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Legal Boundary Conditions and Technologies of Two-Wheeler-, Power-Sport- and Small Engines

MASTER THESIS

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Preface

This master thesis was done at the Institute of Internal Combustion Engines and Thermodynamics, Research Area Design at Graz University of Technology in the course of the generation of a database for two-wheeler-, power-sport- and small engines.

I would like to thank the Head of the Institute Univ.-Prof. Dipl.-Ing. Dr. techn. Helmut Eichlseder for the possibility to perform my master thesis. My special thanks go to the Head of Research Area Design Assoc.Prof Dipl.-Ing. Dr. techn. Roland Kirchberger for the competent support and the patience with me during the realization of this master thesis. Moreover, I would express my gratitude to Mag. Claudia Melde for proofreading and the linguistic support as well as the employees of the Research Area Design for the great support.

The greatest thanks go to my parents for the trust, the support and especially for enabling the studies. This master thesis is dedicated to them.

Graz, August 2017 Florian Steflitsch

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Symbols, Indices und Abbreviations

Latin symbols

a	m/s²	Acceleration
$a_{wot,ref}$	m/s²	Reference acceleration
a_{urban}	m/s²	Target acceleration
b_{e}	g/kWh	BSFC
d	m	Diameter
D_{av}	km	Average Distance
D_{e}	km	Electric range of HEV
D_{OVC}	km	Electric range of HEV with OVC
f	s^{-1}	Frequency
l_{ref}	m	Pre-acceleration length
L_{wot}	dB(A)	Sound level pressure at full-throttle test
L_{crs}	dB(A)	Sound level pressure at constant speed test
L_{urban}	dB(A)	Sound level pressure of a weighted combination of full-throttle and constant speed test
m	kg	Mass
M_{i}	mg/km	Mass emission of the pollutant i
$M_{1\mathrm{i}}$	mg/km	Average mass emission of the pollutant i with a fully charged electrical storage device
$M_{2\mathrm{i}}$	mg/km	Average mass emission of the pollutant i with an electrical storage device in minimum state of charge
p	bar, Pa	Pressure
p_{i}	bar	IMEP
p_{e}	bar	BMEP
P	(k)W	Power
Q	C	Electric-Charge
U	V	Electric voltage
v_{max}	m/s	Maximum velocity
$v_{AA'}, v_{BB'}, v_{PP'}$	m/s	Velocity at the lines AA’, BB’ and PP’

Greek symbols

ε	–	Compression ratio
η	–	Efficiency
λ	–	Air ratio
ρ	kg/m³	Density
τ	s	Time
φ	° KW	Crank angle
ω	s^{-1}	Angular velocity
$\phi = 1/\lambda$	–	Equivalence Ratio

Operators and designations

d	Complete differential
Δ	Difference between two quantities

Further indices and abbreviations

1D	One-dimensional
3D	Three-dimensional
2PHI	2-Phase Injection
ABS	Anti-lock Braking System
aSDI	Air-assisted Stratified Direct Injection
ASEAN	Association of Southeast Asian Nations
ATV	All-Terrain Vehicle
APU	Auxiliary Power Unit
BDC	Bottom Dead Center
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BRP	Bombardier Recreational Products
CAA	Clean Air Act
CARB	California Air Resources Board
CCR	California Code of Regulation
CDI	Capacitor Discharging Ignition
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conformity of Production
CVO	Control Valve Operation
CVT	Continuously Variable Transmission
CVS	Constant Volume Sampling
CWI	Compression Wave Injection
DI	Direct Injection
DITECH	Direct Injection Technology
DME	Digital Motor Electronics
DOLCE	**D**evelopment **O**f Innovative **L**ow Pollutant, Low Noise, Low Fuel **C**onsumption Two-Stroke Engine For Future Vehicles For Individual Urban Mobility
DVT	Desmodronic Variable Timing
ECE	Economic Commission for Europe (United Nations)
ECS	Electronic Carburation System
ECU	Electronic Control Unit
EFI	Electronic Fuel Injection
EFM	Exhaust Mass Flow Meter
EMS	Electronic Management System
EPA	Environmental Protection Agency
EPC	Exhaust Port Closing
EPT	Electronic Power Throttle
EPO	Exhaust Port Opens
EQR	Equivalence Ratio
EUDC	Extra Urban Driving Cycle
EV	Electric Vehicle
FAST	Fully Atomized Stratified Turbulence
FEL	Family Emission Limit
FFI	FICHT Fuel Injection
FHR	Fast Heat Release
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GPS	Global Positioning System
GRPE	Working Party on Pollution and Energy
GTR	Global Technical Regulation
HC	Hydrocarbons
HEV	Hybrid Electric Vehicle

HP	High Pressure
IAPAC	Injection Assistée Par Air Comprimé (compressed air assisted fuel injection)
ICE	Internal Combustion Engine
ICOMIA	International Council of Marine Industry Associations
IDC	Indian Driving Cycle
IFP	Institut Français du Pétrole
IMEP	Indicated Mean Effective Pressure
ISFC	Indicated Specified Fuel Consumption
ISO	International Organization for Standardization
IVT	Institute of Internal Combustion Engines and Thermodynamics
LP	Low Pressure
LPDI	Low Pressure Direct Injection
MC	Motorcycle
MFB	Mass Fraction Burnt
MoRTH	Indian Ministry of Road Transport and Highway
MPI	Multi Point Injection
NMHC	Non-Methane Hydrocarbons
NOVC	Non-Off-Vehicle Charging
NOx	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
NRSC	Non-Road Steady-state Cycle
NRTC	Non-Road Transient Cycle
NTC	Negative Temperature Coefficient
N/U	Speed Utilization
OBD	On-Board Diagnostics
OHV	Over Head Valves
OPC	Orbital Combustion Process
OVC	Off-Vehicle Charging
PC	Passenger Cars
PEMS	Portable Emissions Measurement System
PGM	Platinum Group Metals
PGM-FI	Programmed Fuel Injection
PI	Positive Ignition (mean SI – spark ignition)
PLU	Pierburg Luftfahrtgeräte Union (Pierburg Aviation Union)
PM	Particulate Matter
PN	Particulate Number
RAVE	Rotax Adjustable Variable Exhaust
RDE	Real Drive Emissions
REX	Range-Extender
rl	Relative air mass
RON	Research Octane Number
SCIP	Simplified Camless IAPAC
SI	Spark Ignition
SMD	Sauter Mean Diameter
SOI	Start Of Injection
SORE	Small Off-Road Engines
SPC	Scavenge Port Closing
SPI	Single Point Injection
SPO	Scavenge Port Opening
TA	Type Approval
TDC	Top Dead Center
THC	Total Hydrocarbons
UAV	Unmanned Aerial Vehicles
UDC	Urban Driving Cycle
UDDS	U.S: EPA Urban Dynamometer Driving Schedule
UL	Useful life

UN	United Nations
V-TEC	Variable Valve Timing and Lift Electronic Control
WH-GDIS	Water Hammer – Gasoline Direct Injection System
WMTC	Worldwide harmonized Motorcycle Testing Cycle
WOT	Wide Open Throttle
YCC-T	Yamaha Chip Controlled Throttle
ZEV	Zero Emission Vehicle

According to DIN 1304-1, DIN 1345, DIN 13 345 and ISO 80 0000-5

Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master's thesis.

Florian Steflitsch

Graz, 04.09.2017

Abstract

This master thesis was carried with the aim to create a database for two-wheeler-, power-sport- and small engines. The literature research in this field included as key points the progress of emission legislation, with the focus on Europe, as well as the description of technologies and concepts of small engines, with the focus on mixture formation of gasoline engines.

In the first part of this study, an overview of the legal framework conditions of two-wheelers is given, which accounts for a significant proportion to the market of small engines due to their large global vehicle population. The special focus was on the main sales markets, which are in Europe, the U.S., China and India.
The data for illustrating the development of the emission standards including a brief outlook on future emission legislation was captured by means of published reports and regulations of the competent authorities of the appropriate countries and commissions, indicating the trend towards more and more stringent emission limits. The researched information and emission limits were summarized in overview tables. Furthermore, a brief outlook regarding real drive emissions (RDE) of two-wheelers is given.

Another aspect that is contained in this thesis is non-road mobile machinery (NRMM), which includes small engine applications such as chainsaws, lawn mower, snowmobiles, ATVs, Jet-Skis etc.. The emission legislation of NRMM was also summarized in tables for the markets in Europe and the U.S:.

The second part deals with technologies and concepts of gasoline engines in two-wheelers, recreational vehicles and further applications with small engines, which in part were only designed for the use in small engines. A main focus was on the mixture formation, which, inter alia, can significantly influence the raw emissions of engines. Moreover, a brief insight in engine management systems, in ignition systems as well as in the exhaust gas after treatment of small engine applications is also given.
Finally, some examples of engine concepts are presented, which originate from publications, inter alia, of the Institute of Internal Combustion Engines and Thermodynamics (IVT).

Zusammenfassung

Diese Masterarbeit entstand mit dem Ziel eine Datenbank für Zweirad-, Power-Sport- und Kleinmotoren zu erstellen. Die wesentlichen Punkte dieser Literaturrecherche sind einerseits die Entwicklung der Emissionsgesetzgebung mit dem Schwerpunkt auf Europa, und andererseits, das Aufzeigen von Technologien und Konzepten für den Kleinmotorenbereich, wobei der Fokus auf der Gemischbildung von Ottomotoren liegt.

Im ersten Teil dieser Studie wird ein Überblick über die gesetzlichen Rahmenbedingungen von Motorrädern gegeben, die auf Grund ihres großen globalen Fahrzeugbestandes einen erheblichen Anteil am Markt für Kleinmotoren ausmachen. Das Hauptaugenmerk wurde dabei auf die wichtigsten Absatzmärkte gerichtet, die in Europa, den USA, China und Indien liegen.
Die Daten zur Veranschaulichung der Entwicklung der Emissionsnormen, einschließlich eines Ausblicks in zukünftige Emissionsgesetzgebungen, wurden aus veröffentlichten Berichten und Verordnungen der zuständigen Behörden der entsprechenden Länder und Kommissionen entnommen, mit dem erwarteten Trend hin zu immer strengeren Emissionsgrenzwerten. Die recherchierten Informationen und Daten wurden in den entsprechenden Tabellen zusammengeführt. Darüber hinaus wird ein Blick auf mögliche zukünftige Real Drive Emissions (RDE) bei Zweirädern gegeben.

Die zweite wichtige Kategorie für Kleinmotoren ist die Non-Road Mobile Machinery (NRMM), die Anwendungen wie beispielsweise Kettensägen, Rasenmäher, Schneemobile, ATVs, Jet-Skis usw. beinhaltet. Die Emissionsvorschriften für NRMM wurden ebenfalls im Tabellenformat für Europa und die USA zusammengefasst.

Im zweiten Teil werden Technologien und Konzepte von Ottomotoren in Zweirädern, Freizeitfahrzeugen und weiteren Kleinmotorenanwendungen abgehandelt, die zum Teil nur für den Einsatz in Kleinmotoren konzipiert wurden. Ein Schwerpunkt liegt dabei auf der Gemischbildung, die unter anderem die Rohemissionen signifikant beeinflussen kann. Darüber hinaus wird ein kurzer Einblick in die verwendeten Motormanagementsysteme, Zündanlagen sowie Abgasnachbehandlungssysteme in Kleinmotoren gewährt.
Abschließend werden noch einige Beispiele von ausgeführten Motorkonzepten vorgestellt, die unter anderem auch aus Publikationen des Instituts für Verbrennungsmotoren und Thermodynamik (IVT) stammen.

1 Introduction

Nowadays, one of the most important issues of our time is the climate change and relating thereto also the emitted emissions causing them. A not insignificant part of these emissions are emitted by two-wheelers and other applications of small engines, which are assigned, inter alia, to the transport sector. An approach to halt the rapid progression of climate change, which is also realized, is the implementation of more and more stringent emission standards especially for the transport sector, even though, from the global point of view, not always with the same consequence.

The sector of two-wheeler-, power-sport- and small engines is also affected thereof. In this segment the pollutants carbon monoxide CO, hydrocarbons HC and nitrogen oxides NOx are limited. The regulation of particulate matter PM, non-methane hydrocarbons NMHC and total hydrocarbons THC can only be partly found in current emission regulations, however, almost certainly in future emission standards.
The limitation of the pollutants occurs for each defined category by the appropriate government and commission in regard with the vehicle type, scope of application or engine size. For example, the category motorcycle contains two- and three-wheelers as well as quadricycles, and the non-road mobile machinery (NRMM) includes, inter alia, applications such as chainsaws, lawn mowers, gen sets, Jet-skis, ATVs, etc..

In addition, the driving and test cycles for emission test procedures are also part of the progress of emission reduction. For example, in the early stages the cold start phase was excluded from the emission test procedures, whereby the measured emissions were not really comparable with the emitted emissions in real driving conditions. In the next steps of emission reduction, cold start phases were taken into account at first and then a completely revised driving cycle was introduced, the World Harmonized Motorcycle Test Cycle (WMTC). Finally, this will in all probability lead to Real Drive Emissions (RDE) test procedures for two-wheelers. The RDE test procedure is already valid since September 2017 for passenger cars in the European Union.

Within the scope of this master thesis a current status of emission regulations of two-wheeler-, power-sport- and small engines will be researched to illustrate the progress of emission legislation in different regions and countries. From the technological perspective, the mixture formation plays an important part for raw emissions of engines. The development of some technologies has been advanced, inter alia, by the emission issues referred to above.
With a view on the topic of this thesis, in particular the high HC emissions of the widespread conventional two-stroke engines in the small engine sector, which are caused by the scavenging losses, represent a problem. Therefore, different technologies for mixture formation as well as engine concepts, which range from prototypes to concepts ready for series production, will be shown.

2 Requirements and Legal Boundary Conditions

Series-produced motorcycles were first launched in the late 19th century by Hildebrand & Wolfmüller on the European market. Significant technical developments at this early phase came from Europe. However, in the U.S., developers were actively involved in the progress of design. [1, p. 374]

Some of the first manufacturers of motorcycles in Europe and U.S. are still active today and build up a reputation. In Europe, for example the first Triumph motorcycle was manufactured in 1902 [2] and Husqvarna unveiled their first motorcycle in 1903 [3]. In U.S., the manufacturer Indian built their first motorcycle in 1901 [4] and Harley-Davidson sold the first motorcycle in 1903 [5].

In the 1930s, half of the worldwide approved motorcycles were used in Germany, but with the automobile boom from 1950 onwards the two-wheeler popularity decreased significantly.

From a European point of view, the two-wheeler market today seems almost insignificant with about 1 million produced vehicles in 2010 (see Figure 1), because the number of sold passenger cars, produced in the same period in Europe, was one magnitude higher. [1, p. 374]

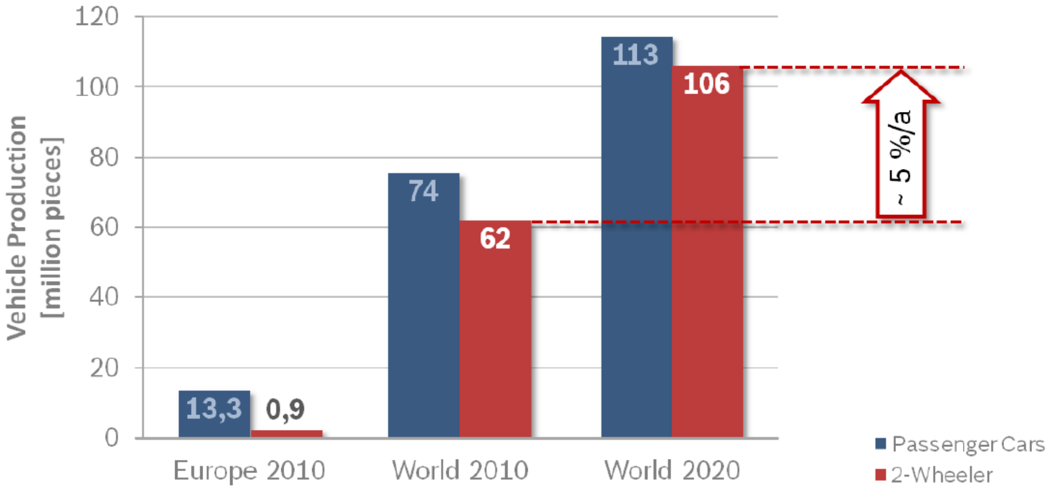


Figure 1 Production figures of passenger cars and two-wheelers in Europe and worldwide [1, p. 375]

To understand the importance of the motorcycle segment, the focus needs to be directed towards to the global demand. In 2010, the numbers of produced motorcycles approximated, with more than 60 million units, the volume of automobile production. The study by Freedonia [6] forecasts for 2020, that the number of two-wheelers worldwide will increase up to nearly 110 million. This corresponds approximately with volume of passengers cars worldwide, and is equivalent to an annual growth rate of approximately 5%.Therefore, it is impossible to generate an overview of the whole future market, if only the European market is considered. [1, p. 374]

The regions India, Southeast Asia (ASEAN), China and South America represent the most important future markets for two-wheelers with internal combustion engine (ICE). In these regions, motorcycle are essential parts of transport and transportation, e.g. for the way to work, for transporting goods or for trips with the family. This market segment in these areas is the so-called commuter segment. In Europe and North America motorized two- and three-wheeled vehicles are usually used as recreational vehicles. The commuter segment will

increase rapidly in the next few years in Asia. In 2019, more than 80% of worldwide sold motorcycles will be driven. In the regions of India and Southeast Asia growths rates of up to 11% will be achieved and major manufacturers will sell more than 5 million units per year in these market segments from 2019 onwards. [1, pp. 375-376]
Motorcycles with combustion engines also continue to take over an essential part of individual mobility in the future, especially in the emerging markets in Asia and South America. Crucial factors for future engine control technologies are the development of emission legislations and customer demands for lower fuel consumption, more comfort and better performance. [1, pp. 385-387]

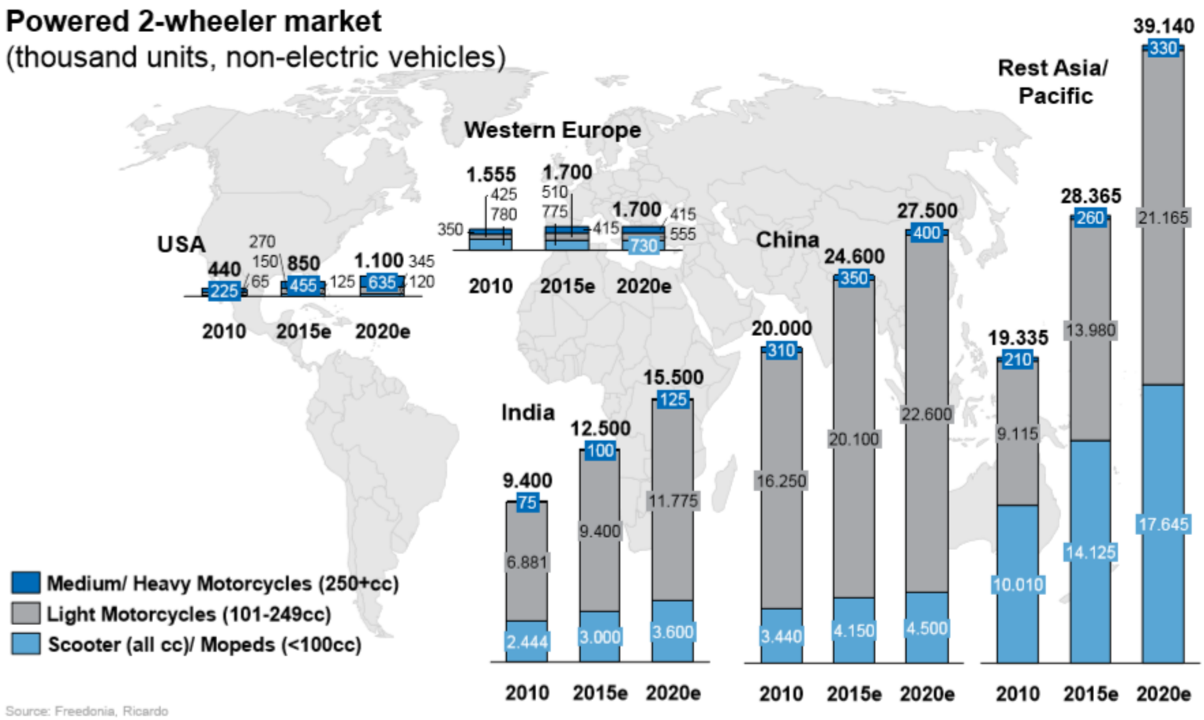


Figure 2 Powered 2-wheeler market in 2010, 2015 and 2020 [7, p. 6]

Figure 2 shows the dominance of the Asian market in smaller two-wheeler segments (light blue). It will be grow quickly in the next few years. The Western markets will stay dominant in the mid-term, by motorcycles greater than 250 cm³, with focus shifting to North America. Figure 3 depicts the percentage division of medium and heavy motorcycles (> 250 cm³) in the regions of Western Europe, North America, India, China and the remaining Asian countries. [7, pp. 6-7]
In order to achieve the required low emission limits and reduced fuel consumption, new technology solutions are necessary, but unfortunately production costs will be increase. The implementation of costly technologies in the two-wheeler sector, e.g. closed loop λ control or even direct injection system, is more difficult on the Asian motorcycle market than on European recreational two-wheeler market, due to higher system costs and system complexities.
In Asia, two-wheelers are regarded as "minimum transport vehicle", whereby it is important for economic growth, that these" two-wheeled transport vehicles" have minimum costs to ensure the individual transport. Therefore, the main challenge is to find new concepts with minimal impact on production costs, and still meet the requirements of future emission limits

and reduced fuel consumption. The most used engine technology for motorcycles in Asian is the two-valve spark ignited engine with air cooled cylinder. Other problems in newly industrialized countries or developing countries are repair shops, which cannot handle electronic engine components or diagnostic tools. Therefore, in these countries, it has to be possible to repair these vehicles at the roadside. Nevertheless, new vehicle generations should improve previous models in performance and drivability to ensure a successful market launch. [8, p. 94]

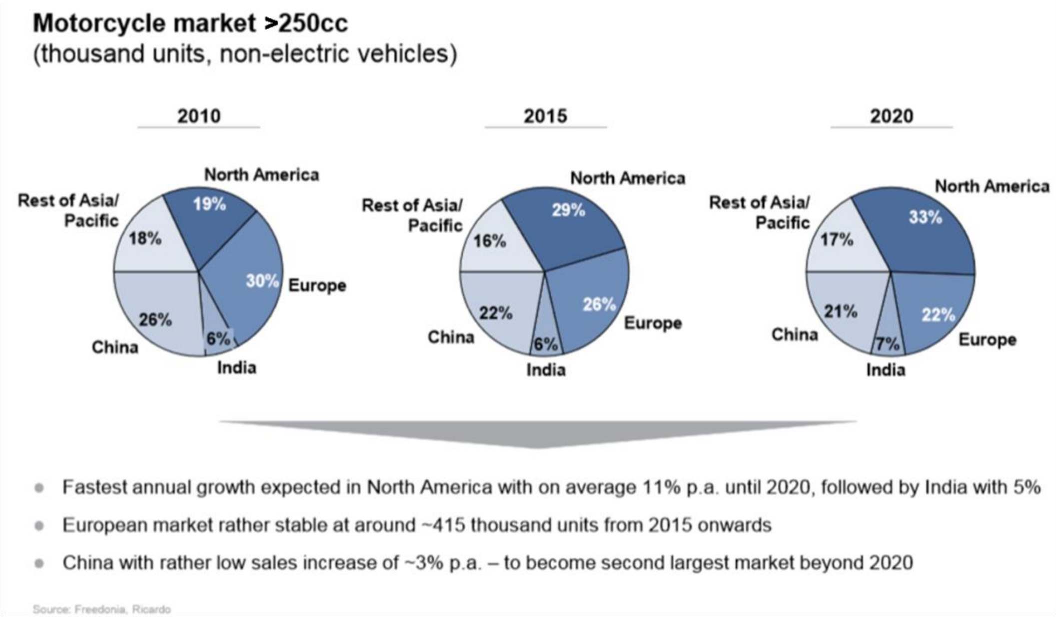


Figure 3 Motorcycle market >250cm³ in 2010, 2015 and 2020 [7, p. 7]

Basically, the emission legislation of motorcycles is lagging behind the emission standards of passenger cars. Therefore, in passenger cars more emission-reducing technologies are applied than in motorcycles, e.g. three-way catalytic converter.

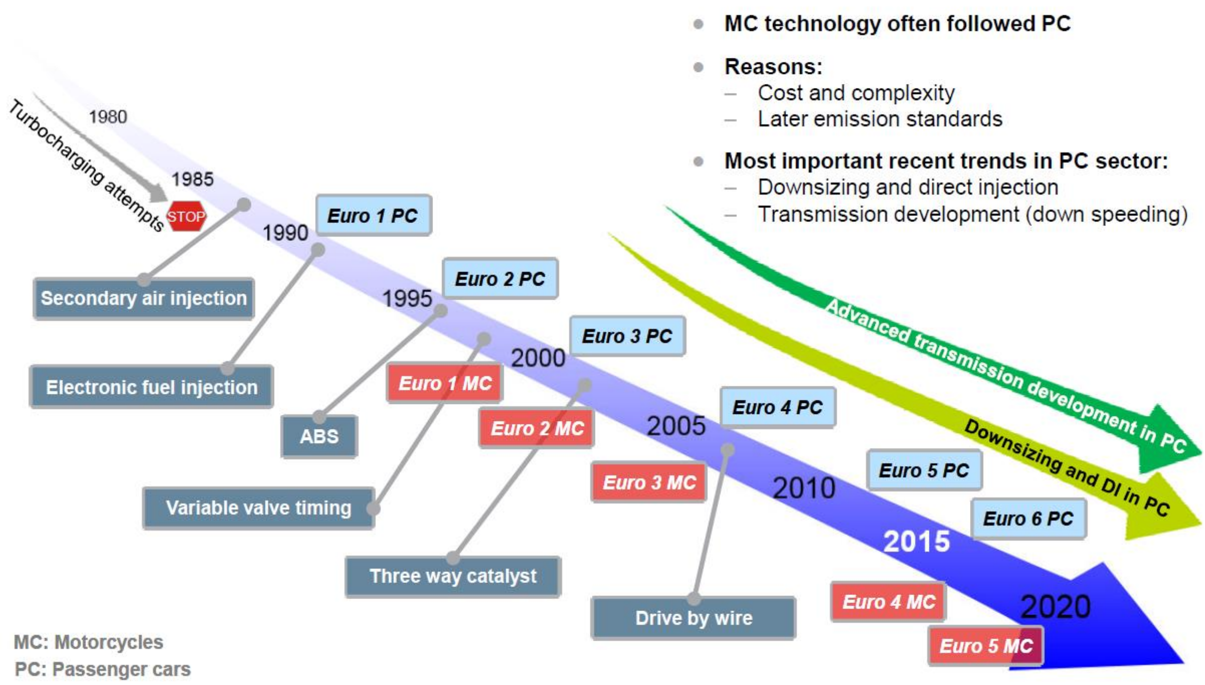


Figure 4 Examples of automotive technology in motorcycles [9, p. 2]

Conversely, performance improving technologies are first used in motorcycles, e.g. Honda VTEC (Variable Valve Timing and Lift Electronic Control) system. Figure 4 shows a short comparison of technologies and emission standards between passenger cars and motorcycles.

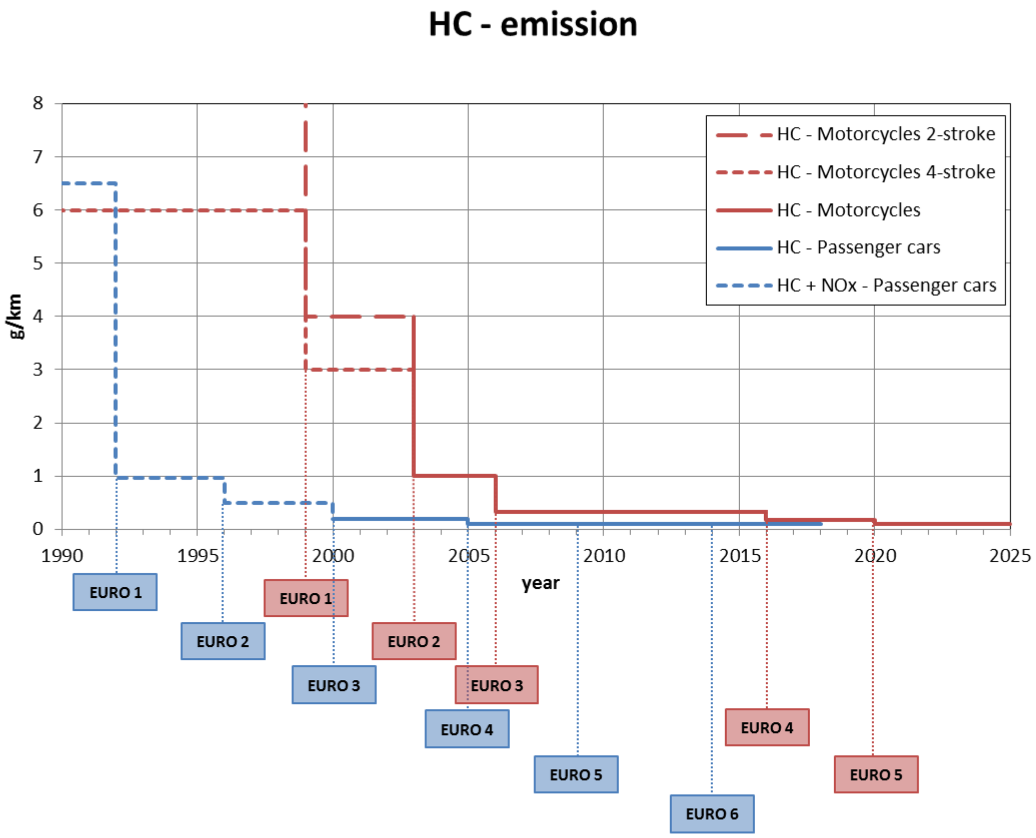


Figure 5 Comparison of HC emission standards of motorcycles and passenger cars in Europe

Figure 5, Figure 6 and Figure 7 display the HC-, CO- and NOx-emission limits for motorcycles and passenger cars with spark ignition (SI). The EURO 1 standard of motorcycles does not distinguish between spark ignition and compression ignition (CI), but between 2-stroke and 4-stroke. The depicted graphs in Figure 5 to Figure 7 for EURO 1 correspond to a 4-stroke engine. The EURO 1 emission limits for a 2-stroke engine can be found in Table 18 in the Appendix.

As indicated previously, it can be seen that equivalent motorcycle emission standards are usually implemented with some delay compared to passenger cars emission standards. The slight increase of CO emission limits of passenger cars at EURO 3 is based on a revised test cycle type compared to EURO 2.

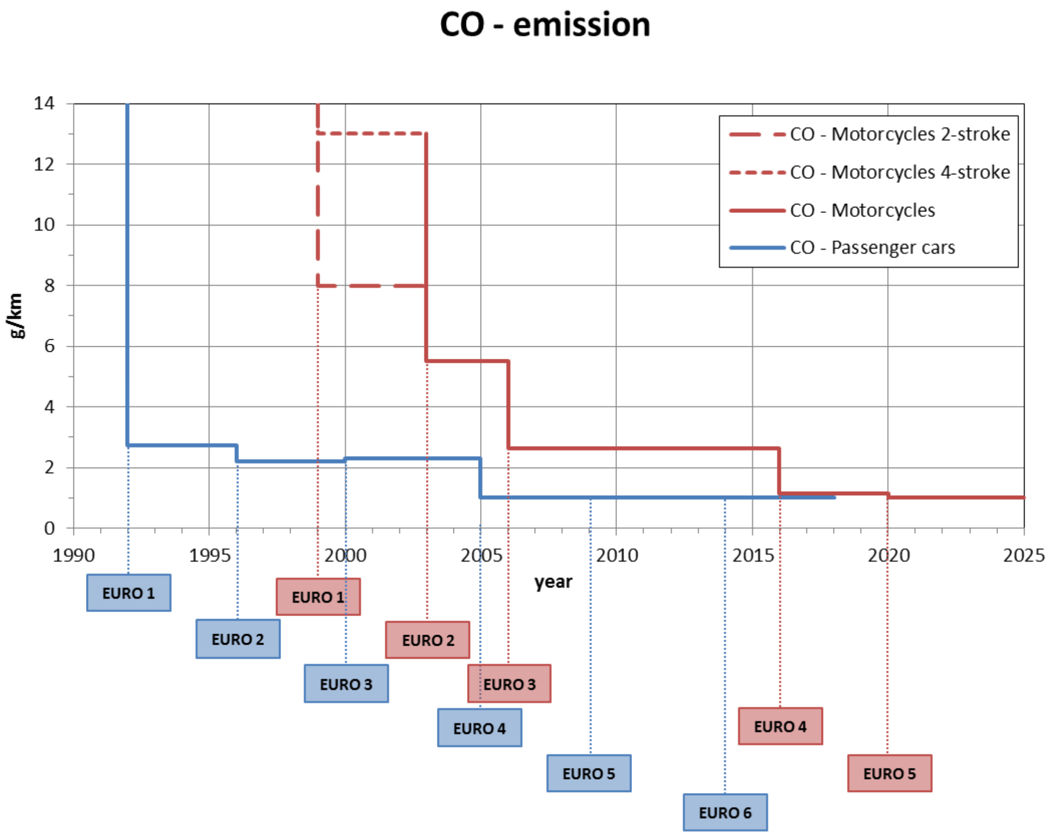


Figure 6 Comparison of CO emission standards of motorcycles and passenger cars in Europe

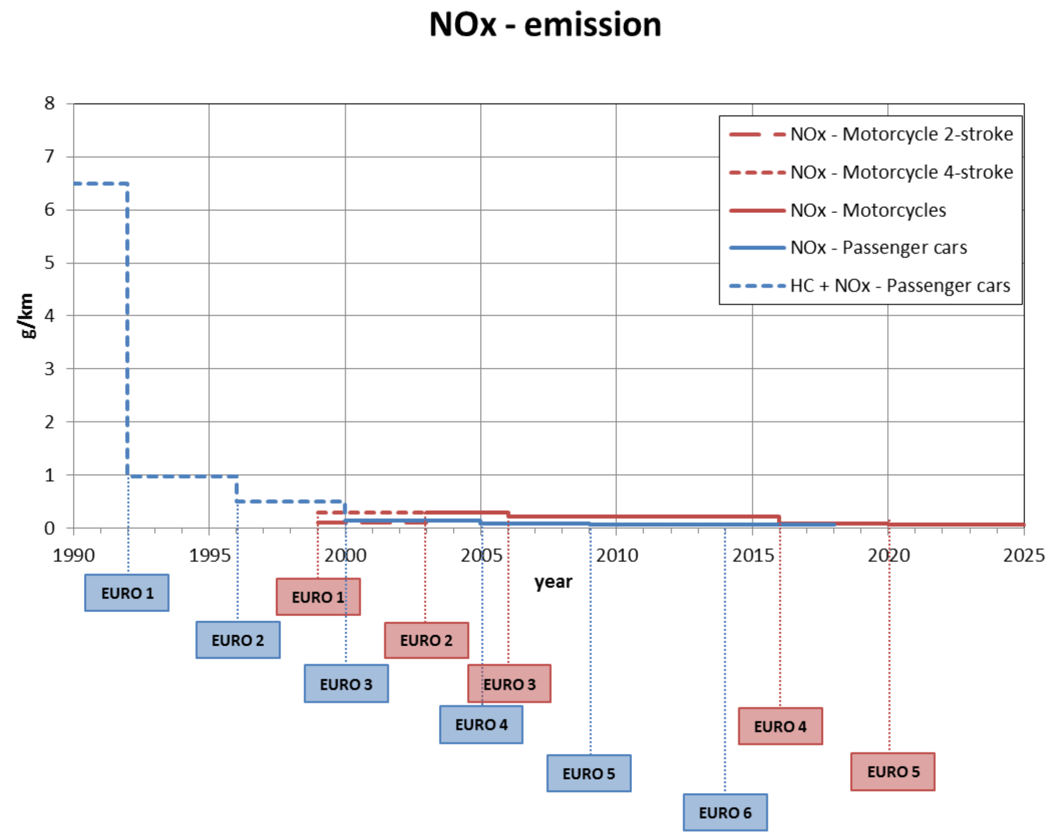


Figure 7 Comparison of NOx emission standards of motorcycles and passenger cars in Europe

2.1 Development of Motorcycle-Emission-Control Legislation

For the first time, two-wheeler emission regulations were introduced in the U.S. in 1978. Over time, more and more countries have committed themselves to regulate emissions from two-wheelers. Unfortunately, the permissible emission limits vary widely. The allowable limits depend on several factors, e.g. the extent of the (local) existing environmental pollution as well as various political and economic factors. Also, high emission pollutants have noticeable negative impact on the environmental and human health. For this reason, regions which suffer from a high pollutant are usually pioneers in the matter of stricter emission legislation, e.g. Beijing in China.

In many countries, certification guidelines for motorcycles were introduced, which have become increasingly stringent with the time. For example, from the mid- to late-1990s the cold start phase was not considered at emission test cycles with no or limited durability requirements. The increasing emission requirements resulted in a reduction of exhaust gas emissions as well as reduced noise emission and improved fuel consumption. Furthermore, the global motorcycle market was shifted to more four-stroke engines.

The current two-wheeler emission legislations focus mainly on CO and HC emissions. There are also NOx standards, which should primarily reduce NOx emissions of 4-stroke engines because 2-strokes are low NOx emitters. PM standards currently only apply to compression-ignition engines in Europe and India; notwithstanding that PM emissions of two-stroke engines can be very high. [10, pp. 3-4]

The main application field of small displacement engines is the propulsion of two-wheeler vehicles. The large numbers of two-wheelers, from the global point of view, indicates the importance of technological improvements for environmental protection. However, the implementation of more efficient and environmentally-friendly technologies is difficult, especially in the Asian region, due to higher system and production costs. Therefore, the main technologies used in Asia are the air-cooled two- and four-stroke engine with carburetor. As a result of a large quantity of two-wheelers in these countries (see Chapter 2 - Figure 2), the air pollution is higher than for example in Europe. The introduction of new technologies is influenced by the legislation. For this reason, more stringent emission limits in Europe facilitates the introduction of advanced technologies.

There is still no global emission legislation, but the individual regulations approximate more and more the European standards. Nevertheless, the market demand shows still local phenomena. The main requirements on the European and U.S. market are the reduction of emissions and the driving pleasure. In Japan, the focus is on small displacement engines with low-emissions and reduced fuel consumption. In India, the fuel consumption of two-wheelers is the main criterion, whereas in China and the rest of the Asian countries, the production costs are the essential issue. [8, pp. 3-4]

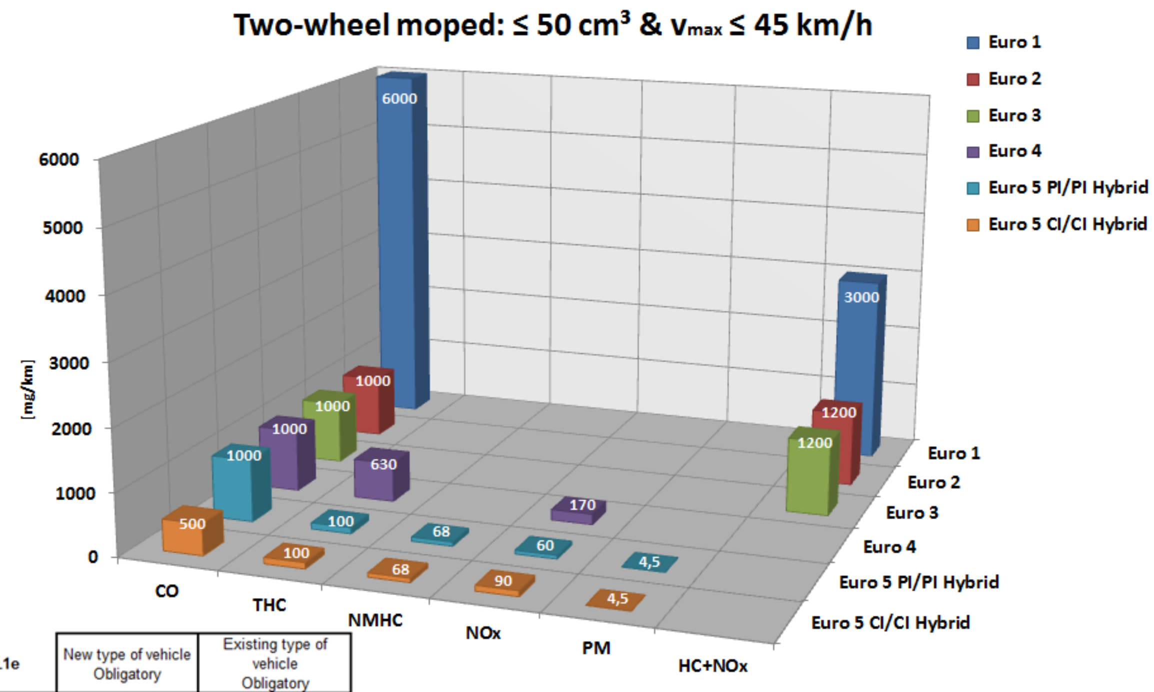
2.1.1 Europe (EU)

The first emission regulation was created by the United Nations Economic Commission for Europe, also called UN-ECE, with support by most of the European countries, the U.S., Japan and China. Member nations may use these emission regulations, but are not obliged to do so.
In the first few years, the European Union adopted the UN-ECE emission regulations. This includes also regulations for motorcycles and mopeds. Over time, the UN-ECE and the European Union have reversed the roles. Today, the European Union takes a leading role in formulating emission standards and so currently the UN-ECE proposals are attuned with them. The European-wide applicable emission standards are published as directives, whereby European countries can not prohibit vehicles which comply with the terms of the directives, but vehicles which do not. [11, p. 1]
Before 1997, the European Union had no standardized emission limits for motorcycles and mopeds. Only few nations in Europe adopted the UN-ECE regulations. Belgium, Finland, France, Germany, Italy, Luxembourg, the Netherlands and the United Kingdom applied the ECE 40.01 for two- and three-wheeled vehicles with cylinder displacement above 50 cm³ and the ECE 47 regulation for two- and three-wheeled vehicles with cylinder displacement below 50 cm³. [11, p. 10]
In addition, Hungary, Romania, the Russian Federation, the Czech Republic and Slovakia also accepted vehicles meeting ECE 40.01 regulation. In September 1979, the ECE 40 regulation was adopted and on May 1988 amended to ECE 40.01 with stricter emission limits than ECE 40.Until 1997, some nations in Europe had their own emission limits for motorcycles and mopeds, which were partly more stringent than the UN-ECE regulations at that time, e.g. like Austria. [12, p. 15]
On 17th June 1997, the so-called multi-directive 97/24/EC was introduced, which includes the EU type approval for mopeds and motorcycles. National type approvals, which were published before 17thJune 1999, retained their validity for a maximum of four years, to the 17th June 2003, in agreeing with the framework directive 92/61/EC. [11, p. 10]
A further brief insight the emission legislation for two-wheeler can be found in [13, pp. 401-403].´Figure 8 and Figure 9 show a graphical trend of European emission limits for mopeds and motorcycles during the last years. Both graphics exhibits the increasingly stringent emission regulations in Europe, from first implementation in 1997 till today. Since 1st January 2016, the current emission stage EURO 4 is valid for the EU type approval of motorcycles and on 1st January 2017, EURO 4 is mandatory for type approval of mopeds, too. Another challenge for motorcycle manufacturers is the obligatory application of OBD I. The use of OBD II is based only on a voluntary basis. The next emission stage EURO 5 will be introduced in 2020, probably with the emission limits shown in Table 18 in the Appendix. The obligatory implementation of ODB II is also being discussed.
Table 18 in the Appendix depicts an overview of the emission regulation stages, vehicle categories, emission limits and test cycles in the European Union. The European Parliament and Council divide two- , three-wheeler and quad vehicles into different L-categories. Criteria are the engine capacity, the maximum design vehicle speed, the maximum continuous rated power, the mass in running order, the number of seating positions and the power-to-weight ratio. The “L” stands for “light”, the number for the category and “e” for Europe. The whole vehicle classification is regulated in Regulation (EU) No 168/2013. Table 1 gives an overview

about the main L-categories, and Table 19 in the Appendix represents the whole vehicle classification, including the sub-categories, in accordance with the EU regulation. [14, pp. 94-101]

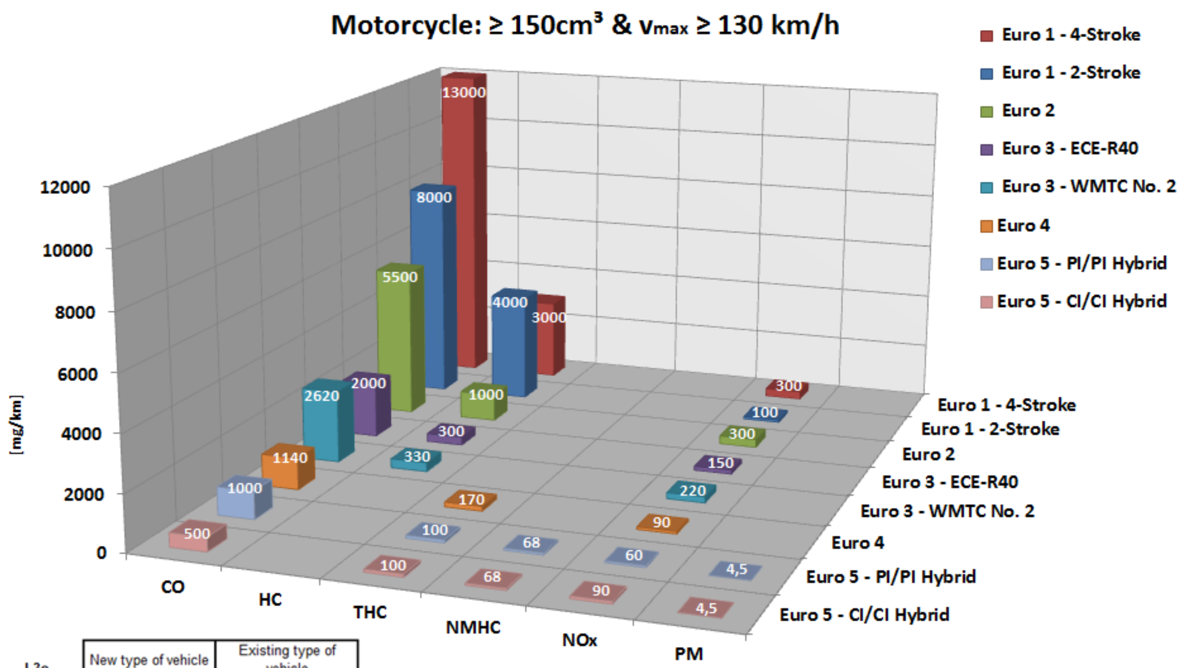
Table 1 Europe - L-category vehicle classification; adapted from [15, p. 8]

Category	Category name		Vehicle classification criteria
L1e	Light two-wheel powered vehicle		➢ Two wheels ➢ Engine capacity ≤ 50 cm³ if SI engine type ➢ Maximum designed vehicle speed ≤ 45 km/h ➢ Maximum continuous rated or net power ≤ 4 kW
L2e	Three-wheel moped		➢ Three wheels ➢ Engine capacity ≤ 50 cm³ if SI engine or ≤ 500 cm³ if CI engine ➢ Maximum designed vehicle speed ≤ 45 km/h ➢ Maximum continuous rated or net power ≤ 4 kW ➢ Mass in running order ≤ 270 kg
L3e	Two-wheel motorcycle		➢ Two-wheels, without side-car ➢ Two-wheel vehicle that cannot be classified as a category L1e vehicle
L4e	Two-wheel motorcycle with side-car		➢ Vehicle complying with the classification criteria for a L3e vehicle and is equipped with one side-car ➢ Maximum of four seating positions (including driver seating position) ➢ Maximum of two seating positions
L5e	Powered tricycle		➢ Three-wheels ➢ Mass in running order ≤ 1000 kg ➢ Three-wheel vehicle that cannot be classified as a category L2e vehicle
L6e	Light quadricycle		➢ Four wheels ➢ Maximum designed vehicle speed ≤ 45 km/h ➢ Mass in running order ≤ 425 kg ➢ Engine capacity ≤ 50 cm³ if SI engine or ≤ 500 cm³ if CI engine ➢ Maximum of two seating positions (including driver seating position)
L7e	Heavy quadricycle		➢ Four wheels ➢ Mass in running order ≤ 450 kg for transport passengers or ≤ 600 kg for transport of goods ➢ L7e vehicles that cannot be classified as a category L6e vehicle



L1e	New type of vehicle Obligatory	Existing type of vehicle Obligatory
EURO 4	1/2017	1/2018
EURO 5	1/2020	1/2021

Figure 8 Comparison of European emission levels of two-wheeler mopeds



L3e	New type of vehicle Obligatory	Existing type of vehicle Obligatory
EURO 4	1/2016	1/2017
EURO 5	1/2020	1/2021

Figure 9 Comparison of European emission levels of motorcycles

Next, test and driving cycles will be explained in more detail. Figure 10 shows the ECE-15 test cycle, also-called urban driving cycle (UDC), and the Extra Urban Driving Cycle (EUDC). The ECE-15 or UDC describes a test cycle with low speed and engine load, which represent city driving conditions. The UDC test cycle is repeated four times without any interruption and achieves a total test time cycle of 780 seconds. The low duties of the ECE-15 test cycle, with maximum speed of 50 km/h, do not produce representative results for many driving conditions. Therefore, the EUDC has been added. This "high speed" part is carried out after the ECE-15 test cycle, with a maximum vehicle speed of 120 km/h and alternatively for low powered vehicles with a maximum speed of 90 km/h.

