Environmental Impact Assessment of Vectrix Electric Motorcycle

Prepared by Dr Ben Lane, Ecolane on behalf of Vectrix Corporation

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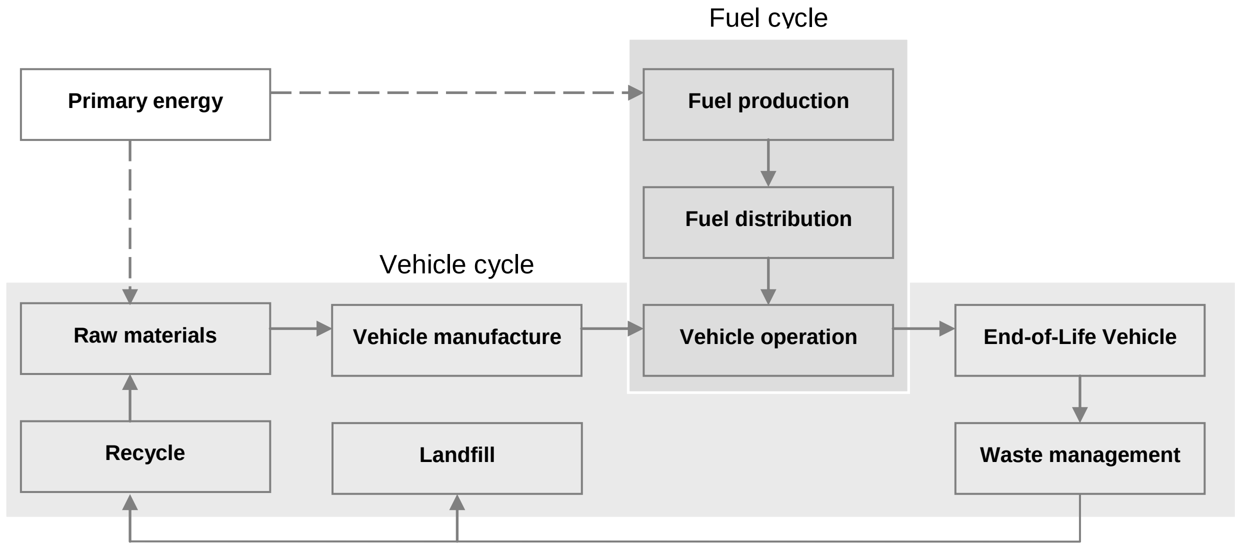
1 Impact assessment - methodology overview

In the case of road transport, air borne emissions are generated during both the fuel and vehicle cycles – i.e. as a result fuel production, vehicle manufacture, vehicle operation, and vehicle recycling/disposal. These emissions can be categorised as either *direct*, produced during operation of the vehicle, or as *indirect*, being generated during the production of the fuel, and the manufacture and disposal of the vehicle.

Any assessment of vehicle emissions must include direct emissions, as for most powered vehicles, these form the majority of total emissions. A more thorough analysis, however, needs also to include indirect emissions, as these form a significant proportion of total emissions generated – in the case of light-duty vehicles, indirect emissions account for around 15% of life cycle emissions.[1] Furthermore, in cases where electric vehicles are used all emissions associated with these modes are produced *upstream* at the power station, and are therefore classed as indirect.

Figure 1 summarises the fuel and vehicle life cycles – direct emissions are those generated during 'vehicle operation', all other sources are indirect.

Figure 1 Road vehicle fuel and vehicle cycles



Only analyses that include indirect emissions are able to compare life-cycle emissions for a large range of vehicle fuels (e.g. gasoline, diesel, biofuels, natural gas) and vehicle technologies (e.g. combustion engines, battery-electric and hybrid-electric vehicles). The analysis conducted by Ecolane, therefore, includes both the fuel and vehicle cycles and is able to compare the environmental impacts for a range of vehicle fuels and vehicle technologies.

