The TSI Engine
Environmental Commendation Background Report

Introduction

Volkswagen develops environmentally friendly technologies that help reduce pollutant and carbon dioxide (CO_2) emissions and makes them available throughout the product range. That way, all our customers benefit from our development work. Many Volkswagen technologies reduce the carbon dioxide emissions of the vehicle fleet and play a key role in climate protection. TSI engines, which offer outstanding fuel economy, are a case in point.

Volkswagen uses Environmental Commendations to document the environmental performance of its vehicles and technologies. Following the DSG dual-clutch transmission, the TSI engine is the second Volkswagen technology to receive an Environmental Commendation. The Environmental Commendations for the Polo, Golf and Passat were very well received both by our customers and by the media. Our Environmental Commendations provide our customers, shareholders and other stakeholders inside and outside the company with detailed information about how we are making our products and production processes more environmentally compatible and what we have achieved in this respect.

The Commendations are based on the results of a detailed Life Cycle Assessment (LCA) in accordance with ISO 14040/44, which has been verified by independent experts, in this case from TÜV NORD. As part of an integrated product policy, the LCA considers not only individual environmental aspects such as the driving emissions of the vehicle but its entire life cycle – from production and use, right through to disposal – in other words “from cradle to grave”.

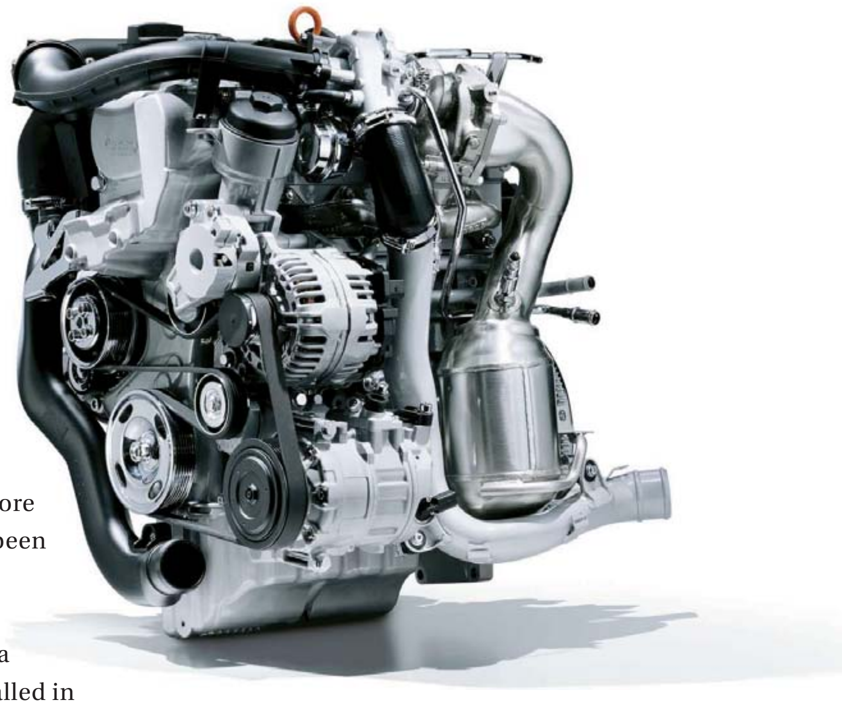
Here, too, Volkswagen has already established a tradition. We have been analysing our cars and their individual components since 1996, using Life Cycle Assessments to enhance their environmental compatibility. The environmental improvement of engines is an especially important step for us as we advance towards sustainable mobility for all. This Environmental Commendation presents the comprehensive results of our Life Cycle Assessment and documents the continuous progress achieved by Volkswagen in the field of environmental product optimisation.

Summary

This Environmental Commendation compares current TSI petrol engines (1.4-litre with 90 kW and 1.2-litre with 77 kW) with their respective normally aspirated predecessors. We have assessed the emissions caused by the engine not only during its service life but over its entire life cycle, from production to disposal.

As in the case of the vehicles assessed for Environmental Commendations, the TSI engines show improvements, in some cases significant, in all the environmental impact categories. The greatest advances have been made in the areas of global warming potential (greenhouse effect), acidification and photochemical ozone (summer smog) creation potential. In other respects, such as water and soil eutrophication and ozone depletion, the changeover from a normally aspirated petrol engine to a turbocharged or twin-charged engine has little impact. It emerged that the improvements were primarily due to reduced fuel consumption and the resultant drop in driving emissions and reduction in environmental impact at the fuel production stage. The drop in fuel consumption, in turn, is the direct result of the reduction in engine capacity and friction and the associated improvement in efficiency.

TSI engines



A reduction in engine capacity combined with a turbocharger or mechanical supercharger, also known as “downsizing”, is one of the most effective ways of saving fuel without sacrificing performance or driving pleasure. Small engines with lower displacements are more efficient because they weigh less, have lower friction losses and reach maximum efficiency more often. While turbochargers have been the accepted solution for diesel engines of all sizes and power outputs for some time now, until a few years ago they were only installed in high-performance petrol engines. That was before climate protection concerns and the need for more efficient use of resources made turbocharging an attractive option for small engines, too.

At Volkswagen, this downsizing trend is symbolised by the three letters of the TSI brand. Despite their relatively low displacement, TSI power plants reach outputs that would have called for much larger engines only a short time ago. A four-cylinder TSI can replicate the power and torque figures of a larger normally-aspirated six-cylinder engine almost effortlessly. The results are emissions and consumption figure normally associated with a smaller engine, combined with high power and torque. These engines use fuel far more efficiently than normally aspirated units with the same rated output.

Volkswagen uses the “TSI” brand for all its direct-injection turbocharged or twin-charged petrol engines. In addition to a turbocharger, the “Twincharger” is fitted with a mechanical supercharger to ensure even torque generation. TSI engines are now available in a variety of size classes with power outputs ranging from 77 to 199 kW. The first TSI engine was the 1.4-litre Twincharger, introduced in 2006. This was followed by several other models with displacements of 1.4, 1.8 and 2.0 litres. The latest addition to the family is the 1.2-litre TSI with 77 kW.

Life Cycle Assessments for ecological product evaluation and optimisation

The environmental goals of the Technical Development department of the Volkswagen brand state that we develop our vehicles and technologies in such a way that, in their entirety, they present better environmental properties than their predecessors (Fig. 1). By "in their entirety", we mean that the entire product life cycle is considered, from production via service life to recycling.

Environmental Objectives

of the Technical Development department of the Volkswagen brand

To attain the highest possible environmental objectives, the Technical Development department is intensifying the continuous improvement of Volkswagen products in respect of environmental compatibility and resource conservation. Our activities and processes are designed for sustainability and to ease the load on the environment. In this way we aim to live up to our responsibilities towards our customers, society and the environment.

In line with this approach, we have derived the following objectives:

1. Climate protection
- reduce greenhouse gas emissions
- reduce fuel consumption in the driving cycle and over the vehicle's service life with the customer
- be fuel-efficiency leader in each class of vehicle
- support fuel-efficient styles of driving
- contribute to/assess eco-compatible traffic management measures

2. Resource conservation
- improve resource efficiency
- pursue best possible recyclability and identification of the materials used
- use renewable and secondary raw materials
- develop and make available alternative powertrain technologies
- enable the use of alternative fuels

3. Healthcare
- reduce regulated and non-regulated emissions
- avoid the use of hazardous and harmful materials
- minimise interior emissions including odours
- attain best possible exterior and interior noise levels

In future, we will develop each model in such a way that, in its entirety, it presents better environmental properties than its predecessor. As we do so, we will always make sure that the entire life cycle is taken into account during the development of our products.

The environmental objectives set out above also serve to differentiate us from the competition to the benefit of our customers.

In addition, we aim to place selected models in various environmental rankings.

18 July 2007

Dr. Ulrich Hackenberg
Leiter der Technischen Entwicklung
Marke Volkswagen

Member of the Board of Management
Volkswagen Brand

G. Damme
Umweltbeauftragter Produkte
Marke Volkswagen

Environment Officer, Product
Volkswagen Brand

Fig 1: Environmental goals of the Technical Development department of the Volkswagen brand

This Environmental Commendation considers the significance of the innovative TSI technology for the environmental profile of a petrol engine. The decisive factor for the environmental profile of a product is its impact on the environment during its entire "lifetime". This means we do not focus solely on a product's service life but also on manufacturing, recycling and disposal. All life cycle phases require energy and resources, cause emissions and generate waste. Different vehicles and technologies can only be effectively compared on the basis of a balance sheet that covers all these individual processes from "cradle to grave". And this is precisely what Life Cycle Assessments or LCAs facilitate. Our Life Cycle Assessments enable the environmental impacts related to a product to be accurately quantified and thus allow the description of its environmental profile on the basis of comparable data. To ensure that the results meet exacting quality and comparability requirements, when drawing up the Life Cycle Assessments we take our lead from the standard series ISO 14040 [ISO 2006]. This specifically includes the verification of the results by an independent expert. In this case, a critical review was conducted by the TÜV NORD technical inspection agency.