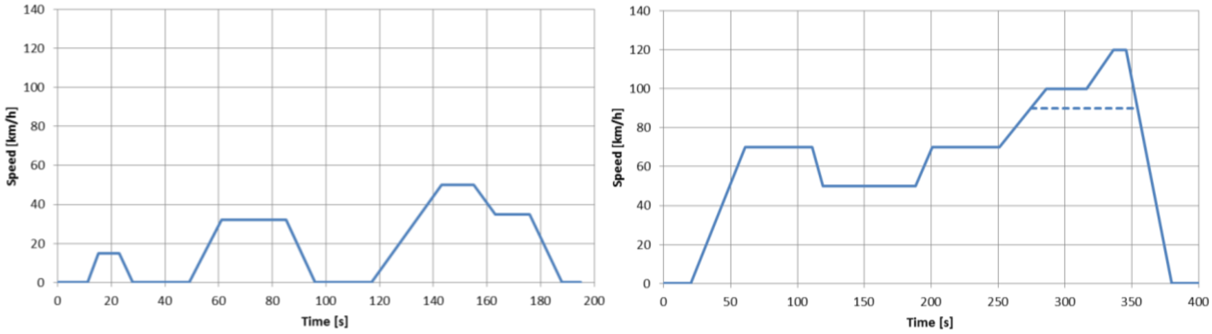


Figure 10 ECE-15 test cycle (left) and EUDC test cycle (right); adapted from [16] [17]

Figure 11 depicts the ECE R47 test cycle and Figure 12 the ECE R40 + EUDC test. Furthermore, Figure 11 shows the difference of the test cycles between EURO 2 and EURO 3 for L1e, L2e or L6e vehicles [18]. At EURO 3 regulation, the emissions of cold start or cold phase are measured the first time. All emissions, emitted in the cold start (phase) of the engine represent a significant proportion of overall emissions in the test cycle. [13, pp. 401-403] [19]

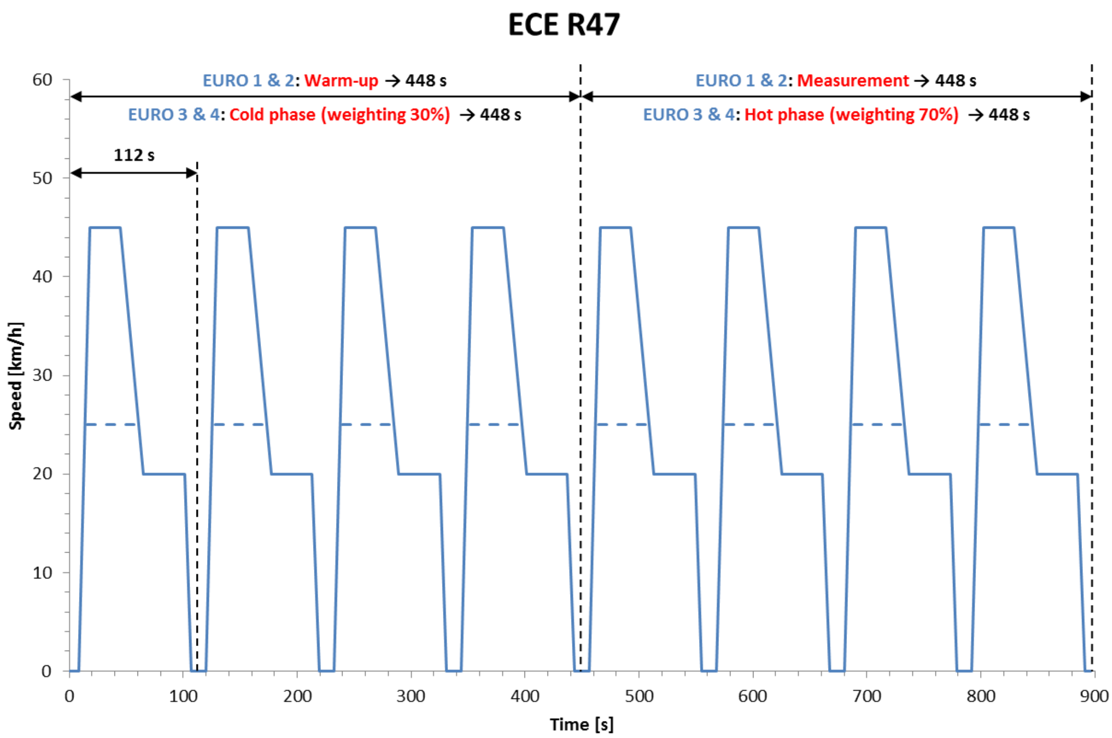


Figure 11 ECE R47 test cycle; adapted from [20, p. 20], [21, p. 169]

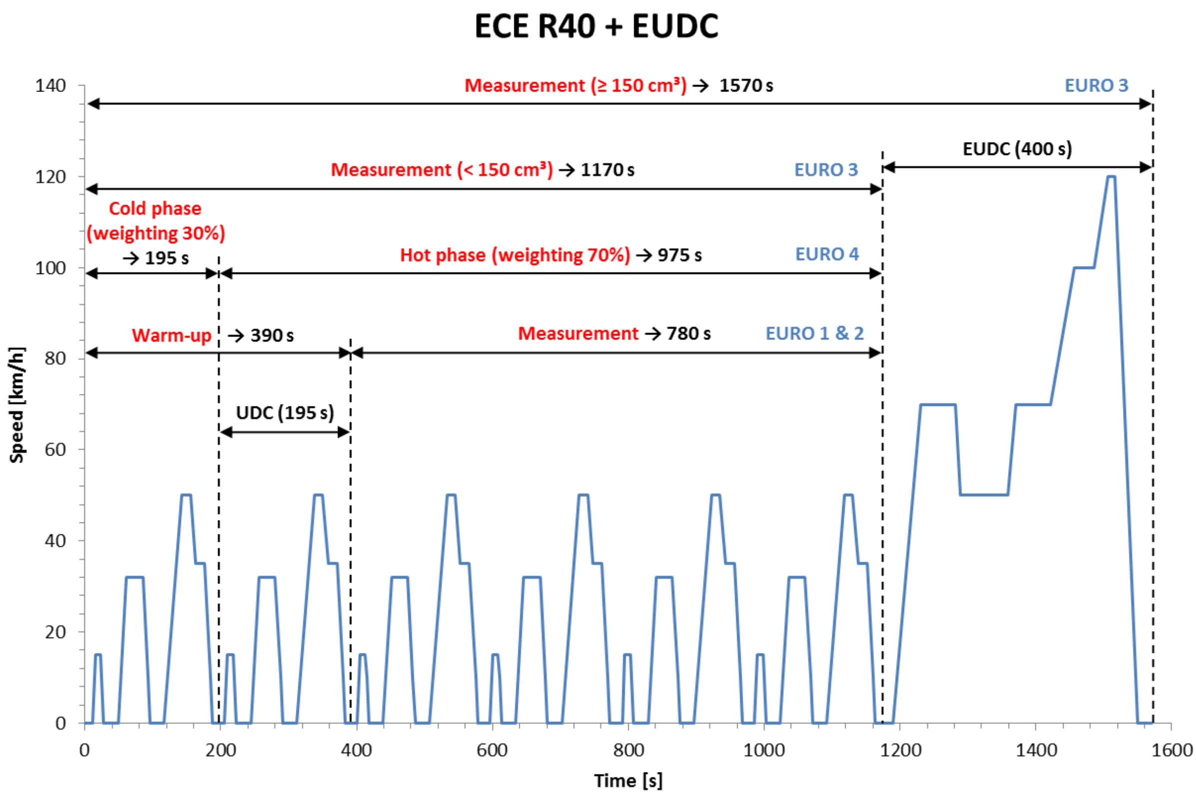


Figure 12 ECE R40 + EUDC test cycle; adapted from [21, p. 172], [22, p. 79]

The ECE R40 test cycle consists of the 6-times repetition of the ECE-15 cycle, and was extended with the EUDC due to the implementation of EURO 3. Figure 12 shows also the difference between the individual emission levels. The Worldwide harmonized Motorcycle Testing Cycle (WMTC) bases on the idea to standardize the motorcycle certification procedure, which requires a harmonized test cycle. [13, pp. 401-403]

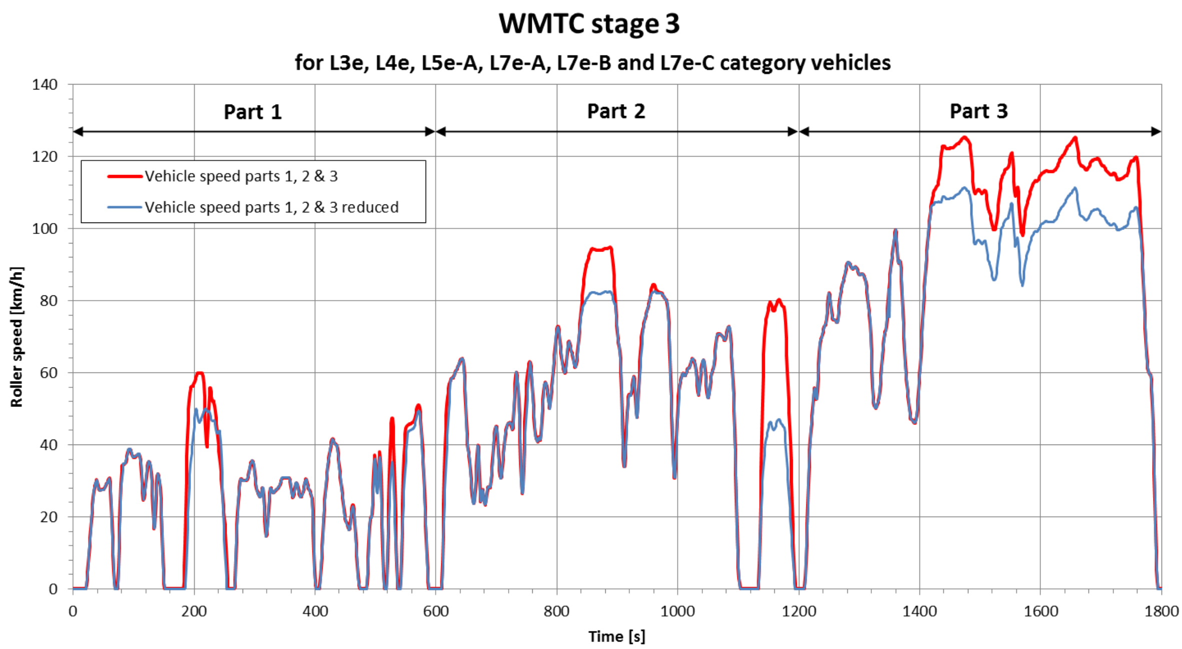


Figure 13 World Harmonized Motorcycle Test Cycle (WMTC) stage 3; adapted from [22, p. 109]

The GRPE informal working group developed a Worldwide Harmonized Motorcycle Emission Certification Procedure and established it as Global Technical Regulation (GTR). The defined measurement methods in the GTR represent the common driving behavior of motorcycles much better than prior methods. This should overcome the unconsidered real driving conditions of too old test cycles. The main problem of old test cycles and test procedures is the fact, that they do not reflect existing driving conditions. [23, pp. 5, 8]
The GTR contains a main test cycle (Figure 13), an alternative test cycle for low-powered motorcycles (Figure 14), a gear-shift procedure and the test conditions. The main test cycle consists of three parts which depends on the vehicle category. The motorcycles are split into three different categories in accordance with their real application (Table 2 and Table 3).
First, the GTR was presented without emission limits, to legalize the harmonized test procedure, whereby contract parties are committed to start with the implementation of the GTR in their national law. But, the contract parties were asked to use emission limits which comply at least with the existing regulations. [24, p. 197]

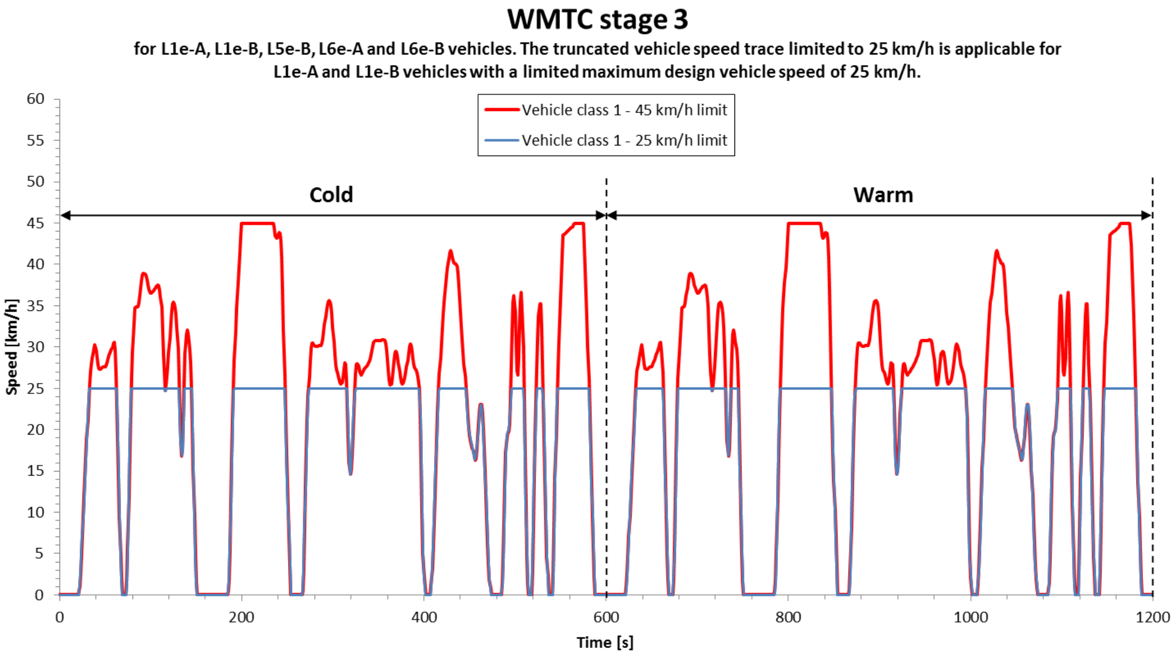


Figure 14 WMTC for mopeds and other low-powered vehicles; adapted from [22, p. 110]

Table 2 GTR No. 2 - motorcycle classification for WMTC [23]

Class	Sub-class	Engine capacity	Max. speed v_{max}
1	1-1	≤ 50 cm³	50 km/h < v_{max} ≤ 60
	1-2	50 cm³ < capacity < 150 cm³	< 50 km/h
	1-3	< 150 cm³ (1)	50 km/h ≤ v_{max} < 100 km/h(1)
2	2-1	< 150 cm³	100 km/h ≤ v_{max} < 115 km/h
		≥ 150 cm³	< 115 km/h
	2-2		115 km/h ≤ v_{max} < 130 km/h
3	3-1		130 km/h ≤ v_{max} < 140 km/h
	3-2		≥ 140 km/h

(1) Excluding subclass 1-1

Table 2 contains the classification of motorcycles in classes and sub-classes by engine displacement and maximum speed, and Table 3 shows the required WMTC test cycle part, the test condition and the weighting factors of each class.

Table 3 GTR No. 2 - required driving schedules [23]

Class	Sub-class	WMTC Cycle Segment	Test conditions	Weighting factor
1	1-1 & 1-2	Part 1	Reduced speed in cold condition	50%
		Part 1	Reduced speed in hot condition	50%
	1-3	Part 1	Cold condition	50%
		Part 1	Hot condition	50%
2	2-1	Part 1	Cold condition	30%
		Part 2	Reduced speed in hot condition	70%
	2-2	Part 1	Cold condition	30%
		Part 2	Hot condition	70%
3	3-1	Part 1	Cold condition	25%
		Part 2	Hot condition	50%
		Part 3	Reduced speed in hot condition	25%
	3-2	Part 1	Cold condition	25%
		Part 2	Hot condition	50%
		Part 3	Hot condition	25%

Table 20 and Table 21 in the Appendix contain the weighting equations and the weighting factors for EURO 4 and EURO 5 according to L-vehicle category and test cycle.

2.1.2 USA

In the U.S., the national emission legislation is controlled by the Environmental Protection Agency (EPA). However, only the government of California, the California Air Resources Board (CARB or ARB) uses their own emission regulations, caused by their big smog problem. The emission standards of CARB are stricter than the federal ones, whereby it is allowed, for other states to follow CARB standards or use the national emission standards.

2.1.2.1 US Federal (EPA)

In 1963, the Clean Air Act was adopted and had the last major amendment in 1990. The aims of the federal law are the improvement of air quality and in more recent times the protection of the ozone layer as well as the reduction of emissions in exhaust gases, in order to prevent the greenhouse effect. Thus, at federal level the EPA is entrusted with the implementation of the law, which contains also a regulation for motorcycles.
In 1978, the first emission standards for motorcycles were introduced by the Environmental Protection Agency and remained unchanged until 2005. Therefore, the next step was to adopt a new EPA regulation, which reduces further the existing emissions limits, in two-phases, for highway motorcycles in the United States. In 2006, Tier 1 was introduced for the motorcycle classes I, II and III. Furthermore, the motorcycle class III was updated to Tier 2, which includes more stringent emission limits in 2010 (see Table 22 in the Appendix).

Small volume manufacturers had further two years to meet Tier 1 standards. Thus, motorcycles of small volume manufacturers are committed to comply with Tier 1 only starting with model year 2008. Moreover, these companies are exempt from the current stricter Tier 2 emission standard. Small volume manufacturers must not have more than 500 employees worldwide and more than 3000 motorcycle sales per year.
The EPA exhaust gas emission standards are in line with CARB regulations, but usually the implementation is delayed by two-years. Furthermore, an emission credit program exists which is comparable to that of California Air Resources Board. This corporate emission averaging allows companies to certify motorcycles at Family Emission Limit (FEL – see Table 4), whereby, motorcycles can be certified above or below the prescribed limits if the sales-weighted average emission level of the motorcycle fleet of a specific model year does not exceed the prescribed emission limits. In accordance with [25], the sales-weighted average emission level is calculated by Eq. 1. Credits of class III fleet can only be applied to compensate the deficit of class I & II fleets of the same model year. The credits are adjusted to account for the different life cycles of motorcycles.
Basically, the legislation did not permit the accumulation of emission credits to compensate emission limit exceedances of later model years. But emission credits generated by the early implementation of class III motorcycles, certified below the Tier 2 emission level between the model years 2003 and 2009, could be applied to meet the more stringent Tier 2 standard from 2010 model year onwards. The credit depends on the year of motorcycle sale and the emission standard. The earlier the sales year and the lower the emission level, the greater the credit is. [25] [26]

$$Average\ Emission\ Level = \frac{\sum_i (FEL)_i * (LC)_i * (Production)_i}{\sum_i (Production)_i * (LC)_i} \quad \text{Eq. 1}$$

(FEL)ᵢ – the certified family emission limit
(LC)ᵢ – the life cycle of the engine family
(Production)ᵢ – the number of vehicles in the engine family

Table 4 EPA - FEL provisions [25]

Class	Model year	Tier level	$HC+NO_X$ FEL
I & II	2006 +	Tier 1	5 g/km
III	2006 – 2009	Tier 1	5 g/km
	2010 +	Tier 2	2,5 g/km

The motorcycle emissions test procedure is very similar to the test procedures for passenger cars and trucks, which are summarized under the collective term light duty vehicles. The regulations allow Class I motorcycles to use a less severe test cycle than in Classes II and III. This test cycle is characterized by reduced acceleration and deceleration rates of some aggressive speed test cycle phases. [27, p. 86]

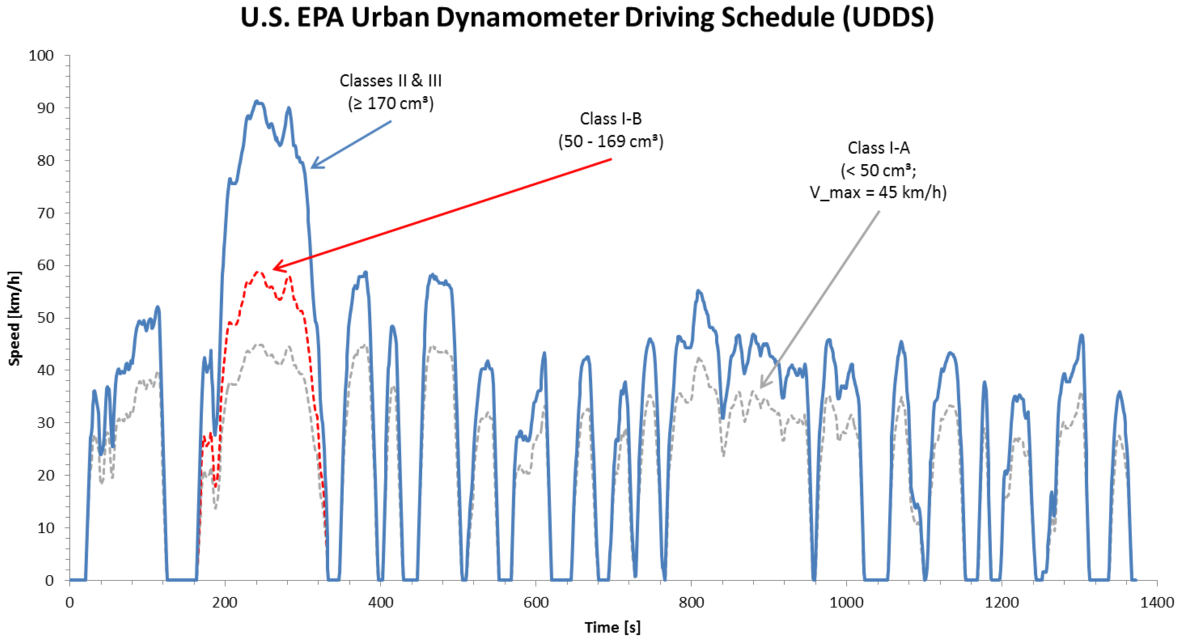


Figure 15 U.S. EPA Urban Dynamometer Driving Schedule (UDDS); adapted from [21, p. 175]

Figure 15 represents the Urban Dynamometer Driving Schedule (UDDS) with a total time length of 1372 seconds.
The Federal Test Procedure 75 (FTP-75), or US EPA Urban Dynamometer Driving Schedule (UDDS), consists of three different phases. Phase I - cold transition period – and phase II – stabilized period – (see Figure 16) base on the original FTP 72 test procedure from 1972. In 1975, the FTP-72 (or LA-4) was expanded by a third phase. This phase III is a repetition of phase I after a 10 minute hot soak. The total test time amounts 1877 seconds plus 600 seconds

of the hot soak period. 11.09 miles or 17.9 km total test length are passed with a maximum velocity of 56.7 mph, which corresponds to 91.3 km/h.
The purpose of this modification was to generate a weighted average emission from both, cold start and hot start tests. The stabilized period after the cold start is not repeated, because it is assumed that the stabilized part is the same after the cold start as well as after the hot start. The emissions of each phase are collected in a separate bag of the Constant Volume Sampling (CVS) system and the calculation model weights the results of the three bags accordingly. [27, p. 81]

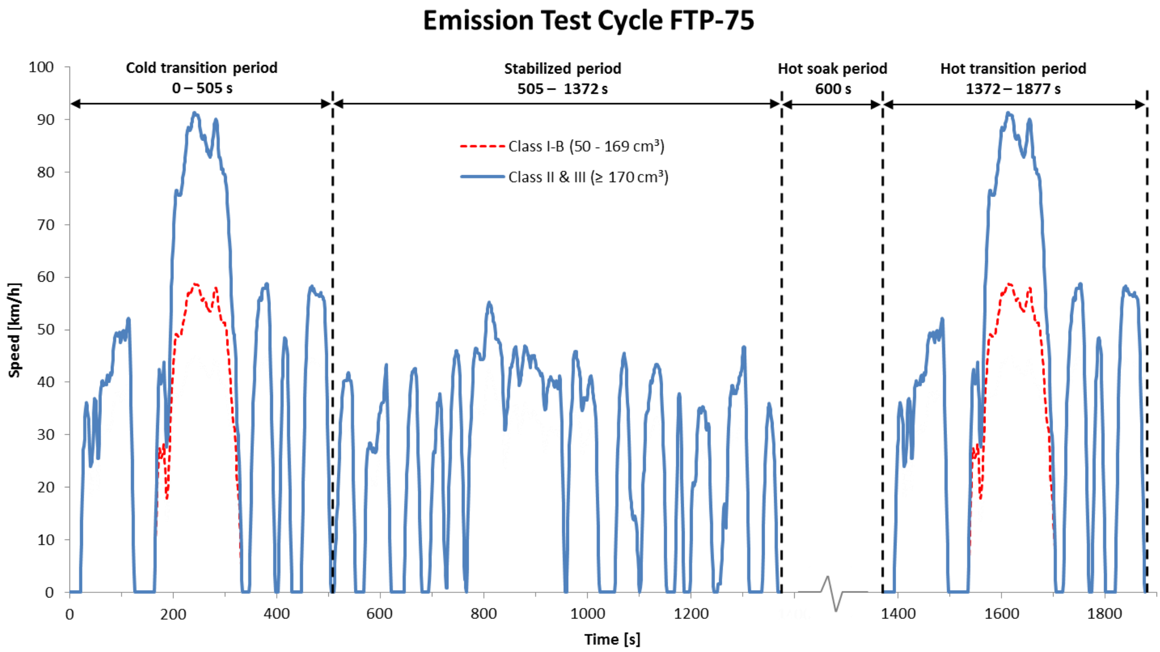


Figure 16 Emission Test Cycle FTP 75; adapted from [27, p. 84]

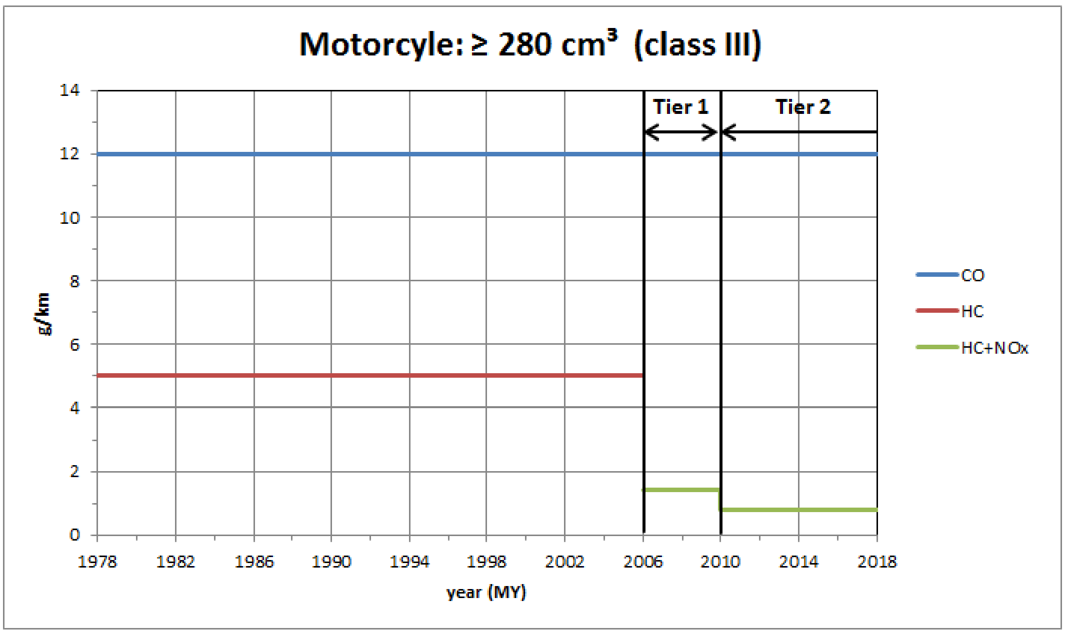


Figure 17 Comparison of US EPA emission level of motorcycle class III (≥ 280 cm³)

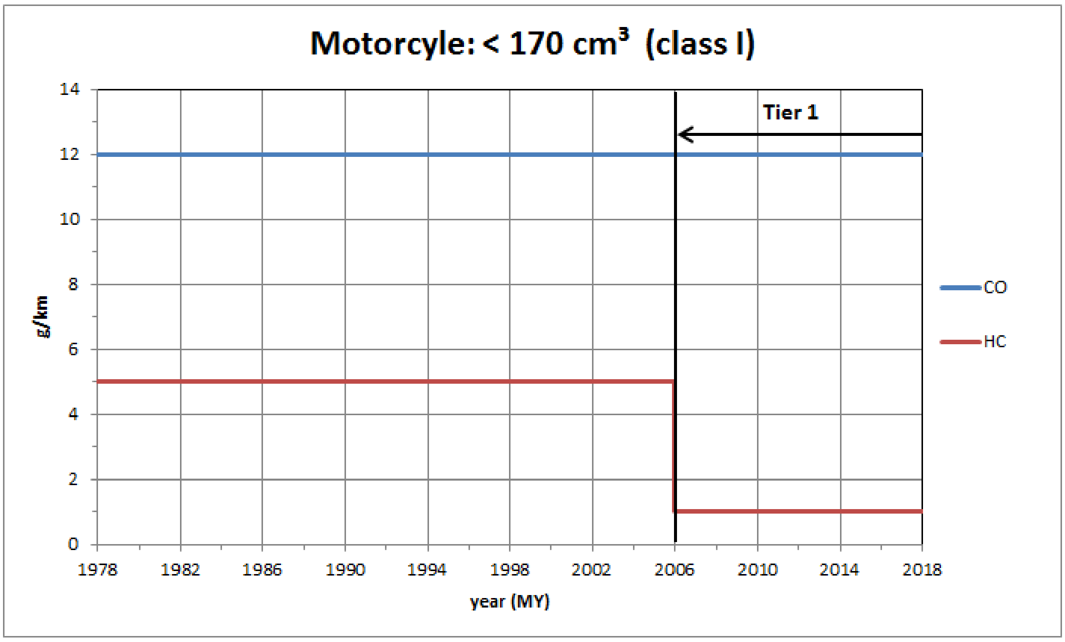


Figure 18Comparison of US EPA emission level of motorcycle class I (< 170 cm³)

The development of the US EPA emission limits for class I and III motorcycles are depicted in Figure 17 and Figure 18. It can be seen that the current CO limits are the same as 35 years ago and only the HC or HC+NOx limits decreased. Table 22 in the Appendix shows the emission limits for all motorcycle classes.

2.1.2.2 US California (CARB)

In California, the California Air Resources Board is responsible for the motor vehicle emission legislation. CARB has been taking a key role in the implementation of stricter emission limits. CARB is thus significantly contrasted to the EPA emission legislation, which is applied in the rest of the United States. The main reason for this emission legislation is the smog and the poor air quality in Los Angeles.

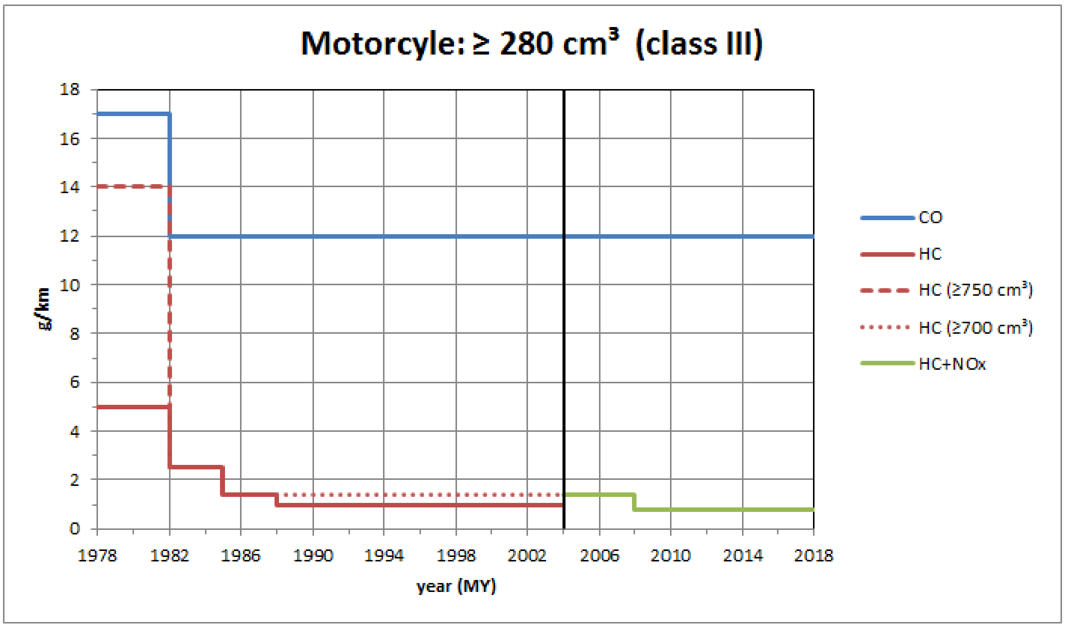


Figure 19 Comparison of US-CARB emission level of motorcycles class III (≥ 280 cm³)

Due to the stringent legal regulation of exhaust emissions, the air quality has improved during the last several decades. However, Los Angeles has still the highest ozone level of all cities in the U.S.. Therefore, the emission legislation in California will further be exacerbated over the next few years.

The Clean Air Act (CAA) is a federal law and was adopted in 1970. The EPA and the Federal States of U.S. are responsible for the implementation of the Clean Air Act, which covers, inter alia, the regulation of emissions of highway motorcycles. Although, the Californian exhaust gas legislation CARB pursues the same aim as the federal government, the CARB emission limits are more stringent than the limits of the federal law.

In 1999, amendments in regard to stricter emission limits were approved, whereby the initial limits, then in force, have been retained. The first of two new emission standards Tier 1 became effective in 2004, and in 2008 the second new emission standard Tier 2 entered into force. The manufacturers were allowed to meet the required standards by using a corporate average basis, but HC+NOx emissions are limited to a maximum of 2.5 g/km per engine family.

For small-volume manufacturers the emission standard Tier 1 is only effective from 2008 onwards. Manufacturers are defined as small-volume manufacturers when the sales total of all three classes (Class I, Class II and Class III) are not more than 300 units per model year, starting in 2004.

To offer an incentive for manufacturers to comply with the stricter exhaust gas emission standard Tier 2 before it is legally obligatory, CARB introduced an emission credit program, which later was adapted to a similar extent by the EPA. Legislation defined a number of multiplying factors, which creates extra credits to manufacturers if their motorcycles meet the Tier 2 standard or lower emission levels before model year 2008. These extra credits made it easier for manufacturers to meet the corporative average limits of the Tier 2 standards in 2008. [27, p. 125]

Manufacturers of off-highway recreational vehicles and engines, e.g. off-road motorcycles, ATV`s, sand cars, off-road sport and off-road utility vehicles, may optionally use an engine-based testing (emission limits in g/kWh – Table 28 in the Appendix) to meet the exhaust emission standards, instead of the chassis-based testing (emission limits in g/km - Table 23 in the Appendix). The utility test procedure of off-highway recreational vehicles, which are tested on engine-basis, uses only the 6-mode test cycle A, as referred to in California Code of Regulation (CCR), title 13, section 2403(d).

2.1.3 India

The large population of two- and three-wheelers in India makes a limitation of the pollutants CO, HC and NOx indispensable. Vehicles with diesel engines must also observe PM limits. The main problem in India is not the emission limits, but the comprehensive control to the compliance of emission limits. The large population of two- and three-wheeled vehicles plays their part in this scenario.

In 1991, the first emission standard for two- and three-wheelers was introduced. Initially, only limits for CO and HC were defined. Subsequently, NOx and PM limits were also added. Since then, the regulation of pollutants has been more stringent with each new emission standard which was introduced (see Table 24 in the Appendix). The emission legislation for two- and three-wheelers in India does not follow the European model, but the emission standards in India are equivalent to European standards. Thus, e.g. the Bharat II is equivalent to the EURO 2 level. [24, p. 171]

Figure 20 shows the progression of the Indian motorcycle emission standards.

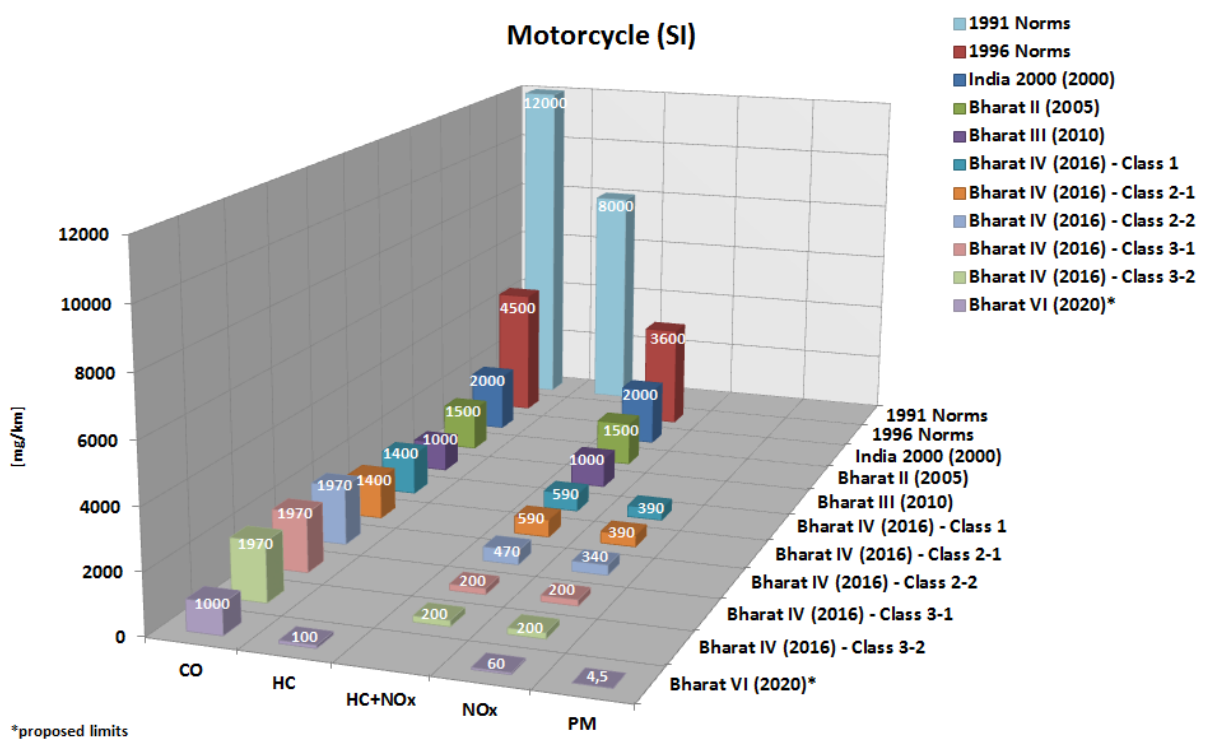


Figure 20 Comparison of Indian emission levels of motorcycles (SI)

The emission test in India for motorcycles is based on the Indian Driving Cycle (IDC), which was developed for two- and three-wheelers in the mid-80s. The IDC was applicable up to and including Bharat stage III. In 2012, the government of India introduced the WMTC as an alternative to the IDC. With the new emission level Bharat IV, the WMTC became obligatory. [28, pp. 2, 4]

Due to the alarming air quality in India, the Indian Ministry of Road Transport and Highways (MoRTH) prepared the draft Bharat VI emission standard for all on-road vehicles in India, including two- and three-wheelers, in February 2016. Bharat VI is equivalent to EURO 5 and will come into force on April 1st 2020 for new motorcycles and one year later for existing two- and three-wheelers. OBD II will become obligatory on April 1st 2023. Important aspects of Bharat VI are the first mandatory application of OBD I for motorcycles as well as the fact that NOx-, CO- and HC-emission limits of two- and three-wheelers are adapted to passenger car Bharat VI standard. [29, pp. 1-2]

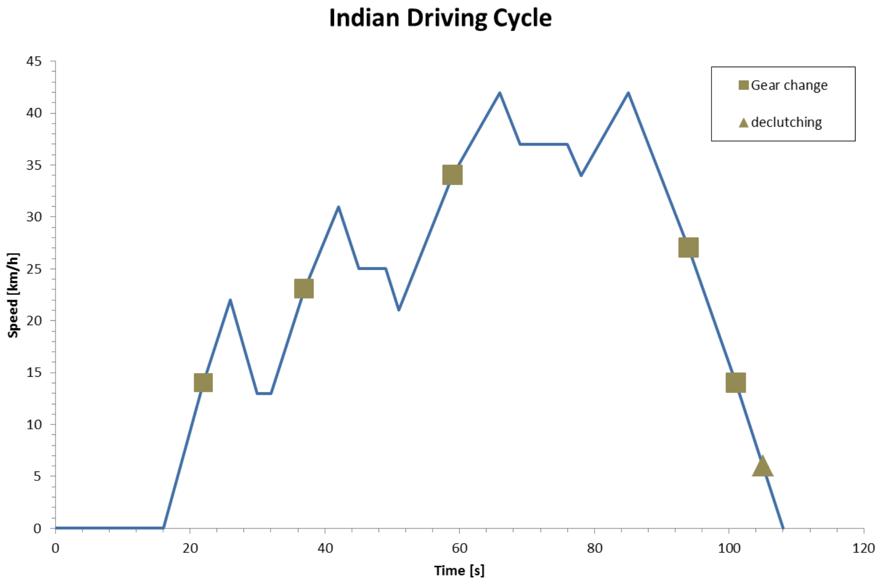


Figure 21 Indian Driving Cycle (IDC) for two- and three-wheeler; adapted from [21, p. 177]

The test time of one IDC is 108 seconds with a maximum speed of 42 km/h (see Figure 21). The whole test procedure consists of the 10-times repetition of one Indian Driving Cycle (see Figure 22 – above). Four cycles form the basis for the warm-up phase, but only for SI engines and the residual six cycles form the emission measurement phase. The main disadvantages of IDC are the non-consideration of the cold start emission and the low dynamic of the driving cycle, which will be compensated by the WMTC.

Table 5 Indian - vehicle classification and weighting factors for WMTC [30]

Class	Classification	WMTC part	Weighting factors BS VI
Class 1	50 cm³ < engine capacity < 150 cm³ and $v_{max} \leq$ 50 km/h or engine capacity < 150 cm³ and 50 km/h < v_{max} < 100 km/h	Part 1 reduced cold	50%
		Part 2 reduced hot	50%
Sub class 2-1	engine capacity < 150 cm³ and 100 km/h < v_{max} < 115 km/h or engine capacity ≥ 150 cm³ and < v_{max} < 115 km/h	Part 1 reduced cold	50%
		Part 2 reduced hot	50%
Sub class 2-2	115 km/h ≤ v_{max} < 130 km/h	Part 1 cold	50%1)
		Part 2 hot	50%2)
Sub class 3-1	130 km/h ≤ v_{max} < 140 km/h	Part 1 cold	25%
		Part 2 hot	50%
		Part 3 reduced	25%
Sub class 3-2	$v_{max} \geq$ 140 km/h	Part 1 cold	25%
		Part 2 hot	50%
		Part 3	25%

1) BS III & IV: 30%

2) BS III & IV: 70%

Table 5 shows the vehicle classes and their assigned WMTC test cycle parts, including weighting factors. Figure 22 presents the IDC compared to the WMTC.

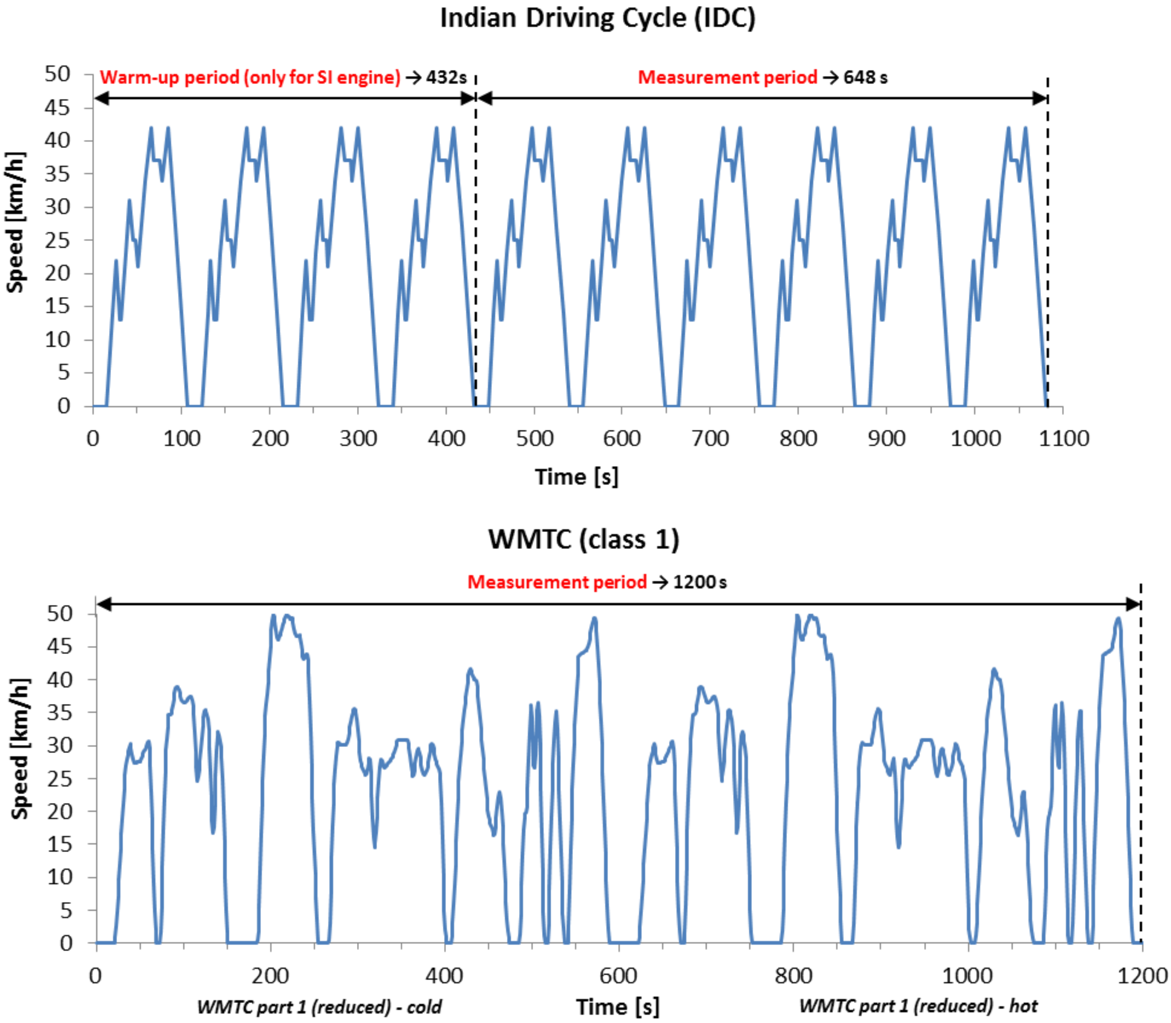


Figure 22 Comparison of IDC and WMTC; adapted from [28, p. 6]

2.1.4 China

The first emission standard Stage I for motorcycles was introduced in 2003 and for mopeds one year later. Stage II for two- and three-wheeled motorcycles was already implemented in 2005 and for two- and three-wheeled mopeds also one year later.

In 2008, the current emission standard Stage III was introduced for two- and three-wheelers. Stage III in China is based on EURO 3 level but with some differences, e.g. Stage III contains additional emission durability requirements, which were not part of the European motorcycle emission program at that time. The emission test procedures in China for two- and three-wheelers use the ECE R40 test cycle (see Figure 12).

The new emission standard Stage IV will become effective on July 1st 2018 for new type approvals of vehicles and one year later for all new vehicles. In addition, OBD I will be obligatory for the first time, and vehicle classification and their WMTC test cycle parts are identical to those in Table 5. [31] [32]

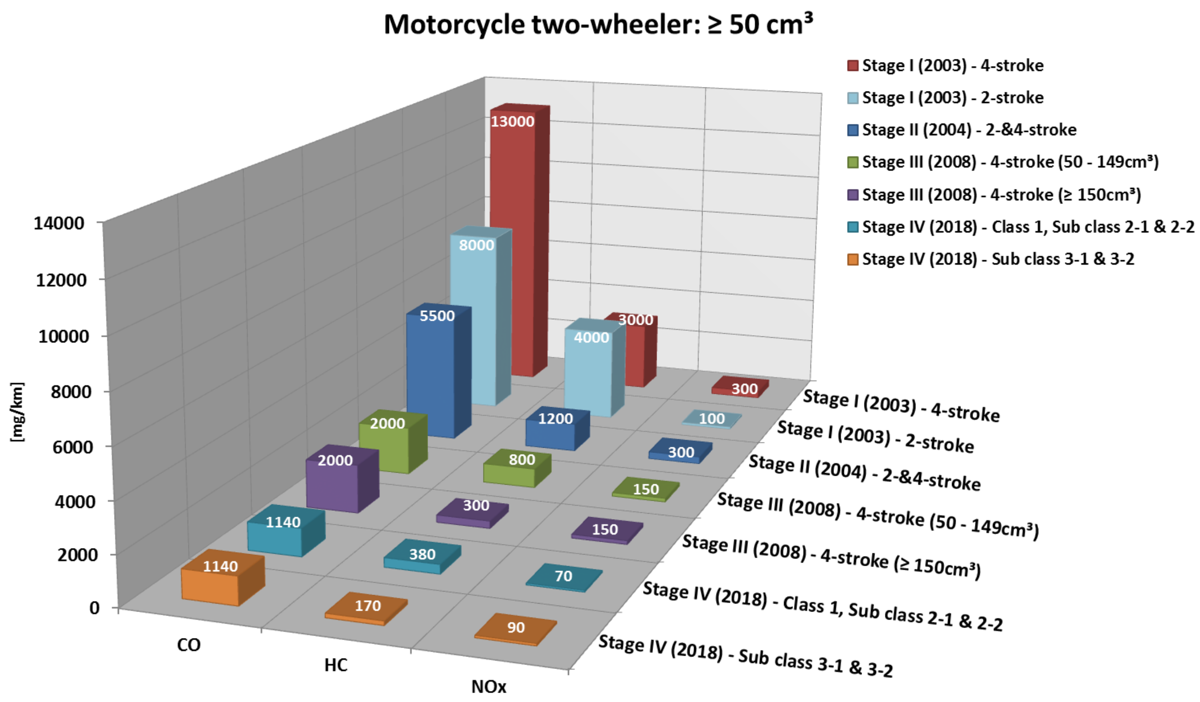


Figure 23 Comparison of Chinese emission levels of two-wheelers (≥ 50 cm³)

Figure 23 and Figure 24 depict different emission stages of two-wheelers in China. Table 25 in the Appendix shows the different emission stages for two- and three-wheeler in China.

Several countries in Asia inter alia China switch from two-stroke engines to more efficient four-stroke engines and to electric vehicles to reduce air pollution and to improve air quality. [33, p. 13]

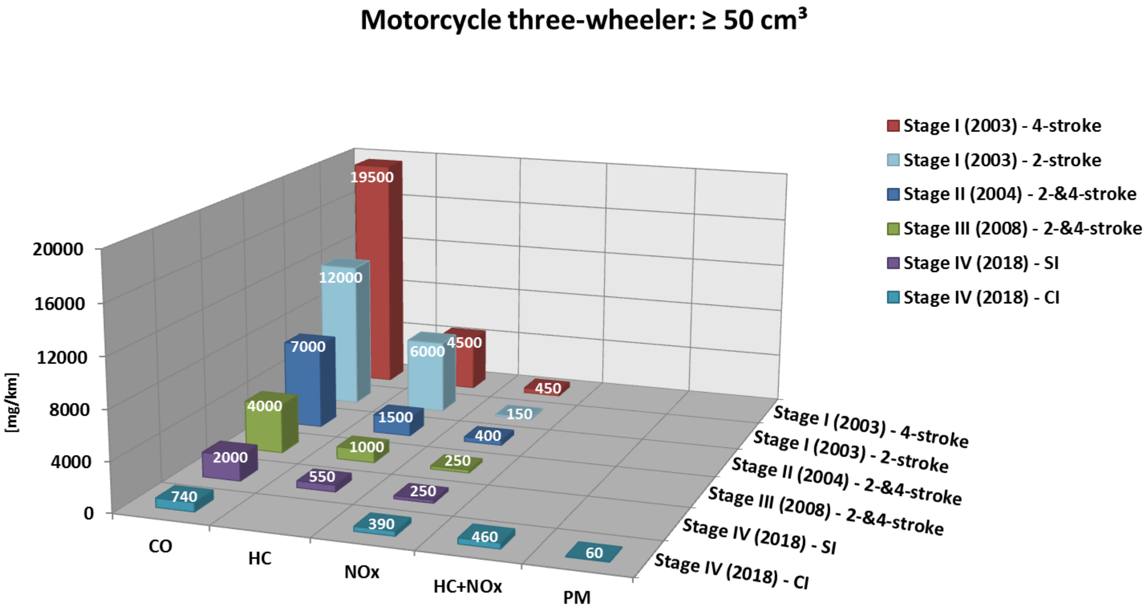


Figure 24 Comparison of Chinese emission levels of three-wheelers (≥ 50 cm³)

2.1.5 Summary

Figure 25, Figure 26 and Figure 27 present the development of emission standards in Europe, the U.S., India and China. A comparison of emission standards demonstrates that the emission legislation for motorcycles in China follows the legislation in Europe. The expected implementation of Bharat VI in 2020, after Bharat V was skipped, leads to a harmonization of India's emission regulation for motorcycles with the European emission standard EURO 5.The emission limits of Bharat VI are identical to that of EURO 5. In China, the implementation of emission Stage IV will be expected in 2018. This Stage IV is equal to emission stage EURO 4 in Europe. Furthermore, the introduction of EURO 4 at the beginning of 2016 entailed not only more stringent emission limits, but also the obligatory implementation of On-Board Diagnostics (OBD) and the Anti-locking Braking System (ABS) for motorcycles with displacements equal or greater than 125 cm³.