Due to the importance of air emissions in the context of road transport, Ecolane's analysis focuses exclusively on quantifying the extent and impacts of life cycle *air emissions* arising from the fuel and vehicle cycles.[2] The emissions analysed include the gaseous pollutants: carbon monoxide (CO), oxides of nitrogen (NOx), hydrocarbons (NCs), particulates (PMs), sulphur dioxide (SO_2) and nitrous oxide (N_2O); and the three main greenhouse gases associated with road transport: carbon dioxide (CO2), methane (CH_4) and nitrous oxide (N_2O).

[1] SMMT Annual CO2 Report. Society of Motor Manufactures and Traders, UK, 2006.
[2] Note that secondary energy and environmental effects are not quantified – these include: impacts associated with the construction of energy generating, refinery, process plants, road infrastructure, changes in land use, resource depletion and waste disposal.

The methodology employed by Ecolane includes a comparison of the life cycle emissions generated for each of the vehicles assessed (i.e. it includes an emissions *inventory*). In this respect, the methodology follows a similar approach to the North American GREET project[3] and the European *Well-To-Wheels Analysis of Future Automotive Fuels and Power-trains*.[4] In contrast to the majority of other vehicle fuel/technology assessments, the methodology also quantifies the environmental *impact* of the pollutants generated. This is achieved by the use of the Car Environmental Rating Tool developed by the European Cleaner Drive Programme. Ecolane's methodology is, therefore, a comprehensive life cycle impact assessment – and is similar to the approach previously used for the recent UK project *Life Cycle Assessment of Vehicle Fuels and Technologies*.[5]

[3] GREET 2.7 —The Transportation Vehicle-Cycle Model. URL: http://www.transportation.anl.gov/software/GREET/index.html [accessed Dec 2007]

[4] Well-To-Wheels Analysis Of Future Automotive Fuels And Power-trains In The European Context. Report by Concawe, Eurcar and the EU Joint Research Centre, 2006.

[5] Life Cycle Assessment of Vehicle Fuels and Technologies. Conducted by Ecolane on behalf of the London Borough of Camden, 2006.

2 Fuel cycle methodology

In the case of most liquid and gaseous vehicle fuels, the fuel cycle includes the following processes during which energy is consumed and emissions are generated:

- Feedstock production – production of the raw materials in order to obtain the fuel needed;
- Feedstock transport –raw materials are transported to refineries or processing plants;
- Fuel production – refining/processing of the raw materials into standard fuel;
- Fuel distribution – distribution of the fuels to fuel stations;
- Fuel use – consumption of fuel during vehicle operation.

For gasoline and diesel, the feedstock production and distribution stages involve the extraction and separation of crude oil or gas, gas flaring and venting, and the use of gas turbines to provide on-site power where required. After transport by tanker or pipeline to the refinery, the crude oil undergoes simple distillation with the possible addition of fluid catalytic cracking or hydro-cracking processes to maximise the yield of useful distillation products. In most cases these are then distributed by pipeline to a terminal and then by road tanker to fuel stations for use.

For battery electric vehicles, electricity is generated using either fossil fuels, nuclear fuel or renewables. When fossil fuels are used, energy and emissions are generated during the extraction, transport and processing of the fuel feedstock. These fuels are then used in either coal-fired, oil-fired or gas-fired (mainly Combined Cycle) generating stations. For nuclear electricity, uranium must first be mined, then enriched and processed into a form suitable for the reactor type (e.g. Gas Cooled, Advanced Gas Cooled or Pressurised Water Reactor). Excluding the construction and infrastructure environmental impacts, renewably generated electricity (from solar, wind and hydro-electric sources) produces virtually no emissions during the generation stage. Whichever sources are used to generate electricity, further energy losses occur during transmission to point of use.

For all vehicle fuels, upstream fuel production emissions are calculated using published data quoted on an energy delivered basis (grams per GJ) for the following emissions: CO, HCs, NOx, PMs, SO2, CO_2, CH_4, and N_2O. For vehicles used in the US, data is sourced exclusively from the North American GREET model. These values are then multiplied by vehicle fuel economy (MJ/km) (sourced from the Environmental Protection Agency database – see below), and a unit conversion factor (0.001), to give the production emission in grams per mile (then converted to SI units of grams per kilometre).