The first stage in preparing a Life Cycle Assessment is to define its objectives and the target groups it is intended to address. This definition clearly describes the systems to be evaluated in terms of the system function, the system boundaries[1] and the functional unit[2]. The methods of Impact Assessment, the impact categories considered, the evaluation methods and, if necessary, the allocation procedures[3] are defined in accordance with ISO 14040. The individual steps involved in preparing a Life Cycle Assessment are described briefly below.

Life Cycle Inventory – LCI

In the Life Cycle Inventory, data is collected for all processes within the scope of the evaluation. Information on inputs, such as raw materials and sources of energy, and outputs, such as emissions and waste, is compiled for each process, always with reference to the defined scope of the evaluation (see Fig. 2).

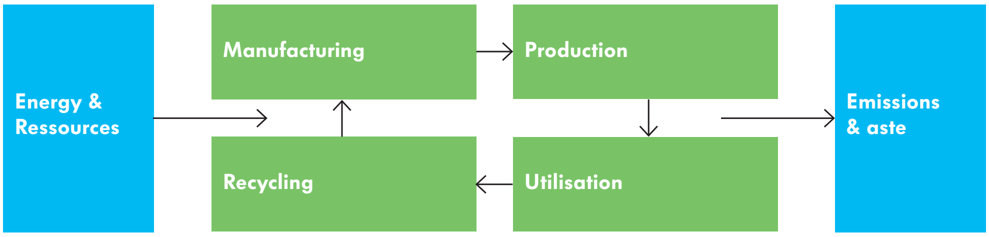


Fig 2: Input and output flows for a Life Cycle Inventory

The Life Cycle Inventory of an entire product life cycle includes numerous different inputs and outputs that are ultimately added up to prepare the inventory.

[1] By defining the system boundaries, the scope of the Life Cycle Assessment is restricted to those processes and material flows that need to be evaluated in order to achieve the defined goal of the study.
[2] The functional unit quantifies the benefit of the vehicle systems evaluated and further ensures their comparability.
[3] Where processes have several inputs and outputs, an allocation procedure is needed to assign flows arising from the product system under evaluation to the various inputs and outputs.

Life Cycle Impact Assessment – LCIA

A Life Cycle Inventory only quantifies the inputs and outputs of the system investigated. The following step – Impact Assessment – allocates the respective material flows to the appropriate environmental impacts. This involves defining a reference substance for each environmental impact category, for instance carbon dioxide (CO_2) for the impact category "global warming potential". Then all substances that also contribute to the global warming potential are converted to CO_2 equivalents using characterization factors.[4]

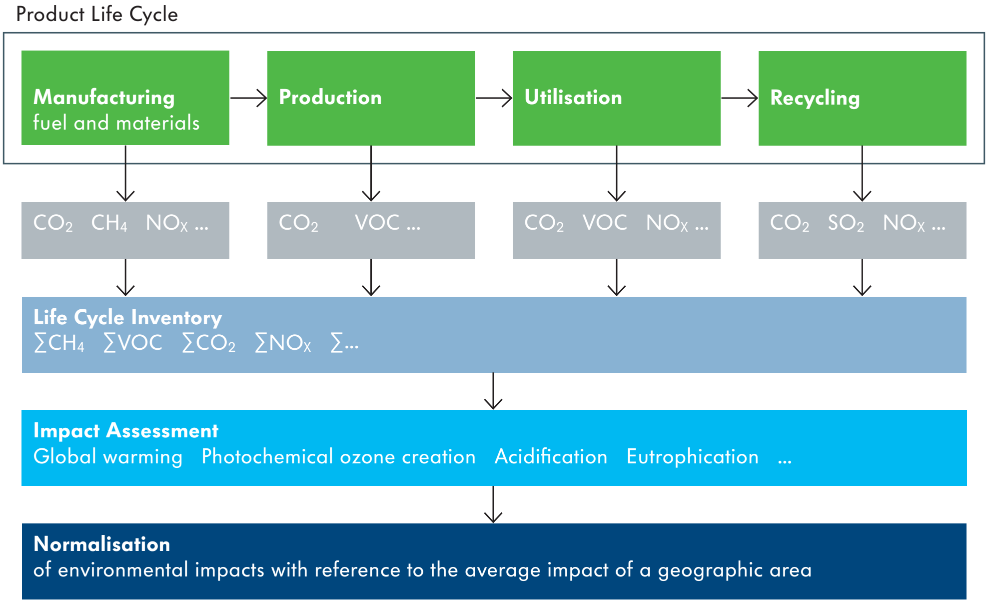


Fig. 3: Procedure for Impact Assessment

Examples of environmental categories are global warming potential, photochemical ozone creation potential, acidification potential or eutrophication potential.

Evaluation

The subsequent final evaluation interprets and evaluates the results of the Life Cycle Inventory and the Life Cycle Impact Assessment. The evaluation is based on the defined goal and scope of the Life Cycle Assessment.

[4] Carbon dioxide (CO_2) is the reference substance for global warming potential. All substances that contribute to the greenhouse effect are converted into CO_2 equivalents through an equivalence factor. For instance, the global warming potential of methane (CH_4) is 25 times higher than for CO_2. In concrete terms this means that the emission of 1 kg of CO_2 and 1 kg of CH_4 leads to a net global warming potential of 26 kg CO_2 equivalents. All the emissions that contribute to the greenhouse effect are measured in this way.

Implementation at Volkswagen

Volkswagen has many years of experience with Life Cycle Assessments for product and process optimisation. We have assumed a leading role in implementing and publishing life cycle inventories of complete vehicles. For instance, in 1996 we were the first car manufacturer in the world to prepare a Life Cycle Inventory study (for the Golf III) and publish it [Schweimer and Schuckert 1996]. Since then we have drawn up Life Cycle Assessments for other cars and also published some of the results [Schweimer 1998; Schweimer et al. 1999; Schweimer and Levin 2000; Schweimer and Roßberg 2001]. These LCAs primarily describe and identify environmental “hot spots” in the life cycle of a car. Since then we have broadened the assessments to include production processes as well as fuel production and recycling processes [Bossdorf-Zimmer et al. 2005; Krinke et al. 2005b]. Since 2007, we have used Environmental Commendations to inform customers and the public about the environmental properties of our vehicles and technologies [Volkswagen AG 2007a, Volkswagen AG 2007b, Volkswagen AG 2008a, Volkswagen AG 2008b, Volkswagen AG 2009a, Volkswagen AG 2009b]. Volkswagen is making long-term investments in further developing and optimising Life Cycle Assessment methods. Thanks to our intensive research we have succeeded in considerably reducing the workload involved in preparing Life Cycle Inventories.

Our research resulted in the development of the VW slimLCI interface system [Koffler et al. 2007]: this interface not only significantly cuts the workload involved in preparing Life Cycle Assessments of complete vehicles by automating the process, but also further improves the consistency and quality of the LCA models produced. This represents substantial progress, since preparing a complete LCA for a vehicle involves registering thousands of components, together with any related upstream supply chains and processes (see Fig. 4).

Fig. 4: Components of the VW Tiguan

The complexity of the modelling process results from the fact that all the parts and components of a vehicle themselves consist of a variety of materials and are manufactured by many different processes – processes that in turn consume energy, consumables and fabricated materials. In addition, the correct replication of all processes calls for considerable expert knowledge, a large database and detailed information on production and processing steps. The VW slimLCI interface system allows these details to be modelled very precisely and sufficiently completely in Life Cycle Assessment models – even for entire vehicles. A Life Cycle Assessment model or product model is based on the vehicle parts lists drawn up by the Technical Development department, as well as on material data drawn from the Volkswagen AG Material Information System (MISS). The VW slimLCI interface system primarily consists of two interfaces that transfer the vehicle data from these systems to the Life Cycle Assessment software GaBi[5], using a defined operating sequence (algorithm) (see Fig. 5).