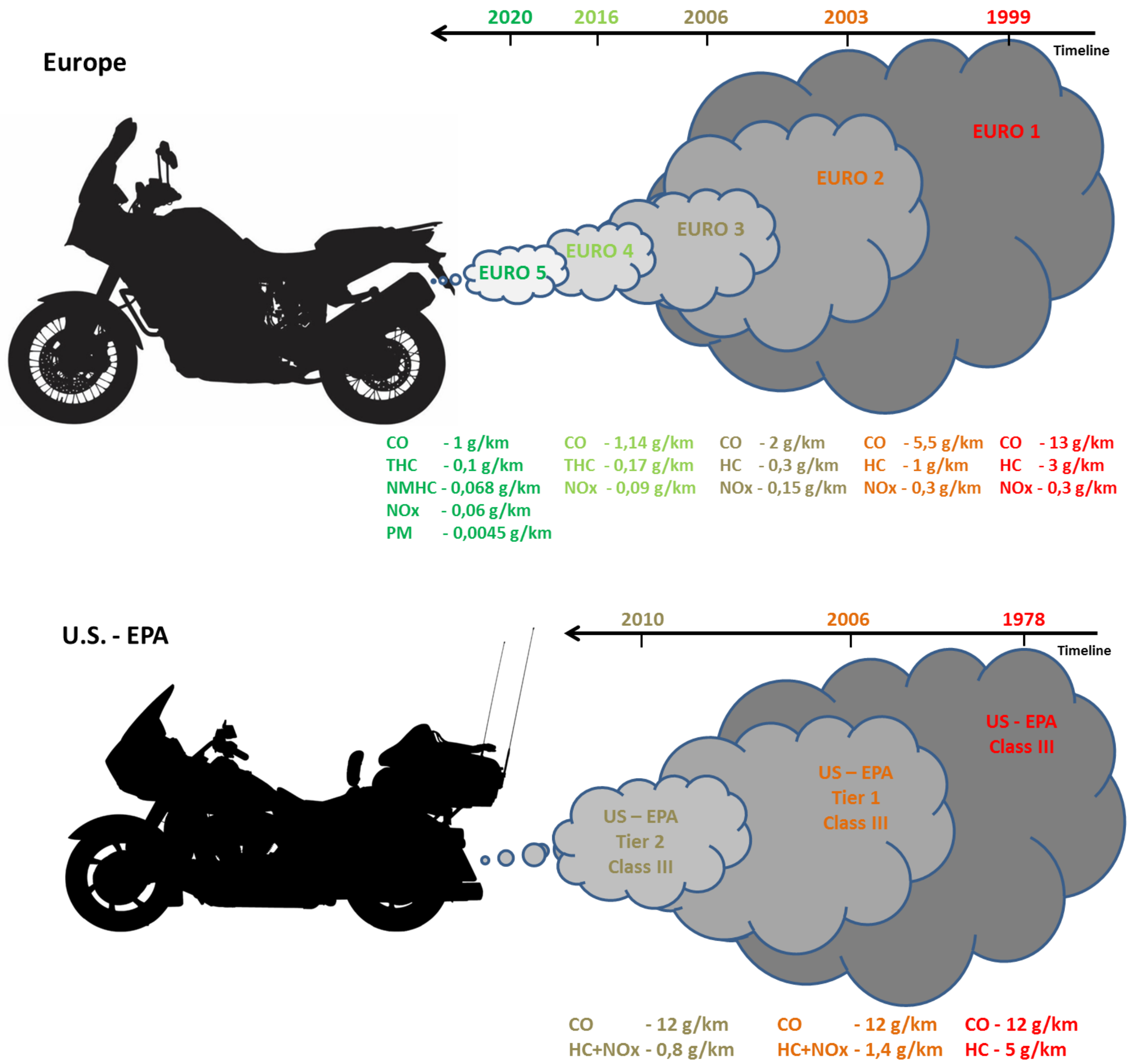


Figure 25 Development of emission standards in Europe and U.S. (EPA)

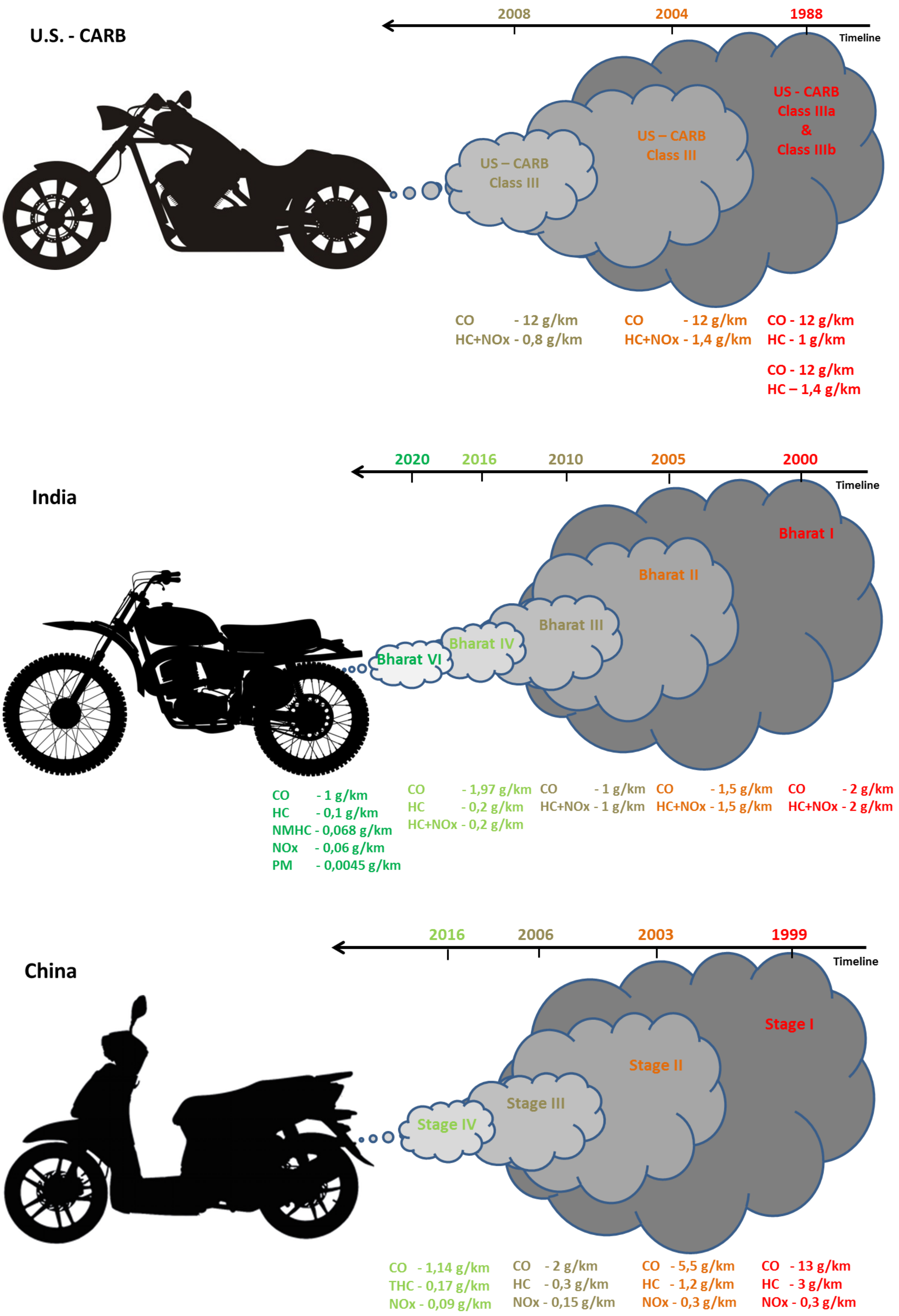


Figure 26 Development of emission standards in U.S. (CARB), India and China

In the U.S., the emission limits for motorcycles are still significantly above the limit values in Europe, India or China (see Figure 27) and have not or only little decreased for years. In particular, the CO limits with 12 g/km are about 10 g/km higher than the permitted limits in the other listed countries. To sum up, the emission legislation for motorcycles in Europe, India and China are approximately in the same magnitude and are progressed in the right direction, whereas the U.S. government does not follow a clear line for more stringent motorcycle emission legislation, such as for passenger cars, for example.

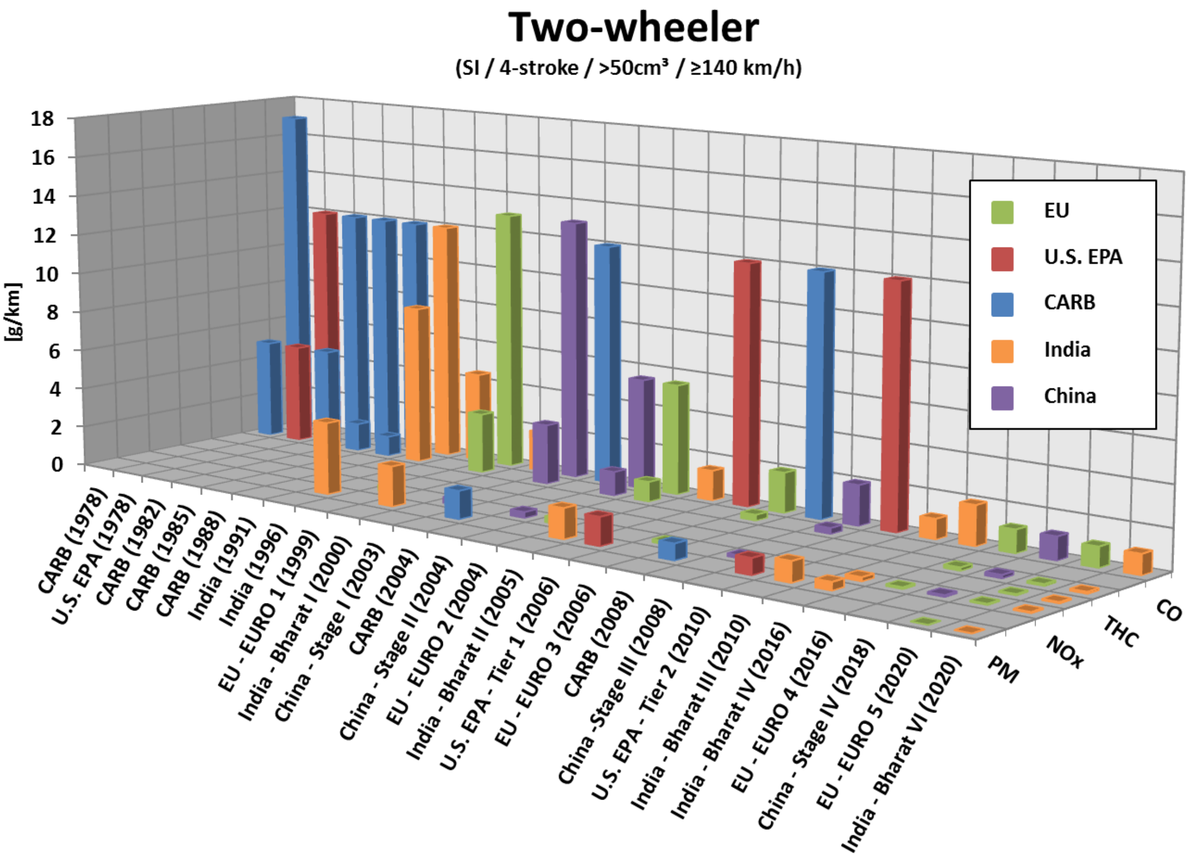


Figure 27 Comparison of the different emission stages from EU, U.S. EPA, CARB, India and China for two-wheeler

2.2 Hybrid-Vehicle - Range Extender

The policy uses more stringent emission legislation to reduce air pollution. This leads to alternative drive concepts, like various hybrid strategies or pure electric vehicles, which are also called zero-emission vehicle (ZEV). [34, pp. 1-2]
At this point, it is worth mentioning that these alternative technologies still have some disadvantages compared to conventional internal combustion engines. For example, a hybrid drive, which consists of an electric motor and an ICE, loses its benefits over an ICE if longer distances have to be traveled. In this regard drive concepts such as ZEV or fuel cells are also to be treated with caution, especially considering the tank-to-wheel emissions (see Figure 28). Looking at the overall efficiency, supposed zero-emission propulsion concepts could cause even more CO_2 emissions than currently used internal combustion engines. Moreover, current alternative concepts and solutions are too expensive and too complex. For example, the (hydrogen) production and the energy storage process are lossy and need high expenditure of energy. [35, pp. 1033-1034]
Figure 28 gives an overview of the Well-to-Wheel analysis for fuel and vehicle systems, which enable an accurate analysis of conventional and alternative propulsion concepts. [36, p. 11]

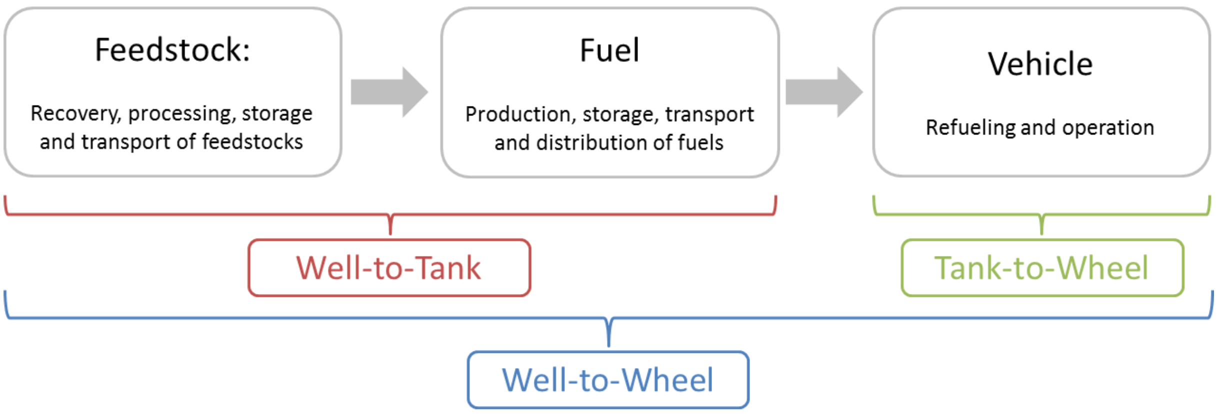


Figure 28 Well-to-Wheel Analysis; adapted from [36, p. 11]

The customer`s acceptance and the market launch are difficult. The main responsibilities are weight and costs of the energy storage (battery) on the one hand, and the achievable range of ZEVs on the other. There are basically two possibilities to increase the range of these vehicles. The first opportunity is to use energy storage with greater capacity and the second is to implement a range extender. An increase of the battery capacity has a negative effect on costs and weight, due to the current low power densities (Wh/kg) of battery storages in comparison to regular fuel, although improvements were made by the lithium technology. An economic alternative is the implementation of a range extender with simultaneous reduction of the battery capacity. A small combustion engine with a generator recharges the battery during longer distance driving.
Today, low-price city scooters with pure electric drive are offered in several models. The reason for this is that the vehicle category L1e has a speed and displacement limit, the driving distances are usually short and no additional comfort, as in passenger cars, is expected from the customers (e.g. air conditioning).

Demand and sales figures can also be influenced by local emission legislation through the implementation of low (or zero) emission areas in inner cities, as is partly the case in major cities in Europe and Asia. The political will to promote zero emission vehicles is high, but current offers of these vehicles are less or not price-competitive in comparison to an internal combustion engine (ICE).

In Europe, the 50 cm^3 two-wheeler market is mainly dominated by a variety of low-cost models, which have been adapted to customer demands in order to provide the cheapest possible solutions for the inner city traffic or young road users. Vehicles from the low-cost sector are mostly powered by a two-stroke engine with carburetor and simple exhaust after treatment, like an oxidation catalyst in combination with secondary air systems. Vehicles which use this technology can only be homologated to EURO 2 without problems. Starting with EURO 3, alternative concepts are needed to comply with emission legislation, which leads to more expensive internal combustion technologies, whereby ZEV becomes more competitive. The future trends in exhaust gas emission legislation also follow this development, which will increase the costs of vehicles with internal combustion engines. But actually, the system costs of ZEV are also high and mainly depend on battery costs, especially for lithium. This results in a negative affect for ZEV, which is up to three times more expensive than equivalent low-cost internal combustion technology. [34, pp. 1-2]

Figure 29 Basic packaging concept studies for a hybrid concept [34]

Hybrid systems exist in various configurations. Figure 29 shows a serial hybrid concept with an electric motor, which is used as drive unit. The electric motor is powered by a battery. A generator, powered by an internal combustion engine (ICE), recharges the battery, if the battery charge is low. The ICE is also called range-extender. If the hybrid configuration is carried out without battery, as described above, it would be referred to as an "electric gearbox" and is not included in the category of hybrid systems [37].

The size and capacity of the battery in hybrid concepts should be adapted to particular applications and the legal framework. Full size batteries in hybrid concepts have basically the same disadvantages, like high costs and weight, in comparison to a pure electric drive. In the case of a small or medium battery in hybrid systems, the costs and weight are reduced in comparison to pure electric vehicles, but the operating frequency of the range-extender (ICE) increases. [34, p. 3]

The trend is towards electrification of vehicles and pure electric vehicles, which offers the opportunity to reduce the energy consumption and greenhouse gas emissions of individual mobility. The REX concept offers a cheaper alternative with higher range and could be a "bridge technology" for a pure electric vehicle.

From today's point of view, conventional combustion engines are the best solution for range extenders, but further simplifications will be necessary to meet future cost targets. Future ICE range extender solutions could be a Wankel-, Stirling- or Stelzer engine [38]. The Wankel engine would be a good solution if the problem with the high hydro carbon emissions and the oil consumption can be handled. In concepts with a Stirling engine the development should be focused on cost reduction. The potential of the Stelzer engine has to be determined by further research projects, but results from already implemented projects indicate the suitability of this solution as REX.

The main criteria for customers are price and range of the electric vehicle. Electric vehicle should be in the same price category or just slightly higher. Furthermore, good drivability and low energy consumption are also important as customer requirements. The ICE range extenders will be further simplified and cost optimized in the coming years. In future, alternative technologies, like fuel cell, could replace the ICE as range-extender as long as costs are similar to the ICE, or even better. [38, pp. 15-16]

2.2.1 Test Procedure for Hybrid L-Category Vehicle in Europe

The test procedure for hybrid L-category vehicles is set out in Regulation (EU) No. 134/2014. The results of the tailpipe emission tests for hybrid vehicles have to meet the same emission limits of L-category vehicles with ICE only. The limits are listed in Table 18 in the Appendix. The test procedure differentiates between the categories externally chargeable and not externally chargeable hybrid vehicles, which are again divided into the sub-categories with and without operating mode switch (see Table 6).

Table 6 Categories of hybrid vehicles [22, p. 139]

Vehicle charging	**Externally chargeable (OVC) 1)**		**Not externally chargeable (NOVC) 2)**	
Operating mode switch	without switch	with switch	without switch	with switch

1) Off-vehicle charging
2) Not-off-vehicle charging

Externally chargeable hybrid vehicles, both with and without operating mode switch, are performed in two different test conditions. The tailpipe emission test in condition A is carried out with fully charged electrical energy storage. In test condition B, the measurement is performed with an electrical energy storage, which has reached the minimum level of charge before the measurement starts. [22, p. 139]

2.2.1.1 Off-Vehicle Charging (OVC) – Hybrid Electric Vehicle (HEV)

2.2.1.1.1 OVC-HEV without operating mode switch

The test procedure in condition A starts with the discharge of the energy storage during driving the vehicle on a test track or a chassis dynamometer. Permissible driving conditions for battery discharge are to drive the HEV at a constant speed of 50 km/h until the ICE starts, or, if the speed of 50 km/h is not achievable, the constant speed is decreased to a lower speed level until the HEV can be driven a prescribed distance or time without the ICE starts. The defined time or distance is carried out in coordination with the technical service and the manufacturer. The last option follows a separate recommendation of the manufacturer. In all three options, the ICE must be stopped within a maximum of 10 seconds after the start.

After this pre-condition and before the test procedure is performed the HEV must be conditioned at room temperature between 20°C and 30°C. The conditioning lasts at least 6 hours or until the engine oil and coolant temperatures have reached the room temperature and the electrical energy storage is fully charged. The electrical energy storage is charged during a hot soak period via an on-board charger, if equipped, or an external charger. The maximum state of charge is considered to be reached, when a charging time of 12 hours is achieved, except in case that the vehicle instrumentation clearly demonstrates that the electrical energy storage is not fully charged. In this case, the maximum charging time corresponds to Eq. 2. [22, pp. 139-141]

$$max.\,charging\ time = \frac{3 * claimed\ electrical\ energy\ storage\ capacity\ (Wh)}{mains\ power\ supply\ (W)} \qquad \textbf{Eq. 2}$$

The tailpipe emission measurement begins at the ICE start and ends after the final idling period of the test cycle. However, for the determination of the test results is it necessary to distinguish between the sampling of a single combined test cycle and the sampling of a series of combined test cycles, since the evaluation differs. The electricity balance is measured during each combined test cycle to determine the point of time of minimum state of charge. Hot soak periods between the combined cycles are allowed, but must not exceed 10 minutes. The emissions are analyzed by the same approach as vehicles with ICE only (see Regulation (EU) No. 134/2014 Appendix 6 and Annex II).

If only a single combined test cycle is run, the average emission result of each pollutant is M_{1i} in mg/km. If a series of combined test cycles are run (N – number of combined test cycles), the test result of each pollutant of each combined test cycle is M_{1ia} in mg/km. The average emission results of each pollutant of each combined test cycle (M_{1i} or M_{1ia}) multiplied with the deterioration factor and other correction factors K_i must not exceed the emission limits in Table 18 in the Appendix. [22, pp. 139-141]

According to [22, pp. 139-141] the average result M_{1i} of a series of combined test cycles is calculated by Eq. 3.

$$M_{1_i} = \frac{1}{N}\sum_{a=1}^{N} M_{1_{ia}} \frac{mg}{km} \qquad \textbf{Eq. 3}$$

Indices i – pollutant

Indices a – test cycle

The test procedure in condition B contains nearly the same process steps, with the difference that the electrical energy storage is not re-charged. The average emission test results of each pollutant in condition B (M_{2i}) multiplied with the deterioration factor and other correction factors K_i must not exceed the emission limits in Table 18 in the Appendix. [22, pp. 141-144]
The test report contains the weighted values of each pollutant, which in accordance with [22, pp. 141-144] are calculated by Eq. 4 for a single combined test cycle or by Eq. 5 for several combined test cycles.

$$M_i = \frac{(D_e * M_{1i} + D_{av} * M_{2i})}{(D_e + D_{av})} \quad \text{Eq. 4}$$

$$M_i = \frac{(D_{OVC} * M_{1i} + D_{av} * M_{2i})}{(D_{OVC} + D_{av})} \quad \text{Eq. 5}$$

M_i - *mass emission of the pollutant i in mg/km*

M_{1i} - *average mass emission of the pollutant i in mg/km with a fully charged electrical energy storage device*

M_{2i} - *average mass emission of the pollutant i in mg/km with an electrical energy storage device in minimum state of charge (maximum discharge of capacity)*

D_e - *electric range of a hybrid electric vehicle (HEV) – only using electric motor*

D_{OVC} - *Off-vehicle charging (OVC) range of a hybrid electric vehicle (HEV)*

D_{av} - *average distance between two battery re-charges, as follows:*
- *4 km for a vehicle with an engine capacity < 150 cm³*
- *6 km for a vehicle with an engine capacity ≥ 150 cm³ and* v_{max} *< 130 km/h*
- *10 km for a vehicle with an engine capacity ≥ 150 cm³ and* v_{max} *≥ 130 km/h*

The electric range D_e and the off-vehicle charging range D_{OVC} of a hybrid vehicle are measured on a chassis dynamometer by applying the appropriate type I test cycle. Test type I means according to European regulation the tailpipe emission test after cold start. The measurements for the electric range (D_e) are performed until the vehicle speed target curve of up to 50 km/h cannot comply, or the on-board instruments indicate stopping the vehicle, or the minimum state of charge is reached. If one criterion is met, the speed is reduced to 5 km/h only by release of the accelerator and afterwards the vehicle is stopped by braking. The criterion for vehicle speeds over 50 km/h is met, if the required speed or acceleration can no longer be held, then the accelerator is turned or remains fully suppressed until the target curve is met again.
The test for OVC range (D_{OVC}) is completed, when the minimum state of charge of the electric storage device is reached. The test cycle is driven until the end of the final idle period. The criterion for speeds over 50 km/h, which is described above for the measurement of the electric range D_e, is valid for the OVC range test too. Between the test sequences of D_e and D_{OVC}, up to three interruptions are allowed, but in total no longer than 15 minutes. If the HEV operates in hybrid and electric mode during the determination of D_e, the pure electric-mode is identified by monitoring the current of ignition or injectors. The measured distances expressed in km are D_e and D_{OVC}. [22, pp. 139-144]

2.2.1.1.2 OVC-HEV with operating mode switch

The operating mode switch of OVC-HEV is to be positioned according to Table 7 for the different hybrid concepts. The test is carried out in the same two battery conditions (condition A – fully charged and condition B – minimum state of charge) as OVC without operating mode switch.

Table 7 Condition A and B depending on different hybrid concepts and the hybrid operating mode switch position [22, p. 144]

Hybrid modes	- pure electric - hybrid	- pure fuel-consuming - hybrid	- pure electric - pure fuel-consuming - hybrid	- hybrid mode n(1) - hybrid mode m(1)
Battery state of charge	**Switch in position**			
Condition A fully charged	hybrid	hybrid	most electric hybrid mode (2)	hybrid
Condition B minimum state of charge	fuel-consuming	fuel-consuming	most fuel-consuming mode (3)	hybrid

(1) for instance: sport, economic, urban, extra-urban, etc.
(2) most electric hybrid mode: the hybrid mode which can be proven to have the highest electricity consumption of all selectable hybrid modes when tested in accordance with condition A
(3) most fuel-consuming mode: the hybrid mode which can be proven to have the highest fuel consumption of all selectable hybrid modes when tested in accordance with condition B

On request of the manufacturer the test in condition A can be performed in pure electric mode, if the pure electric range of the HEV is higher than one complete test cycle.
The test in condition A begins with the discharge of the electric storage device. If the HEV is not intended for pure electric operation, the battery is discharged as described in chapter 2.2.1.1.1. In the case of a pure electrical operation, the electrical energy storage is discharged at a constant vehicle speed of 70% of the maximum vehicle speed. The discharge process ends after 100 km, or when the vehicle cannot be driven at 65% of the maximum speed for 30 minutes, or the on-board instruments indicate stopping the HEV. In the exceptional case that the HEV is demonstrably unable to reach the 30 minutes speed, the 15 minutes speed can be used. The further procedure in condition A is identical as described in chapter 2.2.1.1.1.
The test procedure in condition B for OVC-HEV with operating mode switch is analogous to the test procedure in condition B for OVC-HEV without operating mode switch, with the difference that the electrical storage is discharged according to condition A of OVC-HEV with operating mode switch.
The evaluation of the test results (M_i) of condition A and condition B is also analogical to chapter 2.2.1.1.1. The electric range D_e is determined on a chassis dynamometer in the switch position for pure electric mode. If there is no operation mode switch position defined for pure electric mode, the manufacturer has to ensure a pure electric operation during the

measurement. The test criteria are the same as by the determination of the electric range of OVC-HEV without operating mode switch, which are described above. [22, pp. 144-148]

2.2.1.2 Not-Off-Vehicle Charging (NOVC) – Hybrid Electric Vehicle (HEV)

The test procedure for NOVC-HEV with and without operating mode switch is the same as in vehicles with conventional ICE (see Regulation (EU) No. 134/2014 Annex II). If NOVC-HEV with operating mode switch have more than one hybrid mode, the test has to be carried out in the "normal mode". That means the mode, which is set automatically after start. [22, p. 148]

2.3 Noise Emission Standards and Test procedures

2.3.1 Europe (EU)

In Europe, L-category vehicles must comply with the sound level requirements of the European Union to obtain the type approval (TA) and conformity of production (COP). Quadri-mobiles, two- and three-wheelers are tested in accordance with Regulation (EU) No. 134/2014 and Regulation (EU) No. 168/2013, with the exception of motorcycles - category L3e and L4e. Since the Council Decision 2013/483/EU of September 2013, motorcycles are tested in accordance with UN-ECE Regulation No. 41.
A comparison of Table 8, Table 9 and Table 10 illustrates that the sound level limits of L-category vehicles have not significantly changed in den recent years. The application of the UN-ECE Regulation No. 41 replaced the sound level limits in Table 9 and introduced new limits for category L3e and L4e (see Table 10).

Table 8 Sound level limits of Directive 97/24/EC [39, p. 344]

Vehicle category	Sound level limits
Two-wheel mopeds $v_{max} \leq 25$ km/h	66 dB(A)
Two-wheel mopeds $v_{max} > 25$ km/h	71 dB(A)
Three-wheel mopeds	76 dB(A)
Motorcycles engine capacity ≤ 80 cm³	75 dB(A)
Motorcycles 80 cm³ < engine capacity ≤ 175 cm³	77 dB(A)
Motorcycles engine capacity > 175 cm³	80 dB(A)
Tricycle	80 dB(A)

The sound level test in accordance with UN-ECE Regulation No. 41 is carried out for vehicles in motion and in stationary mode. The test for motorcycles in motion is distinguished in a full throttle acceleration part and a constant speed part.
The test site has to fulfill some requirements to guarantee equal test conditions for determining the sound level of the vehicle. The surface of the test area shall be dry and level in essence, and the rolling noise of the vehicle must be kept low. Furthermore, no large objects, e.g. buildings, fences or rocks, have to be located within a radius of 50 m from the center of the test site, in order to keep the variations in the free sound field within 1 dB(A) (see Figure 30). Meteorological condition values for temperature, wind speed and wind direction, relative humidity and barometric pressure are recorded throughout the entire term of the measurement and the weather conditions must not affect the sound level measurement.
The background noise is measured immediately before and after each noise measurement of the motorcycle for a term of 10 seconds with the same equipment. The maximum A-weighted sound pressure level of the background noise shall be at least 10 dB(A) lower as the measured A-weighted sound pressure levels of the motorcycle. If the difference is between 10 dB(A) and 15 dB(A), the correction values, as shown in the Table 11, must be deducted from the measured values on the sound level instrument. [40, pp. 19-21]

Table 9 EURO 4 sound level limits and EURO 4 & EURO 5 test procedure [14, p. 121]

L-category	L-category specification	Sound level EURO 4	Test procedure EURO 4	Test procedure Euro 5
L1e-A	Powered cycle	63 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 63
L1e-B	Two-wheel moped $v_{max} \leq 25$ km/h	66 dB(A)		
	Two-wheel moped $v_{max} \leq 45$ km/h	71 dB(A)		
L2e	Three-wheel moped	76 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 9
L3e[1)]	Two-wheel motorcycle engine capacity ≤ 80 cm³	75 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 41
	Two-wheel motorcycle 80 cm³ < engine capacity ≤ 175 cm³	77 dB(A)		
	Two-wheel motorcycle engine capacity > 175 cm³	80 dB(A)		
L4e[1)]	Two-wheel motorcycle with side-car	80 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 41
L5e-A	Tricycle	80 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 9
L5e-B	Commercial tricycle	80 dB(A)		
L6e-A	Light on-road quad	80 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 63
L6e-B	Light quadric-mobile	80 dB(A)	Delegated Reg. (EU) No. 134/2014	UN-ECE Reg. No. 9
L7e-A	Heavy on-road quad	80 dB(A)		
L7e-B	Heavy all terrain quad	80 dB(A)		
L7e-C	Heavy quadric-mobile	80 dB(A)		

[1)] Sound level limits and test procedure for EURO 4no longer valid → see Table 10 and UN-ECE Regulation No. 41

Table 10 UN-ECE Regulation No. 41 - sound level limits [40, p. 45]

Category	Limits for sound pressure level – urban L_{urban}
Class I PMR ≤ 25	73 dB(A)
Class II 25 < PMR ≤ 50	74 dB(A)
Class III PMR > 50	77 dB(A)[1)]

[1)] The permitted sound level limit increases by 1 dB(A) until the 1. January 2017, if the motorcycle is tested only in the second gear.

Table 11 Background sound pressure level correction [40, p. 21]

Background sound level pressure level difference to measured sound pressure level, in dB(A)	10	11	12	13	14	≥ 15
Correction, in dB(A)	0,5	0,4	0,3	0,2	0,1	0

The test mass of the vehicle for the sound level test results from the unladen mass plus 75 kg ± 5 kg, which considers the mass of driver and instruments. Sidecars have to be removed for the test.

The motorcycle follows the line CC’ during the test. The measurement starts, when the front of the motorcycle crosses line AA' and ends when the rear of the motorcycle passes line BB'. For test condition full throttle acceleration, the motorcycle has to reach line AA’ at constant speed and immediately subsequent the throttle control is adjusted to the maximum throttle position as quickly as possible and remains in this position until the rear of the motorcycle passes the line BB'. At this time, the throttle control is also set as quickly as possible into the idle position. [40, pp. 21-22]

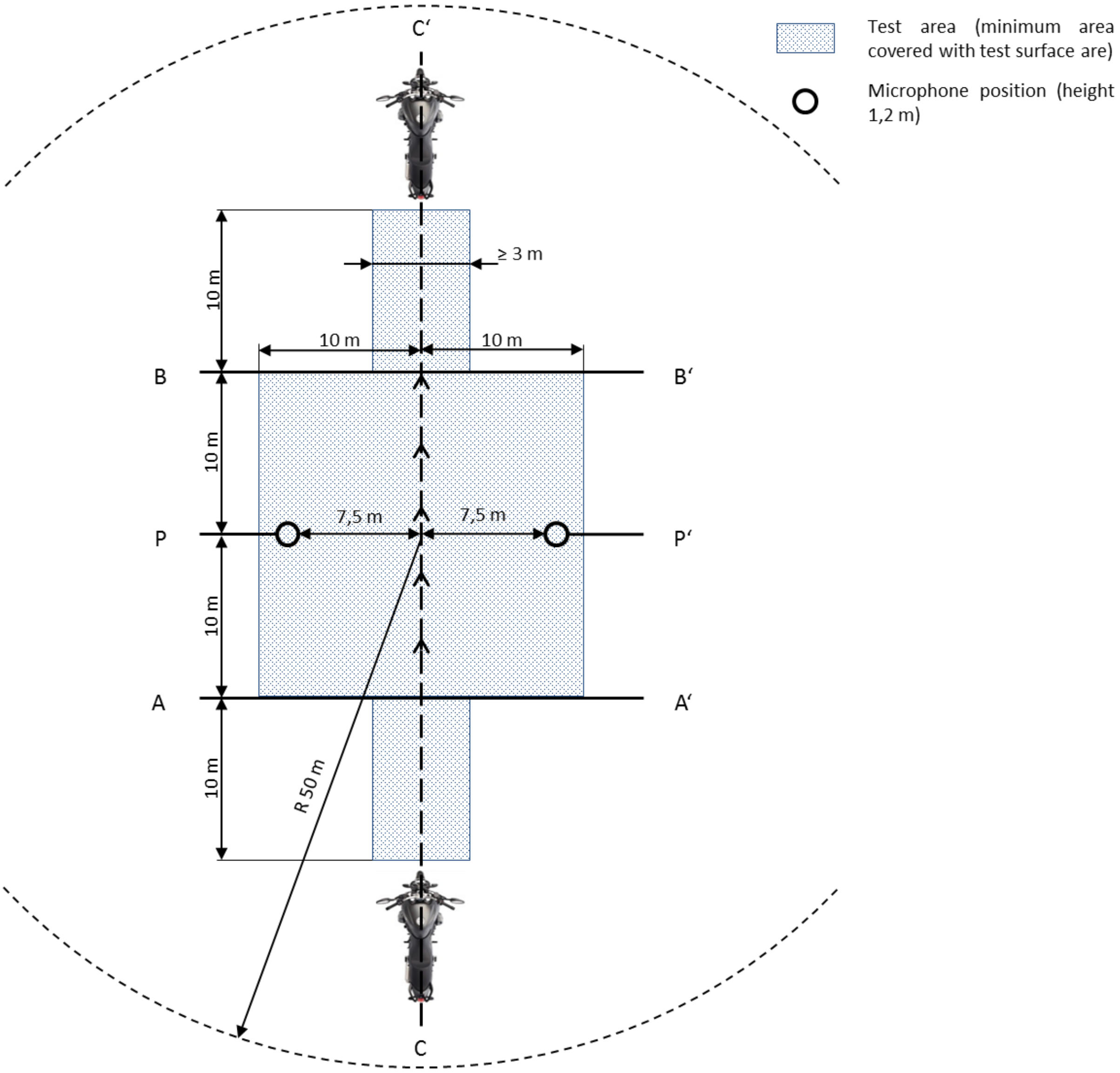


Figure 30 Test setup for sound level measurement - vehicle in motion; adapted from [40, p. 36]

In order to ensure a stable acceleration along the test distance from AA' to BB', manufacturers are allowed to use a so-called pre-acceleration. The test procedure is the same as described previously with the exception that the throttle control is set into the maximum throttle position when the vehicle front reaches the pre-acceleration length l_{PA}, which is before line AA’. For the test condition constant speed, the throttle control shall be adjusted in such a way that the motorcycle velocity is constant along the line CC', between AA' and BB'.

Motorcycles with a power-to-mass ratio (PMR) of less than or equal 25 are only tested with a full-throttle acceleration. This full-throttle acceleration test requires a test speed v_{test} of 40 km/h. The speed of the motorcycle after the rear has passed the line BB' must not exceed the limit of 75% of the maximum vehicle speed v_{max} and, in addition, the rated engine speed S must not be exceeded either. The appropriate gear or gear ratio is determined iteratively by selecting the lowest possible gear at which the above described test specifications in regard to the 75% of v_{max} and the rated engine speed S are fulfilled at BB'. The initial point is the specified speed v_{test}, which is reduced in 10% steps until the requirements are met.

Motorcycles with a PMR of more than 25 are tested with a full-throttle acceleration test as well as a constant speed test. The test speed v_{test} is 40 km/h for motorcycles with a PMR of less than or equal 50 and 50 km/h for vehicles with a PMR of more than 50. In a given gear, the speed of the motorcycle must not exceed 75% of v_{max} at BB'. If the condition is not met, the test speed v_{test} is reduced in 10% steps as long as the test condition is fulfilled. The correct gear or gear ratio depends on the required reference acceleration and speed v_{test} during the test. The manufacturer is responsible for the definition of the appropriate test method of the various transmission types, e.g. manual transmission, automatic transmission or continuously variable transmissions (CVT), which can be tested either with locked or non-locked gears, to reach the required accelerations and speeds. In the case of locked transmission gears, the gear has to be chosen, which is located closest within the tolerance band of ± 10% of the required reference acceleration $a_{wot,ref}$ or, if no gear is within the required tolerance band of $a_{wot,ref}$, then those two adjacent gears i and (i+1) are to choose, which attain an acceleration higher (gear i) and lower (gear i+1) than $a_{wot,ref}$.

The next higher gear is chosen, if the rated engine speed is exceeded before the motorcycle passes line BB'. In addition, vehicles with more than one gear must not use the first gear but the second one, regardless of whether the reference acceleration $a_{wot,ref}$ is only achieved with the first gear.

In the case of non-locked gears of automatic or variable transmissions, the transmissions operate in the full automatic mode, which may include a gear change during the test. An upshift to a higher gear is not permissible; since it leads to a lower acceleration. Furthermore, a downshift into a gear which is untypical for an operation in urban traffic is prevented by means of an electric or mechanical device. In the constant speed test the same gears and speeds are used as in the full-throttle acceleration test before.

The results of both tests, of the full-throttle acceleration test and the constant speed test, are used to imitate the characteristically partial load acceleration of urban driving. [40, pp. 22-24]

Pursuant to [40, pp. 22-24], the reference acceleration $a_{wot,ref}$ (Eq. 6 and Eq. 7) and the target acceleration a_{urban} (Eq. 8 and Eq. 9) depend on PMR.

$$a_{wot,ref} = 2{,}47 * \log(PMR) - 2{,}52 \quad in \quad {}^{m}/_{s^2} \qquad \text{for PMR} \leq 50$$ **Eq. 6**

$$a_{wot,ref} = 3{,}33 * \log(PMR) - 4{,}16 \quad in \quad {}^{m}/_{s^2} \qquad \text{for PMR} > 50$$ **Eq. 7**

$$a_{urban} = 1{,}37 * \log(PMR) - 1{,}08 \quad in \quad {}^{m}/_{s^2} \qquad \text{for PMR} \leq 50 \qquad \textbf{Eq. 8}$$

$$a_{urban} = 1{,}28 * \log(PMR) - 1{,}19 \quad in \quad {}^{m}/_{s^2} \qquad \text{for PMR} > 50 \qquad \textbf{Eq. 9}$$

For each test condition, at least three measurements are carried out in each gear and on each side of the motorcycle. The highest A-weighted sound pressure level L of each test run is reduced by 1 dB(A) in order to take into account the measurement accuracy and then the value is rounded to the closest first decimal. The first three successively measured test results of each test condition are valid for further calculation, if the deviation of the individual measurements from each other does not exceed 2 dB(A). The velocities $v_{AA'}$, $v_{PP'}$ and $v_{BB'}$ at the lines AA', PP' and BB' are also rounded to the closest first decimal. [40, pp. 24-25]
In compliance with [40, pp. 24-25], the acceleration is calculated by the measured velocities at AA' and BB' (Eq. 10), provided that the above described requirements with regard to locked or non-locked transmission gears are met. Otherwise, the velocities at PP 'and BB' are used for the calculation (Eq. 11). The unit of the velocities is km/h.

$$a_{wot,(i),j} = \frac{\left(\frac{v_{BB',j}}{3{,}6}\right)^2 - \left(\frac{v_{AA',j}}{3{,}6}\right)^2}{2 * \left(20 + l_{ref}\right)} \quad in \quad {}^{m}/_{s^2} \qquad \textbf{Eq. 10}$$

$$a_{wot,(i),j} = \frac{\left(\frac{v_{BB',j}}{3{,}6}\right)^2 - \left(\frac{v_{PP',j}}{3{,}6}\right)^2}{2 * \left(10 + l_{ref}\right)} \quad in \quad {}^{m}/_{s^2} \qquad \textbf{Eq. 11}$$

i → *used gear*
j → *number of individual measurement*
l_{ref} → *pre-acceleration length (either 2 m or the vehicle length)*

In literature [40, pp. 26-27], the three valid measurement results of each test condition are arithmetically averaged and rounded to the second decimal.

$$a_{wot,(i)} = \frac{a_{wot,(i),1} + a_{wot,(i),2} + a_{wot,(i),3}}{3} \qquad \textbf{Eq. 12}$$

If the test is carried out in two gears, the acceleration results of both tests are converted into a combined result, the dimensionless gear weighting factor k.

$$k = \frac{a_{wot,ref} + a_{wot,(i+1)}}{a_{wot,(i)} + a_{wot,(i+1)}} \qquad \textbf{Eq. 13}$$

The dimensionless partial power factor k_p is used to combine the test results from the full throttle acceleration test and the constant speed test.

$$k_p = 1 - \frac{a_{urban}}{a_{wot,ref}} \quad \rightarrow \textit{vehicle tested in two gears} \qquad \textbf{Eq. 14}$$

$$k_p = 1 - \frac{a_{urban}}{a_{wot,(i)}} \quad \rightarrow \textit{vehicle tested in one gear} \qquad \textbf{Eq. 15}$$

$$(if\ a_{wot,(i)} \leq a_{urban}\ then\ k_p = 0)$$

The three sound pressure level results for each test condition are averaged individually for each vehicle side.

$$L_{mode,(i),side} = \frac{L_{mode,(i),side,1} + L_{mode,(i),side,2} + L_{mode,(i),side,3}}{3} \qquad \text{Eq. 16}$$

mode → *test condition (full-throttle acceleration or constant speed)*
i → *used gear*
side → *side of the vehicle (left or right)*

The index "wot" designates a full-throttle test, "crs" denotes a constant speed test and "urban" describes a weighted combination of both tests. The higher mean value of both sides of the motorcycle is rounded to the first decimal and is used for further calculation.

$$L_{mode,(i)} = \max\left(L_{mode,(i),left}; L_{mode,(i),right}\right) \qquad \text{Eq. 17}$$

The final test result for vehicles with a PMR of less than or equal 25, which are tested only in a single gear, is the sound pressure level $L_{wot,(i)}$. Motorcycles with a PMR of more than 25 are tested in a full-throttle acceleration test and a constant speed test. If these tests are carried out in two gears, the gear weighting factors have to be used for the calculation of both tests.

$$L_{wot} = L_{wot(i+1)} + k * \left(L_{wot,(i)} - L_{wot,(i+1)}\right) \qquad \text{Eq. 18}$$

$$L_{crs} = L_{crs(i+1)} + k * \left(L_{crs,(i)} - L_{crs,(i+1)}\right) \qquad \text{Eq. 19}$$

Test results from the full-throttle acceleration test and the constant speed test with a single gear directly correspond to the final test result.

$$L_{wot} = L_{wot,(i)} \qquad \text{Eq. 20}$$

$$L_{crs} = L_{crs,(i)} \qquad \text{Eq. 21}$$

The final urban sound level pressure L_{urban} is calculated by the sound pressure level of the full-throttle acceleration test L_{wot} and the constant speed test L_{crs} in consideration of the partial power factor k_p (Eq. 22).

$$L_{urban} = L_{wot} - k_p * (L_{wot} - L_{crs}) \qquad \text{Eq. 22}$$

The vehicle test condition for sound pressure level measurement of stationary motorcycle requires that all engine covers are installed, any existing air-condition is deactivated and, if available, the parking brake is applied. Furthermore, the idle position and the clutch must be engaged – or the parking position by automatic transmissions. If the vehicle is not equipped with a neutral gear position, the rear wheel is to rise off the ground to ensure a freely rotate of the rear wheel during the test. Thereby, the microphone positions must be adapted according to the prescribed distance from the reference point of the exhaust pipe. If fans have an automatic control system, the measurement must not be influenced by the automatic fan control system. For each measurement, the motorcycle must be brought to operating temperature.

The measurements can be carried out either on an outdoor test site or in a semi-anechoic chamber. An outside test has to be performed on a level concrete, dense asphalt or the like, which is free of any sound absorbing materials such as snow, grass, ash, etc. Moreover, no sound reflecting surfaces, e.g. other vehicles, persons, trees, etc., have to be positioned in a radius of 3 m around the microphones and around any point of the motorcycle. The test conditions in regard to ambient noise and wind speed are the same as during the test of the vehicle in motion. [40, pp. 27-28]

The position of the microphones, including dimensions from the reference point of the exhaust pipe, is depicted in Figure 32 and Figure 31 shows the definition of the reference point.

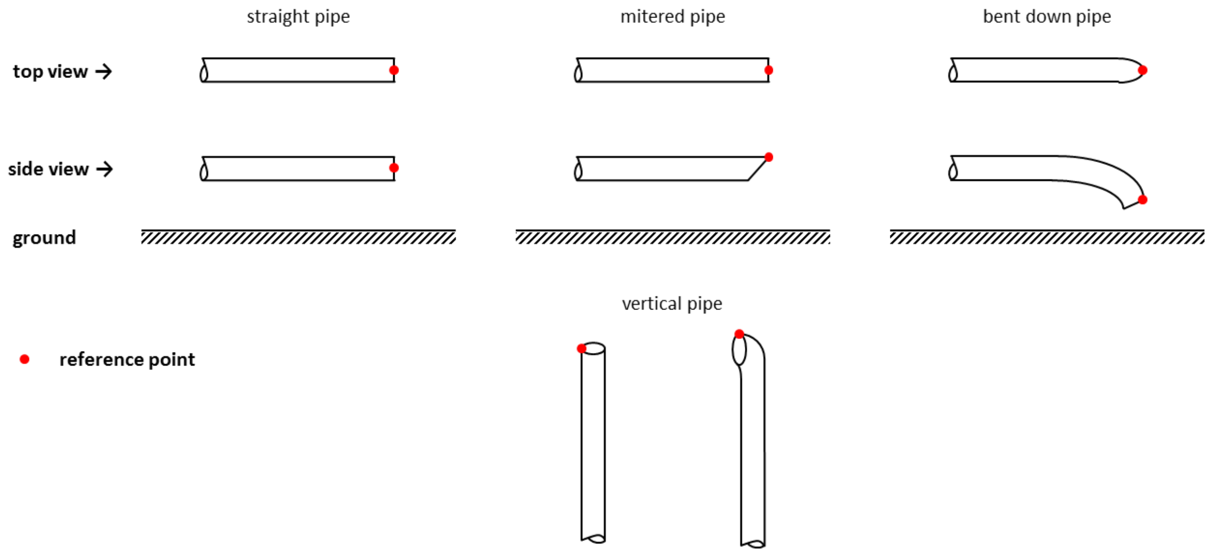


Figure 31 Definition of reference point - stationary sound level measurement; adapted from [40, p. 29]

The position of the microphones is on the level of the reference point, but the minimum distance to the ground must not less than 0.2 m. The microphones must be oriented to the reference point at the exhaust outlet pipe. The reference point is the highest point of the intersection from the vertical plane of exhaust gas flow axis and the end point of the exhaust outlet pipe. If two positions of the microphones are possible, the position with the farthest distance to motorcycle's longitudinal axis has to be selected. This also applies to exhaust pipes with a flow axis normal to the longitudinal axis of the vehicle. For motorcycles with more than one exhaust outlet pipe, only one measurement must be carried out, if their distance from each other is not more than 0.3 m and if only one exhaust silencer is installed for all exhaust outlet pipes. The measurement is performed with the exhaust outlet pipe, which is farthest from the motorcycle longitudinal center line or has the highest distance to the ground. If the distance is more than 0.3 m, the sound pressure level must be measured for each exhaust outlet pipe separately and the highest value represents the test result value.