Table 1 Upstream fuel production emissions data[6]

Fuel production gms/GJ	Passenger car Gasoline	Passenger car Gasoline Hybrid	Motorcycle Gasoline	Motorcycle Electric
Fuel PMs	11.36	11.36	11.36	274.52
Fuel NOx	47.44	47.44	47.44	227.08
Fuel CO	14.29	14.29	14.29	55.40
Fuel HCs	128.67	128.67	128.67	299.25
Fuel SO2	24.09	24.09	24.09	499.76
Fuel CO2	16583	16583	16583	208250
Fuel CH4	103	103	103	281
Fuel N20	1.09	1.09	1.09	2.95

For light duty vehicles (passenger cars) that are powered by gasoline, diesel or biofuels, estimates for vehicle fuel economy are sourced from the Environmental Protection Agency (EPA) which provides fuel economy (in US miles-per-gallon or 'mpg') data for all new cars available in the US.[7] For light-duty vehicles, 2008 vehicle data is used – this fuel economy data is (from 2008 onwards) adjusted to

[6] GREET 2.7 —The Transportation Vehicle-Cycle Model. URL: http://www.transportation.anl.gov/software/GREET/index.html [accessed Dec 2007]
[7] Green Vehicle Guide: US Environmental Protection Agency. URL: http://www.epa.gov/.

reflect real world driving conditions. For motorcycles fuelled by gasoline, 2005 data is used – the most recent year that fuel economy data for current models is available from the EPA.[8] Vectrix energy use per unit distance (in kWh/mile) is calculated from data provided by Vectrix UK based on published battery capacity and typical vehicle range.[9] All fuel economy data quoted in Imperial (US) units are then converted to SI units of litres/100km or kWh/100km.

For passenger cars, estimates for fuel economy and tailpipe emissions generated during vehicle operation are also sourced from the Environmental Protection Agency (EPA) which publishes NOx, NMOG (Non-methane organic compounds), PM, CO emission data for all new cars available in the US.[10] The emissions data used for this assessment is taken from measurements made using the test cycle that conforms to the current California Light-Duty Vehicle Emissions Standards for Air Pollutants, the most stringent vehicle emissions regulations that apply in the US. Motorcycle emissions of these air pollutants are sources from the California Air Resources Board (CARB) and are taken from Air Pollution Test Certificates as published by CARB.[11] As EPA data only includes NMOG emissions, methane emissions (CH_4) are estimated using methodology published by the Victoria Transport policy Institute.[12] Summing NMOG and CH_4 emissions gives total hydrocarbons (HCs).

Table 2 Vehicle fuel economy data – passenger cars (Imperial and SI units)

Model	Year	Displ	Cyl	Trans	Drive	Curb mass (kg)	Fuel	Veh Class	US mpg (comb)	UK mpg (comb)	UK lit/100km (comb)
TOYOTA Prius	2008	1.5	(4 cyl)	Auto-AV	2WD	1330	Gasoline	midsize car	46	55.2	5.1
HONDA Accord	2008	2.4	(4 cyl)	Auto-L5	2WD	1492	Gasoline	large car	24	28.8	9.8
FORD Taurus	2008	3.5	(6 cyl)	Auto-L6	2WD	1697	Gasoline	large car	22	26.4	10.7
HUMMER H3	2008	3.7	(5 cyl)	Auto-L4	4WD	2258	Gasoline	SUV	15	18.0	15.7
CHEVROLET Suburban	2008	6	(8 cyl)	Auto-L4	4WD	2546	Gasoline	SUV	14	16.8	16.8
FORD Focus	2008	2	(4 cyl)	Man-5	2WD	1190	Gasoline	small car	28	33.6	8.4

Table 3 Vehicle fuel economy data – motorcycles (Imperial and SI units)

