(_2)]</th>
<th>Life Cycle [%]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Production</td>
<td>In-Use</td>
</tr>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
<td>64.6</td>
<td>13%</td>
</tr>
<tr>
<td>HEV</td>
<td>Based on Toyota Corolla type vehicle</td>
<td>240,000</td>
<td></td>
<td>46.1</td>
<td>18.8%</td>
</tr>
<tr>
<td>PHEV 30</td>
<td>Li-Ion battery technology</td>
<td></td>
<td></td>
<td>43.9</td>
<td>20.8%</td>
</tr>
<tr>
<td>PHEV 60</td>
<td></td>
<td></td>
<td></td>
<td>43.4</td>
<td>23.2%</td>
</tr>
<tr>
<td>PHEV 90</td>
<td></td>
<td></td>
<td></td>
<td>43.9</td>
<td>24.6%</td>
</tr>
<tr>
<td>Standard Car</td>
<td>C-segment vehicle (e.g. VW Golf)</td>
<td>150,000</td>
<td></td>
<td>40.3</td>
<td>12.9%</td>
</tr>
<tr>
<td>EV</td>
<td>C-segment vehicle (e.g. VW Golf), with 300 kg, 30 kWh Li-Ion battery pack</td>
<td>150,000</td>
<td></td>
<td>19.5</td>
<td>34.7%</td>
</tr>
</tbody>
</table>
To investigate further, Ricardo has compared estimates of life cycle CO\textsubscript{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\textsubscript{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\textsubscript{2}e/kWh (2010 values published by DECC)
- Further information about vehicle and fuel specifications is provided in the Appendix 2
Ricardo results show hybrids and EVs will have lower life cycle CO\textsubscript{2} emissions, but embedded emissions will be more significant.

- Predicted improvements in the conventional ICE powertrain designed to reduce in-use tailpipe CO\textsubscript{2}, will naturally help to lower the life cycle CO\textsubscript{2} emissions compared to current values.
- Life cycle CO\textsubscript{2} reductions for hybridisation and electrification could be 10-20% (compared to a mid-size gasoline passenger car in 2015).
- However, embedded CO\textsubscript{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\textsubscript{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\textsubscript{2}/kWh. Further details on assumptions is provided in the Appendix 2.
Diesel and gasoline passenger cars have similar life cycle CO₂ emissions, which generally increase with vehicle size.

As expected, larger cars have higher life cycle CO₂ emissions.

The embedded CO₂ for diesel vehicles is higher than the embedded CO₂ for gasoline vehicles. However, since tailpipe CO₂ emissions are generally lower, the life cycle CO₂ 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 CO₂ emissions, although this is mainly due to improvements in fuel economy leading to lower tailpipe CO₂.

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 gCO₂/kWh. Further details on assumptions is provided in the Appendix 2.
Increasing the biofuel content helps to reduce Well-to-Wheel CO₂ emissions …

Comparing Alternative Fuels

- The higher the biofuel content, the lower the WTW CO₂ 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 CO₂ emissions reduce, the embedded CO₂ emissions from production and disposal become a more significant part of the whole life cycle CO₂ 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 gCO₂/kWh. Further details on assumptions is provided in the Appendix 2.
Consequences of Technology Evolution on life cycle CO₂ emissions

... for conventional and alternative powertrain technologies

**Comparing Technologies with Alternative Fuels**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Production</th>
<th>Fossil</th>
<th>Biofuel</th>
<th>Electricity</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Size Gasoline</td>
<td>25%</td>
<td>70%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size Gasoline Full Hybrid</td>
<td>32%</td>
<td>62%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size Gasoline PHEV</td>
<td>39%</td>
<td>41%</td>
<td>16%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size Gasoline EREV</td>
<td>42%</td>
<td>30%</td>
<td>24%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size EV</td>
<td>57%</td>
<td>40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size FCV</td>
<td>31%</td>
<td>68%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E20. Electricity carbon intensity assumed to be 310 gCO₂/kWh. Further details on assumptions is provided in the Appendix 2.

- The WTW CO₂ 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 CO₂ emissions for plug-in vehicles.
- But, as a consequence, CO₂ emissions from production become more significant.
  - For an EV, >50% of life cycle CO₂ 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%.

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.