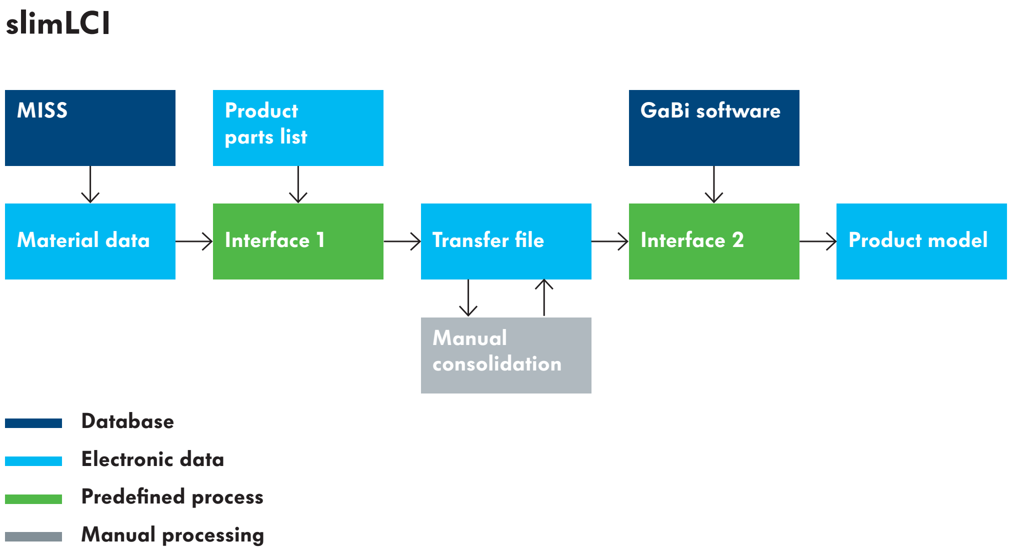


Fig. 5: Process of modelling an entire vehicle with the slimLCI interface system

Interface 1 helps assign information from parts lists (part designations and quantities) to the relevant component information (materials and weights) from MISS and converts it into a transfer file which is then quality-tested (manual consolidation). Interface 2 then allows the transfer file to be linked with the related data sets in the GaBi Life Cycle Assessment software. For example, to each material, such as steel sheet, the interface allocates all the material production and subsequent treatment processes listed in the database. The model generated by GaBi therefore reflects all the processing stages in the manufacture of the entire vehicle being evaluated. In this way, we can prepare Life Cycle Assessments in a very short time with the slimLCI interface system and use them continuously to keep pace with the steadily growing demand for environment-related product information.

[5] GaBi® is a Life Cycle Assessment software package from PE International.

The engines assessed

This Environmental Commendation for the TSI engine describes and analyses the environmental impacts of various petrol engines. To this end we have compared the current 1.2-litre and 1.4-litre TSI units with conventional normally aspirated petrol engines. The results are based on Life Cycle Assessments drawn up in accordance with the standards DIN EN ISO 14040 and 14044. All the definitions and descriptions required for preparing these Life Cycle Assessments were drawn up in accordance with the above standards and are explained below.

Aim and target group of the assessment

Volkswagen has been producing Life Cycle Assessments for over ten years to provide detailed information on the environmental impacts of vehicles and components for our customers, shareholders and other interested parties within and outside the company.

The objective of the Life Cycle Assessment in this case was to compare the environmental profiles of various types of petrol engine. To this end we compared the 1.2-litre and 1.4-litre TSI units with their respective normally aspirated predecessors.

Function and functional unit of the vehicle systems assessed

The "functional unit" for the assessment was defined as the production of propulsion power over a total distance of 150,000 kilometres in the New European Driving Cycle (NEDC).[6] The key technical data of the engines compared are listed in Table 1. In order to ensure comparability and to calculate the reduction in fuel consumption caused solely by the change in engine technology, it was necessary to base the assessment of the service life phase on fuel consumption simulations. For this purpose, the engines were "virtually installed" on the same reference vehicle, a Golf VI with 6-speed manual gearbox, and the resulting consumption figures for the entire vehicle were determined on the basis of otherwise unchanged assumptions.

The consumption figures stated are therefore calculated, rather than measured, values.[7] In line with the functional unit defined above, in what follows we only indicate the resulting consumption benefits compared with the predecessor engine. In other words, only that part of the total consumption attributable to the change in engine technology is considered. This differential approach has also been applied to

[6] Approximately 19 MWh based on a Golf VI with 6-gear manual gearbox

[7] The deviation from the official homologation value determined in the simulation for the Golf 1.2/1.4 TSI with 77/90 kW and 6-speed manual gearbox (combined value, see Table 1) was 1.8%/4.8%. The simulation is therefore considered to be sufficiently accurate.

the production and recycling phases. Since the 1.8 and 2.0 TSI engines have a rather small share in the TSI segment, the study at hand concentrates on the engines with 1.4 and 1.2 litres of cubic capacity. As displayed below, these engines realise a much lower fuel consumption than their predecessors despite their higher output and torque values.

Table 1: Technical data of the engines assessed

	1.6 FSI[a]	1.4 TSI[b]	1.6 MPI[c]	1.2 TSI[d]
Type	4-cyl. in-line	4-cyl. in-line	4-cyl. in-line	4-cyl. in-line
Valves per cylinder	4	4	2	2
Engine capacity [cm^3]	1598	1390	1595	1197
Output [kW]	85	90	75	77
Max. torque [Nm]	155	200	148	175
Drop in consumption [l/100km][e]	Reference	- 0.3	Reference	- 0.9
Engine weight [kg][f]	109.5	125.6	102.5	93.0

[a] Golf 1.6 FSI (85 kW), urban 8.8 / non-urban 5.5 / combined 6.7 l/100 km, 159 g CO_2/km
[b] Golf 1.4 TSI (90 kW), urban 8.2 / non-urban 5.1 / combined 6.2 l/100 km, 144 g CO_2/km
[c] Golf 1.6 MPI (75 kW), urban 9.7 / non-urban 5.6 / combined 7.1 l/100 km, 166 g CO_2/km
[d] Golf 1.2 TSI (77 kW), urban 7.1 / non-urban 4.9 / combined 5.7 l/100 km, 134 g CO_2/km
[e] All values are based on model calculations assuming the same conditions (Golf VI with 6-speed manual gearbox)
[f] Engine weight in accordance with DIN 70020-GZ

Scope of assessment

The scope of the assessment was defined in such a way that all relevant processes and substances are considered, traced back to the furthest possible extent and modelled at the level of elementary flows in accordance with ISO 14040. This means that only substances and energy flows taken directly from the environment or released into the environment without prior or subsequent treatment exceed the scope of the assessment. The only exceptions to this rule are the material fractions formed in the recycling stage.

The engine manufacturing phase was modelled including all manufacturing and processing stages for all components used. The model included all steps from the extraction of raw materials and the manufacture of semifinished products right through to assembly.

As regards the service life of the engine, the model includes all relevant processes from fuel production and delivery through to actual driving. The analysis of the fuel supply process includes shipment from the oilfield to the refinery and the refining process.

Engine maintenance is not included in the assessment as previous studies demonstrated that maintenance does not cause any significant environmental impacts [Schweimer and Levin, 2000].

The model of the recycling phase includes the dismantling and shredding of the engine as well as the recycling of material fractions by appropriate processes. In this Life Cycle Assessment, no environmental credits were awarded for the secondary raw material obtained from the recycling process. Only the environmental impacts of the recycling processes required were included. This corresponds to a worst case assumption[8], since in reality secondary raw material from vehicle recycling is generally returned to the production cycle. This recycling and substitution of primary raw materials could avoid consumption of such materials and the environmental impact of their production.

As a general principle, only emissions and fuel consumption actually caused by the engine are taken into consideration in the Life Cycle Assessment. In order to assess the change in fuel consumption caused by the use of a specific engine, it was necessary to use simulated NEDC consumption figures as no vehicle with measured consumption figures for all four engine variants was available.[9] This differential or 'consumption advantage' approach was also applied analogously to the production and recycling phases. The results of this analysis show the increase or decrease in potential environmental impacts that would be caused by a changeover from a normally aspirated petrol engine to a TSI engine on the same vehicle (Golf VI with six-speed manual gearbox).

Fig. 6 is a schematic diagram indicating the scope of the Life Cycle Assessment. Europe (EU 15 or EU 25) was chosen as the reference area for all processes in the manufacture, service and recycling phases. Where European data are not available, German data are used.