Manufacturer	Model	Year data	Displ	Curb mass (kg)	Fuel	Veh Class	US mpg (combined)	UK mpg (combined)	UK lit/100km (combined)
VECTRIX	Maxi scooter	2008	N/A	210	Electric (renewable)	ZEV	N/A	N/A	4.60
VECTRIX	Maxi scooter	2008	N/A	210	Electric (US average)	ZEV	N/A	N/A	4.60
PIAGGIO	Vespa GT200	2005	198cc	230	Gasoline	Class II	77	92	3.06
SUZUKI	Burgman AN400	2005	400cc	300	Gasoline	Class III	57	68	4.16
HARLEY-DAVIDSON	V-Rod	2005	1247cc	400	Gasoline	Class III	41	49	5.74
HARLEY-DAVIDSON	XL1200 Sportster	2005	1200cc	370	Gasoline	Class III	45	54	5.19

Table 4 Vehicle emissions data – passenger cars (SI units)

Manufacturer	Model	CO2	CO	NMOG	HCs	NOx	PMs
		g/km	g/km	g/km	g/km	g/km	g/km
TOYOTA	Prius MkII	120	0.062	0.006	0.018	0.006	0.000
FORD	Focus	198	0.249	0.005	0.024	0.000	0.000
HONDA	Accord	231	0.062	0.003	0.025	0.006	0.000
FORD	Taurus	253	0.373	0.020	0.044	0.012	0.000
HUMMER	H3	371	0.559	0.032	0.068	0.012	0.000
CHEVROLET	Suburban	396	1.119	0.041	0.079	0.025	0.000

Table 5 Vehicle emissions data – motorcycles (SI units)

Manufacturer	Model	CO2	CO	NMOG	HCs	NOx	PMs
		g/km	g/km	g/km	g/km	g/km	g/km
VECTRIX	Maxi scooter	0	0.000	N/A	0.000	0.000	0.000
VECTRIX	Maxi scooter	0	0.000	N/A	0.000	0.000	0.000
PIAGGIO	Vespa GT200	72	4.000	N/A	0.300	0.100	0.000
SUZUKI	Burgman AN400	100	3.000	N/A	0.375	0.125	0.000
HARLEY-DAVIDSON	V-Rod	136	6.000	N/A	0.600	0.200	0.000
HARLEY-DAVIDSON	XL1200 Sportster	123	4.700	N/A	1.050	0.350	0.000

[8] Private communication, Dec 2007: "... the U.S. is not yet requiring the WMTC for motorcycle certification testing, so [the EPA]... have no WMTC data whatsoever regarding 2007 and 2008 motorcycles. ... the earliest model year that would be subject to the WMTC test would be 2011 or 2012."
[9] Assumes range of 50 miles on full battery charge (3.7 kWh). Source: private communication, Vectrix, UK.
[10] Annual Certification Test Results & Data: US Environmental Protection Agency. URL: http://www.epa.gov/.
[11] California Air Resources Board, 2007. URL: http://www.arb.ca.gov/msprog/onroad/cert/cert.php.
[12] Transportation Cost and Benefit Analysis, Victoria Transport policy Institute, 2006. URL: http://www.vtpi.org/tca/.

3 Vehicle cycle methodology

The vehicle cycle includes the following processes during which emissions are generated:

- Material production – the materials used include steel, plastics, non-ferrous metals such as aluminium, glass, rubber and composites such as glass fibre;
- Vehicle assembly – energy required to assemble components and operate manufacturing plant;
- Vehicle distribution – transport of a vehicle from the assembly line to the dealerships;
- Vehicle maintenance – maintenance and repair over the lifetime of the vehicle;
- Vehicle disposal – end-of-life vehicles (ELVs) are shredded and a proportion of some materials are recycled for further use.

Standardised emission data associated with the vehicle cycle is not available for all vehicle models as it is for the fuel cycle (i.e. fuel production and vehicle tailpipe emissions). Therefore, to quantify vehicle cycle emissions, the methodology developed for the GREET project is used. This method enables an estimate to be made for the emissions associated with vehicle production (the most significant part of the vehicle cycle). Combined with assumptions about lifetime mileages, a value for emissions per mile (and per kilometre) can be calculated.