The target engine speed for the stationary test is 75% of the rated engine speed S for motorcycles with a rated engine speed S of less than or equal 5000 rpm and 50% of the rated engine speed for motorcycles with a rated engine speed S of more than 5000 rpm. If motorcycles cannot reach the required target engine speed, the target engine speed is 95% of the maximum engine speed. [40, pp. 28-29]

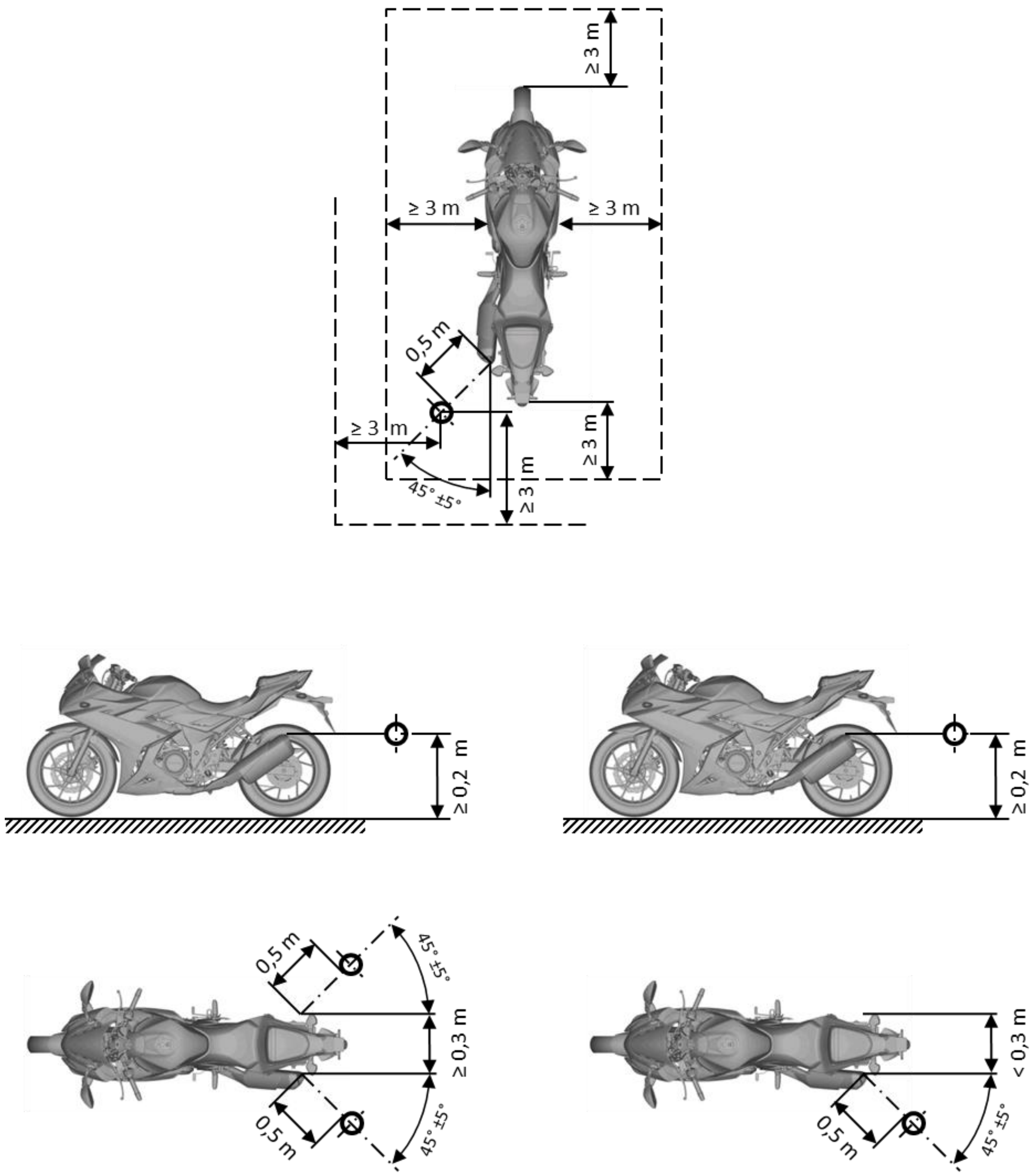


Figure 32 Test setup for stationary sound level measurement; adapted from [40, p. 33]

The test starts at idle speed and is brought to the target speed. The target engine speed is held within a tolerance of ± 5% and is then reduced to idle speed again. The measurement of the sound pressure level is performed over a period of at least 1 s at constant target engine speed and over the entire deceleration period. If motorcycles have an adjustable exhaust system with several operating modes, the measurement must be performed for each operating mode. The maximum A-weighted sound pressure level of a measurement is rounded to the first decimal. The test is valid if three successive measurements do not exceed a deviation of 2 dB(A). The result of these three successive measurements for an exhaust outlet pipe is arithmetically averaged and rounded to the first decimal and represents the final test result. [40, pp. 29-31]
The sound level measurements for mopeds (L1e, L2e), tricycles and quadricycles (L5e, L6e and L7e) are performed according to Regulation (EU) No. 134/2014 Annex IX. The test procedure is nearly identical, only the operating conditions, such as velocities, speeds and correction factors are different. The test sites are identical to Figure 30 and Figure 32 of UN-ECE Reg. No. 41. The implementation of EURO 5 provides new UN-ECE Regulations for sound level test for mopeds (UN-ECE Reg. No. 63), tricycles and quadricycles (UN-ECE Reg. No. 9). [22, pp. 245-287]

2.3.2 USA

The requirements for the test area are similar to those of UN-ECE Reg. No. 41. The microphone position and dimensions of the test area and test side are pictured in Figure 33 and Table 12 contains the valid A-weighted sound pressure level limits. The concrete or asphalt surface of the test side has to be level and free of any foreign material such as snow or the like. Besides, the test area shall have sufficient space so that no sound reflection occurs by objects positioned within a radius of 30 m around the microphone location point as well as around the two points on the vehicle path 15 m before and after the microphone location. [41]

Table 12 Noise emission standards for motorcycles and mopeds (U.S. - EPA) [42]

Vehicle type	Model Year (MY)	Sound pressure level
Motorcycle	1983	83 dB(A)
	1986	80 dB(A)
Moped	1983	70 dB(A)
Off-road motorcycle ≤ 170 cm³	1983	83 dB(A)
	1986	80 dB(A)
Off-road motorcycle > 170 cm³	1983	86 dB(A)
	1986	82 dB(A)

The acceleration point (A) (see Figure 33) is determined by test runs in reverse test direction. The motorcycle approaches the end point (C) in the second gear at closing speed of 10% below the maximum rated speed or at constant speed of 50% of maximum rated speed, whichever speed is lower. The throttle is rapidly opened after the front of the vehicle has approached the end point (C). The microphone target point (B) is passed with fully opened throttle. When the motorcycle reaches the closing speed either the throttle is manually closed or the engine is stopped by an “ignition disable device”. The acceleration point (A) is the position of the front of the motorcycle on the vehicle path at the time of closing the throttle. The closing speed is a fraction of the maximum rated speed in percent and is depicted in

Figure 34. The procedure to establish the acceleration point has to be carried out for a sufficient number of repetitions to determine the acceleration point as precisely as possible. [41]

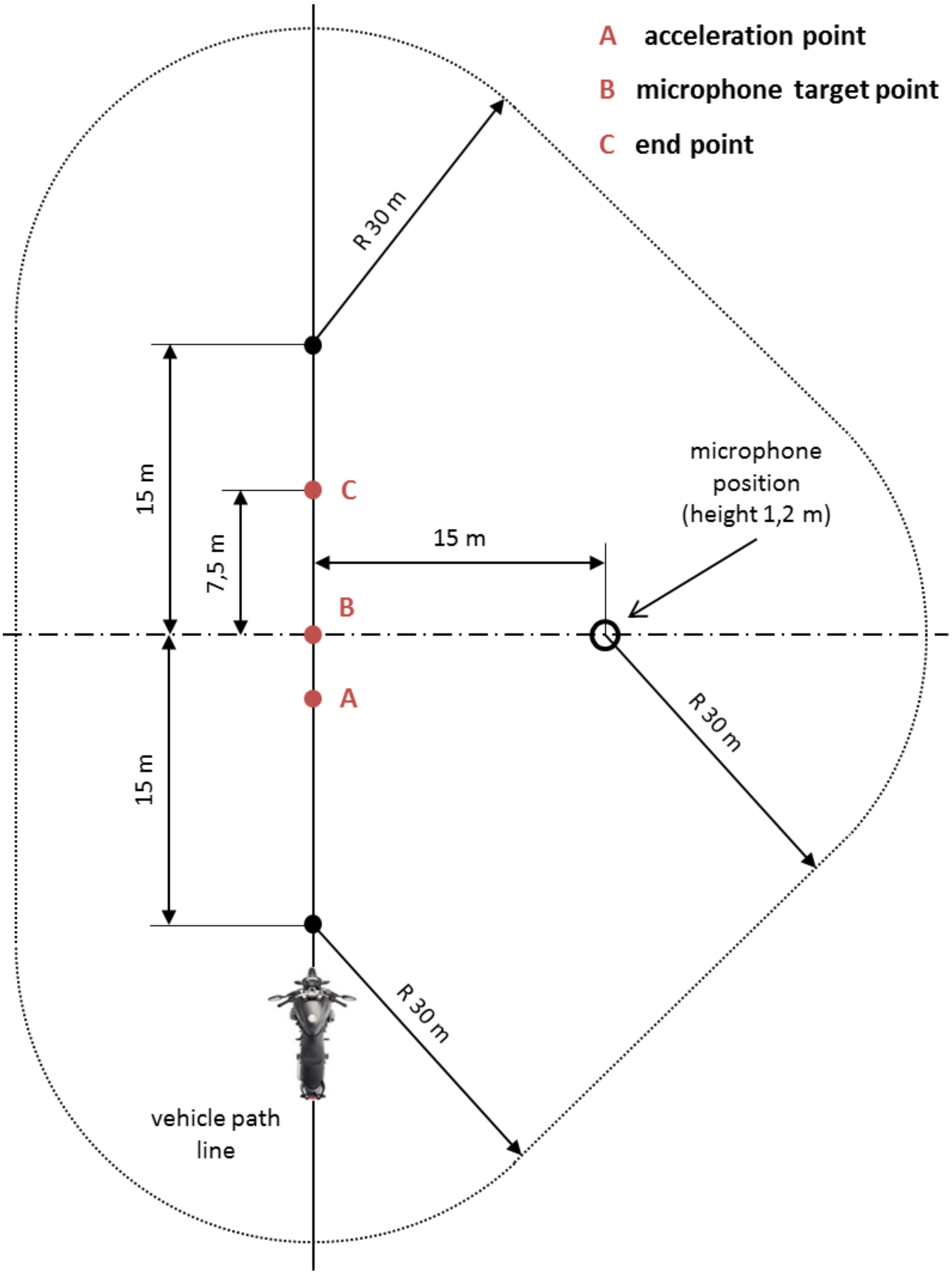


Figure 33 Sound level measurement test area (U.S. - EPA); adapted from [41]

If the distance between the previously determined acceleration point (A) and the end point (C) is less than 10 m, the measurement procedure is performed in the next higher gear, if equipped. This process is repeated until the distance between the acceleration point (A) and end point (C) is 10 m. If the minimum distance of 10 m between the points (A) and (C) cannot be reached in the highest gear, the throttle is opened less rapidly, in such a way that the motorcycle passes the end point (C) with fully opened throttle and closing speed. In the case of an automatic transmission the procedure to establish the acceleration point follows the same scheme as described above, but with the highest selectable range of transmission. [41]

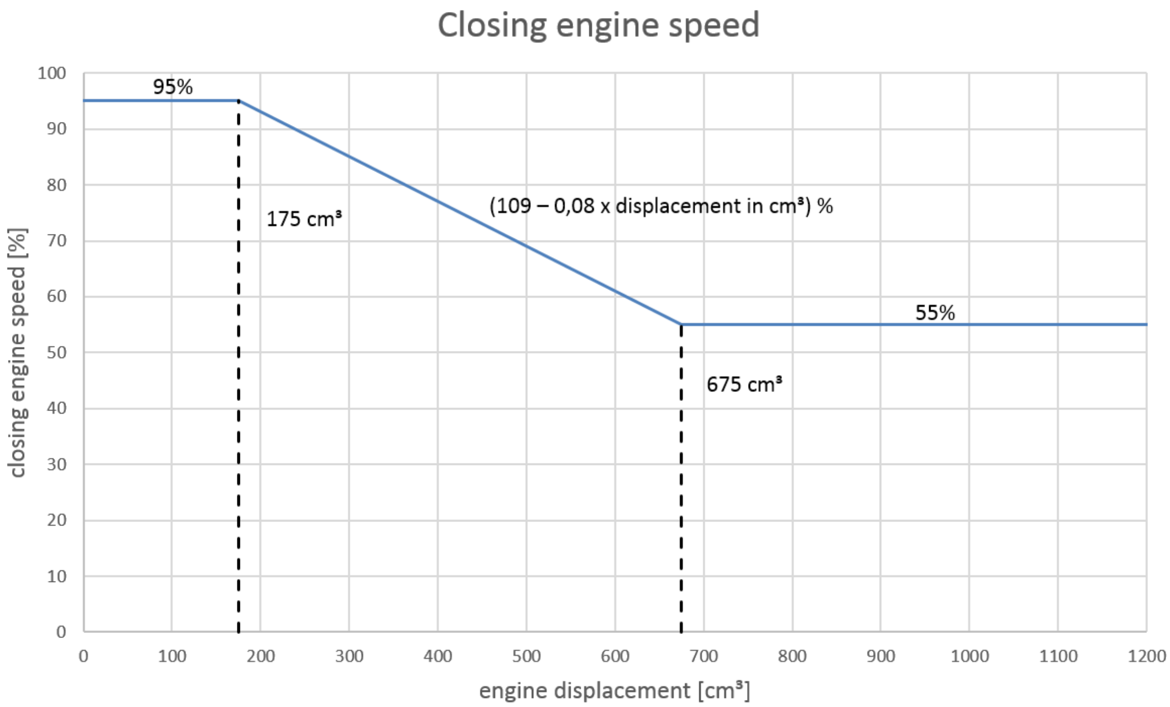


Figure 34 Closing engine speed; adapted from [41]

Moreover, it is important to ensure, that the throttle is controlled within the limits in order to avoid wheel slip or lift-off. The measurement is carried out under the same conditions as the determination of the acceleration point, with the exception of the opposite driving direction. The motorcycle is driven along the vehicle path in the second gear or appropriate higher gears and approaches the acceleration point (A) at constant speed of 50% of maximum rated speed or at closing speed of 10% below the maximum rated engine speed, whichever is lower. Then the throttle is rapidly opened and remains fully opened until the closing speed is reached near the end point (C) (± 1 m), at which the throttle has to be rapidly and fully closed or instead, an "ignition disable device" can be used to stop the engine. Before the measurements start the engine temperature must be brought into the normal operating temperature window.

The highest A-weighted sound pressure level during the whole acceleration period is recorded. The measurements for one side are carried out until the deviation of at least four test results are within 2 dB(A) to each other. The A-weighted sound pressure level result for each side of the motorcycle is the average of the four measurements. The averaged A-weighted sound pressure level of that side of the motorcycle which is the maximum value of both sides is the final test result. The difference between the background noise sound pressure level and the measured sound pressure level must be at least 10 dB(A). The permitted wind speed during the measurements is below of 20 km/h.

The sound pressure level measurement procedure of mopeds differs in some points. The distance perpendicular to the vehicle path between the microphone target point (B) and the location of the microphone can be 7.5 m as an alternative to the 15 m. In this case, 6 dB(A) has to be subtracted from the final test result. Otherwise, the test area of mopeds has the same specifications as those of the motorcycles. The total weight of test driver and measurement equipment shall be between 75 kg and 80 kg. If additional weights are necessary to meet the requirement of 75 kg, the additional weights are placed behind the driver on the saddle. The start point is to be selected that the moped reaches the maximum speed within 7.5 m before the microphone target point (B) and passes this point with fully opened throttle in the highest gear. This state remains until the moped approaches the end point (C), at which the throttle is closed. The measurement is identical to the motorcycle, with the difference that only three measurements from each side of the vehicle have to be within 2 dB(A) and not four. The maximum background sound pressure level is 60 dB(A) for a distance of 15 m between the microphone point (B) and the microphone location or 66 dB(A) for a distance of 7.5 m. [41]

2.4 Development of Non-Road Mobile Machinery -Emission-Control Legislation

Non-Road Mobile Machinery (NRMM) includes internal combustion engines in various specifications and applications. The engines are mainly classified in propulsion class, power level and operating profile. The propulsion class is split in spark ignition (SI) (also referred to as positive ignition - PI) and compression ignition (CI). The operating profiles are constant or variable speed. The range is from small spark ignition engines, which are used e.g. for lawn and garden equipment, to large diesel engines, which are used e.g. in rail cars or inland waterway vessels.

In the next few years, a new emission standard for NRMM will be introduced in Europe. These new regulations intend to cover a wider range of engines. Furthermore, the emission limits will be more and more stringent to improve the air quality and reduce emissions. However, there is a fear that the new emission legislation does not cover the whole segment and therefore a market distortion will be created. Another problem is caused by engines already in use, as some of them are staying in operation since several decades now and cannot meet the new emission standards without any technical modification. Due to difficulties in the course of the implementation of new regulations, the NRMM sector contributes only a small percentage to the improvement of the air quality in the next decades. [43, p. 1]

2.4.1 Europe (EU)

In 1999, the first of two new emissions stages for NRMM with compression ignition was introduced. Stage II was implemented in the period from 2001 to 2004.Emission standards for engines with spark ignition were introduced for the first time at the beginning of 2005. This directive includes engines for handheld and non-handheld machinery. The emission standard Stage III, which was split into Stage III A and IIIB, was introduced in the period from 2006 to 2012 and Stage IV one year later. The new directive Stage V will be implemented in 2019 respectively 2020. A detailed overview with respect to implementation dates and emission limits can be found in Table 26 in the Appendix.

There are two different test cycles for NRMM to measure exhaust emissions, the Non-Road Steady-State Cycle (NRSC) and the Non-Road Transient Cycle (NRTC). The NRSC is also called ISO 8178 test cycle and consists of various load and speed modes. The Non-road Transient Cycle contains no cold start phase, all speed and load modes are measured with warm engine. The ISO 8178 is classified into several categories, which are off-road vehicles (C), constant speed (D), marine applications (E), locomotives (F), utility, lawn and garden (G) and finally snowmobiles (H). Each listed NRMM category is subdivided in subcategories again. The ISO 8178-C1 is used for diesel powered off-road industrial equipment, such as crawler tractors or forestry equipment, and test cycle C2 is used for SI powered off-road industrial equipment with greater-than 20 kW as ,for example, fork-lift trucks or agricultural equipment. Test cycle D1 is applied for power plants and D2 for generating sets with intermittent load, chippers or snow removal equipment.

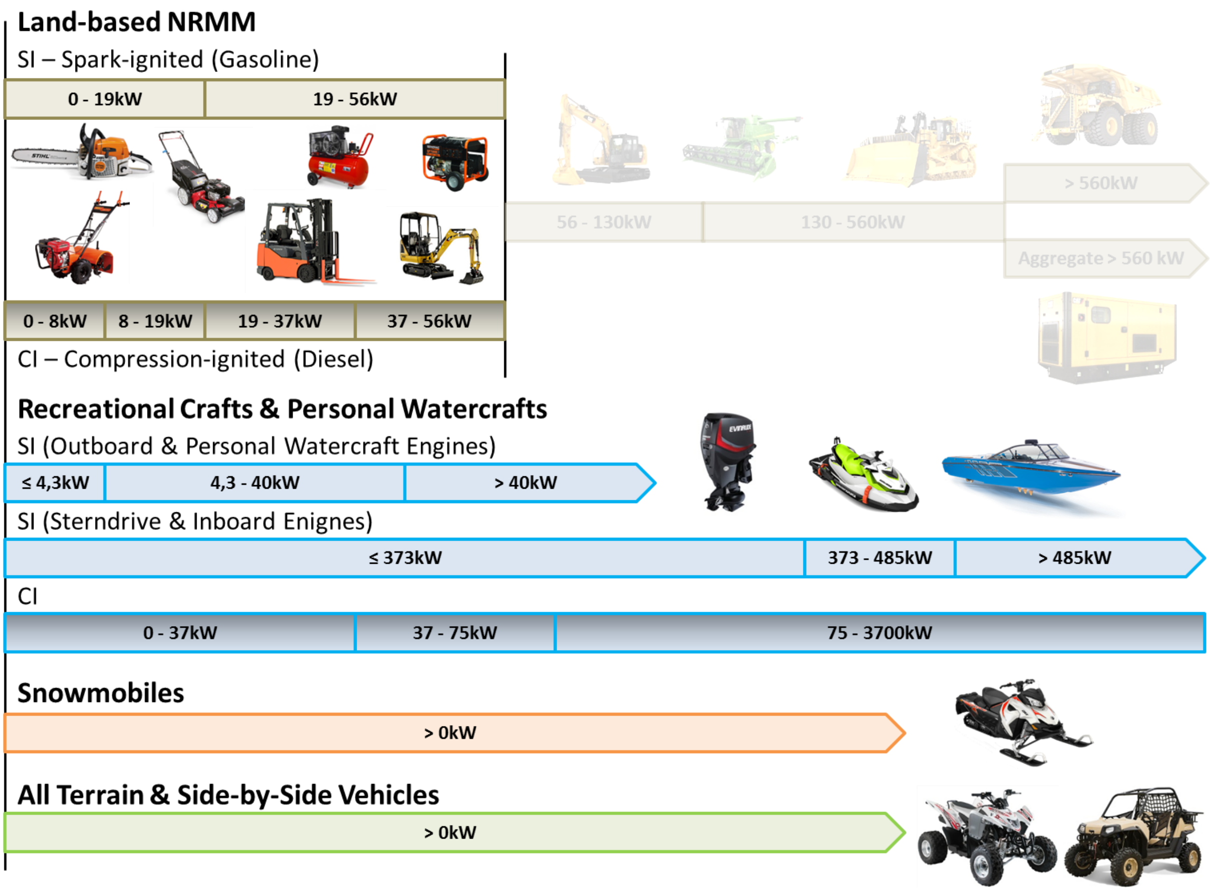


Figure 35 Classification NRMM in Europe; adapted from [44]

Table 13 ISO 8178 cycles for NRMM – C1, C2, D1, D2, E1, E2, G1, G2 and G3 [21, p. 288] [45]

Mode number		1	2	3	4	5	6	7	8	9	10	11
Torque (%)		100	75	50	5	10	100	75	50	25	10	0
Speed		Rated					Intermediate					Low idle
Weighting factors (%)	Off-road Vehicle											
	C1	15	15	15		10	10	10	10			15
	C2				6		2	5	32	30	10	15
	Constant speed engines											
	D1	30	50	20								
	D2	5	25	30	30	10						
	Marine applications (excl. propellerlaw)											
	E1	8	11					19	32			30
	E2	20	50	15	15							
	Utility, lawn and garden											
	G1						9	20	29	30	7	5
	G2	9	20	29	30	7						5
	G3	85										15

- torque is expressed in % of the maximum torque at given speed
- rated speed is defined at rated engine power
- intermediate speed is the peak-torque speed (general between 60% and 75%)

Table 14 ISO 8178 cycles for NRMM - E3, E4 and E5 [45]

Mode number		1	2	3	4	5
Marine application (incl. propeller law)						
E3	Power (%)	100	75	50	25	
	Speed (%)	100	91	80	63	
	Weighting factor (%)	20	50	15	15	
E4	Power (%)	100	71.6	46.5	25.3	0
	Speed (%)	100	80	60	40	idle
	Weighting factor (%)	6	14	15	25	40
E5	Power (%)	100	75	50	25	0
	Speed (%)	100	91	80	63	idle
	Weighting factor (%)	8	13	17	32	30

- torque is expressed in % of the maximum torque at given speed
- rated speed is defined at rated engine power
- intermediate speed is the peak-torque speed (general between 60% and75%)

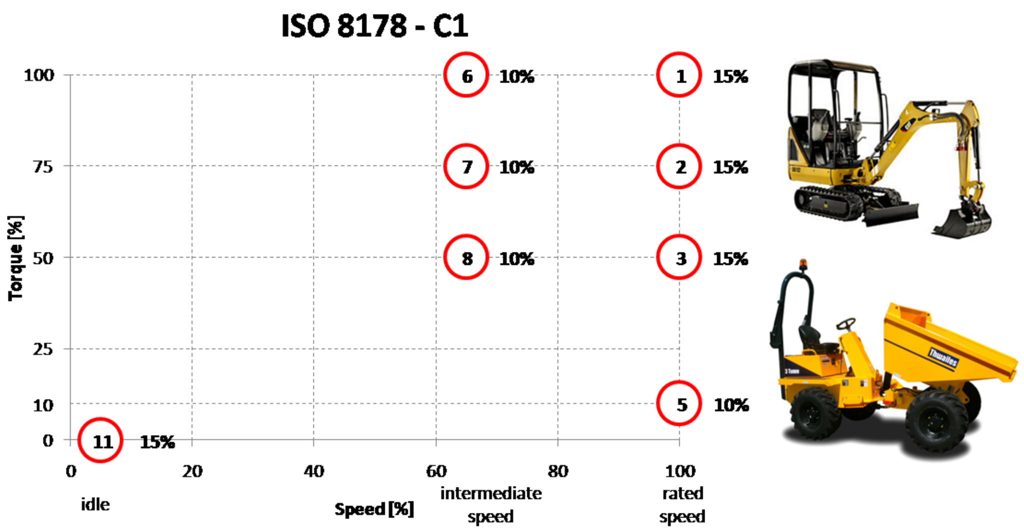


Figure 36 ISO 8178 – C1 test cycle for NRMM; adapted from [21, pp. 292-293]

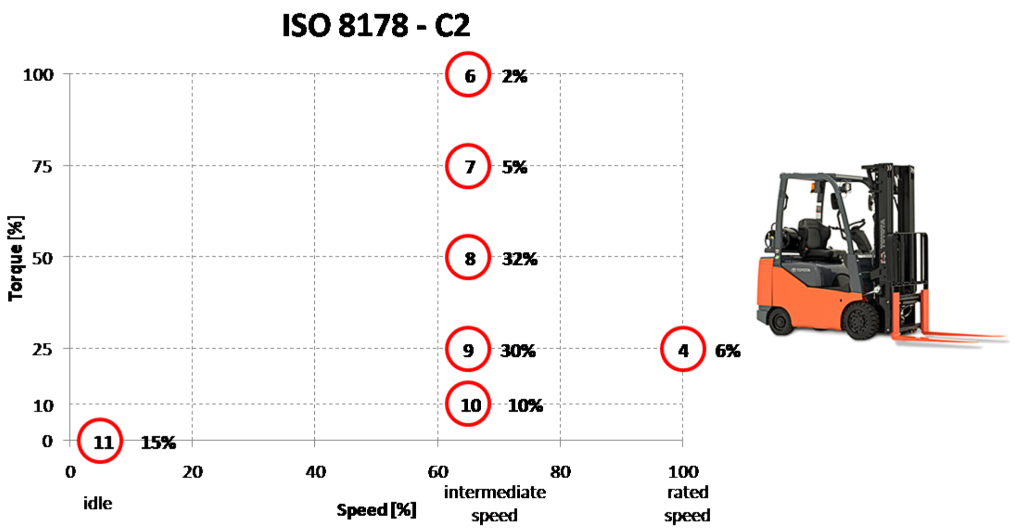


Figure 37 ISO 8178 - C2 test cycle for NRMM; adapted from [21, pp. 292-293]

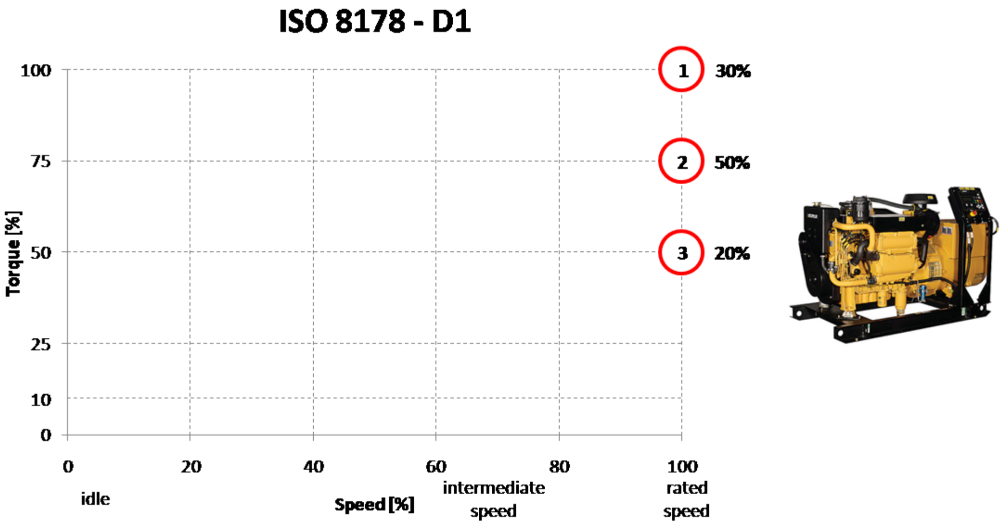


Figure 38 ISO 8178 – D1test cycle for NRMM; adapted from [21, pp. 292-293]

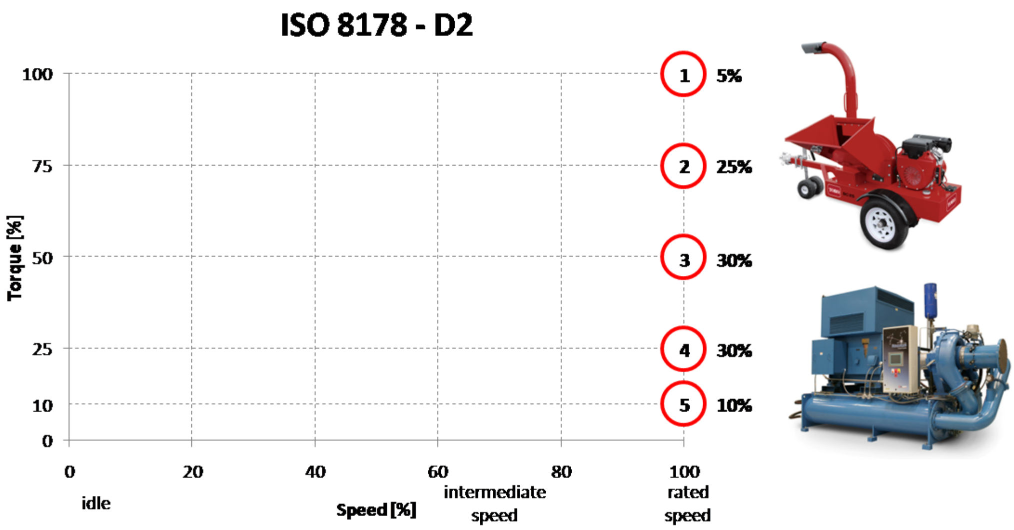


Figure 39 ISO 8178 - D2 test cycle for NRMM; adapted from [21, pp. 292-293]

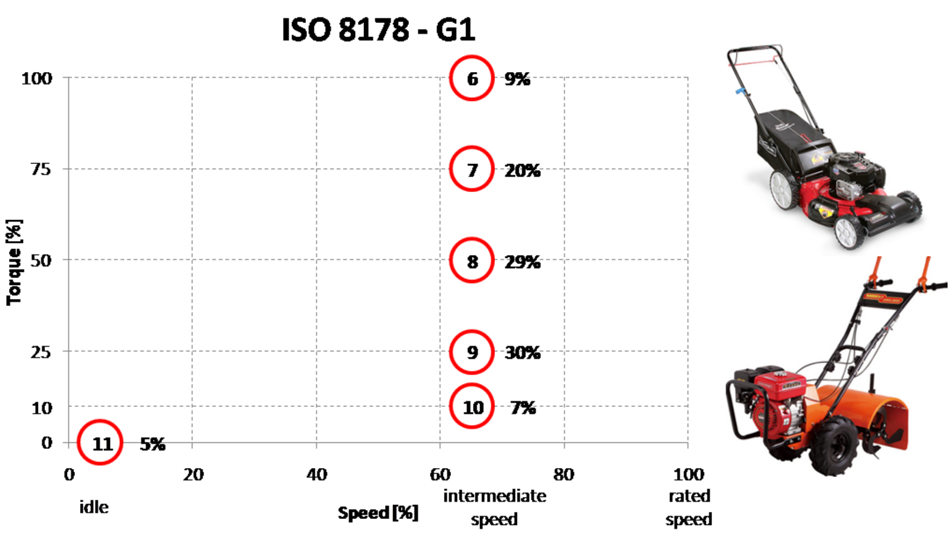


Figure 40 ISO 8178 – G1 test cycle for NRMM; adapted from [21, pp. 292-293]

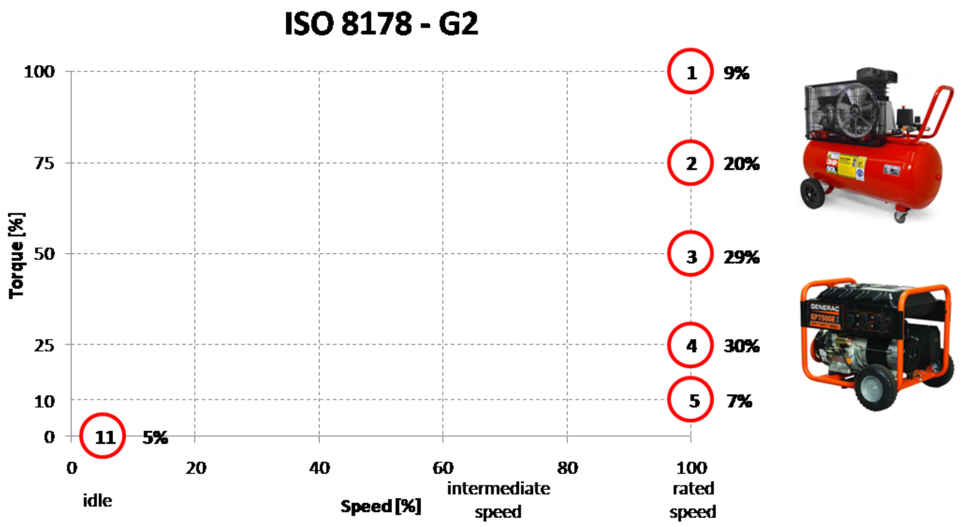


Figure 41 ISO 8178 - G2 test cycle for NRMM; adapted from [21, pp. 292-293]

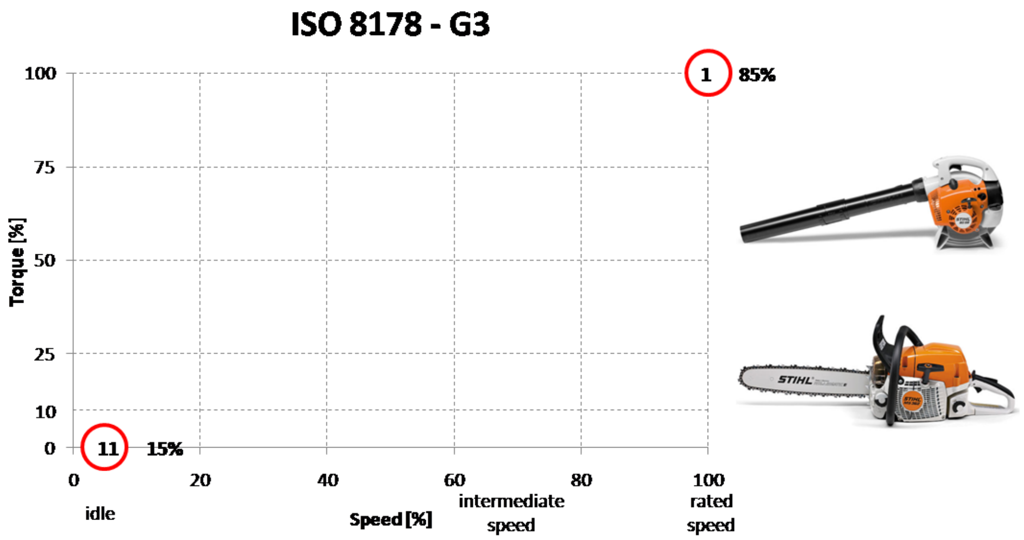


Figure 42 ISO 8178 - G3 test cycle for NRMM; adapted from [21, pp. 292-293]

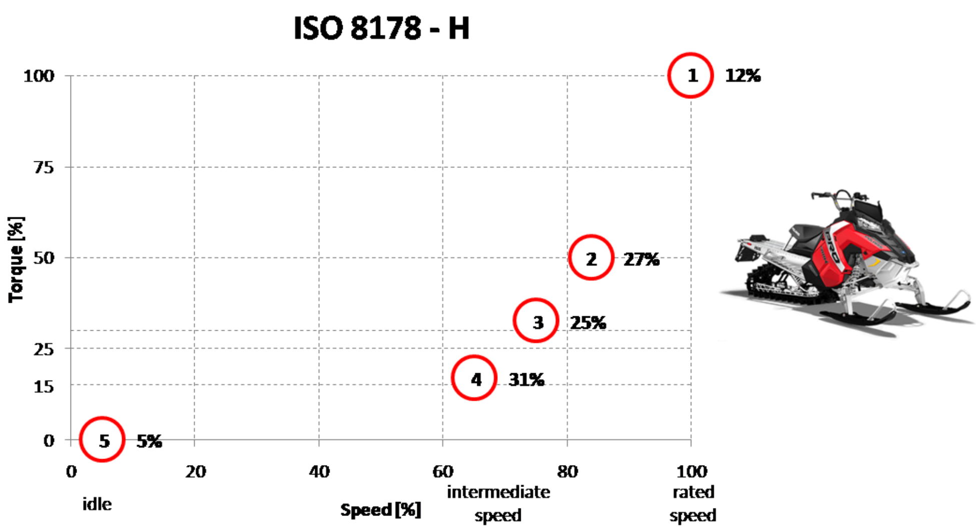


Figure 43 ISO 8178 - H test cycle for NRMM; adapted from [21, pp. 292-293]

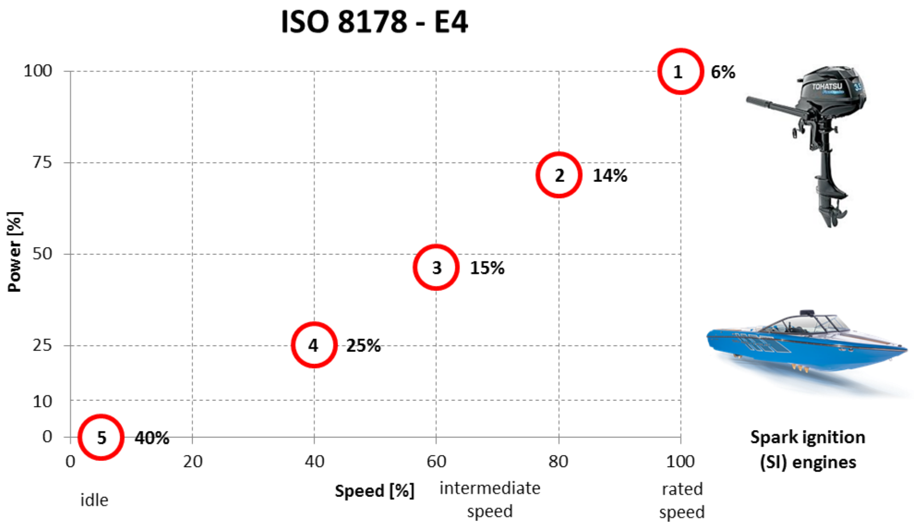


Figure 44 ISO 8178 – E4 test cycle for NRMM; adapted from [21, pp. 292-293]

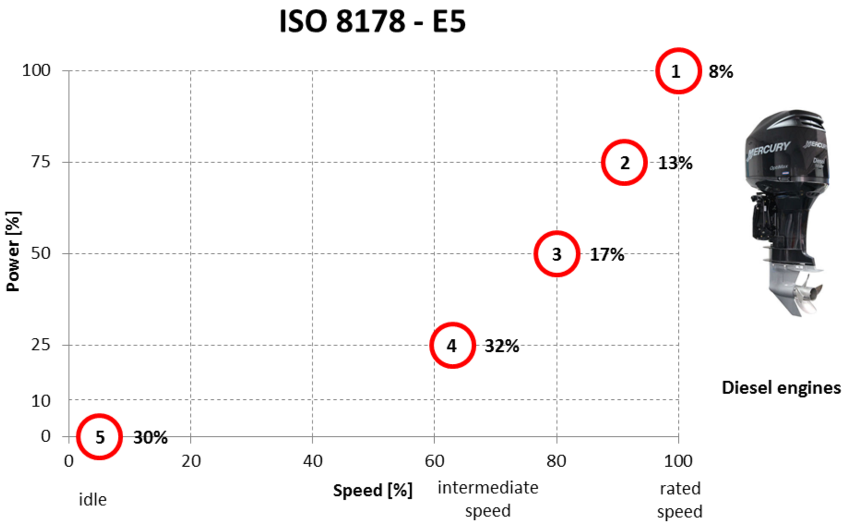


Figure 45 ISO 8178 – E5 test cycle for NRMM; adapted from [21, pp. 292-293]

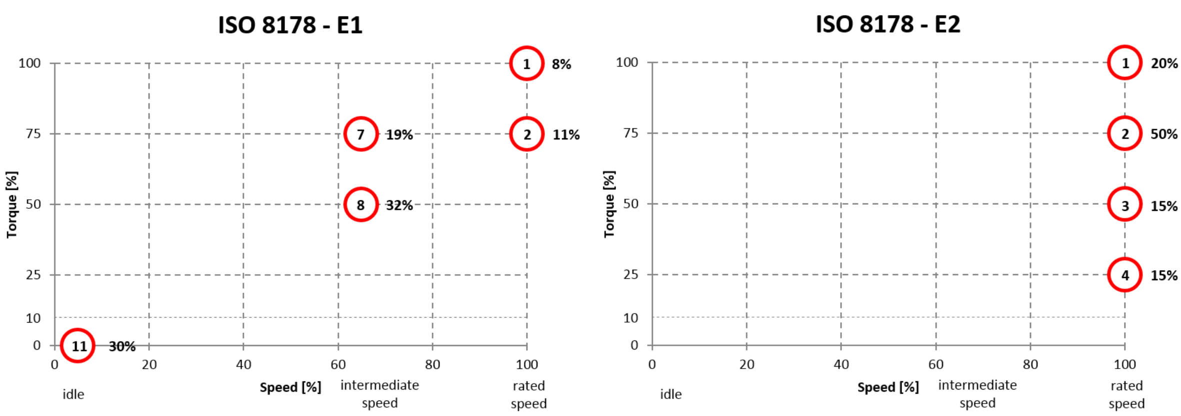


Figure 46 ISO 8178 - E1 and E2 test cycle for NRMM; adapted from [21, pp. 292-293]

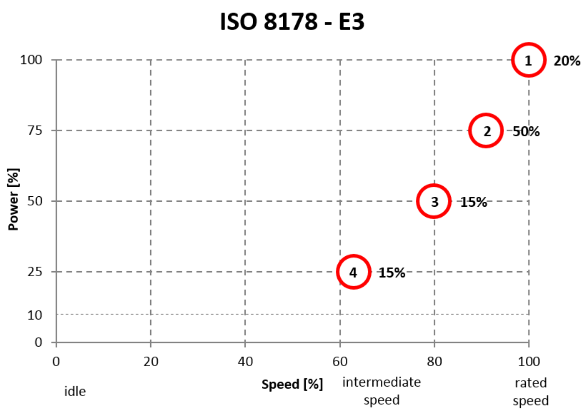


Figure 47 ISO 8178 - E3 test cycle for NRMM; adapted from [21, pp. 292-293]

The class G1 is used for non-hand-held intermediate-speed applications such as cylinder lawn mowers, class G2 is used for non-hand-held rated-speed applications like portable generators or pumps, and class G3 is applied for hand-held rated-speed applications as, for example edge trimmer and chain saws. The class ISO 8178-H is used for snowmobiles. Figure 36 to Figure 47 depicts the above mentioned NRSC test cycles. [21, p. 290] The SAE J1088 test cycles A, B and C are similar to ISO 8178 G1, G2 and G3 test cycles. [46, p. 84] The ISO 8178 E1 test cycle is used for marine applications with diesel engines, their length is ≤ 24 m and the E2 and E3 are used for heavy-duty marine engines.

The following Table 15, Table 16, Figure 48 and Figure 49 contain the steady-state ramped modal test for heavy-duty non-road engines, e.g. excavator or tractors. The ramped transitions of the steady-state ramped tests cycles should cover a wider load and speed range, especially of turbocharged diesel engines, which have a significant proportion on total exhaust emissions. The 9-mode duty cycle is applied for variable speed engines and the 5-mode duty cycle is applied for constant speed engines. [21, pp. 295-297]

Table 15 9-Mode Duty Cycle for variable speed engines [46, p. 98]

Ramped modal cycle	Time in mode (s)	Engine speed	Engine torque
1a – steady state	126	warm idle	0%
1b – transition	20	linear transition	linear transition
2a – steady state	159	intermediate	100%
2b - transition	20	intermediate	linear transition
3a – steady state	160	intermediate	50%
3b – transition	20	intermediate	linear transition
4a – steady state	162	intermediate	75%
4b - transition	20	intermediate	linear transition
5a – steady state	246	rated	100%
5b – transition	20	rated	linear transition
6a – steady state	164	rated	10%
6b - transition	20	rated	linear transition
7a – steady state	248	rated	75%
7b – transition	20	rated	linear transition
8a – steady state	247	rated	50%
8b - transition	20	linear transition	linear transition
9 – steady state	128	warm idle	0%

Table 16 5-Mode Duty Cycle for constant speed engines [46, p. 98]

Ramped modal cycle	Time in mode (s)	Engine speed	Engine torque
1a – steady state	53	engine governed	100%
1b – transition	20	engine governed	linear transition
2a – steady state	101	engine governed	10%
2b - transition	20	engine governed	linear transition
3a – steady state	277	engine governed	75%
3b – transition	20	engine governed	linear transition
4a – steady state	339	engine governed	25%
4b - transition	20	engine governed	linear transition
5 – steady state	350	engine governed	50%

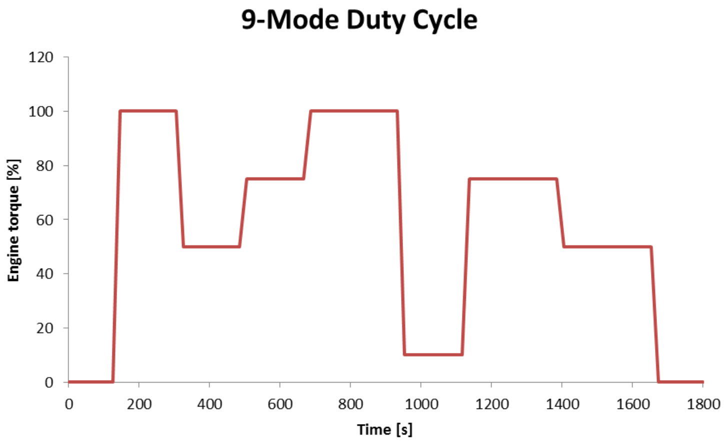


Figure 48 Engine torque of the 9-mode duty cycle for variable speed engines; adapted from [21, p. 297]

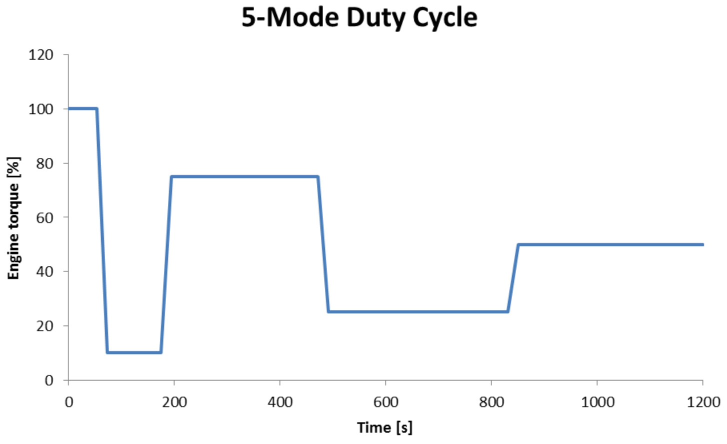


Figure 49 Engine torque of the 5-mode duty cycle for constant speed engines adapted from [21, p. 297]

The Non-Road Transient Cycle (NRTC) was developed by the U.S. EPA in cooperation with the EU, to generate a test condition with equivalent real-world emissions. It is used for the regulation Stage III and IV in Europe and for the US EPA Tier 4.

In principle, the NRTC consist of two phases, the cold start cycle phase and the hot start cycle phase. In the first phase, the NRTC is run after cold start, and subsequently the hot soak phase of the engine starts. In the second phase, the NRTC is run again, but after hot start.