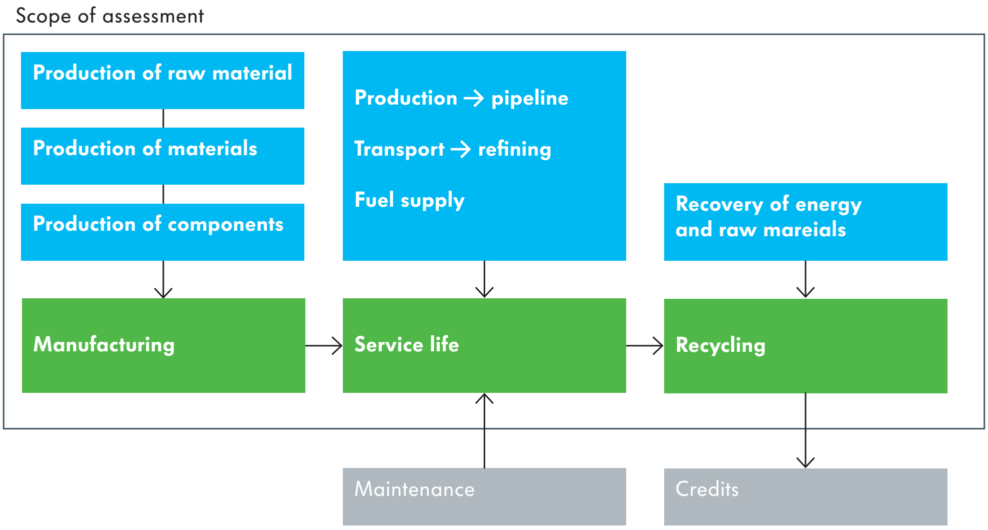


Fig. 6: Scope of the Life Cycle Assessment

[8] Here the worst case is a set of the most unfavourable model parameters of the recycling phase.
[9] The 1.6 FSI is not offered anymore in the current Golf VI. The 1.6 MPI is available only with a 5-speed manual gearbox.

Environmental Impact Assessment

The Impact Assessment is based on a method developed by the University of Leiden in the Netherlands (CML methodology) [Guinée and Lindeijer 2002]. The assessment of environmental impact potentials in accordance with this method is based on recognised scientific models. A total of five environmental impact categories were identified as relevant and were then assessed in this study:[10]

- eutrophication potential
- ozone depletion potential
- photochemical ozone creation potential
- global warming potential for a reference period of 100 years
- acidification potential

The above environmental impact categories were chosen because they are particularly important for the automotive sector, and are also regularly used in other automotive-related Life Cycle Assessments [Schmidt et al. 2004; Krinke et al. 2005a]. The environmental impacts determined in the Life Cycle Assessments are measured in different units. For instance, the global warming potential is measured in CO_2 equivalents and the acidification potential in SO_2 equivalents (each in kilograms). In order to make them comparable, a normalisation process is required. In this Life Cycle Assessment the results were normalised with reference to the annual average environmental impact caused by Western Europe (EU15). For example, in the global warming category, the impact caused by Western Europe is about 4.4 billion metric tons of CO_2 equivalents in the year 2001 (see Table 2).

Table 2: EU 15 normalisation factors in accordance with CML 2001
(in thousand metric tons)

Environmental category		Unit
Eutrophication potential	15906	PO_4 equivalents
Ozone depletion potential	31	R11 equivalents
Photochemical ozone creation potential	7228	C_2H_4 equivalents
Global warming potential	4440050	CO_2 equivalents
Acidification potential	21553	SO_2 equivalents

This normalisation allows statements to be made regarding the contribution of a product to total environmental impacts within Western Europe. The results can then be presented in one graph using the same scale. This approach also makes the results more comprehensible and allows environmental impacts to be compared.

[10] The glossary contains a detailed description of these environmental impact categories.

In this context it must be pointed out that the normalisation does not give any indication of the relevance of a particular environmental impact, i.e. it does not imply any judgement on the significance of individual environmental impacts.

Basis of data and data quality

The data used for preparing the Life Cycle Assessment can be subdivided into product data and process data. “Product data” describes the product itself, and among other things includes:

- Information on parts, quantities, weights and materials
- Information on fuel consumption and emissions during utilisation
- Information on recycling volumes and processes

“Process data” includes information on manufacturing and processing steps such as the provision of electricity, the production of materials and semifinished goods, fabrication and the production of fuel and consumables. This information is either obtained from commercial databases or compiled by Volkswagen as required.

We ensure that the data selected are as representative as possible. This means that the data represent the materials, production and other processes as accurately as possible from a technological, temporal and geographical point of view. For the most part, published industrial data are used. In addition, we use data that are as up-to-date as possible and relate to Europe. Where European data are not available, German data are used. For the various engines, we always use the same data on upstream supply chains for energy sources and materials. This means that differences between the latest models and their predecessors are entirely due to changes in component weights, material compositions, manufacturing processes at Volkswagen and driving emissions, and not to changes in the raw material, energy and component supply chains.

The Life Cycle Assessment model for engine production was developed using Volkswagen‘s slimLCI methodology (see Chapter 1). Engine parts lists were used as data sources for product data, and the weight and materials of each product were taken from the Volkswagen material information system (MISS). This information was then linked to the corresponding process data in the Life Cycle Assessment software GaBi.

Material inputs, processing procedures and the selection of data in GaBi are standardised to the greatest possible extent, ensuring that the information provided by slimLCI is consistent and transparent.

For modelling the service life of the engine, representative data for upstream fuel supply chains were taken from the GaBi database. A sulphur content of 10 ppm was assumed for petrol.[11]

Engine recycling was modelled on the basis of data from the VW SiCon process and using representative data from the GaBi database.

In sum, all information relevant to the aims of this study was collected and modelled completely.[12] The modelling of components on the basis of parts lists ensures that the model is complete, especially with respect to the manufacturing phase. In addition, as the work processes required are automated to a great extent, any differences in the results are due solely to changes in product data and not to deviations in the modelling system.

[11] In some countries, fuel with a sulphur content of 10 ppm is not yet available. However, even if the sulphur content were higher, the contribution of sulphur emissions during the vehicle's service life would still remain negligible.

[12] Completeness, in accordance to ISO 14040, must always be considered with reference to the objective of the investigation. In this case, completeness means that the main materials and processes have been reflected. Any remaining data gaps are unavoidable, but apply equally to all the engines compared.

Model assumptions and findings of the Life Cycle Assessment

All the framework conditions and assumptions defined for the Life Cycle Assessment are outlined below.

Table 3: Assumptions and definitions for the Life Cycle Assessment

Aim of the Life Cycle Assessment
• Comparison of the environmental profiles of normally aspirated petrol engines and turbocharged or twin-charged TSI engines over the entire life cycle
Framework of the Life Cycle Assessment
Function of systems • Production of power in the powertrain
Functional unit • Production of power in the powertrain in the New European Driving Cycle (NEDC) over a defined total distance of 150,000 kilometres[13]
Comparability • Modelling of consumption differences assuming identical framework conditions / the same reference vehicle[14]
System boundaries • The system boundaries include the entire life cycle of the engines (manufacture, service life and recycling phase).
Cut-off criteria • The assessment does not include engine maintenance. • No environmental impact credits are awarded for secondary raw materials produced. • Cut-off criteria applied in GaBi data sets, as described in the software documentation (www.gabi-software.com) • Explicit cut-off criteria, such as weight or relevance limits, are not applied.
Allocation • Allocations used in GaBi data sets, as described in the software documentation (www.gabi-software.com) • No further allocations are used

[13] Approximately 19 MWh based on a Golf VI with 6-gear manual gearbox
[14] Golf VI with six-speed manual gearbox

Data basis

- Volkswagen engine parts lists
- Material and weight information from the Volkswagen Material Information System (MISS)
- Vehicle-performance calculations for computation of consumption
- Technical drawings
- The data used come from the GaBi database or were collected in cooperation with VW plants, suppliers or industrial partners.

Life Cycle Inventory results

- Material compositions in accordance with VDA (German Association of the Automotive Industry) Standard 231-106
- Life Cycle Inventory results include emissions of CO_2, CO, SO_2, NOX, NMVOC, CH_4, and primary energy consumption
- The Impact Assessment includes the environmental impact categories eutrophication potential, ozone depletion potential, photochemical ozone creation potential, global warming potential for a reference period of 100 years and acidification potential
- Normalisation of the results

Software

- Life Cycle Assessment software GaBi 4.3, GaBi DfX Tool and Volkswagen slimLCI interface system

Evaluation

- Evaluation of Life Cycle Inventory and Impact Assessment results, subdivided into life cycle phases and individual processes
- Comparison of Impact Assessment results of the engines compared
- Interpretation of results

Results of the Life Cycle Assessment

Material composition

Fig. 7 shows the material compositions derived from the product data on the basis of VDA (German Association of the Automotive Industry) standard 231-106 for material classification [VDA 1997]. The bar chart shows that all four engines have a similar composition. The engines consist mainly of iron and steel materials and aluminium, as well as small amounts of plastics and non-ferrous metals and the first fill of operating fluids (fuel and coolant). The relatively high share of iron and steel materials in the case of the 1.4 TSI is chiefly due to the fact that this is the only engine of the four compared that has a grey cast iron block.