The approach taken by the GREET methodology requires an analysis of the following information for each vehicle type assessed: vehicle mass (curb weight in pounds and kg), the vehicle composition by mass (pounds and kg) using a system of over 18 material category types, the emissions associated with the production of each material category (grams/lb and grams/kg) and the total energy required for vehicle assembly (MJ). For each vehicle, the mass of each of the constituent materials is multiplied by the respective emissions per unit mass associated with the material's production. This provides an estimate of the manufacture emissions profile associated with that particular vehicle type.

Given the variation in vehicle composition of different vehicle types (gasoline, diesel, gasoline hybrid, battery electric, etc), three vehicle types are assumed to represent all the vehicles analysed as part of this assessment. For gasoline, diesel and gasoline hybrid light-duty vehicles, and conventional motorcycles, GREET data is used. For battery electric motorcycles (e.g. Vectrix), Ecolane data is used (as this vehicle type is not represented in the standard GREET model). The methodology used by Ecolane to estimate vehicle cycle emissions follows a similar approach to that adopted by the GREET model and is based on a set of 12 material types (rather than 18) – a detailed account of the methodology can be found in the report *Life Cycle Assessment of Vehicle Fuels and Technologies*.[13]

Table 6 GREET and Ecolane vehicle cycle emission estimates

Vehicle cycle	Passenger car	Passenger car	Motorcycle	Motorcycle
gms/kg-km	Gasoline	Gasoline Hybrid	Gasoline	Electric
Vehicle PMs	0.034	0.039	0.034	0.012
Vehicle NOx	0.031	0.038	0.031	0.058
Vehicle CO	0.103	0.110	0.103	0.071
Vehicle HCs	0.085	0.100	0.085	0.067
Vehicle SO2	0.064	0.209	0.064	0.519
Vehicle CO2	19.4	24.2	19.4	34.4
Vehicle CH4	0.034	0.040	0.034	0.035
Vehicle N20	0.000	0.000	0.000	0.000

[13] Life Cycle Assessment of Vehicle Fuels and Technologies. Conducted by Ecolane on behalf of the London Borough of Camden, 2006.

4 Environmental impact methodology

To assess the environmental *impact* of fuel and vehicle cycle emissions, the Ecolane analysis adopts the methodology of the Car Environmental Rating Tool developed by the European Cleaner Drive Programme. This uses 'external costs' to establish the relative weight to attach to different emissions – these are monetary values that reflect the damage to the environment and to human health (see below). Using external costs allows the emissions from different vehicle types and different models to be compared on equivalent terms. It also allows for comparisons to be made between different impact categories, e.g. climate change vs. air pollution.

For this analysis, several changes have been made to the Cleaner Drive methodology. Whereas the original project only included the fuel cycle emissions, Ecolane has extended the methodology to include emissions associated with the vehicle cycle. Also, the costs originally used by Cleaner Drive for European vehicles have been adapted to reflect the external costs that apply in a North American context.

As external costs quantify environmental impacts, air quality emissions generated in urban areas have higher values than those in extra-urban areas. The Ecolane methodology uses extra-urban (rural) values for indirect emissions and a weighted average of urban and extra-urban values for direct (tailpipe) emissions – these are weighted to reflect the national average split between urban and extra urban mileage.[14]

Ecolane's impact rating methodology uses a weighted index of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), oxides of nitrogen (NOx), hydrocarbons (HCs), carbon monoxide (CO), particulate matter (PM10) and sulphur dioxide (SOx) emissions to produce a single score out of 100. The rating system also provides separate scores for greenhouse gas and air quality impacts (also out of 100).

Note that Ecolane has reversed the original Cleaner Drive rating system – this results in cleaner vehicles with *lower* emissions having a *lower* environmental rating. A vehicle having a rating of 0 (zero) would have zero environmental impact.