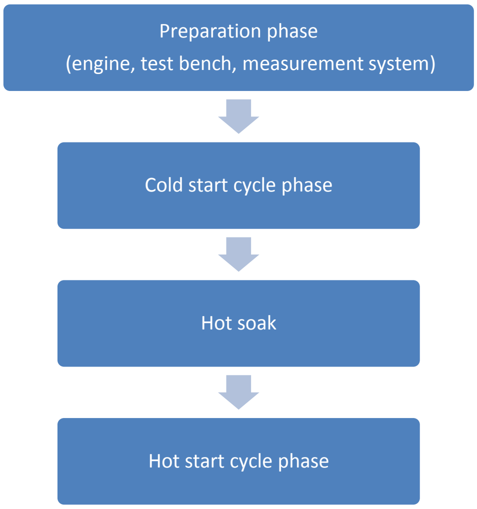


Figure 50 NRTC test sequence; adapted from: [46, p. 99]

Figure 50 depicts the NRTC test sequence. The preparation phase includes all steps necessary to perform an emission test run, e.g. engine and test bench preparation, cooling, ready sampling system and data collection including pre-test runs. If the test set-up ensures a proper function, the emission test run can be started. The NRTC is to be carried out twice, with cold start and after a hot soak phase with hot start. The final result is calculated from the cold start and hot start emissions. In Europe, the cold start emissions are weighted with 10% and the hot start emissions with 90% for Stage III. In the U.S., the cold start emissions are weighted with 5% and the hot start emissions with 95% for Tier 4. Figure 51 shows the speed and torque level during the test cycle. [46, p. 99]

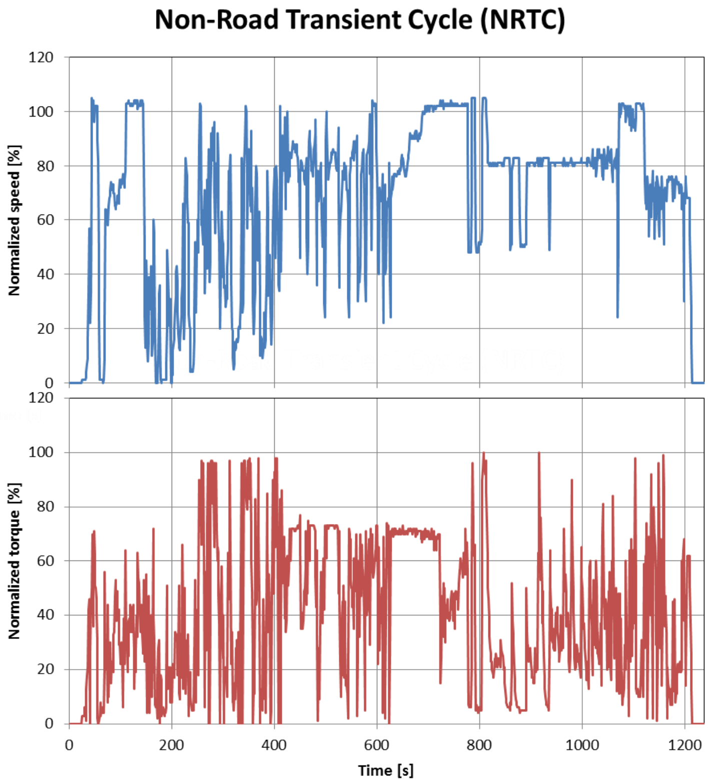


Figure 51 Non-Road Transient Cycle (NRTC)

2.4.2 USA

2.4.2.1 US Federal (EPA)

Tier 1 standard was passed in 1994 for off-road CI and SI engines and was introduced in the period from 1996 to 2000. The Tier 2 and Tier 3 standards were phased-in schedules from 2001 to 2008 with more stringent emission limits than Tier 1. The implementation of the latest directive Tier 4 started in 2008. These emission standards reduced the NOx and PM limits up to the standards for highway engines. [24, pp. 75-83]
NRMM, also known as non-road vehicles and engines in the Federal legislation, is divided in heavy equipment engines with SI and CI, in marine engines with SI and CI, in recreational vehicles and in engines which are used in small equipment and tools. In addition, also aircrafts and locomotives are included, but they are of no relevance here and will not be considered further in this thesis. The category recreational vehicles includes snowmobiles, off-highway motorcycles, all-terrain vehicles (ATVs) and off-road utility vehicles with an engine displacement less than or equal to 1000 cm^3, a maximum engine power less than or equal to 30 kW and a maximum vehicle speed higher than 25 miles per hour (≈ 40 km/h). Furthermore, the category of engines in small equipment and tools includes all SI engines with less than or equal 19 kW and are distinguished in handheld (e.g. chainsaws, string trimmers, leaf blowers, etc.), non-handheld (e.g. lawnmowers, garden tractors, small generators etc.) and auxiliary marine engines. SI engines with more than 19 kW are contained in heavy equipment SI engines, such as industrial equipment, generators, forklifts, etc.. Personal watercraft, outboard marine, sterndrive and inboard engines are covered with the category of marine SI engines. CI engines are split into marine CI engines, heavy equipment CI engines and locomotives. [47] [48]
The U.S. EPA also uses a steady-state test cycle for emission measurement of NRMM. It is equivalent to the ISO 8178 C1 steady-state test cycle. Furthermore, other ISO 8178 test cycles are in use for selected NRMM categories. Tier 4 standard has to use both test cycles, the steady-state test cycle and the new developed non-road transient test cycle NRTC (see Figure 51). Table 27 in the Appendix shows an overview of the NRMM emission standards of the U.S. EPA.

2.4.2.2 US California (CARB)

The NRMM emission legislation in California is similar to the EPA legislation, as CARB implemented the emission standards from the U.S. Federal law in January 2001. [24, pp. 107-108]
Before CARB applied EPA standards in 2001, large non-road engines with spark ignition had to meet the exhaust emission standards of off-road recreational vehicles, from model year 1997 onwards. Non-road engines with compression ignition had to meet their own standards, from 1996 onwards. Table 17 gives an overview of the relevant NRMM categories, which excludes the categories cargo handling equipment at ports and intermodal rail yards, locomotives, commercial marine vessels and harbor craft. Table 28 in the Appendix represents the emission limits and implementation dates of NRMM categories in California.

Table 17 U.S. CARB non-road mobile machinery (NRMM) categories [49]

Category name	Examples
Small off-road engines and equipment < 25 hp (< 19 kW)	➢ Lawn and garden equipment (chainsaw, lawnmowers, etc.) ➢ Small industrial equipment (compressors, generators, etc.)   
Off-road large SI (and LPG) engines and equipment ≥ 25 hp (≥ 19 kW)	➢ Industrial equipment ➢ Forklifts ➢ Portable Generators  
Off-road CI engines and equipment	➢ Excavator ➢ Dumper ➢ Skidders ➢ Bulldozers  
Off-highway recreational vehicles	➢ Off-road motorcycles ➢ Off-road utility vehicles ➢ All-terrain vehicles (ATVs) ➢ Sand cars 
Airport ground support equipment	➢ Tugs ➢ Ground power units  
Recreational marine	➢ Personal water craft ➢ Ski boats ➢ Inboards ➢ Outboards   

2.5 Ultralights

As an extensive research did not yield a positive result with regard to an emission regulation for ICEs in ultralights or unmanned aerial vehicles (UAV), the company BRP Rotax confirmed that there are no emission regulations for engines in such applications, which are offered by BRP Rotax or Hirth Motors, for example.

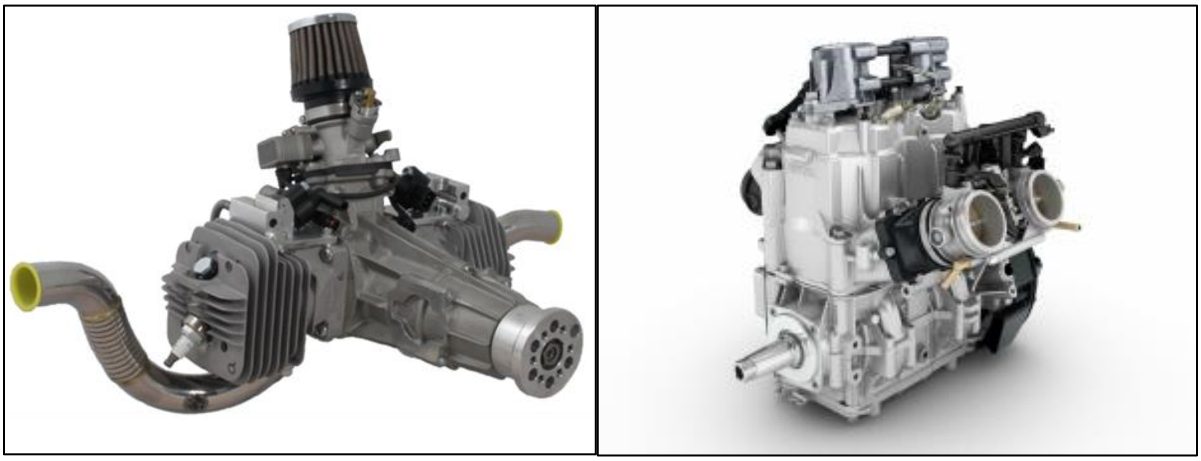


Figure 52 Hirth ultralight engine (left) and BRP Rotax 850 E-TEC engine (right) [50] [51]

2.6 Real Drive Emissions

In the course future emission legislations, the test cycles for type approval are also adapted. Today, some of the used test cycles do not reflect real driving conditions, which in turn affects fuel consumption and emissions emitted during the test cycle. Currently, motorcycle emissions are determined on a dynamometer with the WMTC test cycle, although does not evenly cover the entire load range of engines of all vehicle classes and therefore does not correspond to real driving situations. For this reason, Real Drive Emissions (RDE) is becoming more and more important for passenger cars as well as in future also for motorcycles. By way of example, Real-drive-emissions will be introduced for passenger cars in September 2017 as an additional certification test cycle with the EURO 6c/6d limits. Therefore a master thesis was carried out with this topic at the Institute of Internal Combustion Engines and Thermodynamics at Graz University of Technology.
RDE-measurements were carried out with different motorcycles and RDE-routes and with the aid of portable emission measurement technology, in order to be able to infer the emission and dynamic behavior. The portable emission measurement system had to be adapted for motorcycles. In addition, the influence of the portable measurement system and the driver was quantified, and it was examined whether it was possible to generate a comparable RDE test cycle for a dynamometer with the collected data from RDE-measurements. The generation of an RDE test cycle for the dynamometer requires GPS measured test routes. The feasibility of an RDE test cycle at the dynamometer must also be demonstrated with regard to wheel slip. [52, pp. 1-2]

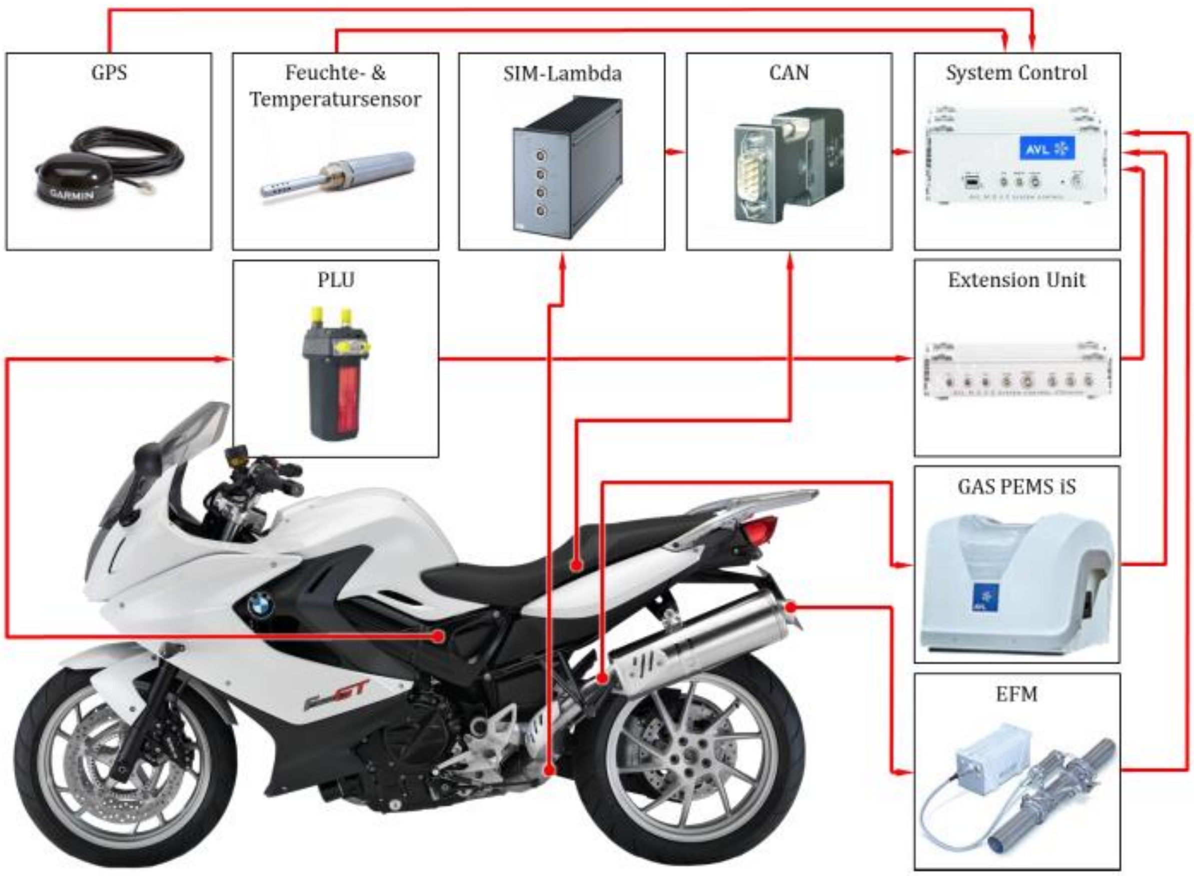


Figure 53 Real drive emission test setup for motorcycle (scheme) [52, p. 7]

Figure 53 and Figure 54 shows the schematic and the real measurement setup of the portable emission measurement system on a motorcycle, which was used for RDE measurements. The Portable Emission Measurement System PEMS measures the NO- or NO_2-, CO- or CO_2 emissions and O_2. The system control consists of a computer for the data acquisition and the control of measuring devices as well as an external GPS receiver, an ambient temperature and humidity sensor. The extension unit provides additional inputs and outputs for measuring devices. The exhaust mass flow is measured with the EFM measuring tube and the fuel consumption measurement is carried out with the PLU displacement flow meter. The lambda meter is connected with two lambda sensors, one is positioned before and one after the catalyst. [52, pp. 8-10]

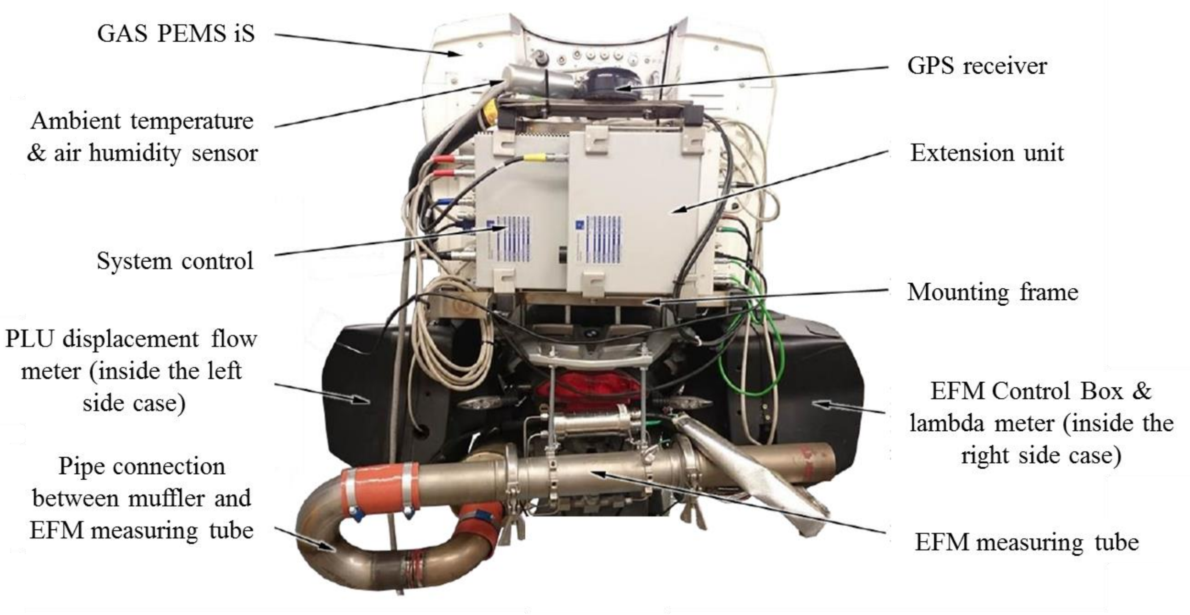


Figure 54 Real drive emission test setup for motorcycle; adapted from [52, p. 8]

But there are still a number of problems, which need to be solved. RDE rides are influenced by a variety of factors, e.g. the driver's influence, the traffic, the gradient of roads and the environmental conditions, which in comparison to laboratory test conditions do not occur or at least to a lesser extent. Thus, RDE results are difficult to reproduce and compare. Therefore, the legislation must define appropriate parameters for the specification of RDE measuring rides in order to determine the limits of validity and to minimize the variance of RDE measuring trips.

An additional problem of motorcycles is the weather, because RDE measuring trips cannot be carried out over the entire year. For that reason, it would be beneficial if RDE measuring sections could be simulated on a dynamometer. [52, p. 5]

The project had shown that RDE and emissions of dynamometers clearly differ from each other, due to the low dynamic of the test cycles. Nowadays, some developments are still necessary to be able to carry out RDE measurements with justifiable efforts.

For example, the portable emission measurement system must be optimized in terms of dimension and weight. Above all, the weight has a significant influence on RDE measuring rides. In addition, appropriate driving indicators are required for the description of driving dynamics. For this purpose, indicators from the already existing passenger car legislation for RDE could be adapted [53]. In particular, this is to reduce the driver's influence on RDE. Furthermore, the question has arisen whether RDE is essential for all motorcycles. The investigation indicated that it would be sufficient to test motorcycles on a dynamometer by means of a test cycle based on real driving profiles with realistic driving dynamics (here also called “real drive dynamometer test”). This presupposes that the maximum engine power do not exceed the power of the dynamometer, so that the entire engine characteristic map can be covered by the real drive dynamometer test cycle. If the engine power increases, the motor characteristic map cannot be equally covered by the real drive dynamometer test as with the RDE test.

The real drive dynamometer cycle improves the covering of the engine characteristic map compared to the WMTC significantly, but the engine characteristic map areas of high performance are not achieved. Therefore, the determination of emissions by using RDE technology is indispensable. The problem with the cycle detection by the engine control for emission reduction can only be avoided with RDE. [52, pp. 74-75]

2.7 Outlook Electrification

The environmental consciousness of today's society, the scarcity of resources and the economic competitiveness are reasons for automobile and other vehicle manufactures to develop and investigate alternative propulsion systems. The focus is on the reduction of greenhouse gases and therefore, the reduction of HC, NOx and CO_2 emissions. The reduction of CO_2 decreases also the fuel consumption.

One possible solution is the electrification of the propulsion system. It provides additional freedom with regard to new technologies and operation modes for future mobility. The greatest challenge is the integration and optimization of these technologies. The electrification of vehicles enables improvements in the area of NVH, drivability, emissions and fuel consumption. Currently, there are two opportunities for electrification of the propulsion: the vehicle is designed as a pure electric vehicle or it has in addition to the electric propulsion an ICE, also called REX, to increase the range (see chapter 2.2).

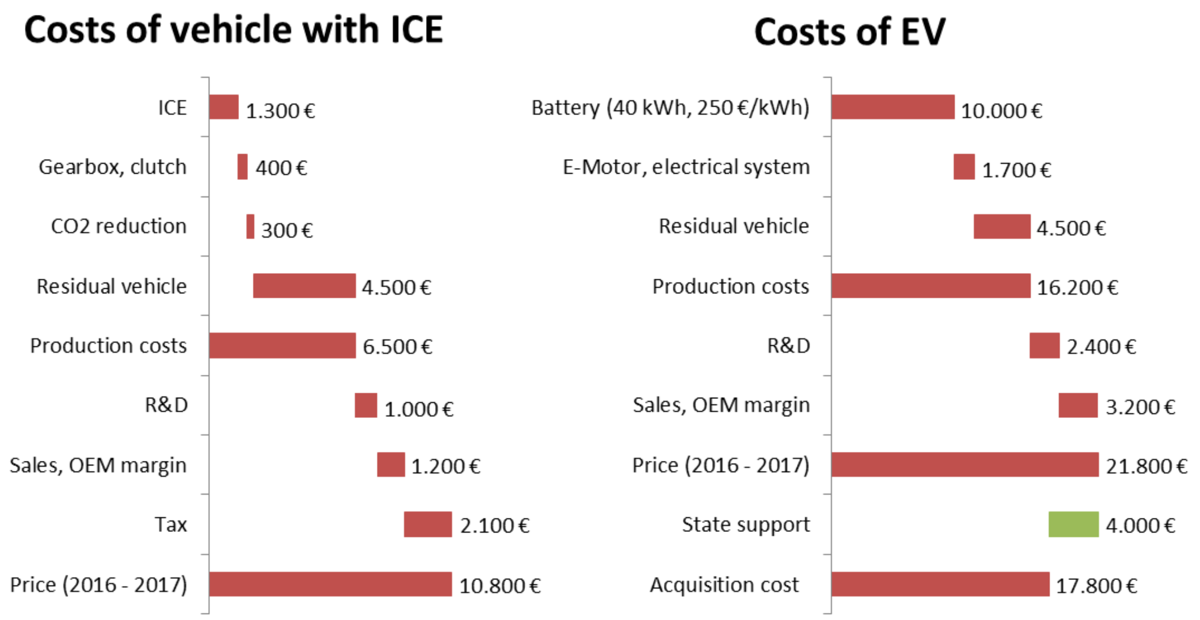


Figure 55 Cost structure of EV (city vehicle) vs. vehicle with ICE (small-sized vehicle); adapted from [38, p. 2]

Figure 55 presents the cost structure of a pure EV (right) and of a vehicle with ICE (left). Both vehicles of the cost comparison come from the small car segment such as, for example, the Fiat Punto or Hyundai i20 (vehicle with ICE) as well as the Renault Zoe or the Nissan Leaf (EV). Figure 55 shows that the battery of EV is the most expensive component and accounts for a third of total costs, although, the battery costs in the last few years significantly decreased and the battery capacities in EV increased. Furthermore, in Europe the majority of states have introduced supports for the acquisition of EV. For example, in Austria the acquisition of a pure electrical passenger cars is supported by the state with about 4000€ and the purchase of a pure electric motorcycle is supported with approximately 750 €. [38, pp. 1-2] [54] [55]

An example for a two-wheel EV is the Johammer J1 (see Figure 56). The electric motorcycle was developed and is manufactured in Austria. Two variants exist of the Johammer J1, one with a range of 150 km and one with 200 km. The maximum speed is 120 km/h and is electronically limited. A self-produced Li-Ion battery by Johammer is used as energy storage. The maximum battery pack capacity is 12.7 kWh by a range of 200 km. The total weight is 159 kg or 178 kg. [56] [57]

Figure 56 Johammer J1 - electric motorcycle developed and manufactured in Austria [56]

2.8 List of Figures

2.9 List of Tables

2.10 References

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2.11 Appendix

The following tables are valid for motorcycles (two- and three-wheeler, quadri-mobiles) and non-road mobile machineries which are defined in the first column of the tables. The second column gives an overview of the engine categories and the subsequent columns, until and including Propulsion class, shows the definition of the individual engine classes. The next columns give information about emission regulation stage and implementation dates (type approval, model year), followed by the emission limits for CO, HC, NMHC, THC, HC+NOx, and PM. Finally, the in use test cycles to determine the emission limits are listed.

Table 18 Europe emission standards for two-, three-wheelers and quadricycles [11] [12] [24] [27] [39] [14] [58] [59] [60] [61] [62]

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h] / reference weight (R) [kg] = Motorcycle weight + 75 kg	Cycle Stroke	Propulsion Class	Emission Standards												Full Durability Distance [km]
					Emission regulation level/stage	Implementation Date		CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	
						Type Approval (TA) / New type of vehicles	First registration (FR) / Existing types of vehicles										
Two-wheeled moped		< 50 & R < 400 kg			UN-ECE Reg.47	Aug.81		8			5				ECE R47	No	
Three-wheeled moped								15			10					No	
Motorcycles		R < 100 kg	2		UN-ECE 40	Sep.79		16			10				ECE R40	No	
		100 kg ≤ R ≤ 300 kg						16+24* [(R-100)/200]			10+5* [(R-100)/200]					No	
		R > 300 kg						40			15					No	
		R < 100 kg	4					25			7					No	
		100 kg ≤ R ≤ 300 kg						25+25* [(R-100)/200]			7+3* [(R-100)/200]					No	
		R > 300 kg						50			10					No	
		R < 100 kg	2		UN-ECE 40.01	Mai.88		12.8			8					No	
		100 kg ≤ R ≤ 300 kg						12,8+19,2* [(R-100)/200]			8+4* [(R-100)/200]					No	
		R > 300 kg						32			12					No	
		R < 100 kg	4					17.5			4.2					No	
		100 kg ≤ R ≤ 300 kg						17,5+17,5* [(R-100)/200]			4,2+1,8* [(R-100)/200]					No	
		R > 300 kg						35			6					No	
Mopeds		≤ 50	2 & 4		Euro 1	17.Jun.99		6 1)					3 1)		ECE R47	No	
Motorcycles, tricycles and quadricycles		> 50	2					8 3)			4 3)	0,1 3)			ECE R40	No	
		> 50	4					13 3)			3 3)	0,3 3)					
Two-wheel moped	L1e	< 50	2 & 4		Euro 2	17.Jun.02		1 2)					1.2		ECE R47 4)	No	
Three-wheel mopeds	L2e	< 50		SI				7			1.5	0.4			ECE R47	No	
				CI				2			1	0.65				No	
Two-wheel motorcycle	L3e	< 150				01.Apr.04	01.Jul.05	5.5			1.2	0.3			ECE R40, UDC	No	
		≥ 150						5.5			1	0.3				No	

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h] / reference weight (R) [kg] = Motorcycle weight + 75 kg	Cycle Stroke	Propulsion Class	Emission Standards												Full Durability Distance [km]
					Emission regulation level/stage	Implementation Date: Type Approval (TA) / New type of vehicles	Implementation Date: First registration (FR) / Existing types of vehicles	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	
Tricycles	L5e	≥ 50	2 & 4	SI	Euro 2	01.Jän.03	01.Jul.04	7			1.5	0.4			UDC	No	
				CI				2			1	0.65			UDC + EUDC	No	
Light quadricycles	L6e	< 50		SI				7			1.5	0.4			ECE R47	No	
				CI				2			1	0.65				No	
Heavy quadricycles	L7e	≥ 50		SI				7			1.5	0.4			UDC	No	
				CI				2			1	0.65			UDC + EUDC	No	
Two-wheel moped	L1e	< 50	2 & 4		Euro 3	28.Nov.13		1					1.2		ECE R47 [5)]	Yes	
Three-wheel mopeds	L2e	< 50		SI		28.Nov.13		7			1.5	0.4			ECE R47 [5)]	Yes	
Two-wheel motorcycle	L3e	< 150				01.Jän.06	01.Jul.07	2			0.8	0.15			ECE R40, UDC [6)]	Yes	
		≥ 150									0.3	0.15			ECE R40, UDC+EUDC [7)]	Yes	
		V_{MAX}< 130 km/h				01.Jul.07		2.62			0.75	0.17			WMTC (GTR No. 2) [8)]	Yes	
		V_{MAX} ≥ 130 km/h									0.33	0.22			WMTC (GTR No. 2) [8)]	Yes	
Light quadricycles	L6e	< 50		SI		28.Nov.13		7			1.5	0.4			ECE R47 [5)]	Yes	
Powered cycle	L1e-A	≤ 50 & ≤ 25 km/h	2 & 4	SI/CI/Hybrid	Euro 4	01.Jän.17 [9)]	01.Jän.18	0.56	0.1			0.07			ECE R47	Yes	5 500
Two-wheel moped	L1e-B	≤ 50 & 25 km/h < V ≤ 45 km/h		SI/CI/Hybrid				1	0.63			0.17			ECE R47	Yes	11 000
Three-wheel mopeds	L2e	≤ 50 & ≤ 45 km/h		SI/CI/Hybrid				1.9	0.73						ECE R47	Yes	11 000
Two-wheel motorcycles with and without side car	L3e [10)] L4e	> 50 & V_{MAX}< 130 km/h		SI/CI/Hybrid		01.Jän16 [9)]	01.Jän.17	1.14	0.38			0.07			WMTC, Stage 2	Yes	20.000 [14)] 35.000 [14)]
Tricycle Heavy on-road quad	L5e-A L7e-A	> 50 & V_{MAX} ≥ 130 km/h		SI/CI/Hybrid					0.17			0.09			WMTC, Stage 2	Yes	
				SI/CI Hybrid				1	0.1			0.3		0.08	WMTC, Stage 2	Yes	

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h] / reference weight (R) [kg] = Motorcycle weight + 75 kg	Cycle Stroke	Propulsion Class	Emission Standards: Emission regulation level/stage	Implementation Date: Type Approval (TA) / New type of vehicles	Implementation Date: First registration (FR) / Existing types of vehicles	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	Full Durability Distance [km]
Commercial tricycle	L5e-B	> 50 & > 45 km/h	2 & 4	SI/PI Hybrid	Euro 4	01.Jän16 [9]	01.Jän.17	2	0.55			0.25			ECE R40	Yes	20 000
				SI/CI Hybrid				1	0.1			0.55		0.08	ECE R40	Yes	
Light on-road quad Light quadri-mobile	L6e-A L6e-B	≤ 50 & ≤ 45 km/h		SI/SI Hybrid		01.Jän.17 [9]	01.Jän.18	1.9	0.73			0.17			ECE R47	Yes	11 000
		≤ 500 & ≤ 45 km/h		CI/CI Hybrid				1	0.1			0.55		0.08	ECE R47	Yes	20 000
Heavy all terrain quad Heavy quadri-mobile	L7e-B L7e-C			SI/SI Hybrid		01.Jän.16 [9]	01.Jän.17	2	0.55			0.25			ECE R40	Yes	11 000
				CI/CI Hybrid				1	0.1			0.55		0.08	ECE R40	Yes	20 000
Powered cycle	L1e-A	≤ 50 & ≤ 25 km/h	2 & 4	SI/CI/Hybrid	Euro 5	01.Jän.20 [11]	01.Jän.21 [11]	0.5	0.1	0.068		0.06		0,0045 [12]	Revised WMTC [13]	Yes	5 500
All other L-category vehicles	L1e-B - L7e			SI/SI Hybrid				1								Yes	11.000 [14] 20.000 [14] 35.000 [14]
				CI/CI Hybrid				0.5				0.09					

[1] The limit values for the masses of CO an HC + NOx are multiplied by a factor of 2 in the case of 3 wheeled mopeds and light quadricycles.

[2] The limit value for the mass of CO must be 3.5 g/km in the case of 3 wheeled mopeds and light quadricycles.

[3] However, for tricycles and quadricycles, the limit values must be multiplied by a factor of 1.5.

[4] Euro 2: sampling start t = 448 s after cold start.

[5] Euro 3 since 28 Nov. 2013, Euro 2 emission limits apply, sampling start t = 0, weighting 30% cold / 70% warm

[6] Emission measured for all six modes - sampling starts at t = 0

[7] Emission measured from all modes - sampling starts at t = 0

[8] UN/ECE GTR 2 is an alternative TA (Type Approval) procedure for Euro 3 stage (Directive 2002/51/EC) based on harmonized WMTC test cycle

[9] Voluntarily as of 11.09.2014; for L1e, L2e and L6e is it obligatory as of 01.01.2016; for L3e, L4e, L5e and L7e is it obligatory as of 01.01.2017

[10] With regards to test type I, the relevant emission limit for L3e-AxE (Enduro, x = 1, 2 or 3) and L3e-AxT (x = 1, 2 or 3) motorcycles shall be the sum of THC and NOx of Annex VI (A). The emission test results NOx + THC shall be smaller than or equal to this limits.

[11] TBD

[12] PM limits only for vehicles equipped with CI (Compression Ignition) or GDI (Gasoline Direct Injection) engines

[13)] WMTC Stage 2 and revised WMTC are set out in Appendix 6 of Annex II to Regulation (EU) No. 134/2014, pending the outcome of the Euro 5 step effect study

[14)] L3e + L4e (with V_{MAX}< 130 km/h) and L5e-A → 20.000 km
L3e + L4e (with $V_{MAX} \geq$ 130 km/h) and L7e-A → 35.000 km

Table 19 Europe - L-category vehicle classification [14, pp. 94-101]

Category/*Sub-categories*	**Category**/*Sub-category* name	**Common**/*Supplemental sub-* classification criteria
L1e	**Light two-wheel powered vehicle**	**(1) Two wheels and powered by a propulsion as listed under Article 4(3) in Regulation (EU) No 168_2013 and** **(2) Engine capacity ≤ 50 cm^3 if a SI internal combustion engine forms a part of the vehicle`s propulsion configuration and** **(3) Maximum design vehicle speed ≤ 45 km/h and** **(4) Maximum continuous rated or net power $^{1)}$≤ 4000 W and** **(5) Maximum mass = technically permissible mass declared by the manufacturer and**
L1e-A	*Powered cycle*	*(6) Cycles designed to pedal equipped with an auxiliary propulsion with the primary aim to aid pedaling and* *(7) Output of auxiliary propulsion is cut off at a vehicle speed ≤25 km/h and* *(8) Maximum continuous rated or net power $^{1)}$≤ 1000 W and* *(9) A powered three- or four-wheel cycle complying with supplemental specific sub-classification criteria (6) to (8) is classified as being technically equivalent to a two-wheel L1e-A vehicle*
L1e-B	*Two-wheel moped*	*(6) Any other vehicle of the L1e category that cannot be classified according to the criteria (6) to (9) of a L1e-A vehicle*
L2e	**Three-wheel moped**	**(1) Three wheels and powered by a propulsion as listed under Article 4(3) in Regulation (EU) No 168_2013 and** **(2) Engine capacity ≤ 50 cm^3 if a SI internal combustion engine forms a part of the vehicle`s propulsion configuration and** **(3) Maximum design vehicle speed ≤ 45 km/h and** **(4) Maximum continuous rated or net power $^{1)}$≤ 4000 W and** **(5) Mass in running order ≤ 270 kg and** (6) **Equipped with a maximum of two seating positions, including the seating position for the driver and**
L2e-P	*Three-wheel moped for passenger transport*	*(7) L2e vehicle other than those complying with the specific classification criteria for a L2e-U vehicle*
L2e-U	*Three-wheel moped for utility purposes*	*(7) Exclusively designed for the carriage of goods with an open or enclosed, virtually even an horizontal loading bed that meets the following criteria* *a. Length $_{loading\ bed}$×width $_{loading\ bed}$≥ 0,3 × length $_{vehicle}$ × width $_{vehicle}$ or* *b. An equivalent loading bed area as defined above in order to install machines and/or equipment and* *c. Designed with a loading bed area which is clearly separated by a rigid partition from the area reserved for the vehicle occupants and* *d. The loading bed area shall be able to carry a minimum volume represented by a 600 mm cube*
L3e$^{2)}$	**Two-wheel motorcycle**	**(1) Two wheels and powered by propulsion as listed under Article 4(3) in Regulation (EU) No 168_2013 and** **(2) Maximum mass = technically permissible mass declared by the manufacturer and** **(3) Two-wheel vehicle that cannot be classified as category L1e**

Category/*Sub-categories*	**Category**/*Sub-category* name	**Common**/*Supplemental sub-* classification criteria
L3e-A1	*Low-performance motorcycle*	*(4) Engine capacity ≤ 125 cm³ and* *(5) Maximum continuous rated or net power 1) ≤ 11 kW and* *(6) power 1)/weight ratio ≤ 0,1 kW/kg*
L3e-A2	*Medium-performance motorcycle*	*(4) Maximum continuous rated or net power 1) ≤ 35 kW and* *(5) power 1)/weight ratio ≤ 0,2 kW/kg and* *(6) not derived from a vehicle equipped with an engine of more than double its power 1) and* *(7) L3e vehicle that cannot be classified under supplemental sub-classification criteria (4), (5) and (6) of a L3e-A1 vehicle*
L3e-A3	*High-performance motorcycle*	*(4) Any other L3e vehicle that cannot be classified according to the classification criteria of a L3e-A1 or L3e-A2 vehicle*
L3e-AxE *(x = 1, 2 or 3)*	*Enduro motorcycle*	*a) Seat height ≥ 900 mm and* *b) Ground clearance ≥ 310 mm and* *c) Overall gear ratio in highest gear (primary gear ratio x secondary gear ratio in the highest speed x final drive ratio) ≥ 6,0 and* *d) Mass in running order plus mass of the propulsion battery in case of electric or hybrid electric propulsion ≤ 140 kg and* *e) No seating position for a passenger*
L3e-AxT *(x = 1, 2 or 3)*	*Trial motorcycle*	*a) Seat height ≤ 700 mm and* *b) Ground clearance ≥ 280 mm and* *c) Fuel tank capacity ≤ 4 liters and* *d) Overall gear ratio in highest gear (primary gear ratio x secondary gear ratio in the highest speed x final drive ratio) ≥ 7,5 and* *e) Mass in running order ≤ 100 kg and* *f) No seating position for a passenger*
L4e	**Two-wheel motorcycle with side-car**	**(1) Base powered vehicle complying with the classification and sub-classification criteria for a L3e vehicle and** **(2) Base powered vehicle equipped with one side-car and** **(3) With a maximum of four seating positions including the driver on the motorcycle with side car and** **(4) A maximum of two seating positions for passengers in the side car and** **(5) Maximum mass = technically permissible mass declared by the manufacturer.**
L5e	**Powered tricycle**	**(1) Three wheels and powered by propulsion as listed under Article 4(3) in Regulation (EU) No 168_2013 and** **(2) Mass in running order ≤ 1000 kg and** **(3) Three-wheel vehicle that cannot be classified as a L2e vehicle**
L5e-A	*Tricycle*	*(4) L5e vehicle other than those complying with the specific classification criteria for a L5e-B vehicle and* *(5) With a maximum of five seating positions, including the seating position of the driver*

Category/*Sub-categories*	**Category**/*Sub-category* name	**Common**/*Supplemental sub-* classification criteria
L5e-B	*Commercial tricycle*	*(4) Designed as a utility vehicle and characterized by an enclosed driving and passenger compartment accessible by maximum three sides and* *(5) Equipped with a maximum of two seating positions, including the seating position for the driver and* *(6) Exclusively designed for the carriage of goods with an open or enclosed, virtually even and horizontal loading bed that meets the following criteria:* *a. Length $_{loading\ bed}$×width $_{loading\ bed}$≥ 0,3 × length $_{vehicle}$ × width $_{vehicle}$ or* *b. An equivalent loading bed area as defined above in order to install machines and/or equipment and* *c. Designed with a loading bed area which is clearly separated by a rigid partition from the area reserved for the vehicle occupants and* *d. The loading bed area shall be able to carry a minimum volume represented by a 600 mm cube*
L6e	**Light quadricycle**	**(1) Four wheels and powered by propulsion as listed under Article 4(3) in Regulation (EU) No 168_2013 and** **(2) Maximum design vehicle speed ≤ 45 km/h and** **(3) The mass in running order ≤ 425 kg and** **(4) Engine capacity ≤ 50 cm³ if a SI engine or engine capacity ≤ 500 cm³ if a CI engine forms part of the vehicle`s propulsion configuration and** **(5) Equipped with a maximum of two seating positions, including the seating position for the driver and**
L6e-A	*Light on-road quad*	*(6) L6e vehicle not complying with the specific classification criteria for a L6e-B vehicle and* *(7) Maximum continuous rated or net power[1)]≤ 4000 W.*
L6e-B	*Light quadri-mobile*	*(6) Enclosed driving and passenger compartment accessible by maximum three sides and* *(7) Maximum continuous rated or net power[1)]≤ 6000 W and*
L6e-BP	*Light quadri-mobile for passenger transport*	*(8) L6e-B vehicle mainly designed for passenger transport and* *(9) L6e-B vehicle other than those complying with the specific classification criteria for a L6e-BU vehicle.*
L6e-BU	*Light quadri-mobile for utility purpose*	*(8) Exclusively designed for the carriage of goods with an open or enclosed, virtually even an horizontal leading bed that meets the following criteria:* *a. Length $_{loading\ bed}$×width $_{loading\ bed}$≥ 0,3 × length $_{vehicle}$ × width $_{vehicle}$ or* *b. An equivalent loading bed area as defined above in order to install machines and/or equipment and* *c. Designed with a loading bed area which is clearly separated by a rigid partition from the area reserved for the vehicle occupants and* *d. The loading bed area shall be able to carry a minimum volume represented by a 600 mm cube*
L7e	**Heavy quadricycle**	**(1) Four wheels and powered by propulsion as listed under Article 4(3) in Regulation (EU) No 168_2013 and** **(2) Mass in running order:** **a. ≤ 450 kg for transport of passengers,** **b. ≤ 600 kg for transport of goods and** **(3) L7e vehicle that cannot be classified as a L6e vehicle and**

Category/*Sub-categories*	**Category**/*Sub-category* name	**Common**/*Supplemental sub-* classification criteria
L7e-A	*Heavy on-road quad*	*(4) L7e vehicle not complying with the specific classification criteria for a L7e-B or a L7e-C vehicle and* *(5) Vehicle designed for the transport of passengers only and* *(6) Maximum continuous rated or net power[1)] ≤ 15 kW and*
L7e-A1	*A1 heavy on-road quad*	*(7) Maximum two straddle seating positions, including the seating position for the rider and* *(8) Handlebar to steer.*
L7e-A2	*A2 heavy on-road quad*	*(7) L7e-A vehicle not complying with the specific classification criteria for a L7e-A1 vehicle and* *(8) Maximum two non-straddle seating positions, including the seating position for the driver.*
L7e-B	*Heavy all terrain quad*	*(4) L7e vehicle not complying with the specific classification criteria for a L7e-C vehicle and* *(5) Ground clearance ≥ 180 mm and*
L7e-B1	*All terrain quad*	*(6) Maximum two straddle seating positions, including the seating position for the rider and* *(7) Equipped with a handlebar to steer and* *(8) Maximum design vehicle speed ≤ 90 km/h and* *(9) Wheelbase to ground clearance ratio ≤ 6.*
L7e-B2	*Side-by-side buggy*	*(6) L7e-B vehicle other than a L7e-B1 vehicle and* *(7) Maximum three non-straddle seats of which two positioned side-by-side, including the seating position for the driver and* *(8) Maximum continuous rated or net power[1)] ≤ 15 kW and* *(9) Wheelbase to ground clearance ratio ≤ 8.*
L7e-C	*Heavy quadri-mobile*	*(4) L7e vehicle not complying with the specific classification criteria for a L7e-B vehicle and* *(5) Maximum continuous rated or net power[1)] ≤15 kW and* *(6) Maximum design vehicle speed ≤90 km/h and* *(7) Enclosed driving and passenger compartment accessible via maximum three sides and*
L7e-CP	*Heavy quadri-mobile for passenger transport*	*(8) L7e-C vehicle not complying with the specific classification criteria for a L7e-CU vehicle and* *(9) Maximum four non-straddle seats, including the seating position for the driver.*
L7e-CU	*Heavy quadri-mobile for utility purposes*	*(8) Exclusively designed for the carriage of goods with an open or enclosed, virtually even horizontal loading bed that meets the following criteria:* *a. Length* $_{loading\ bed}$ × *width* $_{loading\ bed}$ ≥ *0,3 × length* $_{vehicle}$ × *width* $_{vehicle}$ *or* *b. An equivalent loading bed area as defined above in order to install machines and/or equipment and* *c. Designed with a loading bed area which is clearly separated by a rigid partition from the area reserved for the vehicle occupants and* *d. The loading bed area shall be able to carry a minimum volume represented by a 600 mm cube* *(9) Maximum two non-straddle seats, including the seating position for the driver*

[1)] The power limits are based on maximum continuous rated power for electric propelled vehicles and maximum net power for vehicles propelled with a combustion engine. The weight of a vehicle is considered equal to its mass in running order.

[2)] Sub-classification of an L3e vehicle according to whether it has a design vehicle speed of less than or equal to 130 km/h or more than 130 km/h is independent of its sub-classification into the propulsion performance classes L3e-A1 (although not likely to achieve 130 km/h), L3e-A2 or L3e-A3.

Table 20 EURO 4 - test cycles, weighting equations and - factors for L-category vehicles [22, pp. 46-47]

Category	Category name	Test cycle	Equation	Weighting factors
L1e-A	Powered cycle	ECE R47	$R = R_{1\_cold} \times w_1 + R_{2\_warm} \times w_2$ w_1 = weighting factor cold phase w_2 = weighting factor warm phase	w_1 = 30% w_2 = 70%
L1e-B	Two-wheel moped			
L2e	Three-wheel moped			
L6e-A	Light on-road quad			
L6e-B	Light quadri-mobile			
L3e L4e	Two-wheel motorcycle with and without side-car $V_{MAX} < 130$ km/h	WMTC, stage 2	$R = R_1 \times w_1 + R_2 \times w_2$ w_1 = weighting factor cold phase w_2 = weighting factor warm phase	w_1 = 30% w_2 = 70%
L5e-A	Tricycle $V_{MAX} < 130$ km/h			
L7e-A	Heavy on-road quad $V_{MAX} < 130$ km/h			
L3e L4e	Two-wheel motorcycle with and without side-car $V_{MAX} \geq 130$ km/h	WMTC, stage 2	$R = R_1 \times w_1 + R_2 \times w_2 + R_3 \times w_3$ w_n = weighting factor phase n (n = 1, 2 or 3)	w_1 = 25% w_2 = 50% w_3 = 25%
L5e-A	Tricycle $V_{MAX} \geq 130$ km/h			
L7e-A	Heavy on-road quad $V_{MAX} \geq 130$ km/h			
L5e-B	Commercial tricycle	ECE R40	$R = R_{1\_cold} \times w_1 + R_{2\_warm} \times w_2$ w_1 = weighting factor cold phase w_2 = weighting factor warm phase	w_1 = 30% w_2 = 70%
L7e-B	All-terrain vehicles			
L7e-C	Heavy quadri-mobile			

R_{1_cold} = (average) pollutant result of the cold phase of ECE R47 / ECE R40 in mg/km and for CO_2 in g/km
R_{2_warm} = (average) pollutant result of the warm phase of ECE R47 / ECE R40 in mg/km and for CO_2 in g/km
R_1 = (average) pollutant result of Part 1 or Part 1 reduced speed in mg/km and for fuel consumption in liters/100km
R_2 = (average) pollutant result of Part 2 or Part 2 reduced speed in mg/km and for fuel consumption in liters/100km
R_3 = (average) pollutant result of Part 3 or Part 3 reduced speed in mg/km and for fuel consumption in liters/100km

Table 21 EURO 5 - test cycles, weighting equations and - factors for L-category vehicles [22, pp. 46-47]

Category	Category name	Test cycle	Equation	Weighting factors
L1e-A	Powered cycle	WMTC, stage 3	$R = R_1 \times w_1 + R_2 \times w_2$ w_1 = weighting factor cold phase w_2 = weighting factor warm phase	w_1 = 50% w_2 = 50%
L1e-B	Two-wheel moped			
L2e	Three-wheel moped			
L6e-A	Light on-road quad			
L6e-B	Light quadri-mobile			
L3e L4e	Two-wheel motorcycle with and without side-car V_{MAX}< 130 km/h		$R = R_1 \times w_1 + R_2 \times w_2$ w_1 = weighting factor cold phase w_2 = weighting factor warm phase	w_1 = 50% w_2 = 50%
L5e-A	Tricycle V_{MAX}< 130 km/h			
L7e-A	Heavy on-road quad V_{MAX}< 130 km/h			
L3e L4e	Two-wheel motorcycle with and without side-car V_{MAX}≥ 130 km/h		$R = R_1 \times w_1 + R_2 \times w_2 + R_3 \times w_3$ w_n = weighting factor phase n (n = 1, 2 or 3)	w_1 = 25% w_2 = 50% w_3 = 25%
L5e-A	Tricycle V_{MAX}≥ 130 km/h			
L7e-A	Heavy on-road quad V_{MAX}≥ 130 km/h			
L5e-B	Commercial tricycle		$R = R_1 \times w_1 + R_2 \times w_2$ w_1 = weighting factor cold phase w_2 = weighting factor warm phase	w_1 = 30% w_2 = 70%
L7e-B	All-terrain vehicles			
L7e-C	Heavy quadri-mobile			

R_1 = (average) pollutant result of Part 1 or Part 1 reduced speed in mg/km and for fuel consumption in liters/100km
R_2 = (average) pollutant result of Part 2 or Part 2 reduced speed in mg/km and for fuel consumption in liters/100km
R_3 = (average) pollutant result of Part 3 or Part 3 reduced speed in mg/km and for fuel consumption in liters/100km

Table 22 U.S. EPA emission standards for motorcycles, off-highway motorcycles and ATVs [11] [12] [24] [27] [60] [63] [64] [65]

Description	Category / Class	Definition: engine displacement [cm³]	Cycle Stroke	Emission Standards											Warranty [hours/ months/ years/km][4)]	Useful life [hours/ years/ km][4)]
				Emission regulation level/stage	Model Year (MY)	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start		
Motorcycle [1)]	I	50 - 169 [2)]	2 & 4		1978 - 2005	12			5				Modified FTP-75	Yes	-/-/5/12.000	-/5/12.000
	II	170 - 279 [2)]											FTP-75		-/-/5/18.000	-/5/18.000
	III	≥ 280 [2)]													-/-/5/30.000	-/5/30.000
	I-A	< 50 [2)]	2 & 4	Tier 1	2006 +	12			1		1,4 [3)]		Modified FTP-75	Yes	-/-/5/6.000	-/5/6.000
	I-B	50 - 169 [2)]													-/-/5/12.000	-/5/12.000
	II	170 - 279 [2)]											FTP-75		-/-/5/18.000	-/5/18.000
	III	≥ 280 [2)]			2006 - 2009	12					1,4				-/-/5/30.000	-/5/30.000
	III	≥ 280 [2)]	2 & 4	Tier 2	2010 +	12					0,8		FTP-75	Yes	-/-/5/30.000	-/5/30.000
Non-road recreational engines and vehicles	Off-highway Motorcycle		2 & 4	Phase-in 50%	2006	25 [5)]					2 [5)]		Highway motorcycle test cycle [7)] or J1088 California off-highway cycle	Yes	> 70 cm³: -/-/30/5.000 ≤ 70 cm³: -/-/30/2.500	> 70 cm³: -/5/10.000 ≤ 70 cm³: -/5/5.000
				Phase-in 100%	2007 +									Yes		
	ATV		2 & 4	Phase-in 50%	2006	35 [6)]					1,5 [6)]			Yes	≥ 100 cm³: 500/30/-/5000 < 100 cm³: 250/30/-/2500	≥ 100 cm³: 1.000/5/10.000 < 100 cm³: 500/5/5.000
				Phase-in 100%	2007 +									Yes		

[1)] No crankcase emissions allowed. EPA has adopted new regulations in line with CARB regulations with implementation delayed by 2 years. Three wheel vehicles included if they meet the On-Highway Motorcycle criteria. Mopeds and scooters covered under Non-road Recreational standards.

[2)] Class I: 0 to 169 cm³; Class II: 170 to 279 cm³; Class III: ≥ 280 cm³; starting with the 2006 model year EPA re-defined Class I to include motorcycles with engines smaller than 50 cm³; these new previously unregulated vehicles are Class I-A, and the pre-existing Class I became Class I-B;

[3)] 1.4 g/km (HC+NOx): this is an optional standard that allows manufacturers to average their emissions or transfer emission credits across classes

[4)] Useful life and warranty are expressed in hours, month/years and km, whichever comes first

[5)] Maximum allowable FEL: 20 g/km for HC+NOx and 50 g/km for CO. Manufacturers may certify off-highway motorcycles with engines that have total displacement of 70 cm³ or less to an HC+NOx standard of 16.1 g/kWh (with an FEL cap of 32.2 g/kWh) and a CO standard of 519 g/kWh.