Material composition of the engines compared

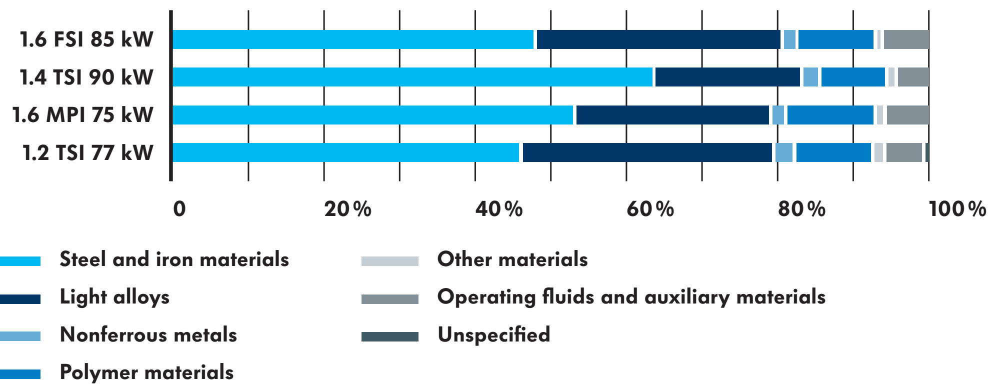


Fig. 7: Material composition of the engines compared

Results of the Life Cycle Inventory

Table 4 shows the results for selected Life Cycle Inventory values. In line with the differential approach adapted, only differences between the TSI engines and predecessor models are relevant for the comparison.

The figures indicate that the environmental impacts caused by the production of the two TSI engines are slightly higher than the corresponding figures for the reference engines. In the case of the 1.4-litre TSI engine, this is largely due to the total weight of the engine, which is the heaviest of the four compared. In the case of the 1.2-litre TSI engine, it is mainly the higher mass of light alloys and non-ferrous metals that offsets the advantage of lower total weight in terms of the Life Cycle Inventory.

As expected, the lower fuel consumption in the service phase leads to a net reduction in all emissions. As it has been assumed for the purpose of fuel consumption calculation that the same exhaust emission standards applied, only the stoichiometric emissions CO_2 und SO_2 show a reduction compared with the reference engines.

Table 4: Selected Life Cycle Inventory values

		CO_2	CO	SO_2	NO_X	NMVOC	CH_4	**Primary energy** [GJ]
Manufacturing	**1.4 TSI** (90kW)	+154.2	+0.6	+0.8	+0.3	0.0	+0.2	+1.6
	1.2 TSI (77kW)	+75.2	0.0	+1.0	+0.3	0.0	+0.1	+0.9
Fuel production	**1.4 TSI** (90kW)	-202.3	-0.2	-1.0	-0.4	-0.4	-1.2	-17.4
	1.2 TSI (77kW)	-607.0	-0.7	-1.4	-0.5	-0.6	-1.6	-23.2
Driving emissions (stoichiometric)	**1.4 TSI** (90kW)	-1200.0	0.0	0.0	0.0	0.0	0.0	–
	1.2 TSI (77kW)	-3450.0	0.0	-0.1	0.0	0.0	0.0	–
Recycling	**1.4 TSI** (90kW)	-1.2	+0.1	0.0	0.0	0.0	0.0	-0.2
	1.2 TSI (77kW)	-0.1	-0.1	0.0	0.0	0.0	0.0	-0.1

Table 4: Selected Life Cycle Inventory Values (difference to reference engine in kg)

Comparison of Life Cycle Impacts

On the basis of the Life Cycle Inventory data, Life Cycle Impact Assessments are drawn up for all the environmental impact categories considered above. The interactions of all the emissions recorded are considered and potential environmental impacts are determined based on scientific models (see Fig. 3).

In Fig. 8, the base line represents the emissions of the reference engine in each case. It can clearly be seen that the greatest reductions in potential environmental impact in relation to the statistical environmental impact of Western Europe (EU15) are achieved in the categories of global warming potential, acidification and photochemical ozone creation potential. In contrast, the changeover to TSI technology does not result in any significant improvement in the categories of ozone depletion and eutrophication.

Life Cycle Impacts
Normalized impacts (delta)

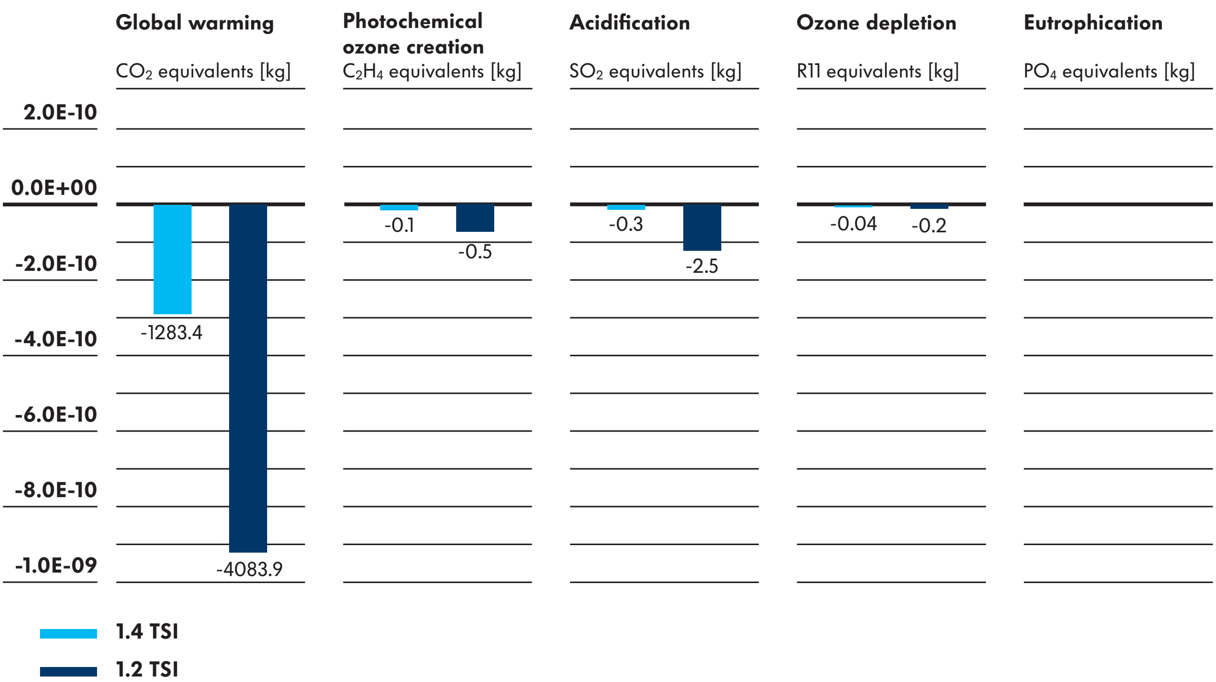


Fig. 8: Life Cycle Impacts (differential) of TSI engines

A more precise analysis of the results shows that the improvements in the environmental profile are chiefly due to the reduction in fuel consumption (Fig. 9). In contrast, the increases and reductions in impacts caused by production and recycling are relatively slight and do not have any significant influence on the overall result.

Detailed life cycle impacts
Normalized impacts (delta)

Fig. 9: Life Cycle Impacts (differential) of TSI engines (detail)

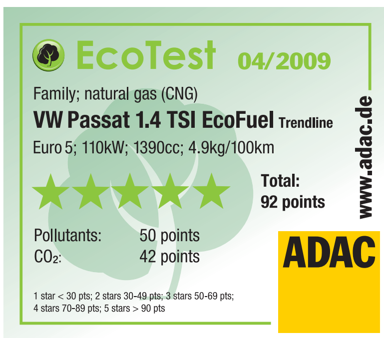
An ideal combination

TSI engines from Volkswagen are not only outstanding performers when running on petrol but also when run on natural gas. The Passat 1.4 TSI EcoFuel, for example, has ushered in a new era of natural gas vehicles (NGVs). In contrast to previous NGVs, which were not exactly dynamic performers, the Passat EcoFuel is both dynamic and highly economical.