Table 7 External costs of air emissions used in this assessment [15,16,17]

Cost per tonne (EU€2007/tonne)	URBAN	RURAL	WEIGHTED AVERAGE
CO	€ 300	€ 0	€ 180
NOx	€ 7,738	€ 4,397	€ 6,404
VOC	€ 6,187	€ 5,074	€ 5,743
PM	€ 5,102	€ 2,500	€ 4,064
CO2	€ 8.63	€ 8.63	€ 8.63
CH4	€ 181	€ 181	€ 181
N2O	€ 2,675	€ 2,675	€ 2,675
SO2	€ 4,171	€ 683	€ 2,780

[14] Figures used are 60% VMT urban and 40% VMT rural. Ref: Contrasting Rural and Urban Fatal Crashes 1994 – 2003. U.S. Department of Transportation, National Highway Traffic Safety Administration, 2005; p19. URL: http://www-nrd.nhtsa.dot.gov/Pubs/809896.PDF.

[15] Transportation Cost and Benefit Analysis, Victoria Transport policy Institute, 2006. URL: http://www.vtpi.org/tca/.

[16] SO2 external costs are taken from: Matthews, H.S. and L.B. Lave. Applications of Environmental Valuation for Determining Externality Costs, Environmental Science & Technology, 2000, 34, 1390-1395.

[17] CH4 and N2O external costs assume relative GWPs of: CH4 – 21; N2O – 310; where CO2 is taken as unity.

For regulated air pollutants affecting air quality (AQ), the environmental rating scale is calibrated such that the maximum score of 100 ('AQ maximum') represents the total environmental impact of the following emissions:

- Direct (tailpipe) emissions equivalent to LEV II emission standard under the California Light-Duty Vehicle Emissions Standards for Air Pollutants (equivalent to EPA Federal Standards Tier 2 Bin 5);
- Indirect fuel cycle emissions generated by a vehicle with fuel consumption of 13.7 US mpg and CO_2 emissions of 650 grams/mile (approx. 404 gCO_2/km);
- Indirect vehicle cycle emissions produced in the manufacture of a vehicle with curb mass of 6000 lb (approx. 2722 kg).

Table 8 Score 100 'AQ Maximum' equivalent emissions

US LEV II grams/mile	CO	HC (NMOG)	NO_x	PM	SO_2
Tailpipe emissions	4.20	0.153 (0.090)	0.070	0.010	-
Fuel production	0.127	1.141	0.421	0.101	0.214
Vehicle production	0.451	0.372	0.136	0.149	0.280
TOTAL emissions	**4.778**	**1.666**	**0.627**	**0.260**	**0.494**
UK grams/km	**CO**	**HC (NMOG)**	**NO_x**	**PM**	**SO_2**
Tailpipe emissions	2.609	0.095 (0.056)	0.043	0.006	-
Fuel production	0.079	0.709	0.261	0.063	0.133
Vehicle production	0.280	0.231	0.084	0.093	0.174
TOTAL emissions	**2.968**	**1.035**	**0.389**	**0.162**	**0.307**

For greenhouse gases (GHGs), the environmental rating scale is calibrated such that the maximum score of 100 ('GHG maximum') represents the total environmental impact of the following emissions:

- Direct (tailpipe) emissions generated by a vehicle with fuel consumption of 13.7 US mpg and CO_2 emissions of 650 grams/mile (approx. 404 gCO_2/km);
- Indirect fuel cycle emissions generated by a vehicle with fuel consumption of 13.9 US mpg and CO_2 emissions of 650 grams/mile (approx. 404 gCO_2/km);
- Indirect vehicle cycle emissions produced in the manufacture of a vehicle with curb mass of 6000 lb (approx. 2722 kg);
- Corresponding methane emissions (CH_4) are estimated using methodology published by the Victoria Transport policy Institute;[18]
- Direct (tailpipe) nitrous oxide emissions (N_2O) are estimated using original Cleaner Drive data.

Table 9 Score 100 'GHG Maximum' equivalent emissions

US grams/mile	CO_2	CH_4	N_2O (gasoline)
Tailpipe emissions	650	0.063	0.008
Fuel production	147	0.913	0.010
Vehicle production	85	0.149	0.000
TOTAL emissions	**882**	**1.125**	**0.018**
UK grams/km	**CO_2**	**CH_4**	**N_2O (gasoline)**
Tailpipe emissions	404	0.039	0.005
Fuel production	91	0.567	0.006
Vehicle production	53	0.093	0.000
TOTAL emissions	**548**	**0.699**	**0.011**

[18] Transportation Cost and Benefit Analysis, Victoria Transport policy Institute, 2006. URL: http://www.vtpi.org/tca/.