6) Maximum allowable FEL for HC+NOx is 20 g/km. Manufacturers may certify all-terrain vehicles with engines that have total displacement of less than 100 cm^3 to an HC+NOx standard of 25 g/kWh (with an FEL cap of 40 g/kWh) and a CO standard of 500 g/kWh)

7) Highway motorcycle test cycle: similar to FTP-75

Table 23 U.S. CARB emission standards for motorcycles, off-road motorcycles, ATVs, sand cars, off-road sport- and –utility vehicles [11] [12] [24] [27] [60] [66] [67] [68] [69]

Description	Category / Class	Definition: engine displacement [cm³]	Cycle Stroke	Emission Standards										Durability Period [years/km]
				Model Year (MY)	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	
Motorcycle	I	50 - 169	2 & 4	1978 - 1979	17			5				Modified FTP-75	Yes	-/12000
	II & III	170 - 749						5 [1]						-/18.000 [2] -/30.000 [2]
	III	≥ 750						14						-/30000
	I	50 - 169	2 & 4	1980 - 1981	17			5				Modified FTP-75	Yes	-/12.000
	II & III	≥ 170										FTP-75	Yes	-/18.000 [2] -/30.000 [2]
	I	50 -169	2 & 4	1982 - 1988	12			1				Modified FTP-75	Yes	-/12.000
	II	170 - 279										FTP-75	Yes	-/18.000
	III	≥ 280		1982 - 1985				2,5						-/30000
	III	≥ 280	2 & 4	1985 - 1987	12			1,4 [3]				FTP-75	Ys	-/30000
	I	50 - 279	2 & 4	1988 - 2003	12			1 [3]				FTP-75	Yes	-/12.000 [2] -/18.000 [2]
	II													
	IIIa	280 - 699												-/30.000
	IIIb	> 700						1,4 [3]						-/30.000
	III	≥ 280	2 & 4	2004 - 2007	12					1,4 [3]		FTP-75	Yes	-/30.000
	III	≥ 280	2 & 4	2008 +	12					0,8 [3]		FTP-75	Yes	-/30.000

Description	Category / Class	Definition: engine displacement [cm^3]	Cycle Stroke	Emission Standards										Durability Period [years/km]
				Model Year (MY)	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	
Off-Highway recreational vehicles and engines [4]	Off-road motorcycles and ATV`S [5]	> 90		1997 +	15			1,2 [6]				FTP-75 with Class I motorcycle test cycle[4]	Yes	5/10.000
		≤ 90		1999 +										
	Off-road sport vehicles & Off-road utility vehicles			2007 +	15			1,2 [6]				FTP-75 with Class I motorcycle test cycle[4]	Yes	5/10.000
	Sand cars			2007 +	15			1,2 [6]				FTP-75 with Class I motorcycle test cycle[4]	Yes	5/10.000

1) 5+0.0155(D-170) : D = engine displacement of motorcycles in cubic centimeters

2) Durability period motorcycles: 50-169cm^3→ 12000 km; 170-279cm^3→ 18000 km; ≥280cm^3 → 30000 km

3) Applied as a corporate average; compliance with a standard to be applied as a [corporate average] shall be determined as follows: [70]

$$\frac{\sum_{j=1}^{n}(PROD_{jx}) * (STD_{jx})}{\sum_{j=1}^{n}(PROD_{jx})} = STD_{ca}$$

n = Class III motorcycle engine families (engines with displacement of 280 cm^3 or greater manufactured after February 28, 1985)
$PROD_{jx}$ = Number of units of Class III engine family j produced for sale in California in model year x
STD_{jx} = The manufacturer designated HC or HC+NOx emission standard, whichever applies, for engine family j in model year x, which shall be determined by the manufacturer subject to the following conditions:

a) for Model Year 1988 through 2003 motorcycle engines and motorcycles with engine displacement of 280 cc or greater, no individual engine family exhaust emission standard shall exceed 2.5 g/km HC, and
b) for Model Year 2004 and subsequent motorcycle engines and motorcycles with engine displacement of 280 cc or greater, no individual engine family exhaust emission standard shall exceed 2.5 g/km HC+NOx, and
c) no engine family designation or engine family exhaust emission standard shall be amended in a model year after the engine family is certified for the model year, and
d) prior to sale or offering for sale in California, each engine family shall be certified in accordance with Section 1958(c) and shall be required to meet the manufacturer's designated HC or HC + NOx standard, whichever applies, as a condition of the certification Executive Order. Prior to certification the manufacturer shall also submit estimated production volumes for each engine family to be offered for sale in California.

STD_{ca} = A manufacturer's corporate average HC or HC + NOx exhaust emissions, whichever applies, from those California motorcycles or motorcycle engines subject to the California corporate average HC or HC + NOx exhaust emission standard, as established by an Executive Order certifying the California production for the model year. This order must be obtained prior to the issuance of certification Executive Orders for individual engine families for the model year and shall include but not be limited to the following requirements:

a) During the manufacturer's production year, for each engine family, the manufacturer shall provide the following information to the Executive Officer within 30 days after the last day in each calendar quarter:
   I. vehicle identification numbers and an explanation of the identification code;
   II. the total number of vehicles or motorcycle engines produced for sale in California and their applicable designated emissions standards.
b) The manufacturer's average HC or HC + NOx exhaust emissions, whichever applies, shall meet the applicable corporate average standard at the end of the manufacturer's production for the model year.
c) Production and sale of vehicles which result in non-compliance with the California standard for the model year shall cause a manufacturer to be subject to civil penalties, per vehicle, pursuant to Health and Safety Code Section 43154. All excess emissions resulting from final non-compliance with the California standard shall be made up in the following model year.
d) For a period of up to one year following the end of the model year, for each model the manufacturer shall submit California sales and registration data as it becomes available.

[4)] Cold start only, if chassis-based testing; Engine-based testing uses SAE J1088 test procedure - test cycle A 6-mode

[5)] Vehicles and engines that do not meet the emission standards noted above, may be certified subject to the use restrictions, described in the Final Regulation Order of 16 July 2007, at § 2415. California off-highway vehicle areas and Riding Seasons for off-highway recreational vehicle with use restrictions.

[6)] Compliance with the 1,2 g/km HC standard to be applied as a "corporate average" shall be determined as provided in subsection (d) of § 2412. Emission Standards and Test Procedures - New off-highway recreational vehicles and engines at Final Regulation Order 16 July 2007. Each engine family shall have only one applicable standard.

Table 24 Indian emission standard for two- and three-wheeler [60] [30] [24] [11] [27] [12]

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h]	Cycle Strokes	Propulsion Class	Emission Standards: Emission regulation level/stage	Implementation Date: Type Approval (TA) / New type of vehicles	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	Durability distance [km]
Two- and three-wheeler		All	2 & 4	SI & CI	1991 Norm	1991	12 - 30 [1)]			8 - 12 [2)]				IDC	No	
Two-wheeler		All	2 & 4	SI	1996 Norm	1996	4,5					3,6		IDC	No	
Three-wheeler				SI & CI			6,75					5,4				
Two-wheeler		All	2 & 4	SI	Bharat I	2000	2					2		IDC	Yes	
Three-wheeler							4					2				
Three-wheeler				CI			2,72					0,97	0,14			
Two-wheeler		All	2 & 4	SI	Bharat II	Apr.05	1,5					1,5		IDC	Yes	30.000
Three-wheeled							2,25					2				
Two- and three-wheeler				CI			1					0,85	0,1			
Two-wheeler		All	2 & 4	SI	Bharat III	Apr.10	1					1		IDC, optional WMTC [11)]	Yes	30.000
Three-wheeler							1,25					1,25				
Two- and three-wheeler				CI			0,5					0,5	0,05			
Two-wheeler		≤ 50 & ≤ 50 km/h	2 & 4		Bharat IV	Apr.16 [4)]	0,75					0,75		WMTC (GTR No. 2) [7)]	Yes	
	Class 1	51 – 149 & V_{MAX} ≤ 50 km/h Or < 150 & 50 < V_{MAX}< 100 km/h					1,403				0,39	0,79 [5)]; 0,59 [6)]			Yes	30.000
	Sub class 2-1	< 150 & 100 ≤ V_{MAX} ≤ 115 km/h or ≥ 150 & V_{MAX}< 115 km/h													Yes	30.000
	Sub class 2-2	115 ≤ V_{MAX}< 130 km/h					1,97				0,34	0,67 [5)]; 0,47 [6)]			Yes	30.000
	Sub class 3-1	130 ≤ V_{MAX}< 140 km/h					1,97				0,2	0,40 [5)]; 0,20 [6)]			Yes	30.000
	Sub class 3-2	V_{MAX} ≥ 140 km/h													Yes	
Three-wheeler		All		SI [3)]			0,94					0,94 [5)]; 0,74 [6)]		IDC	Yes	30.000
				CI			0,38					0,38	0,0425		Yes	

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h]	Cycle Strokes	Propulsion Class	Emission Standards: Emission regulation level/stage	Implementation Date: Type Approval (TA) / New type of vehicles	CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	Durability distance [km]
Two-wheeler		≤ 50 & ≤ 50 km/h	2 & 4	SI	Bharat VI	Apr.20 [8)]	0,5			0,35	0,15			IDC	Yes	
	Class 1	51 – 149 & V_{MAX} ≤ 50 km/h Or < 150 & 50 < V_{MAX}< 100 km/h		SI			1		0,068	0,10	0,06		0,0045[9)]	WMTC (GTR No. 2)	Yes	20.000 [10)] 35.000 [10)]
	Sub class 2-1	< 150 & 100 ≤ V_{MAX} ≤ 115 km/h or ≥ 150 & V_{MAX}< 115 km/h														
	Sub-class 2-2	115 ≤ V_{MAX}< 130 km/h														
	Sub-class 3-1	130 ≤ V_{MAX}< 140 km/h														
	Sub-class 3-2	V_{MAX} ≥ 140 km/h														
				CI			0,5		0,068	0,1	0,09		0,0045		Yes	35.000
Three-wheeler			2 & 4	SI			0,44			0,35	0,085			IDC	Yes	
				CI			0,22			0,1	0,1		0,025		Yes	

1) 150 kg < R ≤ 350 kg: CO limit = 12 + 18((R-150)/200)

2) 150 kg < R ≤ 350 kg: HC limit = 8 + 4((R-150)/200)

3) for CNG/LPG fueled engines, HC+NOx = 0.94 g/km

4) Bharat IV applies to new type approvals in April 2016 and to all vehicle sales and registrations in April 2017.

5) If Evap. Test ≤ 2 g/test

6) If Evap. Test ≤ 6 g/test

7) Values in square brackets are weighting factors:

Class 1 → Part 1 reduced speed cold [0.5] + Part 1 reduced speed hot [0.5];
Class 2-1 → Part 1 reduced speed cold [0.5] + Part 1 reduced speed hot [0.5];
Class 2-2 → Part 1 cold [0.3] Part 2 hot [0.7];
Class 3-1 → Part 1 cold [0.25] + Part 2 hot [0.5] + Part 3 reduced speed [0.25];
Class 3-2 → Part 1 cold [0.25] + Part 2 hot [0.5] + Part 3 [0.25]

8) Bharat VI applies to new type approvals of two-wheeled vehicles and to all three wheeled vehicle sales and registrations on 1 April 2020.

9) for direct injection engines only

10) Class 1, Sub class 2-1 and Sub class 2-2: 20.000 km

Sub class 3-1 and Sub class 3-2: 35.000 km

11) Bharat III emission limits for WMTC, including deterioration factors:

Class	CO [g/km]	HC+NOx [g/km]
Class 1	1,87	1,08
Class 2-1		
Class 2-2	2,62	0,92
Class 3-1	2,62	0,55
Class 3-2	2,62	0,55

Table 25 Chinese emission standards for two- and three-wheeler [11] [12] [24] [27] [31] [32] [60]

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h]	Cycle Strokes	Emission Standards													Full Durability Distance [km]
				Emission regulation level/stage	Implementation Date		CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start		
					Type Approval (TA) / New type of vehicles	First registration (FR) / Existing types of vehicles											
Two-wheeled moped		< 50	2 & 4	Stage I	Jän.03	Jän.04	6					3		ECE R47	No		6.000 [1]
Three-wheeled moped							12					6		ECE R47	No		6.000 [1]
Two-wheeler		≥ 50	2			Jul.03	8			4	0,1			ECE R40	No		6.000 [1]
			4				13			3	0,3			ECE R40	No		6.000 [1]
Three-wheeler			2				12			6	0,15			ECE R40	No		6.000 [1]
			4				19,5			4,5	0,45			ECE R40	No		6.000 [1]
Two-wheeler		≥ 50	2 & 4	Stage II	Jän.04	Jän.05	5,5			1,2	0,3			ECE R40	No		10.000 [1]
Three-wheeler			2				7			1,5	0,4			ECE R40	No		10.000 [1]
Two-wheeled moped		< 50	2 & 4		Jän.05	Jän.06	1					1,2		ECE R47	No		10.000 [1]
Three-wheeled moped							3,5					1,2		ECE R47	No		10.000 [1]
Three-wheeler		≥ 50	4		Jän.04	Jän.05	7			1,5	0,4			ECE R40	No		10.000 [1]
Two-wheeled moped		< 50	4	Stage III	Jul.08	Jul.09	1					1,2		ECE R47	No		10.000
Three-wheeled moped			2 & 4				3,5					1,2		ECE R47	No		10000
Two-wheeler		50-150	4				2			0,8	0,15			ECE R40	No		18.000 [3] 30.000 [4]
		≥ 150					2			0,3	0,15			ECE R40 + EUDC	No		18.000 [3] 30.000 [4]
Three-wheeler		≥ 50	2 & 4				4			1	0,25			ECE R40	No		12.000 [2] 18.000 [3] 30.000 [4]

Description	Category / Class	Definition: engine displacement [cm³] / max. vehicle speed [km/h]	Cycle Strokes	Emission Standards												Full Durability Distance [km]
				Emission regulation level/stage	Implementation Date		CO [g/km]	THC [g/km]	NMHC [g/km]	HC [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [g/km]	Test / Driving cycle	Cold start	
					Type Approval (TA) / New type of vehicles	First registration (FR) / Existing types of vehicles										
Two-wheel moped							1			0,63	0,17			ECE R47	Yes	11.000
Three-wheel moped							1,9			0,73	0,17			ECE R47	Yes	11.000
	Class 1	51 – 149 & $V_{MAX} \le 50$ km/h Or < 150 & $50 < V_{MAX} < 100$ km/h														
Two-wheeler	Sub class 2-1	< 150 & $100 \le V_{MAX} \le 115$ km/h Or ≥ 150 & $V_{MAX} < 115$ km/h		Stage IV	Jul.18	Jul.19	1,14			0,38	0,07			WMTC	Yes	20.000
	Sub class 2-2	≤1500 & $115 \le V_{MAX} < 130$ km/h														
	Sub class 3-1	≤ 1500 & $130 \le V_{MAX} < 140$ km/h					1,14			0,17	0,09					35.000
	Sub class 3-2	> 1500 & $V_{MAX} \ge 140$ km/h														
Three-wheeler	SI						2			0,55	0,25			ECE R40	Yes	20.000
	CI						0,74				0,39	0,46	0,06	ECE R40	Yes	

1) If installed with emission control device

2) Displacement between 50 and 150cm³; Moped: maximum speed under or equal to 50 km/h and displacement under or equal to 50cm³

3) Maximum speed under 130 km/h and displacement above 150cm³

4) Maximum speed equal to or above 130 km/h and displacement above 150cm³

Table 26 European emission standards for non-road mobile machinery [11] [12] [24] [27] [46] [71] [72] [73] [74]

Description	Class / Category	Rated engine Power P_N [kW]	Speed [rpm]	Engine Displacement [cm^3]	Swept volume [liters/ cylinder]	Propulsion Class	Emission Standards: Emission regulation level/stage	Type Approval (TA)	Placing on the market of engines (NR)	CO [g/kWh]	NMHC [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	PN [#/kWh]	A-Factor	Test cycle	Useful Life -EDP[1] [hours/years]
Engines for use in other applications than propulsion of inland waterway vessels, locomotives and railcars	A	130 ≤ P < 560				CI	Stage I	01.Jul.98	01.Jän.99	5		1,3	9,2		0,54			NRSC [5]	
	B	75 ≤ P < 130						01. Jul.98 [3]	01. Jän.99 [4]						0,7				
	C	37 ≤ P < 75						01. Jul.98 [3]	01. Apr.99 [4]	6,5					0,85				
	E	130 ≤ P < 560					Stage II [6]	01.Jän.01	01.Jul.02	3,5		1	6		0,2			NRSC [5]	
	F	75 ≤ P < 130						01.Jän.02	01.Jul.03	5					0,3				
	G	37 ≤ P < 75						01.Jän.03	01.Jän.04			1,3	7		0,4				
	D	18 ≤ P < 37						01. Jän.01 [7]	01. Jän.02 [7]	5,5		1,5	8		0,08				
	SH: 1 [2]	≤ 19		< 20		SI	Stage I	11.Aug.04	11.Feb.05	805		295	5,36					NRSC [8]	
	SH: 2 [2]			20 ≤ D < 50								241							
	SH: 3 [2]			≥ 50						603		161							
	SN: 1 [2]			< 66						519				50					
	SN: 2 [2]			66 ≤ D < 100										40					
	SN: 3 [2]			100 ≤ D < 225										16,1					
	SN: 4 [2]			≥ 225										13,4					
	SH: 1 [2]			< 20			Stage II	01.Aug.07	01.Feb.08	805				50 [9]					50 125 300
	SH: 2 [2]			20 ≤ D < 50															
	SH: 3 [2]			≥ 50				01.Aug.08	01.Feb.09	603				72 [9]					
	SN: 1 [2]			< 66				01.Aug.04	01.Feb.05	610				50 [9]					50 125 300
	SN: 2 [2]			66 ≤ D < 100										40 [9]					125 250 500
	SN: 3 [2]			100 ≤ D < 225				01.Aug.07	01.Feb.08					16,1 [9]					
	SN: 4 [2]			≥ 225				01.Aug.06	01.Feb.07					12,1 [9]					250 500 1.000
	H	130 ≤ P < 560				CI & SI	Stage III A[10]	30.Jun.05	31.Dez.05	3,5				4	0,2			NRSC [11]	8.000
	I	75 ≤ P < 130						31.Dez.05	31.Dez.06	5				4	0,3				8.000
	J	37 ≤ P < 75						31.Dez.06	31.Dez.07					4,7	0,4				8.000

Description	Class / Category	Rated engine Power P_N [kW]	Speed [rpm]	Engine Displacement [cm³]	Swept volume [liters/ cylinder]	Propulsion Class	Emission Standards												Useful Life -EDP[1] [hours/years]
							Emission regulation level/stage	Type Approval (TA)	Placing on the market of engines (NR)	CO [g/kWh]	NMHC [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	PN [#/kWh]	A-Factor	Test cycle	
Engines for use in other applications than propulsion of inland waterway vessels, locomotives and railcars	K	19 ≤ P < 37				CI & SI	Stage III A[10]	31.Dez.05	31.Dez.06	5,5				7,5	0,6			NRSC [11]	3.000 [12] 5.000 [13]
	L	130 ≤ P < 560					Stage III B	31.Dez.09	31.Dez.10	3,5		0,19	2		0,025			NRSC [14] NRTC [14]	8.000
	M	75 ≤ P < 130						31.Dez.10	31.Dez.11	5		0,19	3,3						
	N	56 ≤ P < 75										0,19							
	P	37 ≤ P < 56						31.Dez.11	31.Dez.12					4,7					
	Q	130 ≤ P < 560					Stage IV	31.Dez.12	31.Dez.13	3,5		0,19	0,4		0,025			NRSC [14] NRTC [14]	8.000
	R	56 ≤ P < 130						30.Sep.13	30.Sep.14	5									
	NRE [15]	0 ≤ P < 8	variable and constant			CI	Stage V [16]	01.Jän.18	01.Jän.19	8				7,5	0,4[17]		1,1	NRSC [18]	3.000
		8 ≤ P < 19								6,6					0,4				
		19 ≤ P < 37								5				4,7	0,015	$1x10^{12}$		NRSC [18] NRTC [18]	
		37 ≤ P < 56																	variable speed: 5.000 hours constant speed: 3.000 hours
		56 ≤ P < 130						01.Jän.19	01.Jän.20				0,4	0,19					8.000
		130 ≤ P < 560						01.Jän.18	01.Jän.19	3,5									
	NRSh: 1 [2]	0 ≤ P < 19		< 20		SI				805				50				NRSC [18]	125 250 1.000
	NRSh: 2 [2]			20 ≤ D < 50															
	NRSh: 3 [2]			≥ 50						603				72					
	NRS: 1 [2]			< 66						610				10					
	NRS: 2 [2]			66 ≤ D < 100															
	NRS: 3 [2]			100 ≤ D < 225															
	NRS: 4 [2]			≥ 225										8					
	NRS	19 ≤ P < 56 [19]	variable and constant							4,4 - 20,6				∑2,7 - ∑0,8				NRSC [18] LSI-NRTC [18]	1.000 [20] 5.000 [20]
	NRE [15]	56 ≤ P < 130						01.Jän.19	01.Jän.20	5			0,4	0,19	0,015	$1x10^{12}$	1,1	NRSC [18]	8.000

Description	Class / Category	Rated engine Power P_N [kW]	Speed [rpm]	Engine Displacement [cm^3]	Swept volume [liters/ cylinder]	Propulsion Class	Emission Standards												Useful Life -EDP[1] [hours/years]
							Emission regulation level/stage	Type Approval (TA)	Placing on the market of engines (NR)	CO [g/kWh]	NMHC [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	PN [#/kWh]	A-Factor	Test cycle	
	NRE [15]	130 ≤ P < 560	variable and constant			SI							0,4		0,015	1x10^{12}	1,1		
		> 560	variable					01.Jän.18	01.Jän.19										
Engines for use in other applications than propulsion of inland waterway vessels, locomotives and railcars	NRE (other than Gen-Sets)	> 560	Constant			CI & SI				3,5			3,5	0,19	0,045		6		8.000
	NRG (Gen-Sets)						Stage V [16]						0,67		0,035			NRSC [18]	
	SMB (Snow-mobiles)							01.Jän.18	01.Jän.19	275		75							400
	ATS (ATV & SBS)					SI				400				8					< 100 cm^3: 500 ≥ 100 cm^3: 1.000
	V1:1	≥ 37			< 0,9			31.Dez.05						7,5	0,4				
	V1:2				0,9 ≤ SV < 1,2			30.Jun.05	31.Dez.06						0,3				
	V1:3				1,2 ≤ SV < 2,5									7,2	0,2				
	V1:4				2,5 ≤ SV < 5			31.Dez.06	31.Dez.08										
	V2:1				5 ≤ SV < 15	CI & SI	Stage III A			5				7,8	0,27			NRSC	10.000
	V2:2	< 3300			15 ≤ SV < 20									8,7					
	V2:3	≥ 3300			15 ≤ SV < 20			31.Dez.07	31.Dez.08					9,8	0,5				
	V2:4				20 ≤ SV < 25														
Inland waterway vessels	V2:5				25 ≤ SV < 30									11					
	IWP-v/c-1	37 ≤ P < 75								5				≤ 4,7	0,3				
	IWP-v/c-2	75 ≤ P < 130						01.Jän.18	01.Jän.19					≤ 5,4	0,14				
	IWP-v/c-3	130 ≤ P < 300								3,5		1	2,1		0,1		6	NRSC [18]	10.000
	IWP-v/c-4	> 300	variable and constant					01.Jän.19	01.Jän.20			0,19	1,8		0,015	1x10^{12}			
	IWA-v/c-1	19 ≤ P < 75				CI & SI	Stage V [21]							≤ 4,7	0,3				
	IWA-v/c-2	75 ≤ P < 130						01.Jän.18	01.Jän.19	5				≤ 5,4	0,14				
	IWA-v/c-3	130 ≤ P < 300										1	2,1		0,1		6	NRSC [18]	10.000
	IWA-v/c-4	> 300						01.Jän.19	01.Jän.20	3,5		0,19	1,8		0,015	1x10^{12}			

Description	Class / Category	Rated engine Power P_N [kW]	Speed [rpm]	Engine Displacement [cm³]	Swept volume [liters/ cylinder]	Propulsion Class	Emission Standards											Test cycle	Useful Life -EDP[1] [hours/years]
							Emission regulation level/stage	Type Approval (TA)	Placing on the market of engines (NR)	CO [g/kWh]	NMHC [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	PN [#/kWh]	A-Factor		
	two-stroke					SI			Dez.05	150 + (600/P_N)		30 + (100/$P_N^{0,75}$)	10						
	four-stroke							Dez.03	Dez.04	150 + (600/P_N)		6 + (50/$P_N^{0,75}$)	15					NRSC	480/10 [24] 350/5 [25] 350/10 [26]
	two- & four-stroke					CI				5		1,5 + (2/$P_N^{0,5}$)	9,8		1				
		< 37										1,5 + (2/$P_N^{0,5}$)	9,8		1				
		37 ≤ P < 75 [23]			< 0,9									4,7	0,3				
		75 ≤ P < 3700												5,8	0,15				
					0,9 ≤ SV < 1,2	CI				5					0,14				480/10
					1,2 ≤ SV < 2,5														
Recreational craft and personal watercraft [22]		< 3700			2,5 ≤ SV < 3,5									5,8	0,12				
					3,5 ≤ SV < 7			18.Jän.16	18.Jän.17						0,11			NRSC [27]	
		≤ 373								75				5					480/10
	Stern-drive and inboard engines	373 ≤ P < 485								350				16					150/3
		> 485												22					50/1
		≤ 4,3				SI				500 - (5xP_N)				30					350/5 [28] 350/10 [29]
	Outboard engines and PWC engines	4,3 ≤ P < 40												15,7 + (50/$P_N^{0,9}$)					
		> 40								300									

1) Emission Durability Period (EDP)-category shall be the category which most closely approaches the expected useful lives of the equipment into which the engines will be installed.

2) SH: Engines for handheld machinery; SN: Engines for non-handheld machinery

3) 01.Jan.01 for agricultural and forestry tractors

4) 01.Jul.01 for agricultural and forestry tractors

5) ISO 8178-C1 for CI engines operated under intermittent speed; ISO 8178-D2 for CI engines operated under constant speed

Variable speed engines: 9-mode test cycle or ramped modal cycle (RMC)

Constant speed engines: 5-mode test cycle or ramped modal cycle (RMC)

Engines with periodic regenerating after-treatment systems need to be tested 3 times on RMC, 2 times without regeneration and 1 time with the regeneration process occurring at least once.

6) For constant speed engines, implementation date: 01Jan.07

7) 1 year later for agricultural applications and forestry tractors

8) Test cycles: Stage I, II and III A NRSC only (engines 19-560 kW constant and variable speed operation); Stage III B, IV NRSC and NRTC (engines 19-560 kW variable speed operation)

9) Maximum limit NOx (Stage II) for all engines: 10 g/kWh

10) Other than constant speed engines

11) The NRSC shall be used for stages I, II and III A, as well as for constant speed engines at all stages. The NRTC can be used for Stage III A testing by the choice of the manufacturer.

12) Constant speed engines

13) Not constant speed engines

14) Both NRSC and NRTC cycles shall be used for Stage III B and IV testing (gaseous and particulate pollutants).

NRSC → ISO 8178-C1 for variable speed engines; ISO 8178-D2 for constant speed engines

15) Note that for engines > 56kW, SI and CI engine limits are now (Stage V) the same

16) Proposed Limits

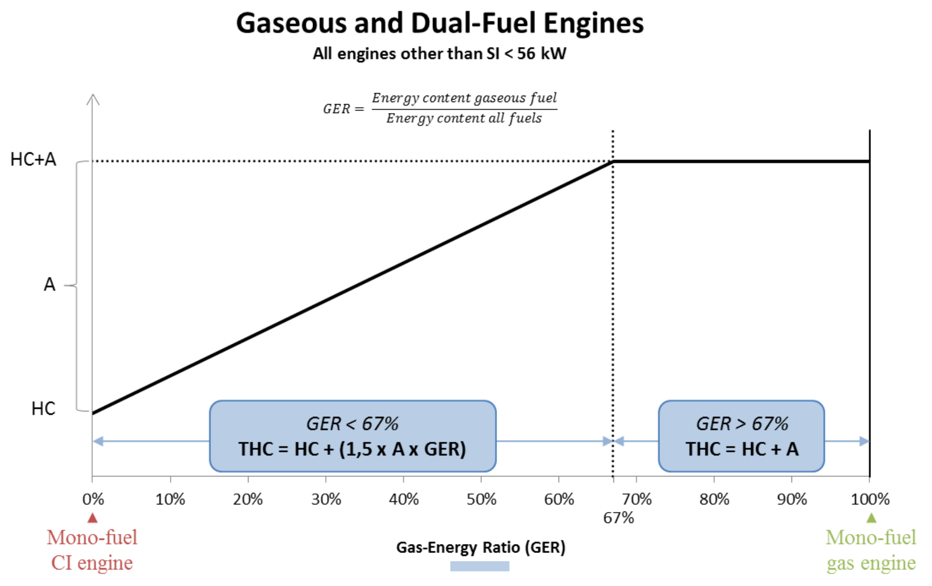
17) For hand-start able, air-cooled direct injection engines: 0.6 g/kWh

18)

Category	Purpose	Sub-category	Test cycle
NRE	Variable speed engine having a reference power less than 19 kW	NRE-v-1 NRE-v-2	NRSC G2 or C1
	Variable speed engine having a reference power greater than or equal to 19 kW but not more than 560 kW	NRE-v3 NRE-v-4 NRE-v-5 NRE-v-6	NRSC C1 NRTC
	Variable speed engine having a reference power greater than 560 kW	NRE-v-7	NRSC C1
	Constant speed engine	NRE-v-1 NRE-v-2 NRE-v3 NRE-v-4 NRE-v-5 NRE-v-6 NRE-v-7	NRSC D2
NRG	Variable speed engine for generating set	NRG-v-1	NRSC C1
	Constant speed engine for generating set	NRG-c-1	NRSC D2
ATS	Variable or constant speed engine for propulsion of ATV or SbS	ATS-v-1	NRSC G1

Category	Purpose	Sub-category	Test cycle
SMB	Variable or constant speed engines for propulsion of snowmobiles	SMB-v-1	NRSC H
NRS	Variable speed engine having a reference power of not more than 19 kW, intended for operation < 3600 rpm	NRS-vi-1a NRS-vi-1b	NRSC G1
	Variable speed engine having a reference power of not more than 19 kW, intended for operation ≥ 3600 rpm; constant speed engine having a reference power of not more than 19 kW	NRS-vr-1a NRS-vr-1b	NRSC G2
	Variable or constant speed engine having both a reference power between 19 kW and 30 kW and a total swept volume of less than 1 liter	NRS-v-2a	NRSC G2
	Variable or constant speed engine having a reference power of greater than 19 kW, other than engine having both a reference power between 19 kW and 30 kW and a total swept volume of less than 1 liter	NRS-v-2b NRS-v-3	NRSC C2 LSI-NRTC
NRSh	Variable or constant speed engine having a reference power of not more than 19 kW, for use in handheld machinery (LSI-NRTC only for engines with maximum speed of ≤ 3400 rpm)	NRSh-v-1a NRSh-v-1b	NRSC G3
IWP	Variable speed engine intended for propulsion that operates on a fixed-pitch propeller curve	IWP-v-1 IWP-v-2 IWP-v-3 IWP-v-4	NRSC E1
	Constant speed engine intended for propulsion that operates with a controllable-pitch or electrically coupled propeller	IWP-c-1 IWP-c-2 IWP-c-3 IWP-c-4	NRSC E2
IWA	Variable speed engine intended for auxiliary use on inland waterway vessels	IWA-v-1 IWA-v-2 IWA-v-3 IWA-v-4	NRSC C1
	Constant speed engine intended for auxiliary use on inland waterway vessels	IWA-c-1 IWA-c-2 IWA-c-3 IWA-c-4	NRSC D2

[19)] Limit values depending on (HC+NOx)/CO combinations: optionally, as alternative, any combination of values satisfying the equation (HC+NOx) x (CO) x 0.784 ≤ 8.57 as well as the following conditions: CO ≤ 20.6 g/kWh and (HC+NOx) ≤ 2.7 g/kWh



[20] 19 ≤ P < 30 and ≤ 1000 cm³ → 1.000 hours; 19 ≤ P < 30 and > 1000 cm³ → 5.000 hours; 30 ≤ P < 56 → 5.000 hours

[21] Emission limits from: ST 7795 2016 INIT - 2014/0268 (OLP)

[22] P_N is the rated engine Power in kW

[23] Alternatively, compression-ignition engines with rated engine power at or above 37 kW and below 75 kW and with a swept volume below 0.9 L/cyl. shall not exceed a PT emission limit of 0.2 g/kWh and a combined HC+NOx emission limit of 5.8 g/kWh.

[24] For inboard or stern-drive engines

[25] For personal watercraft engines

[26] For outboard engines

[27] For variable speed CI engines test cycles E1 or E5 shall be applied or alternatively, above 130 kW, test cycle E3 may be applied. For variable speed SI engines test cycle E4 shall be applied

[28] For personal watercraft engines

[29] For outboard engines

Table 27 U.S. EPA emission standards for non-road mobile machinery [11] [12] [24] [27] [46] [65]

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards: Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle	Useful Life/EDP [hours/years]	Warranty [hours/years]
Off-road CI engines		< 8		CI 1)	Tier 1	2000 - 2004	8		10,5				1	NRSC	3.000/5	1.500/2
		8 ≤ P < 19					6,6		9,5				0,8			
		19 ≤ P < 37				1999 - 2003	5,5								5.000/7 2)	3.000/5 3)
		37 ≤ P < 56				1998 - 2003					9,2				8.000/10	3.000/5
		56 ≤ P < 75														
		75 ≤ P < 130				1997 - 2002										
		130 ≤ P < 225				1996 - 2002	11,4	1,3 4)					0,54			
		225 ≤ P < 450				1996 - 2000										
		450 ≤ P < 560				1996 - 2001										
		560 ≤ P < 900				2000 - 2005										
		> 900														
		< 8			Tier 2	2005 - 2007	8		7,5				0,8	NRSC	3.000/5	1.500/2
		8 ≤ P < 19					6,6									
		19 ≤ P < 37				2004 - 2007	5,5						0,6		5.000/7 2)	3.000/5 3)
		37 ≤ P < 56					5						0,4		8.000/10	3.000/5
		56 ≤ P < 75														
		75 ≤ P < 130				2003 - 2006			6,6				0,3			
		130 ≤ P < 225				2003 - 2005	3,5						0,2			
		225 ≤ P < 450				2001 - 2005			6,4							
		450 ≤ P < 560				2002 - 2005										
		560 ≤ P < 900				2006 - 2010										
		37 ≤ P < 56			Tier 3	2008 - 2011 5)	5		4,7				0,4	NRSC	8.000/10	3.000/5
		56 ≤ P < 75				2008 - 2011										
		75 ≤ P < 130				2007 - 2011			4				0,3			

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards: Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle	Useful Life/EDP [hours/years]	Warranty [hours/years]
Off-road CI engines		130 ≤ P < 225		CI [1]	Tier 3	2006 - 2010	3,5		4				0,2	NRSC	8.000/10	3.000/5
		225 ≤ P < 450														
		450 ≤ P < 560														
		560 ≤ P < 900				2011 - 2014	3,5	0,4			3,5		0,1			
		< 8			Tier 4	2008 +	8		7,5				0,4 [6]	NRSC [10] NRTC [10]	3.000/5	1.500/2
		8 ≤ P < 19					6,6						0,4			
		19 ≤ P < 37				2008 - 2012	5,5						0,3		5.000/7 [2]	3.000/5 [3]
						2013 +			4,7				0,03			
		37 ≤ P < 56				2008 - 2012	5						0,3		8.000/10	3.000/5
	(Option 1)					2012 [7]							0,03			
	(Option 2)					2013 + [7]										
		56 ≤ P < 75				2012 - 2013 [8]							0,02			
						2014 + [31]		0,19			0,4					
		75 ≤ P < 130				2012 - 2013 [8]			4							
						2014 +		0,19			0,4					
		130 ≤ P < 225				2011 - 2013 [8]	3,5		4							
						2014 + [9]		0,19			0,4					
		225 ≤ P < 450				2011 - 2013 [8]			4							
						2014 + [9]		0,19			0,4					
		450 ≤ P < 560				2011 - 2013 [8]			4							
						2014 + [9]		0,19			0,4					
		560 ≤ P < 900				2015 + [9]					3,5 [11]		0,04 [12]			
	Generator sets	≥ 900				2011 - 2014		0,4			0,67		0,1			
						2015 +		0,19					0,03			
	All engines except gen-sets					2011 - 2014		0,4			3,5		0,1			
						2015 +		0,19					0,04			

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards										Useful Life/EDP [hours/years]	Warranty [hours/years]
					Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle		
Off-road SI engines	I - Non-handheld		< 225	SI	Phase I	1997	519					16,1				
	II - Non-handheld		≥ 225				519					13,4				
	III - Handheld		< 20				805			295	5,36					
	IV - Handheld		20 ≤ D < 50				805			241						
	V - Handheld		≥ 50				603			161						
	I - Non-handheld		100 ≤ D < 225		Phase II	01. Aug.07 [13]	610		14,8 [14]			16,1		SAE J1088 cycles A, B and C [15]	125 [16] 250 [17] 500 [18]	
	I-A - Non-handheld		< 66			2001			N/A [14]			50			50 [16] 125 [17] 300 [18]	
	I-B - Non-handheld		66 ≤ D < 100						37 [14]			40			125 [16] 250 [17] 500 [18]	
	II - Non-handheld		≥ 225						16,7 [14]			18			250 [16] 500 [17] 1.000 [18]	
						2002			15,3 [14]			16,6				
						2003			14 [14]			15				
						2004			12,7 [14]			13,6				
						2005 +			11,3 [14]			12,1				
	III - Handheld		< 20			2002	805					238			50 [16] 125 [17] 300 [18]	
						2003						175				
						2004						113				
						2005						50				
						2006										
						2007 +										

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards										Useful Life/EDP [hours/years]	Warranty [hours/years]
					Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle		
Off-road SI engines	IV - Handheld		20 ≤ D < 50	SI	Phase II	2002	805					196		SAE J1088 cycles A, B and C [15]	50 [16] 125 [17] 300 [18]	
						2003						148				
						2004						99				
						2005						50				
						2006										
						2007 +										
	V - Handheld		≥ 50			2004	603					143				
						2005						119				
						2006						96				
						2007 +						72				
	I - Non-handheld		< 225		Phase III [19]	2012 +	610					10[20]			125 [21] 250 [22] 500 [23]	2 years
	II - Non-handheld		≥ 225			2011 +	610					8[20]			250 [21] 500 [22] 1000 [23]	
Large SI engines	Includes non-road equipment such as forklift, sweeper, pump and generator			SI	Tier 1 [24]	2004 - 2006 [25]	50 [26]					4		Duty cycle [27]	5.000/7 [28]	min. first half of engine`s useful life or 3 years
												5,4		Field testing		
					Tier 2 [24]	2007 + [29]	4,4 [26]					2,7		Duty cycle [27]		
							6,5 [26]					3,8		Field testing		
Recreational vehicle	Snowmobile			CI & SI	Phase-in 50%	2006	275			100				SAE 982017	400/5 (min. 8.000 km)	200/ 30 months (min. 4.000 km)
					Phase-in 100 %	2007 - 2009										
						2010 - 2011				75						
						2012 [30]	400 [31]			150 [31]						

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards									Test cycle	Useful Life/EDP [hours/years]	Warranty [hours/years]
					Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]			
Personal Watercraft & Outboard Marine Engines [32)]		≤ 4,3		SI		1998						278		ISO 8178 E4 5-Mode Steady-State Test Cycle	350/5	All Emission Related Components: 1 year
		> 4,3										$0{,}917 \times (151 + 557/P_N^{0,9}) + 2{,}44$				
		≤ 4,3				1999						253				
		> 4,3										$0{,}833 \times (151 + 557/P_N^{0,9}) + 2{,}89$				
		≤ 4,3				2000						228				
		> 4,3										$0{,}750 \times (151 + 557/P_N^{0,9}) + 3{,}33$				
		≤ 4,3				2001						204				All Emission Related Components: 1 year Specified Major Emission Control Components: 200/3
		> 4,3										$0{,}667 \times (151 + 557/P_N^{0,9}) + 3{,}78$				
		≤ 4,3				2002						179				
		> 4,3										$0{,}583 \times (151 + 557/P_N^{0,9}) + 4{,}22$				
		≤ 4,3				2003						155				
		> 4,3										$0{,}500 \times (151 + 557/P_N^{0,9}) + 4{,}67$				
		≤ 4,3				2004						130				All Emission Related Components: 200/2 Specified Major Emission Control Components: 200/3
		> 4,3										$0{,}417 \times (151 + 557/P_N^{0,9}) + 5{,}11$				
		≤ 4,3				2005						105				
		> 4,3										$0{,}333 \times (151 + 557/P_N^{0,9}) + 5{,}56$				
		≤ 4,3				2006 - 2009						81				

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards										Useful Life/EDP [hours/years]	Warranty [hours/years]
					Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle		
Personal Watercraft & Outboard Marine Engines [32]		> 4,3		SI		2006 - 2009						0,250 x (151 + 557/$P_N^{0,9}$) + 6,00		ISO 8178 E4 5-Mode Steady-State Test Cycle	350/5	All Emission Related Components: 200/2 Specified Major Emission Control Components: 200/3
		≤ 4,3				2010 + [33]	500 - 5xP_N					30			Personal Watercraft: 350/5 [34] Outboard: 350/10 [34]	Personal Watercraft: 175 or 30 months Outboard: 175/5
		> 4,3					300					2,1 + 0,09 x (151 + 557/$P_N^{0,9}$)				
Sterndrive & Inboard Engines	Conventional Engines					2010 +	75					5		ISO 8178 E4 5-Mode Steady-State Test Cycle	480/10 [35]	Electrical & mechanical components: 480/3
	High Performance Engines	≤ 485				2010	350					20			P ≤ 485 kW: 150/3 P < 485 kW: 50/1	Electrical components: 480/3 Mechanical components: P ≤ 485 kW: 150/3 P < 485 kW: 50/1
		> 485										25				
		≤ 485				2011 +						16				
		> 485										22				

1) Smoke emissions may not exceed 20% during the acceleration mode, 15% during the lugging mode and 50% during the peaks in either mode. Smoke emission standards do not apply to single-cylinder engines, constant-speed engines, or engines certified to a PM emission standard of 0.07 g/kWh or lower. Smoke emissions are measured using procedures in 40 CFR Part 86 Subpart I.

2) Useful life for constant speed engines with rated speed 3.000 rpm or higher is 5 years of 3.000 hours, whichever comes first.

3) Warranty period for constant speed engines with rated speed 3.000 rpm or higher is 2 years or 1.500 hours, whichever comes first.

4) For Tier 1 engines the standard is for total hydrocarbons

5) These Tier 3 standards apply only to manufacturers selecting Tier 4 Option 2. Manufacturers selecting Tier 4 Option 1 will be meeting those standards in lieu of Tier 3 standards.

6) Hand-start able air-cooled direct injection engines may optionally meet PM standard of 0.60 g/kWh. These engines may optionally meet Tier 2 standards through 2009 Model Year, in 2010 these are required to meet PM standard of 0.60 g/kWh

[7] A manufacturer may certify all their engines to either Option 1 or 2 sets of standards starting in the indicated Model Year. Manufacturers selecting Option 2 must meet Tier 3 standards in the 2008 - 2011 Model Year.

[8] These standards are phase-out standards. Not more than 50% of a manufacturer´s engine production is allowed to meet these standards in each Model Year of the phase out period. Engines not meeting these standards must meet the final Tier 4 standards.

[9] These standards are phased in during the indicated years. At least 50% of a manufacturer´s engine production must meet these standards during each year of the phase in. Engine not meeting these standards must meet the applicable phase-out standards.

[10] Tier 4 standards have to be met on both NRSC and NRTC cycles; NRTC required from 2011 for engines 130-560 kW, 2012 for engines 56-130 kW and 2013 for engines <56 kW

[11] NOx standard generator sets is 0.67 g/kWh

[12] PM standard for generator sets is 0.03 g/kWh

[13] Effective Date, also incl. any Class 'I engine family produced ≥ 01.Aug.03 before introduce into commerce

[14] Natural Gas (NG) engine

[15] Test Procedure: SAE J1088 cycles A, B and C

Cycle A: non-handheld engines to operate at an intermediate speed, similar to ISO 8178-G1

Cycle B: non-handheld engines to operate at rated speed, similar to ISO 8178-G2

Cycle C: handheld engines, similar to ISO 8178-G3 except weighting Mode 1: 85% and Mode 2: 15%

[16] Category/cycle C

[17] Category/cycle B

[18] Category/cycle A

[19] Class III - V: The Phase III Exhaust standards are the same as the long-term Phase II

[20] ABT Program: Phase II handheld engines and Class I-A and I-B non-handheld engines have to fulfill a certification, averaging, banking & trading program. Non-handheld engines < 1 liter and < 19 kW: useful life 1.000 hours

[21] Extended Life Residential

[22] Residential

[23] Commercial

[24] Alternative according to the following formula: (HC+NOx) x (CO) 0.784 ≤ 8.57

Field testing limits use: (HC+NOx) x (CO) 0.791 ≤ 16.78

[25] Test Procedure: ISO 8178-4 C2, D2

[26] Alternate emission standard for serve duty engines

[27] Tier 1: Steady-State cycle; Tier 2: Steady-State + transient cycles

[28] Serve duty 1.500 hours/ 7 years

[29] Test Procedure: additional requirements

a) Warm up Segment
b) Transient Segment
c) Steady-State Segment

[30] Or equivalent per § 1051.103

[31] These are the maximum allowable family emission limits (FEL). The HC and CO standards are defined by a functional relationship as described in 40 CFR 1051.103(a)(2).

[32] The numerical emission standards for hydrocarbons (HC) must be met based on the following types of HC emissions for engines powered by the following fuels: (1) total hydrocarbon equivalent for alcohol; (2) non-methane hydrocarbon for natural gas; (3) total hydrocarbons for other fuels

[33] Not-to-exceed emission standards specified in 40 CFR 1045.107 also applies.

[34] A longer useful life in terms of hour must be specified for the engine family if the average service life is longer than the minimum value as described in 40 CFR 1045.103(3).

[35] The useful life may not be shorter than (see [32]): (1) 150 hours of operation; (2) the recommended overhaul interval; or (3) the engines mechanical warranty. A longer useful life must be specified in terms of hour if the average service life is longer than minimum value as described in 40 CFR 1045.105(e)(3)

Table 28 U.S. CARB emission standards for non-road mobile machinery [11] [12] [24] [27] [46] [49]

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards: Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle	Useful Life [hours/years]	Warranty [hours/years]
All diesel cycle engines in the given power categories used for agricultural, forestry, constructional and industrial applications		< 8		CI	Tier 1	2000 - 2004	8		10,5				1	SAE J1088 cycles A, B and C [2)]	8.000/10	3.000/5
		8 ≤ P < 19					6,6		9,5				0,8			
		19 ≤ P < 37				2000 - 2003	5,5									
		37 ≤ P < 56									9,2					
		56 ≤ P < 75														
		75 ≤ P < 130				2000 - 2002										
		130 ≤ P < 225				1996 - 2002	11,4			1,3			0,54			
		225 ≤ P < 450														
		450 ≤ P < 560														
		> 560				2000 - 2005										
		< 8			Tier 2	2005 - 2007 [1)]	8		7,5				0,8		3.000/5	1.500/2
		8 ≤ P < 19					6,6									
		19 ≤ P < 37				2004 - 2007 [1)]	5,5						0,6		5.000/5 [3)]	3.000/5 [3)]
		37 ≤ P < 56					5						0,4		8.000/10	3.000/5
		56 ≤ P < 75				2004 – 2007										
		75 ≤ P < 130				2003 -2006							0,3			
		130 ≤ P < 225					3,5		6,6				0,2			
		225 ≤ P < 450				2003 – 2005			6,4							
		450 ≤ P < 560														
		> 560				2006 – 2010										
		37 ≤ P < 56			Tier 3 [4)]	2008 - 2011	5		4,7				0,4		8.000/10	3.000/5
		56 ≤ P < 75														
		75 ≤ P < 130				2007 - 2011							0,3			
		130 ≤ P < 225				2006 - 2010	3,5		4				0,2			

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards: Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle	Useful Life [hours/years]	Warranty [hours/years]
All diesel cycle engines in the given power categories used for agricultural, forestry, constructional and industrial applications		225 ≤ P < 450		CI	Tier 3 [4]	2006 - 2010	3,5		4				0,2	SAE J1088 cycles A, B and C [2]	8.000/10	3.000/5
		450 ≤ P < 560														
		< 8 [5]			Tier 4	2008 +	8		7,5				0,4 [6]		3.000/5	1.500/2
		8 ≤ P < 19 [5]					6,6									
		19 ≤ P < 37 [5]				2008 - 2012	5,5						0,3		5.000/5 [3]	3.000/5 [3]
						2013 +			4,7				0,03			
		37 ≤ P < 56 [7]				2008 - 2012	5						0,3		8.000/10	3.000/5
						2013 +							0,03			
		56 ≤ P < 75				2012 - 2014 [8]		0,19			0,4		0,02			
									4,7							
								0,19			3,4 [9]					
						2015 +					0,4					
		75 ≤ P < 130				2012 - 2014 [8]										
									4							
								0,19			3,45					
						2015 +					0,4					
		130 ≤ P < 560				2011 - 2013	3,5									
									4							
								0,19			2					
						2014 +					0,4					
	ELSE [10]	> 560				2011 - 2014		0,4			3,5		0,1			
						2015 +		0,19					0,04			
	GEN [11]	560 ≤ P < 900				2011 - 2014		0,4					0,1			
						2015 +		0,19			0,67		0,03			
	GEN	> 900				2011 - 2014		0,4					0,1			
						2015 +		0,19					0,03			

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards										Useful Life [hours/years]	Warranty [hours/years]
					Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle		
Large off-road SI engines ≥ 19 kW, **except construction and farm equipment engines < 130 kW, off-road motorcycle, all-terrain vehicles, snowmobiles**			≤ 825	SI		2002 - 2010	549					12		Steady-state test cycle ISO 8178 C2/D2 or U.S. EPA Transient Cycle [12]	1.000/2	
						2010 +						8				
			825 < D ≤ 1000			2002 - 2010						12				
						2011 - 2014	375					6,5				
						2015 +	20,6 [13]					0,8 [13]				
			> 1000			2001 - 2003	49,6 [14]					4 [14]				
						2004 - 2006	49,6					4			3.500/5	
						2007 - 2009	4,4 [15]					2,7 [15]			5.000/7	
						2010 +	20,6					0,8				
						2007 - 2009	4,4 [15]					2,7 [15]				
						2010 +	20,6					0,8				
						2007 +	6,5 [16]					3,8 [16]		Field Testing		
Small Off-Road Engines (SORE)	I		65 ≤ D < 225	SI		1995	402					16,1	1,2 [18]	SAE J1088 cycles A, B and C [2]		
	II		≥ 225									13,4	1,2 [18]			
	III [17]		< 20				805			295	5,36					
	IV [17]		20 ≤ D < 50							241						
	V [17]		50 ≤ D < 65				402			161						
	I		65 ≤ D < 225			1996 - 1999	467					12 [19]	0,9 [18]	SAE J1088 cycles A, B and C [2]		
	II		≥ 225									10 [19]	0,9 [18]			
	III [17]		< 20				805			295 [19]	4 [19]					
	IV [17]		20 ≤ D < 50							241 [19]						
	V [17]		50 ≤ D < 65				402			161 [19]						
			≤ 65			2000 - 2001 [19]	536					72	2 [17]	SAE J1088 cycles A, B and C [2]	50 [20]/- 125 [21]/- 300 [22]/-	
			65 < D < 225				467					16,1				
			≥ 225									13,4				

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards: Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle	Useful Life [hours/years]	Warranty [hours/years]
Small Off-Road Engines (SORE)			≤ 65	SI		2002 - 2004 [19]	536					72	2 [17]	SAE J1088 cycles A, B and C [2]	50 [20]/- 125 [21]/- 300 [22]/-	
	horizontal-shaft engine		65 < D < 225				549					16,1			125 [20]/- 250 [21]/- 500 [22]/-	
	vertical-shaft engine		65 < D < 225				467									
			≥ 225				549					12			125 [20]/- 250 [21]/- 500 [22]/-	
			< 50			2005 +	536					50	2 [17]	SAE J1088 cycles A, B and C [2]	50 [20]/- 125 [21]/- 300 [22]/-	
			50 ≤ D ≤ 80									72			50 [20]/- 125 [21]/- 300 [22]/-	
	horizontal-shaft engine		80 < D < 225			2005	549					16,1			125 [20]/- 250 [21]/- 500 [22]/-	
	vertical-shaft engine		80 < D < 225				467									
			≥ 225				549					12,1			125 [20]/- 250 [21]/- 500 [22]/-	
			80 < D < 225			2006	549					16,1		SAE J1088 cycles A, B and C [2]	125 [20]/- 250 [21]/- 500 [22]/-	
			≥ 225									12,1			125 [20]/- 250 [21]/- 500 [22]/-	
			80 < D < 225			2007	549					5		SAE J1088 cycles A, B and C [2]	125 [20]/- 250 [21]/- 500 [22]/-	
			≥ 225									12,1			125 [20]/- 250 [21]/- 500 [22]/-	
			80 < D < 225			2008 +	549					5		SAE J1088 cycles A, B and C [2]	125 [20]/- 250 [21]/- 500 [22]/-	

Description	Class / Category	Rated engine Power P_N [kW]	Engine Displacement [cm³]	Propulsion Class	Emission Standards										Useful Life [hours/years]	Warranty [hours/years]
					Emission regulation level/stage	Model Year (MY)	CO [g/kWh]	NMHC [g/kWh]	NMHC+NOx [g/kWh]	HC [g/kWh]	NOx [g/kWh]	HC+NOx [g/kWh]	PM [g/kWh]	Test cycle		
Small Off-Road Engines (SORE)			≥ 225	SI		2008 +	549					4		SAE J1088 cycles A, B and C [2]	125 [20]/- 250[21]/- 500[22]/- 1000[22]/-	
Outboard and Personal Watercraft Marine Engine		4,3 < P_{tx} [23]		SI		2001 - 2003						81		ISO 8178 E4 5-Mode Steady-State Test Cycle	Personal watercraft: 9 years Outboard engines: 16 years	
		4,3 ≥ P_{tx} [23]										0,25 x (151 + 557/$P_{tx}^{0,9}$) + 6				
		4,3 < P_{tx} [23]				2004 - 2007						64,8				
		4,3 ≥ P_{tx} [23]										0,20 x (151 + 557/$P_{tx}^{0,9}$) + 4,8				
		4,3 < P_{tx} [23]				2008						30				
		4,3 ≥ P_{tx} [23]										0,09 x (151 + 557/$P_{tx}^{0,9}$) + 2,1				
		≤ 40				2009 +	500 - 5 x P_N					30				
		> 40					300					0,09 x (151 + 557/$P_{tx}^{0,9}$) + 2,1				
Inboard & Sterndrive engines		≤ 373		SI		2003 - 2008						16 [24]		ISO 8178 E4 5-Mode Steady-State Test Cycle	480/10	
						2007 + [25]						5				
Specialty Vehicle engines		< 25	< 225			1995 - 1998	402					16	1,2	SAE J1088 6-mode test cycle A	10.000 km or 5 years	
			≥ 225									13,4				
						1999 - 2007	134					4,3	0,34			
Go-Karts & specialty vehicles		> 25				1997 - 2007	134					4,3	0,34	SAE J1088 6-mode test cycle A		
ATV`s [26]			< 225			1997 +	400					16,1 [27]		SAE J1088 6-mode test cycle A	10.000 km or 5 years	
			≥ 225									13,4 [27]				
Off-road sport vehicles & Off-road utility vehicles [26]						2007 +	400					12 [27]		SAE J1088 6-mode test cycle A		
Sand cars [26]						2007 +	400					13,4 [27]		SAE J1088 6-mode test cycle A		

[1] Tier 2 standards for propulsion marine CI engines below 37 kW in effect beyond the 2007 end date

[2] Test Procedure: SAE J1088/cycle A: engine > 65 cm³ configured for intermediate speed; SAE J1088/cycle B: engine > 65 cm³ configured for rated speed; SAE J1088/cycle C: engine > 65 cm³;

SAE J1088 cycle A, B and C similar to ISO 8178 G1/G2/G3; No Small Off-Road Engine (SORE) may be equipped with a defeat device

3) for constant speed ≥ 3000 rpm:

Useful life: 3.000 hours/ 5 years

Warranty: 1.500 hours/ 2years

4) Manufacturers may optionally certify engine families to the interim Tier 4

5) Propulsion marine CI engines below 37 kW are not subject to Tier 4 standards or requirements. All previously adopted requirements remain applicable for these engines

6) Tier 4 PM standard for hand-start, air cooled, direction injection engines below 8 kW is 0.6 g/kWh but is not required until 2010

7) Engine families in this power category may alternately meet Tier 3 PM standards from 2008 - 2011 in exchange for introduction final PM standards in 2012.