Despite its performance characteristics, the NGV version of Volkswagen‘s mid-range bestseller boasts a fuel consumption of only 4.5 kilograms of natural gas per 100 kilometres (in the New European Driving Cycle – NEDC).[15] Coupled with the 7-speed DSG, the natural gas Passat even beats the magic figure for its class of 120 g CO_2/km.[16] This is made possible by the very low emissions of the standard engine and the optimum adaptation of the engine control unit to operation on compressed natural gas (CNG).

The 1.4-litre TSI is a duel-fuel engine that can run on both natural gas and petrol and is equipped with a mechanical supercharger as well as a turbocharger. This “Twincharger” principle combines outstanding pulling power with high efficiency. The 1.4-litre unit in the Passat develops 110 kW on petrol and CNG. The 1.4-litre TSI was selected as the standard engine for the EcoFuel models as it offers considerable advantages in terms of cylinder charge at low engine speeds. Natural gas is an ideal fuel for turbo- and supercharged engines with high boost pressures because of its good anti-knock properties. As the engine control unit can switch automatically and imperceptibly from CNG to petrol operation, the Passat achieves a total range of over 900 kilometres.

The Passat TSI EcoFuel not only boasts outstanding performance, it also turns in an impressive set of environmental figures. It is the first car in the history of the ADAC EcoTest to be awarded five stars.[17] To date, Europe‘s largest motoring organisation has subjected some 800 vehicles to its EcoTest, widely considered one of the most demanding emissions tests for automobiles. At the ADAC Technology Centre, emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X) and particulates (PM) are determined; with the same measurements being made for vehicles of all classes. In the “regulated emissions” category, the Passat achieved the best values ever recorded and was awarded the maximum score of 50 points. CO_2 emissions are determined as a function of the vehicle class. Here the test team reported outstanding results for the TSI engine, especially under acceleration in the autobahn cycle.



In environmental terms, CNG is certainly an attractive option. In natural gas mode, the TSI EcoFuel produces some 80 percent less carbon monoxide, 80 percent less nitrogen oxides and up to 23 percent less carbon dioxide than in petrol mode. That makes CNG

[15] Passat 1.4 TSI EcoFuel (110 kW) urban 6.1 / non-urban 3.5 / combined 4.5 kg CNG/100km, 123 g CO_2/km
[16] Passat 1.4 TSI EcoFuel (110 kW) urban 5.7 / non-urban 3.5 / combined 4.4 kg CNG/100km, 119 g CO_2/km
[17] www.adac.de/Tests/Autotest/Ecotest

The biomethane production process

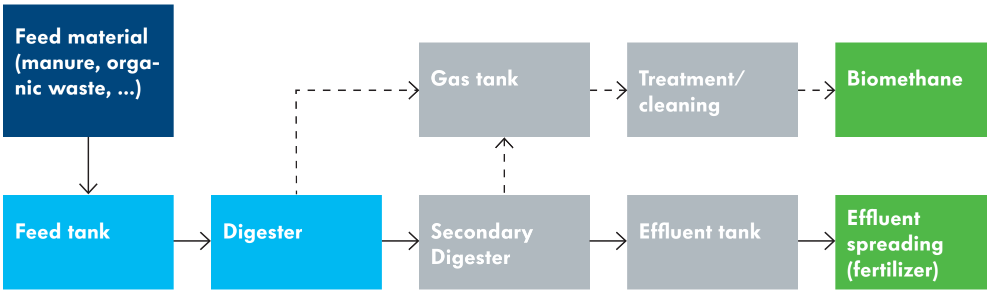


Fig. 10: Biomethane production process

the cleanest fossil fuel. And with fuel costs of only four (euro-)cents per kilometre, the Passat EcoFuel also offers unbeatably low running costs.[18]

The environmental balance is even better if the vehicle is run on biomethane. Biomethane meets the same quality specifications as natural gas but is not a fossil fuel. It is produced by the fermentation of manure, energy crops such as maize, and organic waste. Unwanted substances such as carbon dioxide, hydrogen sulphide and other trace gases are then removed from this raw biogas to produce biomethane.

If biomethane is produced from organic waste, there is a further improvement in the environmental compatibility of the fuel. This is not just our opinion; a recent EU directive to promote the use of energy from renewable sources states that the CO_2 reduction potential of “biogas from municipal organic waste as compressed natural gas” is at least 73 percent.[19]

There are also other reasons for using biomethane. It can be injected into the existing natural gas pipeline system without any problems and allows very high specific yields per unit area. With the yield of one hectare, a car could travel up to 67,000 kilometres.[20] Volkswagen is promoting this biofuel under the “SunGas” brand as part of its Powertrain and Fuel Strategy and supports the operation of the first biomethane filling station in Germany at Wendland in Lower Saxony. SunGas can be used without any restrictions in all NGVs produced by the Volkswagen Group.

[18] Natural gas price: € 0.91/kg (www.erdgasfahrzeuge.de; November 2009)
[19] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources
[20] According to data from Fachagentur Nachwachsende Rohstoffe e.V. (FNR – Agency for Renewable Resources)

Conclusion

Volkswagen TSI engines not only fulfil high expectations in terms of economy and driving performance but are also one of the basic technologies of our BlueMotion-Technologies brand, representing an important step towards sustainable mobility for everyone. The Life Cycle Assessment of the TSI engine documents all the progress that has been made in this area compared with conventional normally aspirated petrol engines. The information given in this Environmental Commendation is based on the Life Cycle Assessment of TSI technology, which has been inspected and certified by TÜV NORD. The report issued by TÜV confirms that the Life Cycle Assessment is based on reliable data and that the methods used to compile it are in accordance with the requirements of ISO standards 14040 and 14044.

Compared with normally aspirated engines, TSI engines offer lower fuel consumption and emissions during their service life, as well as comparable environmental impacts during the manufacturing and recycling phases. The overall environmental profile of the TSI engine therefore represents a substantial improvement over that of a normally aspirated petrol engine.

Validation

The statements made in this environmental commendation are supported by the Life Cycle Assessment of the TSI engines. The certificate of validity confirms that the Life Cycle Assessment is based on reliable data and that the method used to compile it complies with the requirements of ISO standards 14040 and 14044.

CERTIFICATE OF VALIDITY TÜV NORD

DIN EN ISO 14040 : 2006-10
(LCA - life cycle assessment)

Evidence that the application conforms to the regulations was delivered, and is herewith certified according to the TÜV NORD CERT - procedure for

Volkswagen AG
Berliner Ring 2
38346 Wolfsburg
Germany

Range of application

Environmental Commendation TSI Technology

for the TSI engines 1,2 TSI (77 KW) and 1,4 TSI (90 KW) (version 2009)

The requirements were fulfilled and proven by a critical review concerning

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

Report no. 3505 3525

Certification office of the TÜV NORD CERT GmbH

Essen, dated 2009-12-15

Dr. Winfried Hirtz
Environmental verifier

Dr. Annika Blarr
Environmental verifier

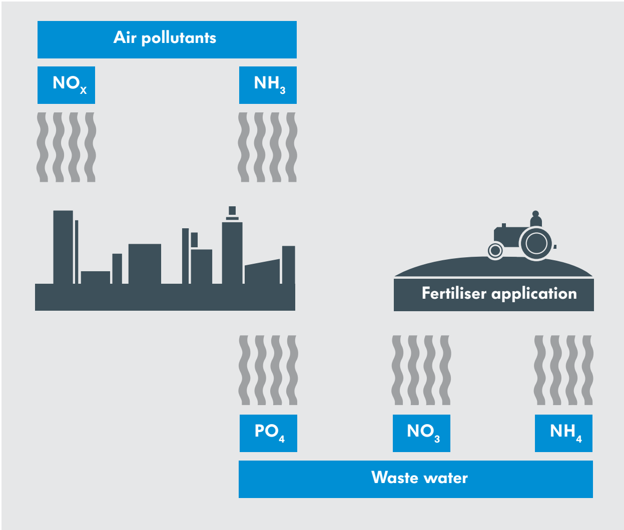
TÜV NORD CERT GmbH Langemarckstrasse 20 45141 Essen www.tuev-nord-cert.com

You will find the detailed report from TÜV NORD in the Appendix, beginning on page 33.