5 Environmental impact calculation

The **maximum air quality ('AQ maximum') external cost** is calculated from the sum of the products of maximum emissions and external costs for each of the individual AQ pollutants, according to the following formula:

$$Q_{AQ} \text{ (maximum)} = \textstyle\sum_i p_i . c_i \qquad (1)$$

Q_{AQ} = maximum AQ external cost in €/km
p_i = emission of pollutant *i* in grams/km
c_i = external cost of emission of pollutant *i* in €/grams

For the purposes of the current assessment, the rural external cost factors are used to calculate the cost of indirect AQ emissions to reflect the fact that the majority of these emissions occur away from urban areas. A weighted average of urban and rural vehicle miles travelled (VMT) in the ratio of 60:40 is used to calculate the cost of direct (tailpipe) AQ emissions (for reasons explained above). Using these values, the maximum air quality external cost is shown in Table 10.

Table 10 Score 100 'AQ Maximum' external cost

Units: €/km	CO	HC	NO_x	PM	SO_2	TOTAL
Tailpipe emissions	0.00047	0.00054	0.00028	0.00003	0.00000	
Fuel production	0.00000	0.00360	0.00115	0.00016	0.00009	
Vehicle production	0.00000	0.00117	0.00037	0.00023	0.00012	
AQ external costs	**0.00047**	**0.00531**	**0.00180**	**0.00041**	**0.00021**	**0.00821**

For a particular vehicle, the **vehicle air quality ('AQ vehicle') external cost** is also calculated from the sum of the products of maximum emissions and external costs for each of the individual AQ pollutants, according to the following formula:

$$Q_{AQ} \text{ (vehicle)} = \textstyle\sum_i p_i . c_i \qquad (2)$$

Q_{AQ} = vehicle AQ external cost in €/km
p_i = emission of pollutant *i* in grams/km
c_i = external cost of emission of pollutant *i* in €/grams

The **air quality** (**AQ) rating** for a particular vehicle is then calculated using the following formula:

$$\textbf{AQ rating} = 100 \times Q_{AQ} \text{ (vehicle)} / Q_{AQ} \text{ (maximum)} \qquad (3)$$

The **maximum greenhouse gas ('GHG maximum') external cost** is calculated from the sum of the products of maximum emissions and external costs for each of the individual GHG emissions, according to the following formula:

$$Q_{GHG} \text{ (maximum)} = \textstyle\sum_i p_i . c_i \qquad (4)$$

Q_{GHG} = maximum GHG external cost in €/km
p_i = emission of greenhouse gas *i* in grams/km
c_i = external cost of emission of greenhouse gas *i* in €/grams

Using values as detailed in previous sections, the maximum greenhouse gas external cost is shown in Table 11.

Table 11 Score 100 'GHG Maximum' external cost

Units: €/km	CO_2	CH_4	N_2O	TOTAL
Tailpipe emissions	0.00348	0.00001	0.00001	
Fuel production	0.00079	0.00010	0.00002	
Vehicle production	0.00046	0.00002	0.00000	
GHG external costs	**0.00473**	**0.00013**	**0.00003**	**0.00488**

For a particular vehicle, the **vehicle greenhouse gas ('GHG vehicle') external cost** is also calculated from the sum of the products of maximum emissions and external costs for each of the individual GHG emissions, according to the following formula:

$$Q_{GHG}\text{ (vehicle)} = \sum_i p_i.c_i \qquad (5)$$

Q_{GHG} = vehicle GHG external cost in €/km
p_i = emission of greenhouse gas *i* in grams/km
c_i = external cost of emission of greenhouse gas *i* in €/grams

The **greenhouse gas** (**GHG) rating** for a particular vehicle is then calculated using the following formula:

$$\textbf{GHG rating} = 100 \times Q_{GHG}\text{ (vehicle)} / Q_{GHG}\text{ (maximum)} \qquad (6)$$

The **maximum overall ('Overall maximum') external cost** is calculated from the sum of the maximum air quality ('AQ maximum') external cost and the maximum greenhouse gas ('GHG maximum') external cost, according to the following formula:

$$Q_{OVERALL}\text{ (maximum)} = Q_{AQ}\text{ (maximum)} + Q_{GHG}\text{ (maximum)} \qquad (7)$$

Using values as detailed above, the maximum overall external cost is shown in Table 12.