8) Manufacturers have the option of complying with the Tier 4 standards over 2 years period at 50% per year using banked Tier 2 credits or over 3 year period at 25% per year without the use of Tier 2 credits. The 3 year phase-in period is shown. The 2014 Model Year cannot extend beyond 31 Dec. 2014, when the 3 year phase-in option is use

9) Manufacturers may comply with the standards during the transitional implementation years using either a phase-in/phase-out approach or by using the alternate NOx approach. The 3 years 25% alternate NOx standard is shown in the table. The 2 years 50% phase-in NOx standard would be 2.3 g/kWh

10) "ELSE" refers to all mobile machinery excluding generator engines

11) "GEN" refers to generator engines only

12) Test cycle for large off-road SI engines: (engines with characteristics similar to SORE - < 19kW: ISO 8178 G1)

Year	Large off-road SI engines, including portable engines	Large off-road SI engines with constant-speed operation
Pre- 2007	Steady-state test cycle ISO 8178 C2 or EPA transient test cycle	Steady-state test cycle ISO 8178 D2 or EPA transient test cycle
2007 and later	EPA transient test cycle	EPA transient test cycle

13) For 2011 and subsequent Model Year large SI engines used in off-highway motor vehicles that, with the exception of payload capacity, meet the "Off-Road Sport Vehicle" or " Off-Road Utility Vehicle" definitions need not meet the 2015 and subsequent exhaust emissions standards

14) A manufacturer must show that a least 25% of its California engine sales comply with the standards in 2001, 50% in 2002, 75% in 2003.

15) For the 2007-2009 Model year manufacturers may alternatively certify their engines according to the following formula: (HC+NOx) x (CO) 0.784 ≤ 8.57

16) Starting in 2007 manufacturers may apply the following formula to determine alternate emissions standards: (HC+NOx) x (CO) 0.791 ≤ 16,78

17) Applicable to all tow-stroke engines

18) Applicable to all diesel-cycle engines

19) Engines used exclusively in snow throwers and ice augers need not certify to or comply with the HC and NOx standards or the crankcase requirements at the option of the manufacturer.

20) Descriptive term: moderate

[21] Descriptive term: intermediate

[22] Descriptive term: extended

[23] P_{tx} is the average power in kW (sales-weighted) of the total number of spark-ignition marine engines produced for sale in California in model year x. Engine Power must be calculated using the Society of Automotive Engineers (SAE) Standard J1228, November 1991, incorporated herein by reference. Power outputs of outboard engines are determined separately from those of personal watercraft engines.

[24] Compliance with the HC+NOx standard may be averaged on a sales-weighted basis, across the engine manufacturers California production, based on projected California sales or the projected California percentage of national sales.

[25] For model year 2007, engine manufacturers shall certify a minimum of 45% of their California production (projected California sales or projected California percentage of national sales) to the standard. For model year 2008, engine manufacturers shall certify a minimum of 75% of their California production (projected California sales or projected California percentage of national sales) to the standard.

[26] Optional Engine-Based Testing: ATV´s, off-road sport vehicles, off-road utility vehicles and sand cars may use the utility test procedures set forth in the " California Exhaust Emission Standards and Test Procedures for 1995-2004 Small Off-Road Engines", as incorporated by reference in CCR, title13, section 2403 (d). The test cycle is limited to the 6-mode Test Cycle A only.

[27]Compliance with the optional HC+NOx standard to be applied as a"corporate average" shall be determined as provided in subsection (d), at § 2412. Emission Standards and Test Procedures - New Off-Highway Recreational Vehicles and Engines, in Final Regulation Order of 16 July 2007

3 Mixture Formation, Working Process and Engine Management

3.1 Gasoline Engines

3.1.1 Engine Components and Subsystems

3.1.1.1 Carburetion Systems

The mixture formation of gasoline engines are divided into internal and external mixture formation. External mixture formation is subdivided into carburetors and manifold injection for two- and four-stroke engines, and semi-direct injection only for two-stroke engines. Internal mixture formation for two- and four-stroke engines is split into low pressure- (LP) and high pressure (HP) direct injection systems. A detailed classification of mixture formation is depicted in Figure 57.

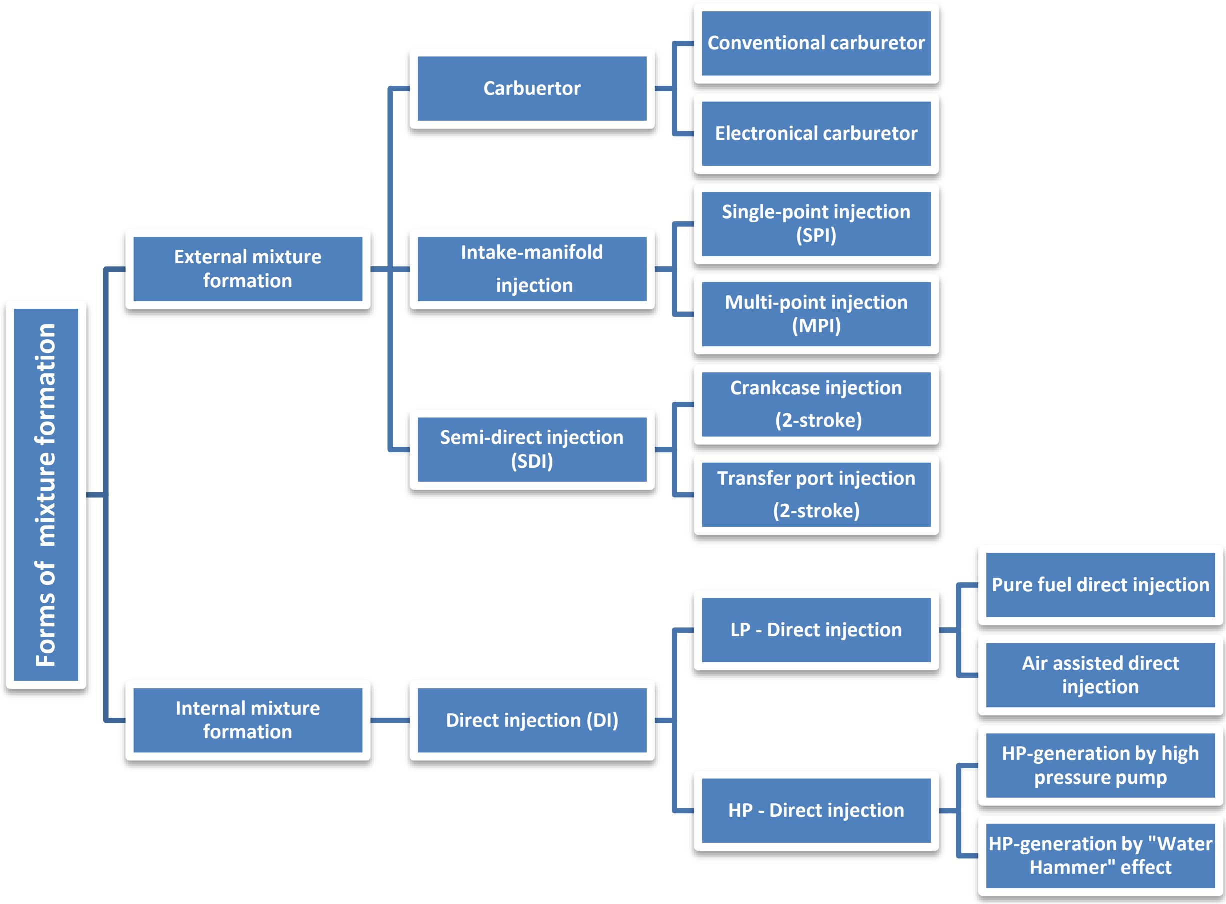
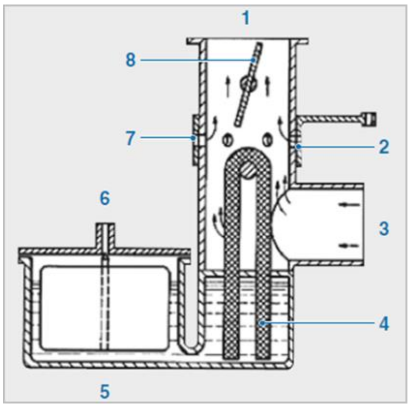


Figure 57 Forms of mixture formation; adapted from [75, p. 18]

3.1.1.1.1 Carburetors

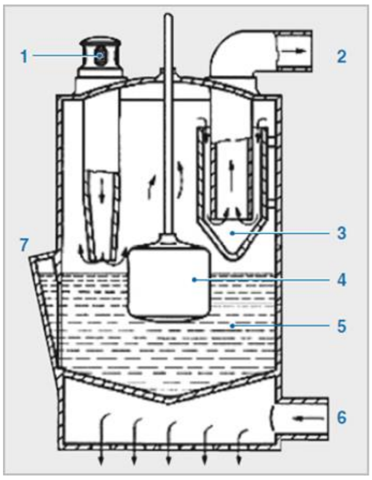
In the second half of the 19th century, all major engine developers were concerned with the issue of the utilization of liquid hydrocarbons. One of the first carburetor designs was the wick carburetor. The principle of a wick carburetor is similar to that of a petroleum lamp, the intake engine air flow and the fuel are mixed during the air flow passes the wick, which is submerged in liquid fuel and absorbs it.



1 Air-fuel mixture towards to the engine
2 Annular valve
3 Air intake
4 Wick
5 Float chamber including float
6 Fuel supply
7 Auxiliary air
8 Throttle valve

Figure 58 Wick carburetor [76, p. 291]

In 1865, the Viennese Siegfried Marcus filed a patent for the so-called brush carburetor, to carbonate the atmospheric air. The brush carburetor consists of a gasoline tank heated by exhaust gases and an atomizer disc with bristles, which is driven by the engine via a belt. The gasoline is taken from the fuel reservoir by the rotating bristles and is wiped at a fixed edge, and thereby, it is finely atomized. In addition, the surface carburetors were another development of this period. The liquid fuel of the surface carburetor is heated by exhaust gases and the evaporated fuel volume is taken away by the intake engine air flow. The main disadvantage of this carburetor type was an inconstant air fuel ratio (λ), since the volatile ingredients of the fuel were evaporated first and thus the air fuel ratio becomes lean over time.



1 Air intake
2 Air-fuel mixture towards to the engine
3 Fuel separator
4 Float
5 Fuel
6 Exhaust gas
7 Filler neck

Figure 59 Surface carburetor [76, p. 292]

Before the turn of the 20th century, two essential components of today's carburetors were introduced. The first innovation was the float system for a constant fuel level in carburetors and the second improvement, implemented with the spray nozzle carburetor, was the liquid fuel metering system via nozzles.

The further development of the carburetor is characterized by the expansion of functionalities by mechanical, hydraulic and electrical systems. However, increasing demands on mixture formation systems with respect to temporal and quantitative accuracy required more considerable complex mechanical and electronical expenditure, and resulted in an almost complete elimination of this technology in passenger cars. Today, carburetors are only used in niche applications, e.g. in two-wheelers and small engines, such as chainsaws. [77, p. 74]
Examples of some well-known carburetor manufacturers are Dell' Orto, Bing, Zama, Weber, Solex, Zenith, Tillotson, etc.. The renowned enterprise STIHL took over the company Zama towards the end of the year 2008 and the manufacturers Weber and Solex are meanwhile part of the company Magneti Marelli.

3.1.1.1.1.1 Slide Carburetor

The slide carburetor regulates the amount of air-fuel mixture by a slide (2), which changes the venturi (1) cross section. The slide is arranged perpendicular to the flow direction and can be cylindrical or flat – then it is also called flat-slide carburetor – but the cylindrical design is common. The conical needle (3) is fixed on the slide and dunks into the nozzle (7). The venturi generates below atmospheric pressure, which draws fuel from the float chamber through the jet (5) and the atomizer (6). The more the slider opens, the larger the enabled cross sectional area in the venturi and in the nozzle, which is enabled by the tapered needle. The increase of the air flow results in an increase of the flow velocity and the below atmospheric pressure, thus more fuel can be drawn from the float chamber. [78, pp. 176-180]

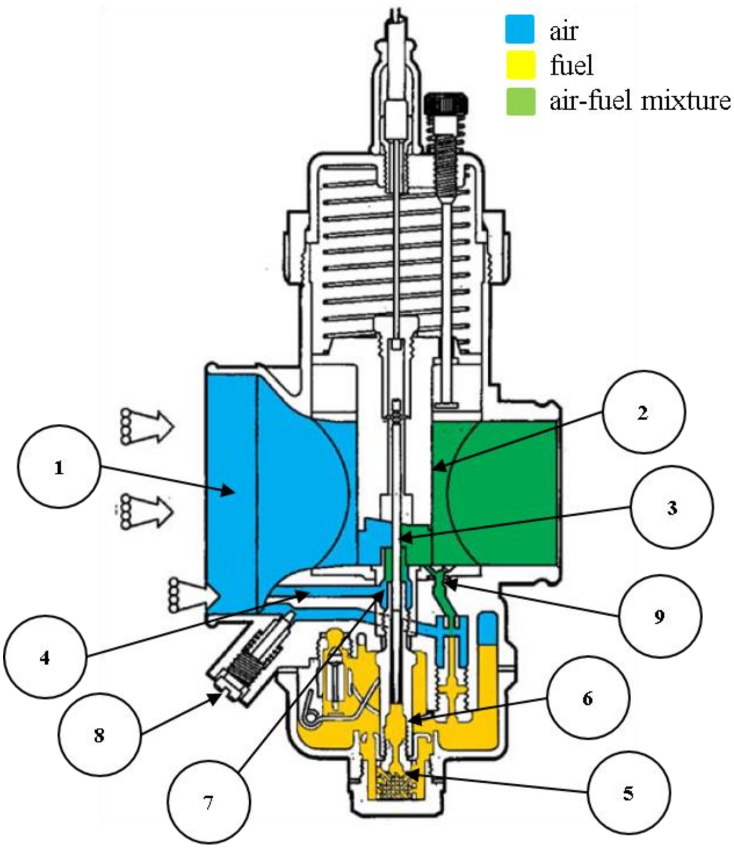


Figure 60 Dell`Orto slide carburetor; adapted from [79, p. 3]

The slide carburetor distinguishes between the idle circuit (9), for idle and part load, and the main circuit (5, 6, and 7), for high part load and full load. Two air supply channels (4) at the venturi intake, one for the main circuit and one for the idle circuit, are used to emulsify the fuel with the air. The float ensures a constant fuel level in the float chamber. This is necessary because the fuel metering depends on the fuel level in the float chamber and the resulting suction height as well as the diameter of the needle valve and the venturi cross section. These configurations affect the air fuel ratio (λ). The amount of air in the air supply channel for the idle system can be adjusted by the idle screw (8). The size of the idle jet is important for the idle operation condition and the engine response during transitions. [78, pp. 176-180]
Figure 60 shows a slide carburetor from Dell' Orto. Some additional systems are required to enable a proper operation of the carburetor. Examples are a cold starter device to compensate the fuel condensation on cold intake manifolds by a richer air-fuel mixture [80, pp. 564-565], an acceleration pump for additional fuel to counteract a lean mixture at acceleration processes [80, pp. 563-564], an altitude correction to compensate the lower oxygen content with increasing altitude [80, p. 567] or a power jet for 2-stroke engines [79, pp. 29-30].

3.1.1.1.1.2 Constant Pressure Carburetor

The constant pressure carburetor has been and in some regions still is state of the art in modern serial motorcycles. This carburetor type consists of a throttle valve (2) and a slide (3), similar to a slide carburetor. The throttle valve is controlled by the accelerator cable, which transmits driver`s request. The slide position adjusts itself by the prevalent pressure conditions in the venturi (1), since the slide hangs moveable via diaphragm (4) and a small auxiliary spring. The below atmospheric pressure (6) from the venturi is applied to the top of the diaphragm via a bore (7) in the slide and the ambient pressure is applied to the bottom of the diaphragm via a bore (5) in the carburetor housing. [79, pp. 31-33] [78, pp. 180-182]

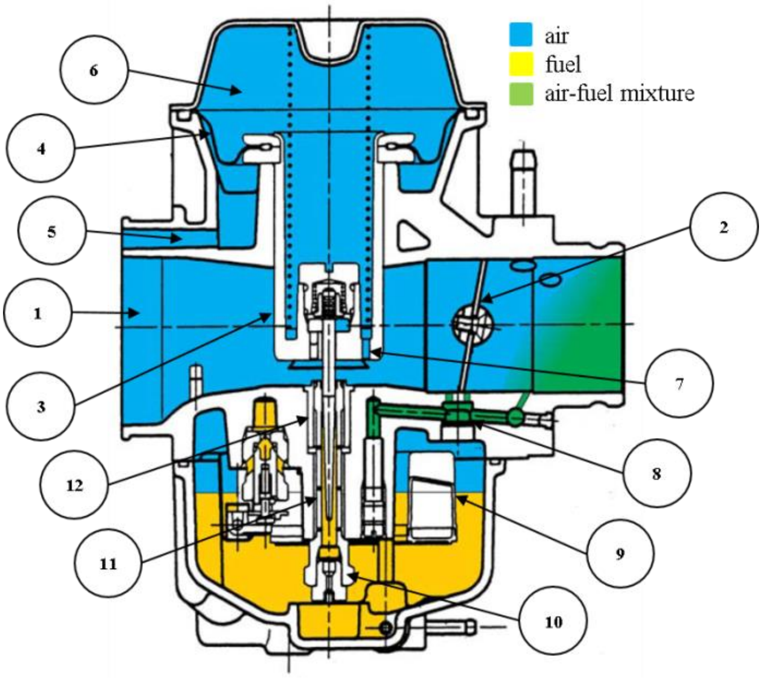


Figure 61 Dell`Orto constant pressure carburetors [79, p. 31]

When the throttle valve is almost closed and the flow velocity is low, the below atmospheric pressure is also low, whereby a low differential pressure appears at the membrane, and thereby, the slide sinks down by its weight and the small auxiliary spring force. When an acceleration process is carried out and thereby the throttle valve opens quickly, the slide does not open abruptly. Instead, the slide gradually opens only as far as until the equilibrium position at the diaphragm is achieved. The equilibrium at the diaphragm is determined between the gravitation force, the spring force and the resultant force of the pressure difference. This procedure is repeated during the acceleration phase until a steady state is reached. By this approach, the below atmospheric pressure remains almost constant in the venturi and is independent of the air flow - hence the name constant pressure carburetor.

Figure 61 depicts a constant pressure carburetor from Dell' Orto. Constant pressure conditions are an advantage for fuel delivery and mixture formation. Thereby, this type of carburetors needs no acceleration pump, due to of its operating principle of the slowly and gradually lift of the slide, with the disadvantage that the response is slower in comparison to slide carburetor. Due to the constant pressure conditions, the below atmospheric pressure would always draw the same amount of fuel, which results in a too rich mixture, if the air flow is low. Hence, this carburetor requires appropriate tuned needle jet (10) as well as atomizer (11) and nozzle (12), which regulate the fuel delivery.

The design of the constant pressure carburetor requires theoretically no idle system, but normally an idle jet (8) is arranged near the throttle valve, since the air flow on the slide edges will be disturbed and thus aggravates the atomization of fuel. A float (9) in the float chamber ensures a constant fuel level. [78, pp. 180-182] [79, pp. 31-33]

3.1.1.1.1.3 Diaphragm Carburetor

Some engines are used in applications, which also have to operate far away from the horizontal position, such as chainsaws or hedge trimmers for example, and hence no conventional carburetor with a float can be used. These engines use a so-called diaphragm carburetor that guarantees an operation in all positions. A diaphragm carburetor consists of the following main components (see Figure 62): a venturi (1), a throttle valve (2), a fuel pump (red marked) and a jet system (blue marked). [81, pp. 9-10] [82]

The air flow is controlled by the throttle valve. The fuel pump is designed as diaphragm pump, which is actuated by the pulsating crankcase pressure. The pump diaphragm (5) separates the impulse chamber (3) from the fuel chamber (6). The fuel inlet valve (8) and outlet valve (9) are stamped flaps of the pump diaphragm, which are still connected to it. When the piston is moving towards Top Dead Center (TDC), a below atmospheric pressure is generated in the crankcase that applies on the fuel pump diaphragm via impulse port (4) and flexes it. Thus, a below atmospheric pressure is also generated in the fuel chamber of the diaphragm pump. The ambient pressure in the tank pushes the fuel via fuel fitting (7) and inlet valve (8) into the fuel chamber of the diaphragm pump. Meanwhile, the outlet valve is pressed against the valve seat and the port to the metering system is closed. When the piston is moving towards Bottom Dead Center (BDC), a pressure is generated, that deforms the pump diaphragm to opposite direction than at the intake process, and thereby the volume of the fuel chamber decreases. As a consequence, the outlet valve is opened and the inlet valve is pressed against the valve seat and closes the intake port. [81, pp. 9-10] [82]

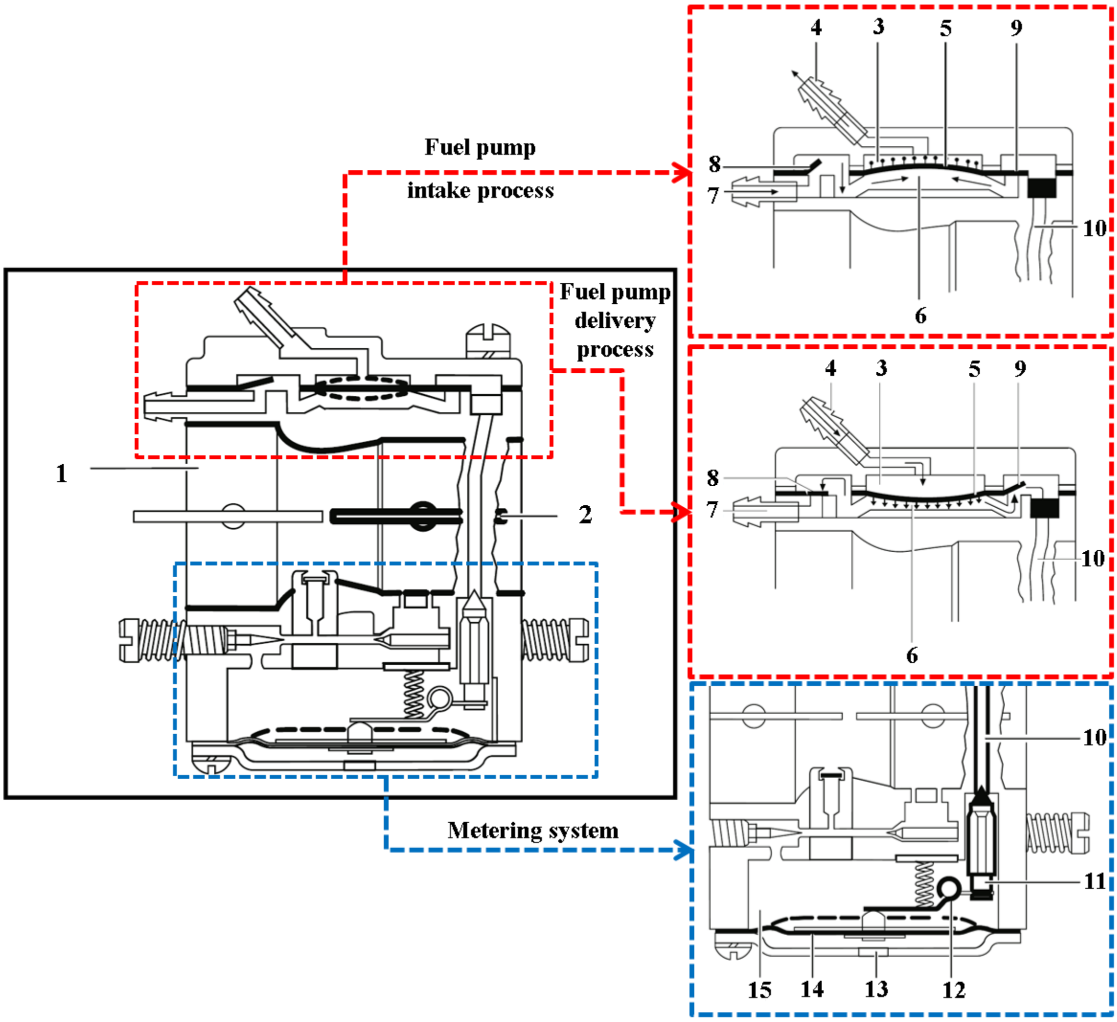


Figure 62 STIHL diaphragm carburetors; adapted from [81, pp. 9-10]

As a result, an amount of fuel flows through the fuel port (10) into the chamber (15) above the metering diaphragm (14). The bottom side of the metering diaphragm is applied with ambient pressure via bore (13) in the housing. When the throttle valve opens, air flows through the venturi and generates a below atmospheric pressure and fuel is drawn from the metering diaphragm chamber through the main jet respectively idle jets. Thus, the volume in the chamber (15) decreases and the metering diaphragm is pushed upwards by the ambient pressure. The metering diaphragm actuates the inlet needle (11) of the metering diaphragm chamber via lever-system (12), whereby the chamber is refilled with fuel, until the pressure in the chamber and the ambient pressure are balanced. [81, pp. 9-10] [82]

Some diaphragm carburetors use a so-called compensator to compensate a reduced air flow that is caused by a dirty air filter. The air filter and the fuel metering system are connected to provide the metering diaphragm with internal system pressure and not with ambient pressure, as described above. When the air filter is contaminated, the pressure in the system drops down and falls below the ambient pressure, whereby the equilibrium at the metering diaphragm is achieved faster and consequently the amount of fuel in the metering diaphragm chamber is reduced. This ensures that the air fuel mixture cannot become over-rich, when the air filter is contaminated. In addition, systems such as an acceleration pump, an automatic choke or electric carburetor heating are also used. [81, pp. 20-21]

3.1.1.1.1.4 Electronic Carburetor

The electronic carburetor represents a further development of conventional carburetors. The mixture formation in electronic carburetors follows the same principle as in typical carburetors, but with the difference that all main functions are electronically controlled. The engine operating point is electronically determined via sensors and the fuel metering is also electronically controlled by an electronic control unit (ECU). The sensors transmit the information to the ECU, which controls the fuel metering device according to the optimal air-fuel ratio. Thus, the complexity of carburetor systems as well as the emissions and the fuel consumption was reduced.

In the early 1990s, such concepts were already developed. These concepts were based on standard carburetors which were equipped with actuators, such as the “Ecotronic” system from Pierburg and BOSCH. [83, pp. 191-193] [76, p. 298]

The Ecotronic was mainly used in automobile sector, but also in the two-wheeler sector [84] [85] and for handheld tools (see Chapter 3.1.1.3.3 – STIHL M-Tronic) has been done some efforts in this field. Dell`Orto developed the Electronic Carburation System (ECS) to meet the more stringent emission limit EURO 3 for two-stroke engines for the first time. Dell`Orto ECS regulates the mixture formation as a function of engine speed and throttle valve position. The deposited maps in the ECU are similar to those, which are used for electronic injection system. [86] [85]

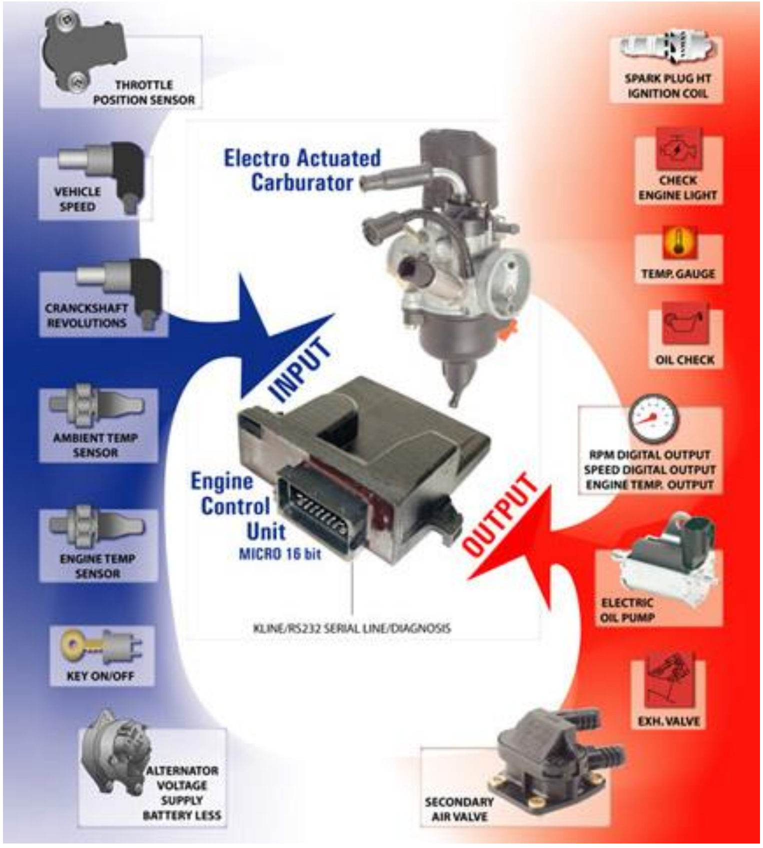


Figure 63 Scheme of Dell'Orto ECS [79]

In 2006, STHIL introduced the carburetor based engine management system M-Tronic for handheld power tools, e.g. chainsaws or cut-off machines, to meet future emission regulations. The STIHL M-Tronic system expands a diaphragm carburetor by an ECU and a small solenoid valve. The solenoid valve functions as fuel metering valve that is controlled by the ECU. Such electronic carburetors offer substantial advantages in comparison to conventional systems, especially with regard to performance and fuel consumption. Furthermore, the ECU storage capacity facilitates the adaptation to different fuels and environmental conditions, e.g. ambient temperature or altitude. [80, pp. 436-437]

3.1.1.1.2 Injection Systems

In 1859, Jean-Joseph Etienne Lenoir developed the first single-cylinder two-stroke spark ignition engine and patented it 1860, even before Nikolaus August Otto patented his four-stroke spark ignition engine in 1876. A two-stroke propulsion engine for vehicles was described for the first time in the patent submitted by Julius Söhnlein in 1891. Between the two world wars intensive research was carried out on four-stroke direct injection engine concepts. As a result the first two cylinder two-stroke passenger car engine with direct injection, the Goliath/Gutbrod Superior, was developed and produced in small series. Despite the improved fuel saving with about 30% in comparison to conventional two-stroke engines at that time, the success remained limited and the number of units low. Hans List, former head of the Institute of Internal Combustion Engines and Thermodynamics at Graz University of Technology and later founder of the AVL List GmbH recognized early the potential of direct injection in regard to fuel saving and specified it with about 25% in 1950. [87, pp. 14-15]

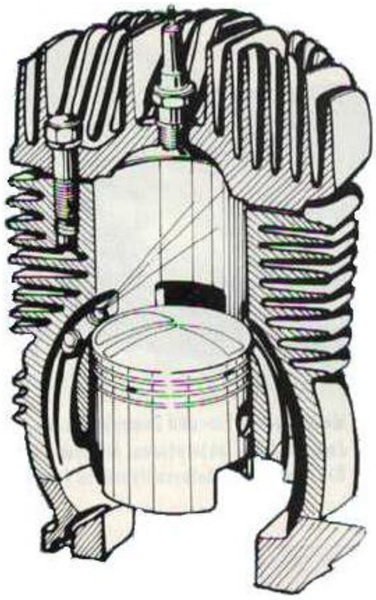


Figure 64 Sectional drawing of the Motobecane 125 cm³ single cylinder [88, p. 427]

The French company Motobecane undertook intensive efforts to develop an engine with internal mixture formation for low cost two-wheelers. As a consequence that no electronic fuel injection systems for these vehicles were available, Motobecane designed an engine with optical-electronic fuel metering system. Figure 64 pictures the 125 cm³ two-stroke single cylinder engine which was introduced by Motobecane in 1971. Initial approaches for two-stroke engines to take over cost-effective components from large-scale production of four-stroke passenger car engines and to use electronic engine management systems were semi-direct injection concepts.

In 1986, a 50 cm³ close-to-production engine concept with semi-direct injection was developed by the company PUCH in cooperation with the Institute of Internal Combustion Engines and Thermodynamics (IVT) at Graz University of Technology (see Figure 65). The fuel is injected into the transfer port, thus this concept provides a longer period for mixture formation and a moderate injection pressure is sufficient. The crank case pressure amplitude is used to provide the required system pressure of about 2.5 bar via membrane and pressure ratio. Although the scavenging losses cannot be completely avoided, a substantial improvement is achieved in comparison with two-stroke engines with external mixture formation. [87, pp. 14-15] [88, pp. 426-429]

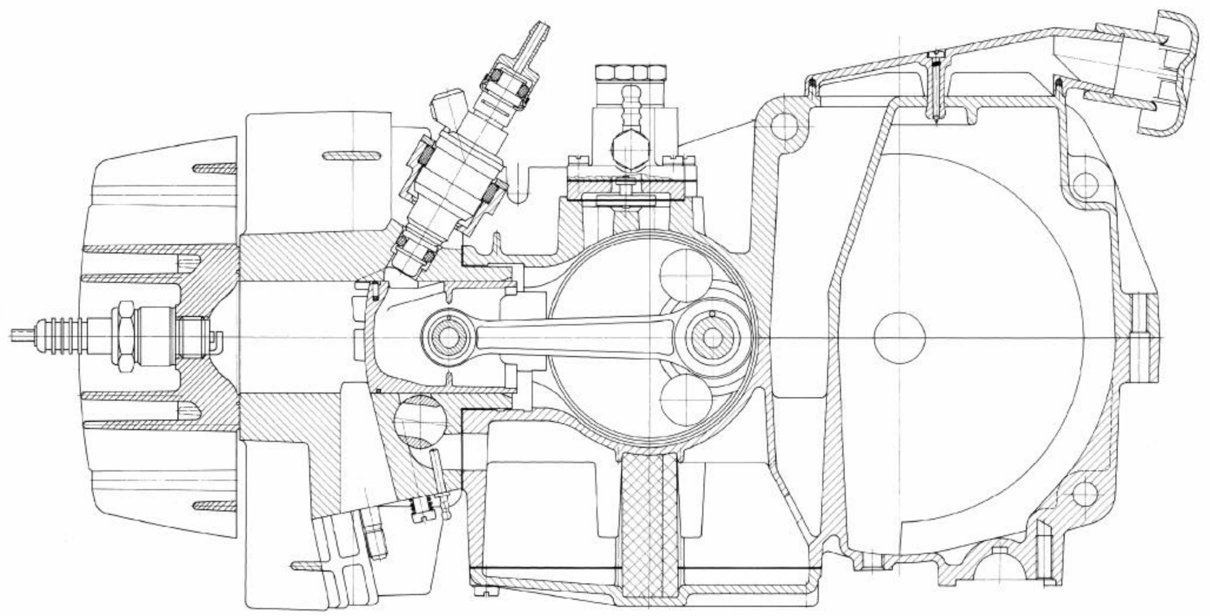


Figure 65 PUCH Maxi 50cm³ engine concept with semi-direct injection [88, p. 428]

In the course of time, further direct injection concepts for two-stroke engines were developed. In the scope of the EU-project DOLCE an air-assisted direct injection system was developed [89] by several project partners consisting of renowned manufacturers and research institutes, inter alia Piaggio, Magneti Marelli, Institut Francais du Petrole (IFP) and Graz University of Technology. The precursor of this DOLCE injection system is the Piaggio FAST (Fully Atomized Stratified Turbulence) injection system [90] [91]. The FICHT Fuel Injection System [92], also known as E-TEC Injection, is a direct injection concept for two-stroke engines and is used in series application. The air-assisted direct injection Orbital Combustion Process (OPC) [93] [94] is also applied in series vehicles, such as the Aprilia SR 50 with DITECH system [95] [96]. The OPC forms the basis of the Synerject aSDI Injection System [97]. The Ram-Tuned Injection System by C. Stan [98] is another direct injection concept, which is based on the “Water-Hammer” effect. The FICHT Injection System and the Ram-Tuned Injection System are, in contrast to above-mentioned concepts, high pressure direct injection systems as well as the Compression Wave Injection (CWI) System [99] and the High Pressure Direction Injection System for two-stroke outboard engines by Yamaha [100].

The Institute of Internal Combustion Engines and Thermodynamics at Graz University of Technology designed in cooperation with Bombardier Rotax a High Pressure Direct Injection (HPDI) system [101] [88, pp. 435-438] for a 500 cm³ single cylinder engine. Furthermore, the IVT developed an innovative Low Pressure Direct Injection (LPDI) system [102] for a 50 cm³ scooter and a 300 cm³ Enduro two-stroke engine. Some of these technologies are also used in hand-held power tools [103]. [87, pp. 16-18] [88, pp. 429-434]

3.1.1.1.2.1 Intake-Manifold Injection

State of the art in intake manifold injection systems is the electronically controlled fully sequential port fuel injection with n-α control, which is a form of multi-point injection (MPI), as shown in Figure 66. The fuel is directly injected into the combustion chamber by an injector positioned ahead of the intake valve during the induction stroke when the intake valve is open. Due to the shift of the fuel evaporation into the combustion chamber (see Figure 67), the internal cooling in the cylinder leads to lower temperatures during the compression phase and to a higher cylinder charge. As a result, the tendency to knocking is reduced and the compression ratio can be raised moderately. [77, pp. 79-85] [78, pp. 179-187] [76, pp. 100-117] [104, pp. 331-343]

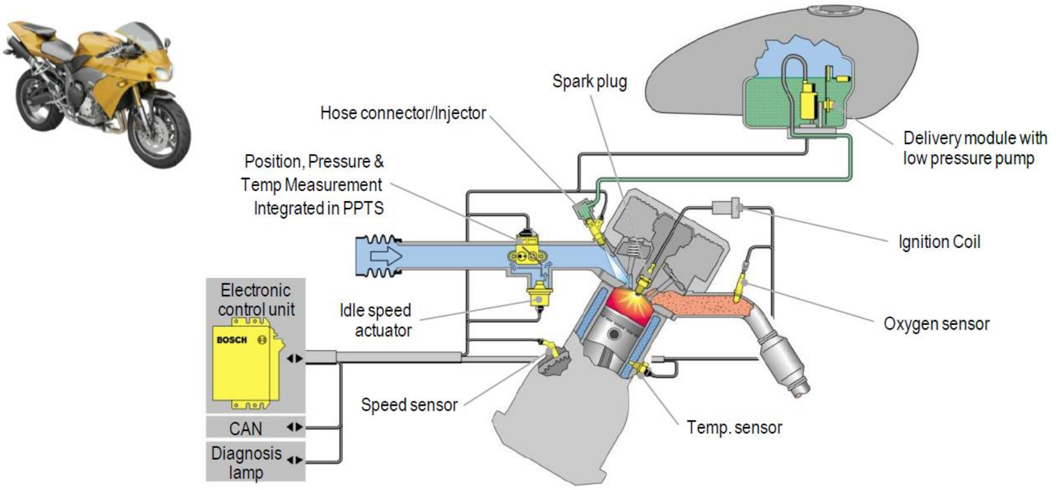


Figure 66 ICE with intake-manifold - scheme [105, p. 379]

For four-stroke engines, Synerject introduced a "low cost" intake manifold solution for small one or two cylinder engines with the SePI – Synerject electronic Port Injection. The SePI dispenses with unnecessary functionalities, such as additional inputs for EGR or electronic throttle control. [97, pp. 9-10]

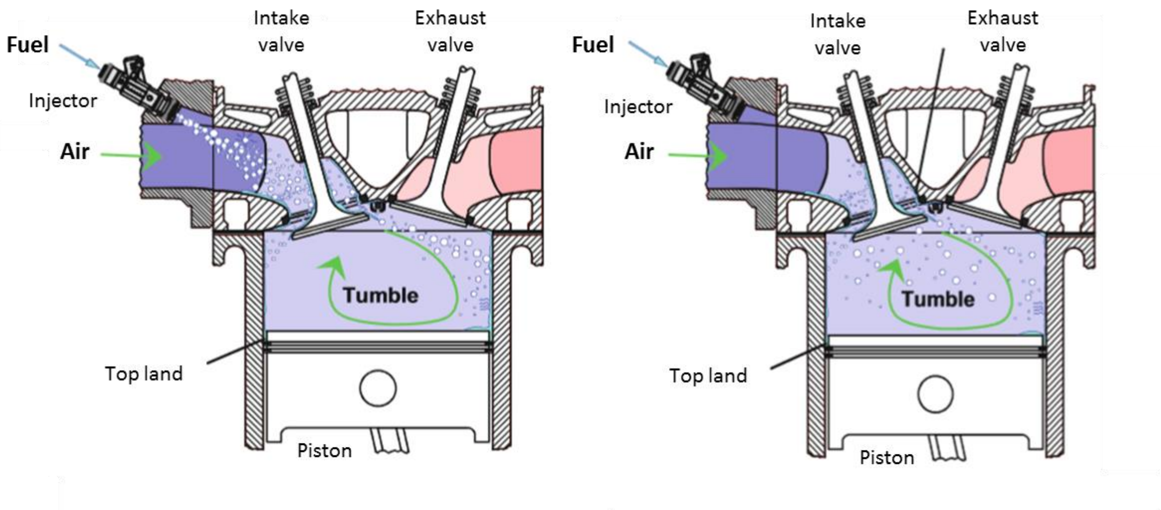


Figure 67 Comparison of injection strategies at intake manifold injection systems; adapted from [104, p. 340]

The electromagnetically EV 14 injection valve from BOSCH is a standard injection valve for intake manifold injection systems in passenger cars. There also exists a compact version of the EV 14 injection valve for the two-wheeler segment (see Figure 69). Figure 68 depicts an electromagnetic injection valve, which basically consist of the valve housing (3) with a hydraulic port (1) and an electrical connection (4), the valve spring, the solenoid valve (9), the flexible valve needle with armature (10) and the valve ball (11) and the valve seat (12) with injection-orifice plate (13). When the solenoid valve is energized, the valve needle with the armature is raised by the created magnetic field, whereby, the valve ball lifts from the valve seat and the fuel is injected. [76, pp. 100-117] [104, pp. 331-343]

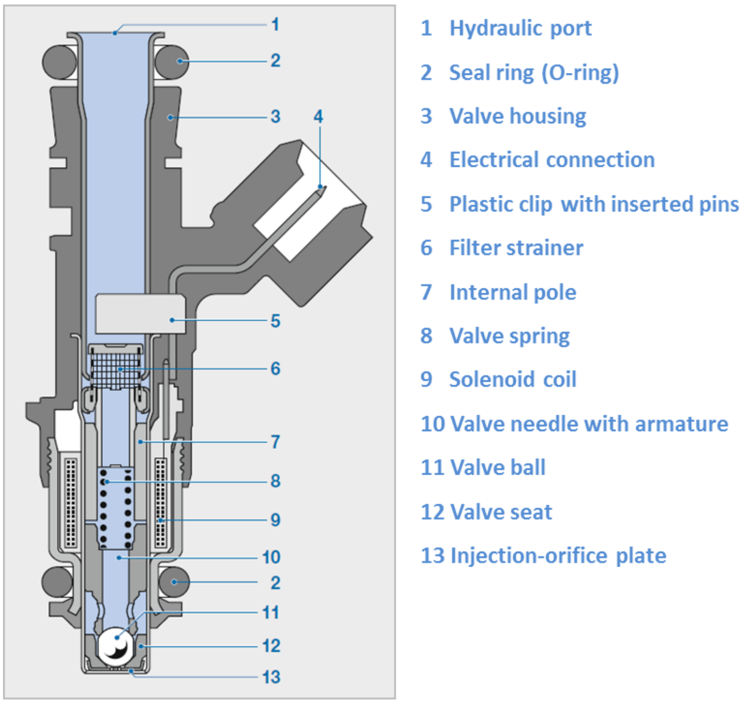


Figure 68 EV 14 fuel injector from BOSCH for intake-manifold fuel injection; adapted from [76, p. 112] [106]

The atomization of the fuel depends on the design of the injection-orifice plate and the injection pressure. The normal injection pressure at intake manifold injection systems is approximately 2.5 – 5 bar. Thus, SMD are achieved of about 50 – 100 µm with appropriate valve-orifice plate design (for more details see [77]). [77, pp. 79-85]

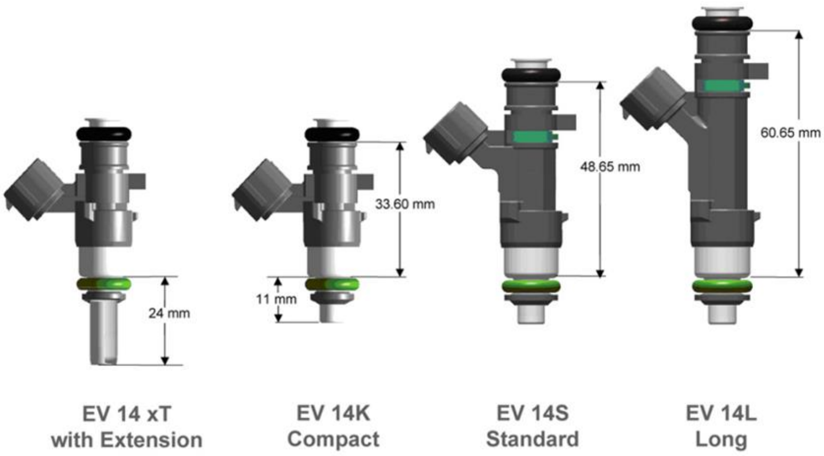


Figure 69 Variants of the EV 14 injection valves [104, p. 337] [107, p. 3]

Figure 70 and Figure 71 illustrates the fuel jet for different injector nozzle types. The difference between a pencil stream and a cone spray pattern at 2.5 bar and 4 bar fuel pressure is shown in Figure 70. In contrast to the pencil stream, the cone spray provides a more even and finer fuel distribution at the fuel injection process than the pencil stream. Figure 71 shows the fuel jet of a three-hole nozzle at a fuel pressure of 5 bar.