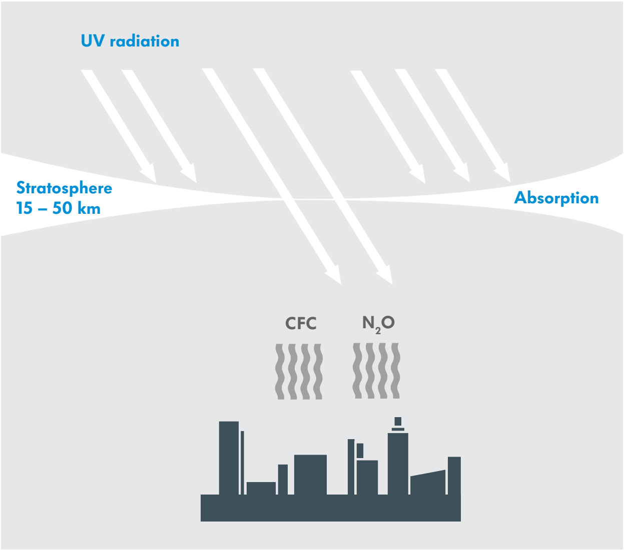
Glossary

Allocation
Allocation of Life Cycle Inventory parameters to the actual source in the case of processes that have several inputs and outputs.

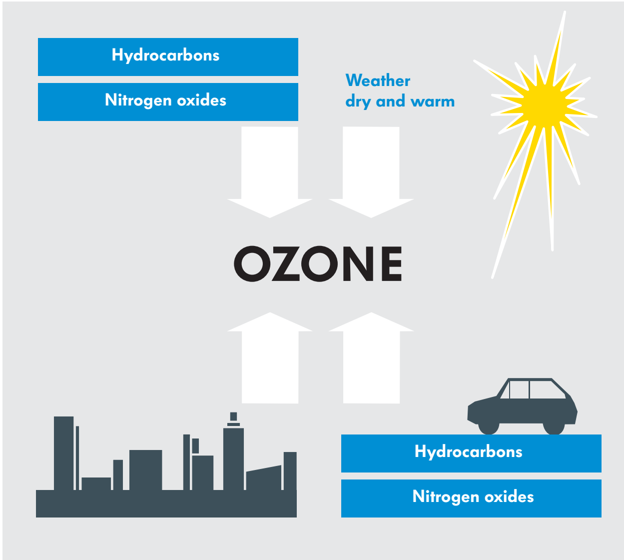
Eutrophication potential
describes excessive input of nutrients into water [or soil], which can lead to an undesirable change in the composition of flora and fauna. A secondary effect of the over-fertilisation of water is oxygen consumption and therefore oxygen deficiency. The reference substance for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



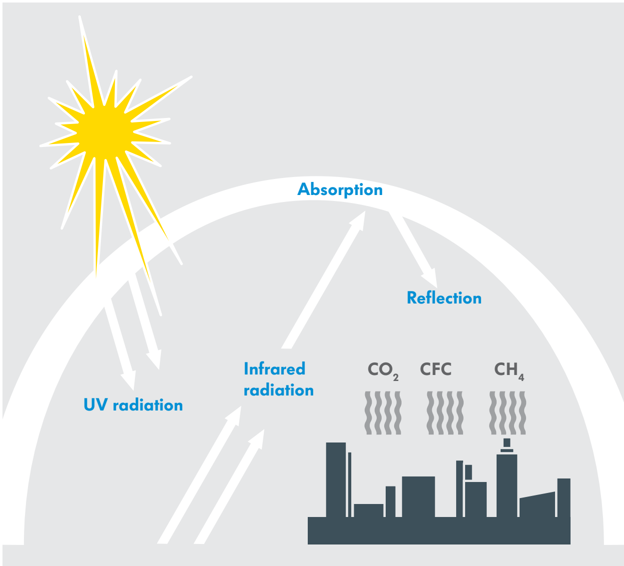
Ozone depletion potential
describes the ability of trace gases to rise into the stratosphere and deplete ozone there in a catalytic process. Halogenated hydrocarbons in particular are involved in this depletion process, which diminishes or destroys the protective function of the natural ozone layer. The ozone layer provides protection against excessive UV radiation and therefore against genetic damage or impairment of photosynthesis in plants. The reference substance for ozone depletion potential is R11, and all other substances that impact on this process (for instance CFC) are measured in R11 equivalents.



Photochemical ozone creation potential
describes the formation of photooxidants, such as ozone, PAN, etc., which can be formed from hydrocarbons, carbon monoxide (CO) and nitrogen oxides (NO_X), in conjunction with sunlight. Photooxidants can impair human health and the functioning of ecosystems and damage plants. The reference substance for the formation of photochemical ozone is ethene, and all other substances that impact on this process (for instance VOC, NO_X and CO) are measured in ethene equivalents.



Global warming potential
describes the emissions of greenhouse gases, which increase the absorption of heat from solar radiation in the atmosphere and therefore increase the average global temperature. The reference substance for global warming potential is CO_2, and all other substances that impact on this process (for instance CH_4, N_2O, SF_6 and VOC) are measured in carbon dioxide equivalents.



Acidification potential
describes the emission of acidifying substances such as SO_2 and NO_X, etc., which have diverse impacts on soil, water, ecosystems, biological organisms and material (e.g. buildings). “Acid rain” and fish mortality in lakes are examples of such negative effects. The reference substance for acidification potential is SO_2, and all other substances that impact on this process (for instance NO_X and NH_3) are measured in sulphur dioxide equivalents.

Environmental impact category
An environmental indicator that describes an environmental problem (e.g. the formation of photochemical ozone).

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List of abbreviations

AP	Acidification potential
CFC	Chlorofluorocarbons
CH_4	Methane
CML	Centrum voor Milieukunde Leiden (Centre for Environmental Sciences, Netherlands)
CO	Carbon monoxide
CO_2	Carbon dioxide
DIN	Deutsche Industrienorm (German Industrial Standard)
DPF	Diesel particulate filter
EN	European standard
EP	Eutrophication potential
GJ	Gigajoule
GWP	Global warming potential
HC	Hydrocarbons
IMDS	International Material Data System
KBA	Kraftfahrtbundesamt (Federal Motor Transport Authority)
kW	Kilowatt
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MISS	Material Information System
MPI	Intake-tube multipoint injection petrol engine
N_2O	Nitrous oxide
NEDC	New European Driving Cycle
NH_3	Ammonia
Nm	Newton metre
NMVOC	Non-methane volatile organic compounds (hydrocarbons without methane)
NO_X	Nitrogen oxides
ODP	Ozone depletion potential
PAN	Peroxyacetylnitrate
PO_4	Phosphate
POCP	Photochemical ozone creation potential
ppm	Parts per million
PVC	Polyvinyl chloride
R11	Trichlorofluoromethane (CCl_3F)
SET	Simultaneous engineering team
SF_6	Sulphur hexafluoride
SO_2	Sulphur dioxide
TDI	Turbocharged direct injection diesel engine
TSI	Turbocharged or twin-charged stratified injection petrol engine
VDA	Verband der Automobilindustrie e.V. (Association of the German Automotive Industry)
VOC	Volatile organic compounds

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Appendix

Hannover, 06.02.2010
TNC Umweltgutachter-H

Report

Critical Review of Life Cycle Assessment

TSI Engines - Environmental Commendation,

Report No.:	8000 375 575
Client:	Volkswagen AG 38436 Wolfsburg
Author of Life Cycle : Assessment	Volkswagen AG K-EFUP Dr. Koffler
External reviewer :	Dr. Winfried Hirtz
Length of report:	9 pages

TÜV NORD CERT Umweltgutachter GmbH
Geschäftsstelle Hannover
Am TÜV 1, 30519 Hannover, Tel.: +49(0)511/986-2420
Fax.: +49(0)511/986-2899 9287, E-Mail: whirtz@tuev-nord.de

1 General

1.1 Object and Terms of Reference

Volkswagen AG, Department K-EFUP, Environment Affairs Product, has drawn up a comparative Life Cycle Assessment "TSI Engines - Environmental Commendation" .

Volkswagen AG, Department K-EFUP Environment Affairs Product, commissioned TÜV NORD CERT Umweltgutachter GmbH to carry out a critical review of the Life Cycle Assessment as an independent body in accordance with DIN ISO 14040 and DIN ISO14044.

The review was carried out for TÜV NORD Cert GmbH by Dr.-Ing. Winfried Hirtz, Environmental Assessor licensed under the Environmental Audit Act.

Under the terms of reference, the objective of the critical review was to verify the reliability, transparency, relevance and representative nature of the methods used for Life Cycle Assessment with respect to

- Objective and scope of assessment
- Life Cycle Inventory
- Life Cycle Impact Assessment and
- Evaluation of assessment

1.2 Procedure

Taking into account the general quality criteria (chiefly transparency, reproducibility, quality of the computer programs and data used, and information on the sources of data), the procedure used for the critical review was as follows:

- Review of the objective and scope of the assessment, especially the function and functional equivalence of system boundaries and cut-off criteria (space, time, technology), allocation procedures together with the allocation and distribution rules adopted, and the selection of significant parameters and materials.