Table 12 Score 100 'Overall Maximum' external cost

Units: €/km	TOTAL
AQ external costs	0.00821
GHG external costs	0.00488
TOTAL external costs	**0.01309**

For a particular vehicle, the **vehicle overall ('Overall vehicle') external cost** is calculated from the sum of the vehicle air quality ('AQ vehicle') external cost and the vehicle greenhouse gas ('GHG vehicle') external cost, according to the following formula:

$$Q_{OVERALL}\text{ (vehicle)} = Q_{AQ}\text{ (vehicle)} + Q_{GHG}\text{ (vehicle)} \qquad (8)$$

The **overall** (**GHG) rating** for a particular vehicle is then calculated using the following formula:

$$\textbf{Overall rating} = 100 \times Q_{OVERALL}\text{ (vehicle)} / Q_{OVERALL}\text{ (maximum)} \qquad (9)$$

6 Worked example – Toyota Prius MkII

Table 13 Toyota Prius MkII air pollutant emissions

UK grams/km	CO	HC	NO_x	PM	SO_2
Tailpipe emissions	0.062	0.018	0.006	0.000	-
Fuel production	0.023	0.211	0.078	0.019	0.040
Vehicle production	0.146	0.133	0.051	0.052	0.278
TOTAL emissions	**0.232**	**0.362**	**0.134**	**0.071**	**0.317**

Table 14 Toyota Prius MkII greenhouse gas emissions

UK grams/km	CO_2	CH_4	N_2O (gasoline)
Tailpipe emissions	120	0.012	0.005
Fuel production	27	0.169	0.002
Vehicle production	32	0.053	0.000
TOTAL emissions	**179**	**0.234**	**0.007**

Table 15 Toyota Prius MkII air pollutant external costs

Units: €/km	CO	HC	NO_x	PM	SO_2	TOTAL
Tailpipe emissions	0.00001	0.00010	0.00004	0.00000	-	
Fuel production	0.00000	0.00107	0.00034	0.00005	0.00003	
Vehicle production	0.00000	0.00067	0.00022	0.00013	0.00019	
AQ external costs	**0.00001**	**0.00185**	**0.00060**	**0.00018**	**0.00022**	**0.00285**
Maximum AQ ext cost	**0.00047**	**0.00531**	**0.00180**	**0.00041**	**0.00021**	**0.00821**

Table 16 Toyota Prius MkII greenhouse gas external costs

Units: €/km	CO_2	CH_4	N_2O	TOTAL
Tailpipe emissions	0.00104	0.00000	0.00001	
Fuel production	0.00023	0.00003	0.00000	
Vehicle production	0.00028	0.00001	0.00000	
GHG external costs	**0.00155**	**0.00004**	**0.00002**	**0.00161**
Maximum GHG ext cost	**0.00473**	**0.00013**	**0.00003**	**0.00488**

Equation (3) AQ Score = 100 × Q_{AQ} (vehicle) / Q_{AQ} (maximum)

AQ Score = 100 × 0.00285 / 0.00821 = 34.8

Equation (6) GHG Score = 100 × Q_{GHG} (vehicle) / Q_{GHG} (maximum)

GHG Score = 100 × 0.00161 / 0.00488 = 33.0

Equation (9) Overall Score = 100 × $Q_{OVERALL}$ (vehicle) / $Q_{OVERALL}$ (maximum)

Overall Score = 100 × (0.00285+0.00161) / (0.00821+0.00488)

Overall Score = 100 × 0.00447 / 0.01301 = 34.1

7 Results chart