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.
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- Introduction
- Strengths and Limitations of the existing tailpipe CO₂ measure
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- Gaps, Accuracy and Further Work

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

**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

- 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

Source: Ricardo (2008)

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.
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.
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.

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

**Existing LCA Initiatives**

  - 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](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](http://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 CO₂ 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 initiatives 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 CO₂ footprint (“Clean ‘n’ Lean”)
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- **Recommendations**
  - Conclusions
  - Appendices
Europe currently has specific targets for reducing the environmental impact of a vehicle during the fuel, use and disposal phases, ...

Recommendations

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

Currently, there are no automotive targets specifically aimed at reducing CO₂ from production of the whole vehicle.

Production

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

"Fuel"

Generate

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

Distribute

Distribution network efficiency
- Power lines
- Pipelines
- Tankers
- …

The fleet average tailpipe CO₂ 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.

Disposal

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

“In-Use”

- Tailpipe CO₂ from driving
- Impact from maintenance and servicing

Source: Ricardo
… but there are no specific CO₂ targets for the production of the whole vehicle

Recommendations for a life cycle CO₂ measure

- Consider a new CO₂ metric based on the GHG emissions emitted during vehicle production [tCO₂e]
  - The vehicle’s life cycle CO₂ can then be calculated for a defined use, fuel and disposal scenario
- Consider targets aimed at reducing the life cycle CO₂ [tCO₂e]. For example:
  - Cap on production CO₂, dependent on vehicle segment
  - Reduction target for production or life cycle CO₂, compared to an appropriate baseline
  - Maximum “pay back period” for trading increased embedded emissions against reductions in tailpipe / WTW CO₂ 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 CO₂
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Future \( \text{CO}_2 \) 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 \( \text{CO}_2 \) from production and disposal is becoming a greater portion of the life cycle \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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
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Appendix 1

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Appendix 2

Further information on Ricardo analysis of impact of technology evolution on life cycle CO₂ 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

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Vehicle Description</th>
<th>Vehicle Mass [kg]</th>
<th>Tailpipe CO₂ [gCO₂/km]</th>
<th>EV Driving Range * [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Size Gasoline</td>
<td>1.4L 91kW I4 DI engine with VVT and FGT</td>
<td>1340</td>
<td>109</td>
<td>-</td>
</tr>
<tr>
<td>Mid-Size Gasoline Full Hybrid</td>
<td>1.4L 91kW I4 DI engine with VVT, 1.8 kWh NiMH battery pack, 56 kW Motor</td>
<td>1430</td>
<td>84</td>
<td>-</td>
</tr>
<tr>
<td>Mid-Size Gasoline PHEV</td>
<td>1.4L 91kW I4 DI engine with VVT, 4.8 kWh Li-ion battery back, 56 kW Motor</td>
<td>1460</td>
<td>47</td>
<td>20</td>
</tr>
<tr>
<td>Mid-Size Gasoline EREV</td>
<td>1.0L 44kW I3 PFI engine, 13.4 kWh Li-ion battery back, 72 kW Motor</td>
<td>1510</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>Mid-Size EV</td>
<td>32.2 kWh Li-ion battery back, 71 kW Motor</td>
<td>1480</td>
<td>0</td>
<td>180</td>
</tr>
<tr>
<td>Mid-Size FCV</td>
<td>73 kW PEM fuel cell system, 1.8 kWh Li-ion battery back, 67 kW Motor</td>
<td>1410</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Small Gasoline</td>
<td>1.0L 59kW I3 PFI engine with VVT</td>
<td>1080</td>
<td>103</td>
<td>-</td>
</tr>
<tr>
<td>Mid-Size Diesel</td>
<td>2.0L 101kW I4 engine with VGT Turbo</td>
<td>1420</td>
<td>105</td>
<td>-</td>
</tr>
<tr>
<td>Large Diesel</td>
<td>3.0L 123kW V6 engine with VGT Turbo</td>
<td>1720</td>
<td>113</td>
<td>-</td>
</tr>
<tr>
<td>Large Diesel, with downsized ICE and reduced vehicle weight</td>
<td>2.0L 123kW I4 engine with 2 stage turbocharging</td>
<td>1680</td>
<td>90</td>
<td>-</td>
</tr>
</tbody>
</table>

* 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 …

Fuel Specifications, and assumptions regarding Well-to-Tank CO₂ emissions (1/2)