- Review of the Life Cycle Inventory drawn up, especially with regard to the input/output analyses (major process chains), the input and output data used and the reliability of such data, the systematic nature, completeness and plausibility of the input/output analysis, the sensitivity analysis and the assessment of errors, the plausibility and reliability of computer programs, and the consideration of upstream process chains, by-products and secondary post-use effects

- Review of the Life Cycle Impact Assessment, concentrating on the selection of impact categories (with respect to subject areas and problems) and the concentration of data with reference to impact categories

- Review of the evaluation and the comparative statements made on the basis of the evaluation

System representations, data files and other representative documents were inspected and compared on a random sample basis and some data collection and calculation procedures were reproduced on the computer, in some cases with targeted variation. For example, were viewed with respect to limit values, consumption and the utilisation phase. The assessment of the technology under consideration here was performed based on model calculations. Protocols of the model calculations were viewed and inspected. In general, duplication of effort was avoided during the critical review. Relevant literature concerning life cycle assessment techniques was taken into consideration.

2 Result of Critical Review

2.1 Objective of Assessment

The objectives of the Life Cycle Assessment are defined clearly and unambiguously; external and internal target groups for the assessment are also stated. The presentation adopted for the Environmental Commendation for the Passat provides sufficient appropriate information to make the intended environmentally holistic approach clear and comprehensible.

2.2 Scope of Assessment

The Life Cycle Assessment considers the manufacture, use and disposal of comparable engines in the TSI-Generation 2010. Various variants were considered. Despite differences, for example as regards the cubic capacity, the engines are equivalent as regards function. This supposition was intensively investigated as a prerequisite for the study. The scope and system boundaries of the assessment are clearly and unambiguously defined in relation to the entire system with respect to space, time and technology. The boundaries are compatible with the selected function unit and are defined over the life cycle.
Environmental impact is presented and assessed in the categories greenhouse gas emissions (CO_2 equivalent), photochemical ozone creation potential (POCP), acidification potential (AP), eutrophication potential (EP) and ozone depletion potential (ODP). As the impacts in this particular assessment are generally concerned with the greenhouse effect and POCP, these are described in more detail.

Within the scope of the assessment, all relevant materials, components and processes were logged, analysed and finally grouped together for the subsequent Life Cycle Inventory into four main modules appropriate for the object of the assessment :

- Manufacture and raw material production
- Fuel provision and transport
- Utilisation phase / Driving emissions
- Recycling

In the case of the TSI engine, fuel consumption should be seen in terms of the official consumption figures (admission value of authority) and can have a different effect on the overall assessment depending on different equipment levels. In the calculation, the basis of comparison was always the previous model.

The graphs and tables in the assessment confirm the systematic nature and completeness of the procedure selected.

The effects and factors considered negligible for the definition of the Life Cycle Assessment system are explained and, where appropriate, listed.

In summary it can be stated that all relevant factors have been identified and taken into consideration within the area investigated in accordance with the state of the art of Life Cycle Assessments.

2.3 Life Cycle Inventory

The input/output analyses for the main modules mentioned above were carried out and the Life cycle Inventory for the Life Cycle Assessment was documented using a computer system. The calculations themselves were performed using the internationally recognized software package "GaBi".

2.3.1 Data sources

The main processes in the individual areas have been modelled realistically. The data sources are based on generally accepted files, they are comprehensible and representative as regards this Life Cycle Assessment. The data basis of the "GaBi" system is extremely comprehensive. The data can be understood and traced.

2.3.2 Plausibility and completeness review

The computer system reflects the system boundaries systematically and are consistent with the assessment area defined. Boundaries are drawn at points where no (significant) impact on the results of the individual areas or the overall assessment is expected (see also the sensitivity analyses conducted). The data are of high quality and are highly symmetrical. The data used is drawn from databases (IMDS) into which the available information regarding the individual components and parts lists which are used is entered. This information is regularly verified by means of information requested from manufacturers.

All four Life Cycle Inventory areas (raw material production, fuel provision, vehicle utilisation and recycling/disposal) were verified on the basis of random samples. The correctness and plausibility of the calculations and the results were verified by reviewing selected parameters (e.g. GWP (global warming potential), POCP, AP, material input and engine parts lists, all add-on parts, transportation etc.) e.g. aluminium and magnesium partial assessments, DB plan for coolants etc.). In this way, the links between the various areas and the hierarchy of data used for the assessment calculations were verified with respect to the process plans, the inclusion of partial assessments and the data basis.

In order to ensure that the data used could be traced back to the original data sources, both the calculations and the documentation were investigated and found to be very clear and transparent.

All significant parameters are available and representative and have been systematically derived and duly assessed. The assessments and the underlying data collection and calculation procedures are transparent and traceable.

2.3.3 Allocations

Allocations arise in connection with vehicle production; they are included in a database and it was possible to represent them appropriately. They are represented in the computer system completely, clearly and plausibly.

To the extent that allocations are imported to the process plan from databases, the data basis is adequate. Allocations from the databases have already been taken into consideration in the process plan.

2.3.4 Error assessments

Separate error assessments were drawn up for the manufacturing phase. In view of the numeric stability and proven quality of the data used, there is no need to include the separate error assessments (see also 2.3.5). The error assessment for the manufacturing phase amounts to approximately 1%.

2.3.5 Sensitivity Analysis

Sensitivity analyses were not carried out because the variants had the same level of equipment. In addition, the same calculated and therefore lesser values result for the equipment variants. Zudem ergeben sich über die Ausstattungsvarianten die gleichen berechneten und somit verringerten Werte.
In order to verify this statement, calculations regarding sensitivities and the associated parametering were performed at the client's premises. There were no indications that special sensitivity calculations were needed. This also has a basis in the experience of VW AG from the many studies that have been drawn up.

2.4. Life Cycle Impact Assessment

The Life Cycle Impact Assessment is based on the results of the Life Cycle Inventory and is an integral part of the process plans.
In order to carry out a Life Cycle Impact Assessment on the basis of data and information derived from the Life Cycle Inventory, it is necessary to compress the data for defined impact categories.
Taking into consideration the objectives of the assessment, the functional unit selected and the (standard) technologies used in the assessment area, the following impact categories were defined:

- GWP global warming potential
- ODP ozone depletion potential
- AP acidification potential
- NP nutrification potential
- POCP photochemical ozone building potential

The impact categories were therefore selected in accordance with the objectives and scope of the Life Cycle Assessment.

These quantifiable impact categories represent the system assessed and the technologies used in terms of key local, regional and global categories. Individual data were properly allocated to the various categories. Data was aggregated in accordance with the environmental impact concerned; this approach is already defined in the computer program used in accordance with the scientific dose-effect relationship.

The calculations were checked. The factors stored in the computer program are internationally recognized. With reference to the objectives of the assessment, other impact categories are of secondary importance.

Data compression within these categories has been carried out on the basis of generally accepted equivalence factors in a way which is clear, reliable and easy to follow. The presentation and discussion of the results for the case of the TSI engines examined in the Life Cycle Assessment and covered by the Environmental Commendation is balanced and consistent.

2.5 Evaluation

The evaluation section of the Life Cycle Assessment includes specific recommendations for users and target groups.

The evaluation of the results of the Life Cycle Inventory and Life Cycle Impact Assessment which was submitted to us is based consistently and appropriately on the objectives defined for the Life Cycle Assessment.
Further statements and recommendations are strictly separated from the Life Cycle Assessment itself.

3 Summary of the critical review

The critical review of the Life Cycle Assessment "TSI Engines - Environmental Commendation" conducted by the undersigned in accordance with the requirements of international standards DIN EN ISO 14040:2006 and DIN EN ISO 14044:2006 may be summarised as follows:

- The methods used for drawing up the Life Cycle Assessment are in accordance with the requirements of DIN EN ISO 14040:2006 / DIN EN ISO 14044:2006. The

methods are scientifically well-founded and are in accordance with the state of the art of Life Cycle Assessments.
- The data used are adequate, appropriate and well-founded with reference to the objective of the assessment.
- The evaluations take into consideration the objective of the assessment and the limitations which were identified.
- The Life Cycle Assessment is consistent and transparent.

A certificate of validity has been issued concerning the critical review which was conducted (cf. Appendix). The report of the critical review will become part of the detailed version of the Life Cycle Assessment.

W. Hirtz

Dr. Winfried Hirtz
Environmental Verifier
DE-V-0151

Group Research
Environment Affairs Product
P.O. Box 011/1774
38436 Wolfsburg
Germany

December 2009