- The study has considered three grades of gasoline:
  - E10 containing 10%\textsuperscript{vol}, 7%\textsuperscript{energy} ethanol
  - E20 containing 20%\textsuperscript{vol}, 14%\textsuperscript{energy} ethanol
  - E85 containing 80%\textsuperscript{vol}, 73%\textsuperscript{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 gCO₂e/MJ\textsubscript{fuel}, derived from RED typical values
    - Carbon intensity of gasoline is assumed to be 83.8 gCO₂e/MJ\textsubscript{fuel}, RED default value

- The study has considered three grades of diesel:
  - B7 containing 7%\textsuperscript{vol}, 6%\textsuperscript{energy} FAME
  - B10 containing 10%\textsuperscript{vol}, 9%\textsuperscript{energy} FAME
  - B100 containing 100%\textsuperscript{vol}, 100%\textsuperscript{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 gCO₂e/MJ\textsubscript{fuel}, derived from RED typical values
    - Carbon intensity of diesel is assumed to be 83.8 gCO₂e/MJ\textsubscript{fuel}, RED default value

... including electricity and hydrogen

Fuel Specifications, and assumptions regarding Well-to-Tank CO₂ emissions (2/2)

- Electricity for plug-in vehicles assumed to be from UK National Grid
  - 2010 UK electricity carbon intensity assumed to be 500 gCO₂e/kWh, 139 gCO₂e/MJ (DECC)
  - 2020 UK electricity carbon intensity assumed to be 310 gCO₂e/kWh, 86 gCO₂e/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 gCO₂e/MJ_{fuel}
Ricardo have developed a top-down methodology for estimating life cycle CO\textsubscript{2} emissions for a range of vehicle technologies

### Ricardo’s methodology for calculating high level estimates of life cycle CO\textsubscript{2} emissions

<table>
<thead>
<tr>
<th>Vehicle Production</th>
<th>In-Use</th>
<th>Fuel Production</th>
<th>Disposal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divide vehicle into key sub-systems</td>
<td>Build a vehicle simulation model to predict fuel consumption, energy requirements, and tailpipe CO\textsubscript{2} emissions [kgCO\textsubscript{2}e]</td>
<td>Use energy consumption data, split by fuel type, from Use phase</td>
<td>For this study, assume CO\textsubscript{2} emissions from Disposal is 5% of CO\textsubscript{2} emissions from production [kgCO\textsubscript{2}e]</td>
<td>Sum together the CO\textsubscript{2} emissions from each phase to obtain the total life cycle CO\textsubscript{2} emissions of the vehicle [kgCO\textsubscript{2}e]</td>
</tr>
<tr>
<td>For each system, determining the system mass and split by material</td>
<td>Calculate embedded emissions associated with the materials used</td>
<td>Identify carbon intensity for each fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculate embedded emissions resulting from production processes (e.g. energy mix)</td>
<td>Estimate embedded emissions resulting from production processes (e.g. energy mix)</td>
<td>Calculate the Well-to-Wheels CO\textsubscript{2} emissions resulting for the use of each fuel [gCO\textsubscript{2}e/km]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum together to calculate embedded CO\textsubscript{2} emissions for vehicle production [kgCO\textsubscript{2}e]</td>
<td></td>
<td>Multiply by life time mileage to obtain total CO\textsubscript{2} emissions from Use and Fuel [kgCO\textsubscript{2}e]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

* 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 CO₂ emissions from passenger cars

Other assumptions

- Ricardo’s top-down methodology provides a high level estimate of the production, in-use and disposal CO₂ emissions of a generic vehicle, useful for providing an indication of future trends in life cycle CO₂. This process does not currently confirm with ISO 14040.
- Assume tailpipe CO₂ is equal to tailpipe CO₂e, 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.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Production</th>
<th>Battery Replacement</th>
<th>Fossil</th>
<th>Biofuel</th>
<th>Electricity</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Size Gasoline</td>
<td>23%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size EV (without battery replacement)</td>
<td>31%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Size EV (with battery replacement)</td>
<td>55%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If the battery has to be replaced during the vehicle’s life, then the embedded CO₂ 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 gCO₂/kWh. Further details on assumptions is provided in the Appendices.
Appendix 3
Vehicle Type Approval
**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 referred 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)
To obtain European Type Approval, a vehicle has to comply with ~50 EC Directives

Europe: Application Standards for Vehicle Type Approval