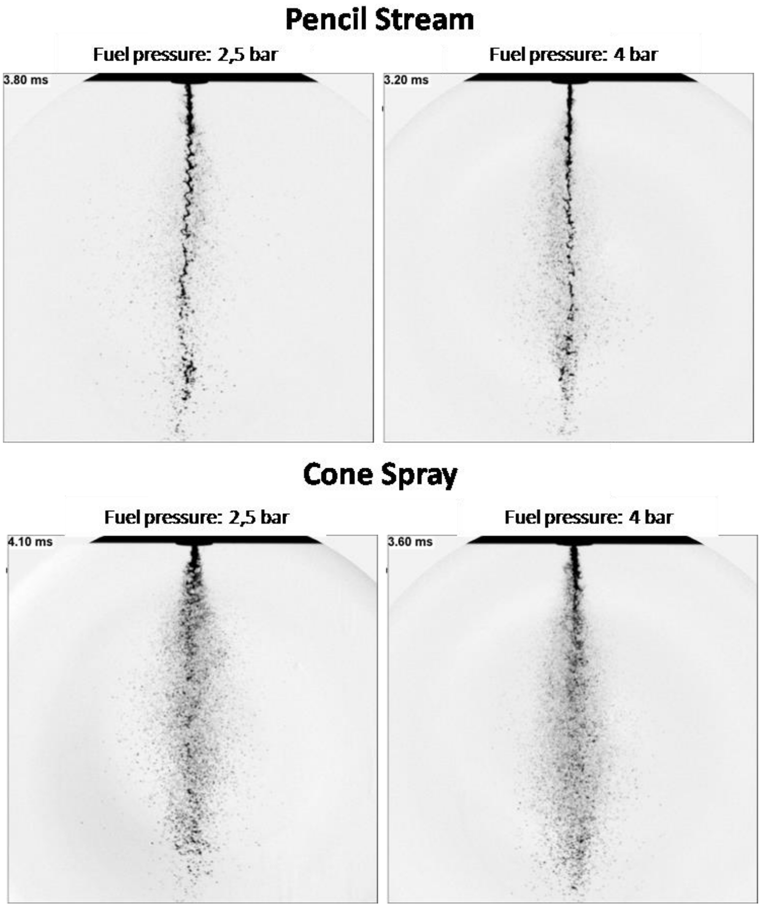


Figure 70 Comparison of injectors with pencil stream and with cone spray for 2.5 bar and 4 bar fuel pressure

Figure 71 Fuel jet of an injector with a three-hole nozzle

3.1.1.1.2.2 Semi-Direct Injection

Semi-Direct Injection systems (SDI) is used in two-stroke engines and does not directly inject the fuel into the combustion chamber, instead either into the crankcase, such as in the case of the STIHL Injection system, or into the transfer ports. Thus, two-stroke engines with SDI systems have the opportunity to operate with stratified scavenging and it allows using standard low pressure injectors.

3.1.1.1.2.2.1 STIHL Injection

The STIHL Injection system is a battery-less, electronically controlled injection system for handheld devices with two-stroke engines. The electronic control unit (ECU) with integrated ignition coil is the key element of the low pressure crankcase injection system. The ECU controls the injection and the ignition. The injection valve is supplied with a system pressure of 100 mbar above the atmospheric pressure by the injection pump, which is designed as a diaphragm pump with integrated pressure regulator using the pulsating crankcase pressure to generate the system pressure. [80, p. 437] [108, pp. 674-679] [109] [110, p. 2]

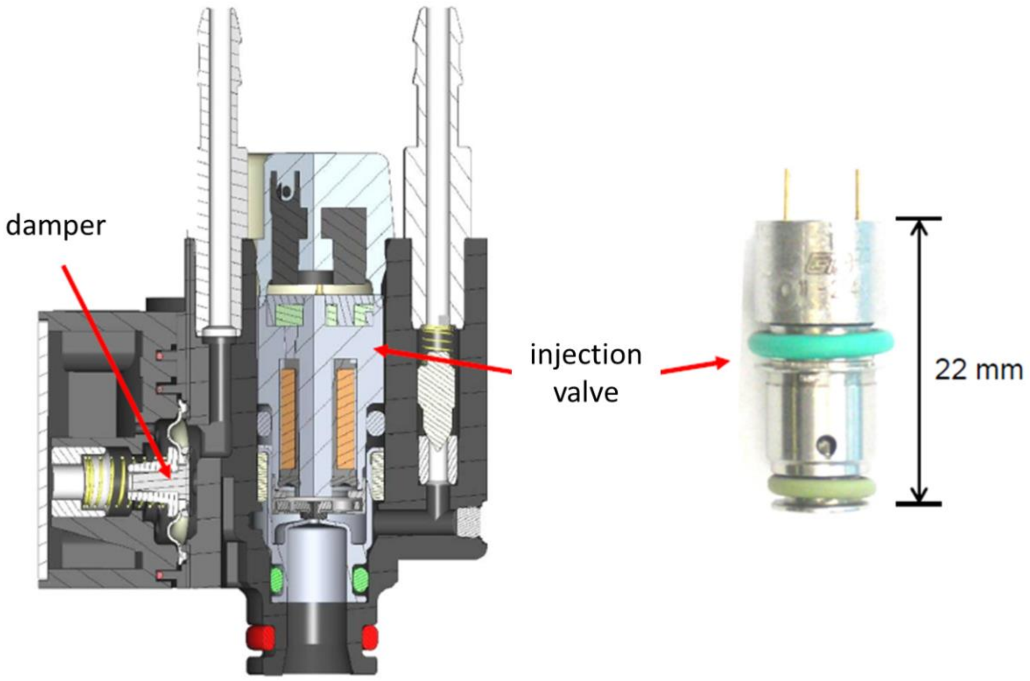


Figure 72 Injection valve - sectional drawing (left) and real-life injector (right) [109, p. 18]

The fuel injection is carried out cycle-synchronous once per revolution, i.e. one working cycle into the crankcase, whereby the frequency of the injections varies between 0 and 170 Hz with injection volumes from 1 mg up to 45 mg. This requires a high dynamic capability of the metering valve design, which is reached by normally closed plate-type armature valve. Figure 72 depicts the metering valve including pressure damper. The compact design of the injector valve meets the claim of low system inertia. The pressure damper consists of a spring-loaded diaphragm and is positioned upstream the valve in the plastic housing. The damper ensures constant pressure and smooths the pressure peaks which are caused in the high dynamic operation. The injection valve is cooled by the air of flywheel. Figure 73 shows the fuel pump of the STIHL injection system that guarantees the fuel supply in all positions. The fuel pump consists of a diaphragm pump, a pressure regulator and a manual pump. The diaphragm pump is controlled by the crankcase pressure. The additional manual pump facilitates the start, if the engine has been operated as long as until the fuel system was empty. The spring-loaded diaphragm pressure regulator adjusts the system pressure to 100 mbar above the atmospheric pressure. [80, p. 437] [108, pp. 674 - 679] [109] [110, pp. 4-5]

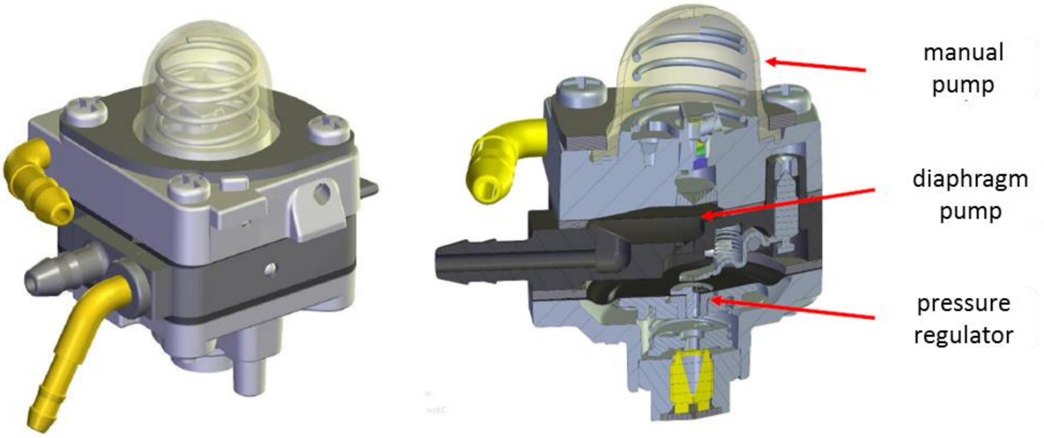


Figure 73 STIHL Injection system - fuel pump [109, p. 19]

The fuel injection timing takes place during the compression phase – piston is moving towards TDC – into the crankcase when below atmospheric pressure exists. The pressure drops below the system pressure at the metering valve and enable the fuel injection into the crankcase. The pressure varies between approximately 100 mbar and 450 mbar. Figure 74 demonstrates schematic the pressure ratios during the injection process into the crankcase. Due to the low system pressure of 100 mbar no primary atomization of the fuel is done at the metering valve such as at conventional injectors. The atomization is achieved by the turbulent air flow generated by the rotating crankshaft in the crankcase and in the transfer ports via the gas exchange. A correct tuning of the transfer port and the control timings permits stratified scavenging. [80, p. 437] [108, pp. 674 - 679] [109] [110, p. 6]

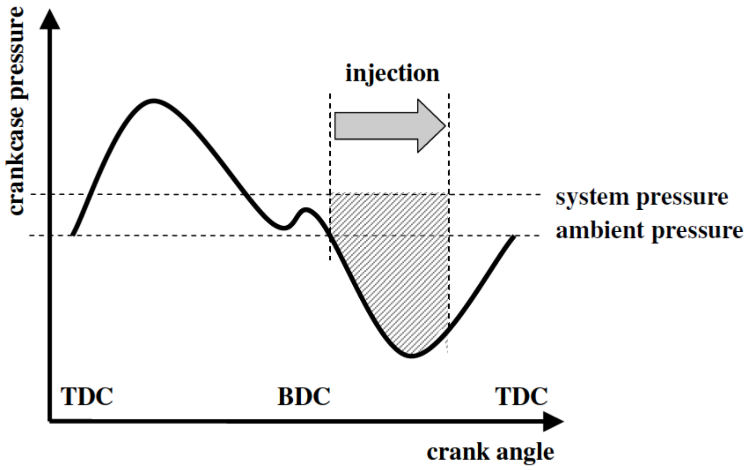


Figure 74 STIHL Injection – schematic pressure ratios in the crankcase [110, p. 6]

3.1.1.1.2.3 Low Pressure Direct Injection

3.1.1.1.2.3.1 2PHI – 2-Phase-Injection

The 2-Phase Injection system [102] [111] [112] [113] [114] [115] or also called LPDI for two-stroke engines was developed on the Institute of Internal Combustion Engines and Thermodynamics at Graz University of Technology and presented in late 2008. The main motivation of this development was to reduce the high HC emissions of two-stroke engines, which are caused by the scavenging losses with the air-fuel mixture especially with symmetrical port timing, to meet the increasingly stringent emission standards for mopeds and motorcycles. The limits of earlier standards could be reached with carbureted 2-stroke engines by exhaust after-treatment, such as with secondary air or at lean concepts with oxidation catalytic converter. [88, pp. 438-439] [111, p. 3]
The LPDI concept uses standard low pressure intake manifold injectors from the automobile sector. The fuel is injected by the standard low pressure injector, which is positioned opposite the exhaust port in the cylinder wall and is connected via a small duct with the combustion chamber. The LPDI differs between the direct injection mode – see Figure 75 – and the stratified mode – see Figure 76. At the direct injection port, the fuel is injected towards the piston surface into the air flow of the transfer passages. The direct injection can only be carried out, when the injection pressure is higher than the cylinder pressure and the duct into the combustion chamber is opened and not covered by the piston. At the stratified mode, the fuel is injected through an opening in the piston skirt towards the piston bottom. During the scavenging process, the “boost port” carries a rich air-fuel mixture (Figure 76 – green arrow) into the combustion chamber and the scavenging is done by the sideward transfer passages with lean air-fuel mixture. [88, pp. 438-439] [111, p. 3]

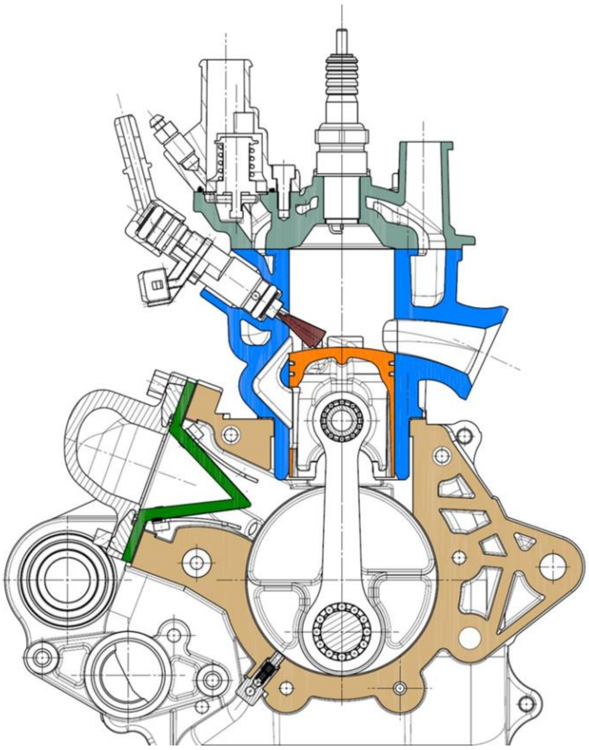


Figure 75 LPDI – direct injection mode [111, p. 4]

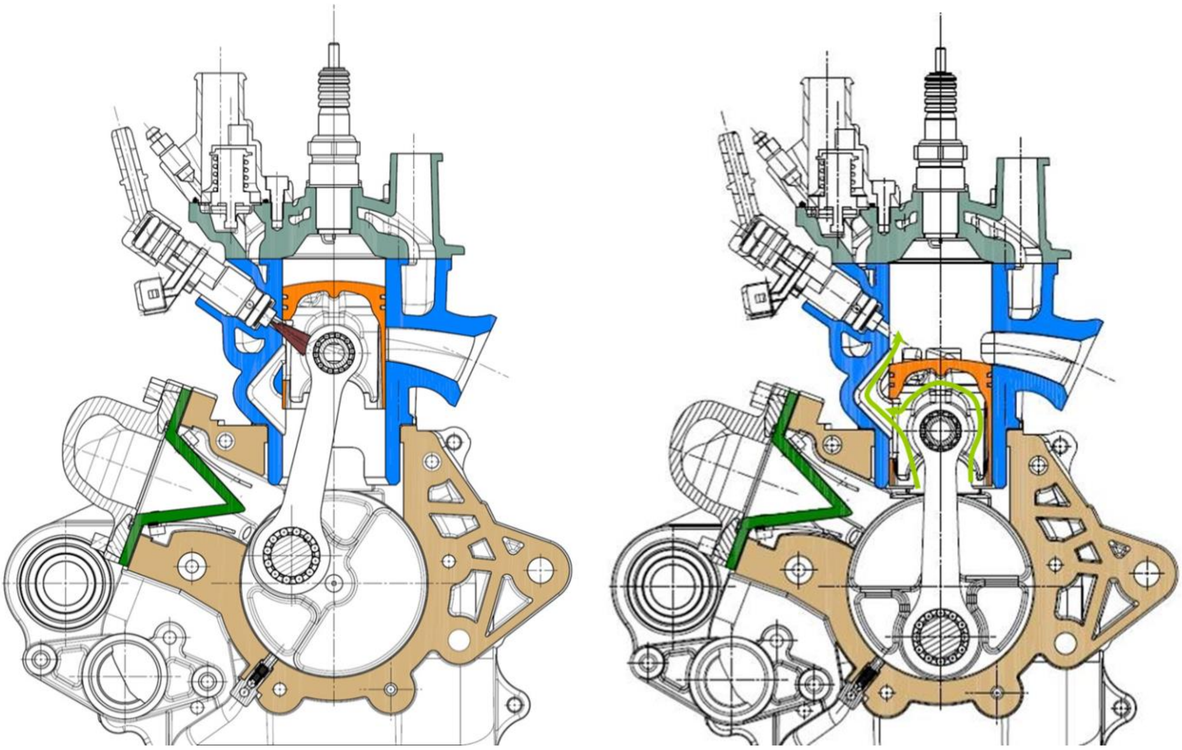


Figure 76 LPDI – stratified mode [111, p. 4]

The boost port causes less scavenging losses than the sideward transfer ports, and the HC emissions caused in the stratified mode are lower compared with a conventional scavenging process with air-fuel mixture. The switch between the direct injection mode and the stratified mode is done by the change of control timing. [111, pp. 3-4]

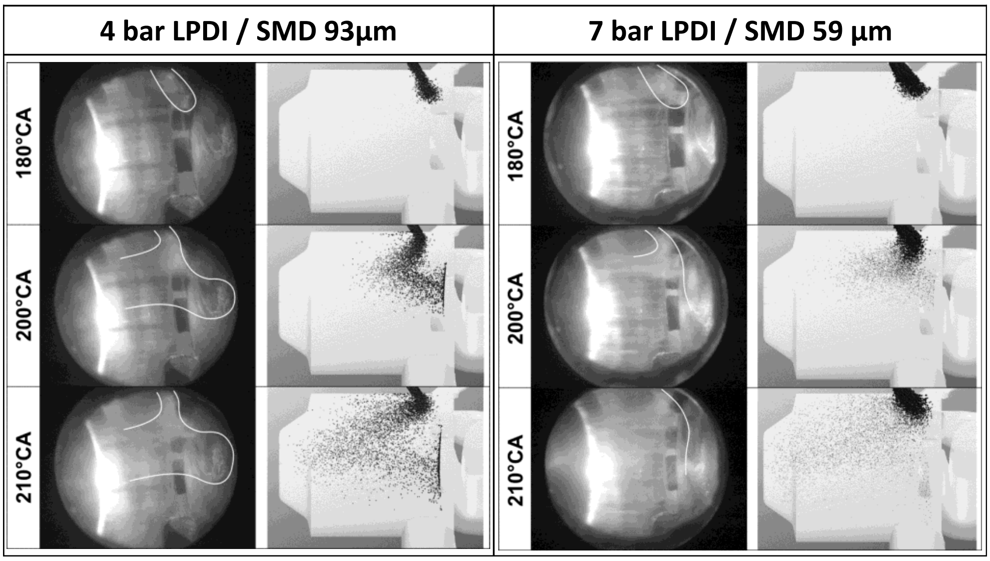


Figure 77 Comparison of the visualization and simulation results of a 4 bar and 7 bar LPDI injector at 6000 rpm, 5 bar BMEP and 160°CA SOI [111, p. 5]

Figure 77 shows the investigation of the direct injection process with a 4 bar two-hole injector and a 7 bar three-hole injector by visualization as well as simulation. The smaller droplets of the 7 bar injector lead to an earlier vaporization of the fuel [111, pp. 6-7]

3.1.1.1.2.4 Low Pressure Air-Assisted Direct Injection

3.1.1.1.2.4.1 ORBITAL Combustion Process (OCP) - Synerject aSDI

The Orbital Combustion Process (OCP) [77, pp. 93-94] [116] is an air-assisted direct injection system, which was first released in 1996 by the Orbital Corporation Ltd. company. The aim of the OPC was to create a dense air-fuel mixture with very fine fuel droplets by a low injection pressure. The OCP was developed as no suitable high-pressure injection systems were available to meet the requirements regarding mixture formation in dynamic operation of the engine that at that time. In cooperation with Siemens VDO, Synerject was founded and this enterprise marketed the injection system based on the OPC technology under the name of aSDI – air-assisted Synerject Direct Injection – for two-stroke engines. Figure 78 show the schematic diagram of aSDI. [88, pp. 118-119] [97] [101, pp. 48-49]

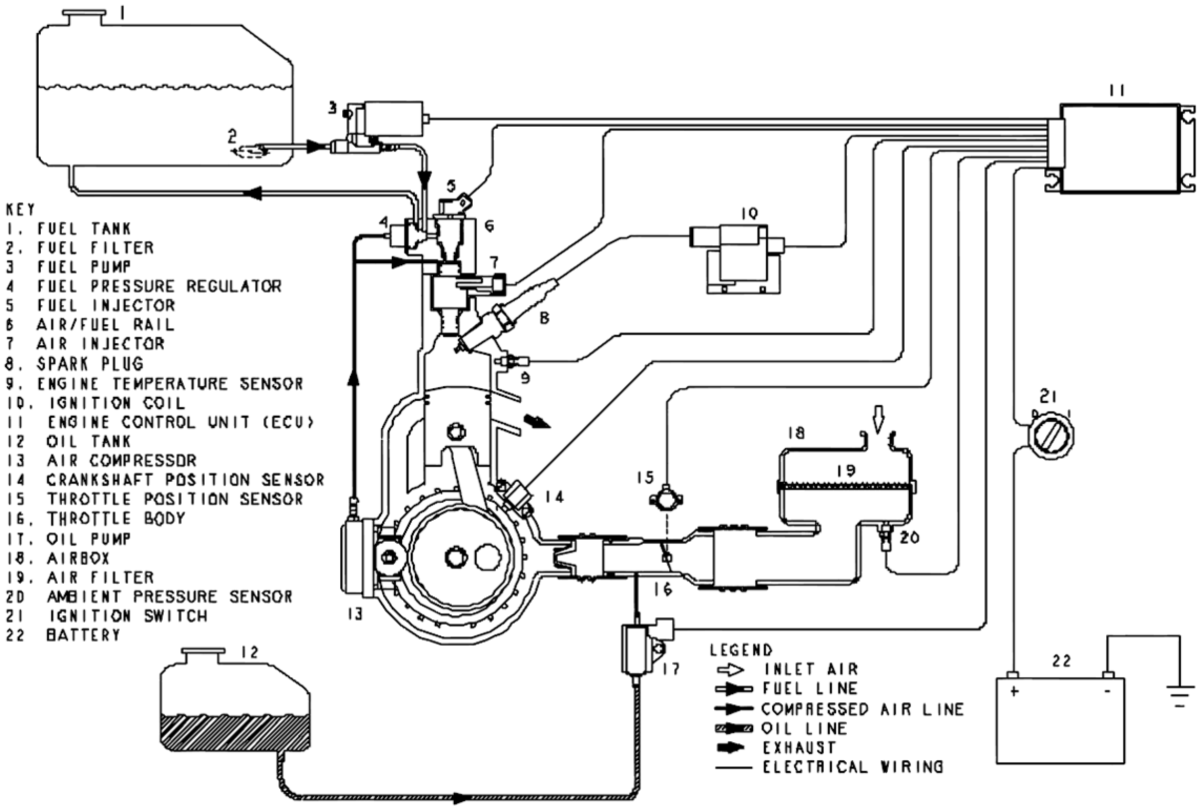


Figure 78 Synerject aSDI - schematic diagram [97, p. 191]

The air-assisted direct injection system essentially consists of an air compressor for the pressure generation, an air/fuel-rail and an electronically controlled admixture for air and the air-fuel mixture. Synerject aSDI injects a pre-mixed air-fuel mixture into the combustion chamber. The pre-mixed air-fuel mixture is prepared in the pre-mixing chamber, which represents the air/fuel-rail at the same time. The required compressed air for the air-assisted injection system is provided by the air compressor. The compressor is either driven via V-belts, gears or directly by the crankshaft. The compressed air is directly pressed, without a metering valve, into the pre-mixing chamber with approximately 5 bar. The fuel is injected by a standard low-pressure injector, into the pre-mixing chamber with about 6.5 bar, thus a considerable proportion of fuel is already evaporated before the actual injection into the combustion chamber. The pre-mixed air-fuel mixture is injected by a metering valve into the combustion chamber. Both, the standard low-pressure injector and the metering valve are controlled by the ECU. [88, pp. 118-119] [101, pp. 48-49]

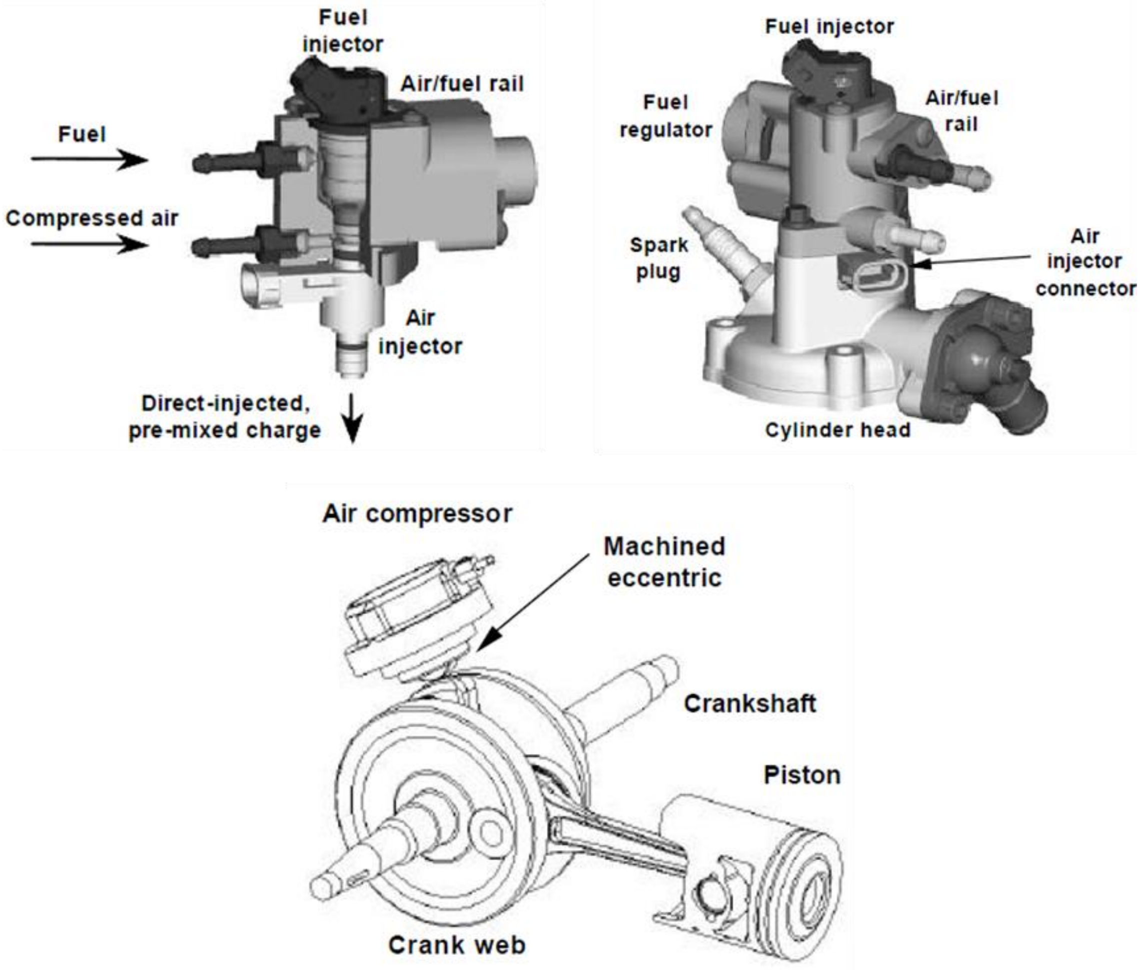


Figure 79 Synerject aSDI – injector unit including mounting position on the cylinder head (above) and air compressor drive (below) [97, pp. 9, 11]

Figure 79 depicts, on the left side above, the injection unit of the Synerject aSDI consisting of the inlets for the compressed air and fuel, the fuel injector, the pre-mixing chamber alias air/fuel rail and the metering valve for the injection into the combustion chamber. The mounting position of the injector unit on the cylinder head is shown above on the right side and the air compressor is pictured below, which is directly driven by the crankshaft. This air-assisted direct injection system was used in series applications such as in a 50 cm^3 two-stroke scooter engine from Aprilia [95] [96], in the 50 cm^3 engine of the Peugeot JetForce and in the two-stroke engines of marine applications up to 500 cm^3 by BRP Rotax, Tohatsu and Mercury. [101, pp. 48-49]

The Direct Mixture Injection (DMI) system [117] [118] [119] [120] from AVL List GmbH uses the combustion pressure to create overpressure in a mixing chamber for the fuel injection. At the compression phase, compressed gas is taken from the combustion chamber and is led into the mixing chamber. The high pressure gas together with fuel is used to generate a very rich air-fuel mixture, which is injected into the cylinder through an injector. [101, p. 51]

3.1.1.1.2.4.2 DOLCE – Air-assisted Direct Injection System

The air-assisted direct injection system DOLCE for two stroke engines was developed in the course of a European project – **D**evelopment **O**f innovative **L**ow pollutant, low noise, low fuel **C**onsumption two-stroke spark ignition **E**ngines for future vehicles for individual urban mobility – by Piaggio, Institut Français du Pétrole (IFP), Graz University of Technology Magneti Marelli and ROSI – now Meritor. [89, pp. 8-9] [121, pp. 417-420] [122]

An electrically driven low-pressure fuel pump ensures the fuel supply with 3 bar to a maximum of 5 bar. A standard low-pressure single-jet injector – “MMAR Pico Injector” – (in Figure 80 described as injection valve) from the automobile industry injects once per piston stroke the appropriate amount of fuel into the cylinder of a piston compressor (in Figure 80 designated as injection cylinder) with a displacement of 10 cm³. Due to the fuel injection into the piston compressor a first mixture formation reaction occurs. The rich air-fuel mixture is pressed by the external driven piston compressor (injection pump in Figure 80) through the spring-loaded valve (DOLCE injection valve in Figure 80) into the combustion chamber. The high velocities during the injection process into the combustion chamber effects a fine distribution of fuel droplets – second mixture formation. The air mass flow into the piston compressor is controlled by integrated metering slots in the crankshaft. The phasing for the injection process into the combustion chamber is chosen at the control time close to “exhaust port closes” to prevent scavenging losses. [89, pp. 172-173]

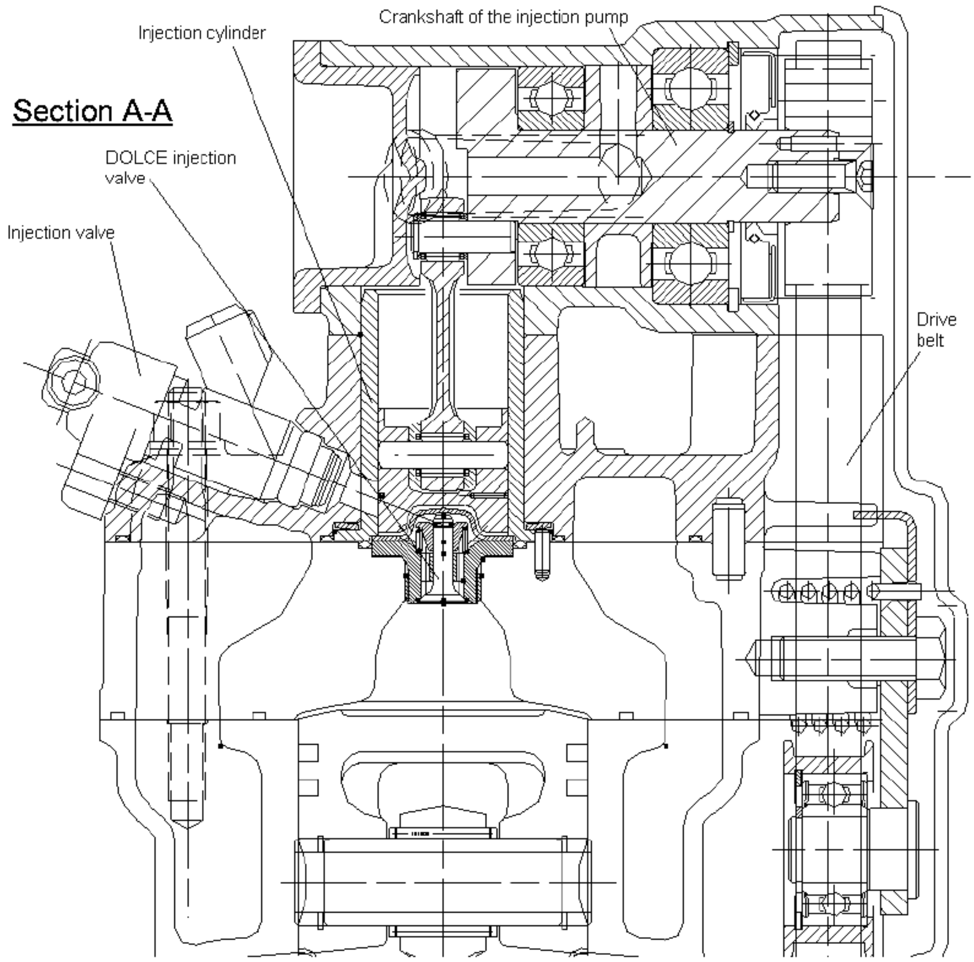


Figure 80 DOLCE Injection System - cross section [89, p. 19]

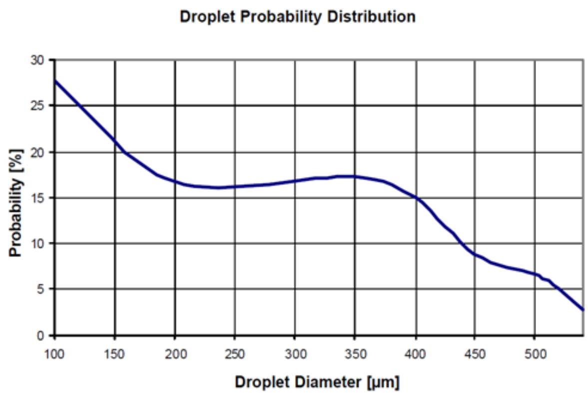


Figure 81 Distribution of fuel droplet diameter measured by the supplier of the MMAR Pico Injector [89, p. 67]

3.1.1.1.2.4.3 IAPAC/SCIP – Air-assisted Injection System

The "Injection Assistée Par Air Comprimé" (IAPAC) [123] [124] [125] [126] or "crankcase compressed air-assisted fuel injection" system for two-stroke engines was developed at the Institut Français du Pétrole (IFP), mainly for the application in marine outboards and small two-stroke engines. The IAPAC was developed with the claim to reduce the HC emissions of two-stroke engines, which are caused by the scavenging losses and the poor combustion at partial load. [101, p. 47] [126, pp. 101-111]

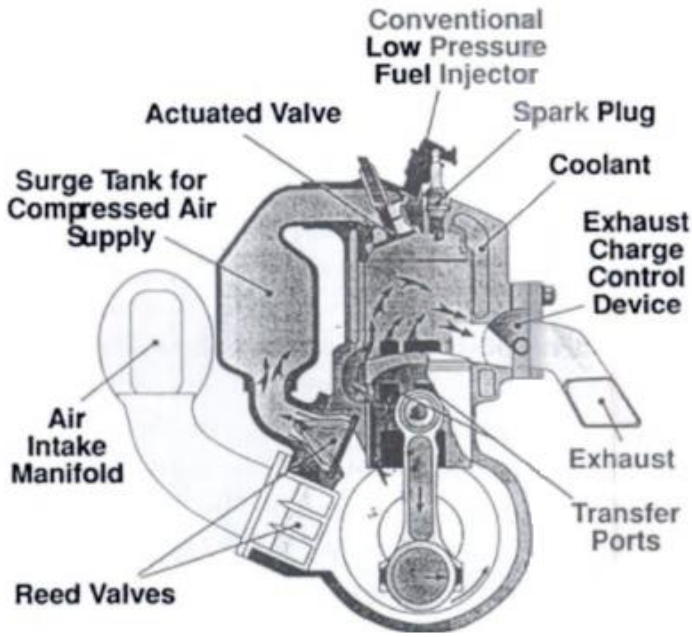


Figure 82 IAPAC two-stroke engine – schematic view [126, p. 102]

Figure 82 presents a schematic view of the IAPAC injection system. It consists of a surge tank for compressed air supply of the fuel injection device, an intake valve designed as poppet valve with venturi inlet cross section which is actuated by a camshaft and a standard single injector from a multipoint fuel injection system. [126, pp. 102-104]

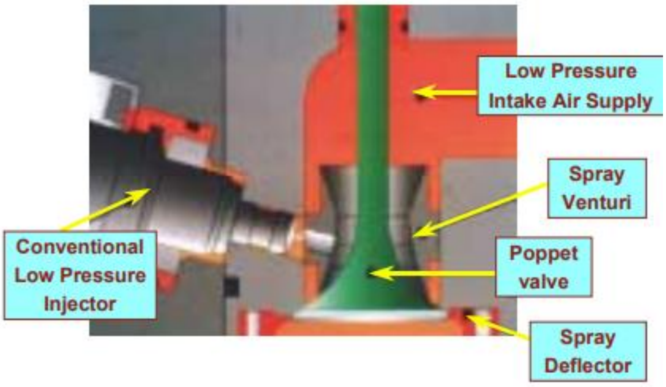


Figure 83 Cross section of the IAPAC system [123, p. 3]

The “crankcase compressed air-assisted fuel injection” system stores the compressed air generated in the crankcase in the surge tank. The surge tank is connected via reed valve to the crankcase and through a flexible pipe with the cylinder head, and supplies the injection unit with compressed air for the injection. The single injector injects the fuel in front of the intake valve and creates a rich air-fuel mixture at low pressure. When the intake valve opens, the mixture flows into the combustion chamber and the venturi inlet cross section of the intake valve ensures a good atomization at low penetration. [101, p. 47] [126, pp. 102-106]
The SCIP system – Simplified Camless IAPAC” – was also developed at the IFP France and is based on the IAPAC system with the difference that no external driven camshaft for the actuation of the intake valve is used [127] [128] [129]. Instead, the intake valve is actuated by a diaphragm, which is controlled by the pressure conditions at the transfer passages and need a considerable developing effort for the correct tuning. Figure 84 depicts the SCIP bolt-on injector unit with diaphragm actuation. [89, p. 17] [128, pp. 1-3]

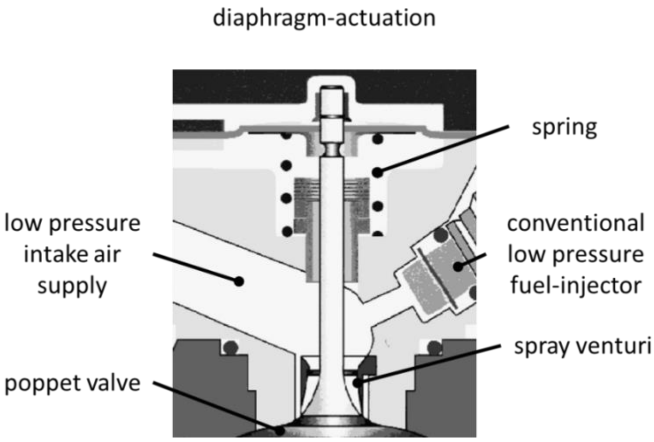


Figure 84 SCIP camless air-assisted bolt-on injector unit; adapted from [89, p. 17] [128, p. 3]

The “Delayed Charging” system by P. Rochelle [130] [131] [132] is another air-assisted injection system for two-stroke engines and represents in principle a modification of both injection systems described above. An additionally surge tank is supplied with pressure via the crankcase and provides the required compressed air for the injection and the scavenging process by a separate transfer passage into the combustion chamber. The fuel is injected into the separate transfer passage by an electronically controlled injector. [101, p. 48]

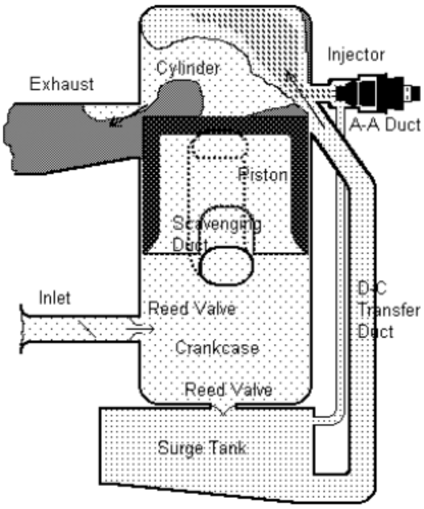


Figure 85 Schematic view of the "Delayed Charging" system by P. Rochelle [132, p. 4]

3.1.1.1.2.5 High Pressure Direct Injection

In general, gasoline direct injection systems offer benefits with regard to an improvement of fuel consumption and emissions, and besides it allows effective downsizing. High pressure direct injection system uses an electric fuel pump (low pressure circuit) to pump the fuel through a filter to the high pressure pump. The pressure is either constant or variable adjustable between 2 bar to 6 bar, but it is always chosen in such way that no vapor-bubble formation occurs. The high pressure pump generates according to the engine operating point an appropriate system pressure of about 50 bar to 200 bar, in current developments system pressures beyond 300 bar are reached. The distribution of the fuel is done via a high pressure rail, which is connected with the high pressure injectors. The system pressure in the rail is monitored by the ECU via a pressure sensor and is used to control the pressure and the amount of fuel of the high pressure pump. Moreover, the ECU controls the injection timing of the high pressure injectors. [76, pp. 117-120] [104, pp. 344-350]
The main use of the following high pressure injectors is in the automotive sector. The electromagnetic high pressure injector is also used in few small-engine applications (for example see [101]). Piezo injectors are mentioned here only for the sake of completeness.

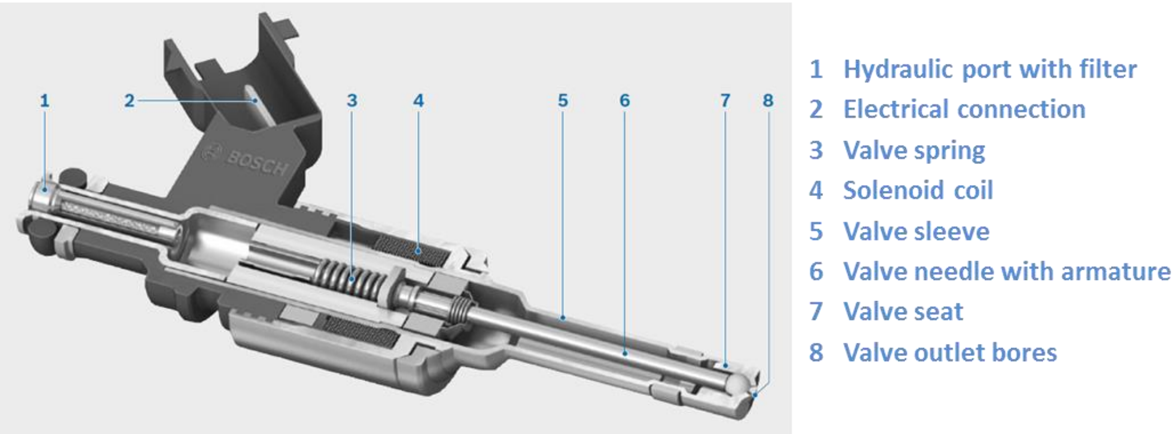


Figure 86 Electromagnetic high pressure injector; adapted from [76, p. 130] [104, p. 347]

Figure 86 shows the structure of an electromagnetic high pressure injector. When the solenoid coil (4) is energized, the valve needle with armature is lifted from the valve seat (7) against the valve spring (3) force by the resulting magnetic field. Thus, the valve outlet bores (8) are released from the valve needle and the fuel is injected with system pressure into the combustion chamber. The amount of injected fuel depends on system pressure and on the duration of valve opening. When the current is powered off, the spring force closes the valve. [76, p. 130]
Piezo injectors (Figure 87) are characterized by extremely short switching times and a variable needle lift (full- and partial-lift), whereby an exact fuel metering is possible. The nozzle module consists of the spring-loaded valve needle and the valve body. The valve needle is directly actuated by the piezo-stack and opens outwardly, whereby the opening and closing occurs without delay. The piezo actuator module contains the piezo-stacks and is pre-loaded by a surrounded compression spring. Neither in the restricted position nor in deflected position is a tensile stress allowed for the actuator. The coupler functions as a compensation

element between valve housing and piezo-stack, which is necessary due to the different elongations that are caused by the temperature influence. Piezo-injectors reach switching times below of 0.2 ms and are especially suitable for multiple injections due to their function principle. In addition, piezo-injectors show an excellent reproducibility and a high accuracy of the valve needle lift from cycle to cycle. Typical piezo-injectors achieve SMD of below 15 μm. [77, pp. 91-93] [104, pp. 348-349]

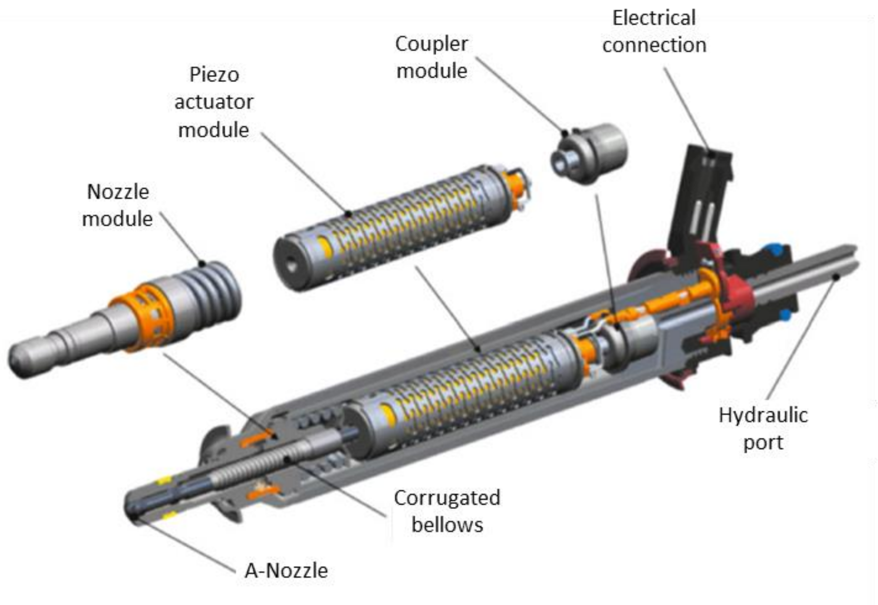


Figure 87 Piezo-injector; adapted from [104, p. 348]

3.1.1.1.2.5.1 "Ram Tuned" Injection Systems

The "ram tuned" or also called "water hammer" effect was developed at the University of Zwickau by C. Stan and is described in [133] as follows:

"The ram- tuned effect is based on the sudden impact between a fluid and a solid body, when a relative velocity between both is stopped. On principle both the acceleration of the fluid and its impact on a stationary body, respectively the acceleration of the solid body and its impact on a stationary fluid are possible. For the same reached relative velocity between both at the moment of the impact and for similar physical conditions the pressure rise at the impact will attempt the same level."

Two different concepts exist to utilize the principle of the accelerated fluid and its impact on a stationary solid. On the one hand the "Ram Tuned" injection system by C. Stan and, on the other, the "Water Hammer Gasoline Direct Injection System" (WH-GDIS) by Bartolini. [101, pp. 44-45]

The "Ram Tuned" injection system by Stan [98] [134] [133] [135] [136] uses the high pressure impulse caused by the "ram tuned" effect to control directly a spring-loaded fuel injector for the injection. Figure 88 presents the schematic diagram of this system. The fuel flows through the damper, the acceleration pipe, the solenoid valve and the return pipe back into the fuel reservoir, when the electrically controlled solenoid valve is opened. The maximum flow velocity of the fuel depends on the pressure difference between the reservoir and the initial pressure of the pump. The sudden closure of the solenoid valve results in a flow impact on the armature and consequently generates a pressure impulse that is 10 to 15 times higher than the initial pressure. The pressure wave propagates with sound velocity through the acceleration pipe and is reflected at the damper. The amplitude of the reflected pressure wave depends on the fluid-dynamic characteristics of the damper. The spring-loaded injector is actuated by the high pressure wave and starts the injection process. [101, pp. 44-45] [133, pp. 2-3]

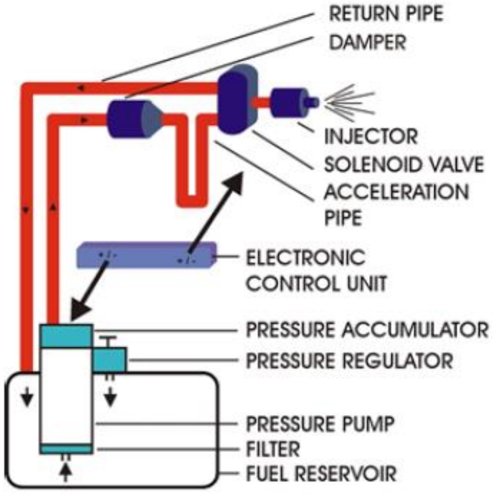


Figure 88 Schematic diagram of the “Ram-Tuned” injection system by C. Stan [87, p. 18]

The WH-GDIS by Bartolini [137] [138] consists of a low pressure and a high pressure circuit. The low pressure circuit acts as “water hammer oscillating circuit”. The fuel is delivered with high flow-rate by the pump through the acceleration pipe and the automatic valve back in the reservoir. In contrast to the electrically control of solenoid valve of the “Ram Tuned” injection system, the automatic valve is controlled by the fluid pressure. A closure of the automatic valve starts the oscillating process and causes the “ram tuned” effect. The resulting pressure wave passes through the acceleration pipe to the fuel pump and is reflected. When the reflected wave has reached the automatic valve, the valve opens and the fuel circulates again in the low-pressure circuit. A further oscillating cycle begins at a renewed closure of the automatic valve. The high pressure circuit is connected through a check valve with the low pressure circuit. At the moment, when the pressure in the acceleration pipe exceeds the pressure level in the high pressure capacity owing to the “ram tuned” effect, the check valve opens and the low pressure circuit provides the high pressure fuel for the high pressure capacity for the injection. The check valve is closed by a drop in pressure in the acceleration pipe. The high pressure capacity is equipped with a pressure regulator, which is designed as relief valve, to ensure the injection pressure constant. The injection is carried out by a conventional electrically controlled high pressure injector. In contrast to the “Ram Tuned” injection system, the injection frequency is separated from the pressure supply frequency, thus, this system is more flexible but also more expensive. [101, pp. 44-45] [137, pp. 3-4]

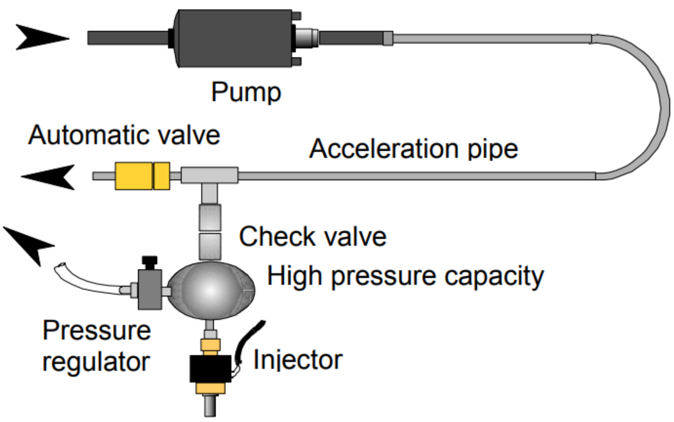


Figure 89 Schematic view of the WH-GDIS by Bartolini [137, p. 3]

3.1.1.1.2.5.2 FICHT RAM/E-TEC Direct Fuel Injection

In contrast to the "Ram Tuned"/"WH-GDIS" injection systems, the FICHT Fuel Injection (FFI) system [139] [140] [141] [115] is based on the principle of the accelerated solid and its impact on a stationary fluid. As of 1988, the company FICHT GmbH – today Provenion – has further developed this principle and, in 1993, the research for applying this injection system in outboard engines in cooperation with OMC – today BRP – was continued. OMC licensed the FFI and marketed it in ENVIRUDE outboard engines, starting with two-cylinder in-line engine up to V6 engines, from 1995 until the acquisition of the company by BRP. Then the FFI was replaced by a further developed FFI system, the E-TEC system. Even Kawasaki used the FFI system in a two-stroke three-cylinder engine, which is applied in Jet Skis. [92] [101, pp. 43-44] [102, p. 38]

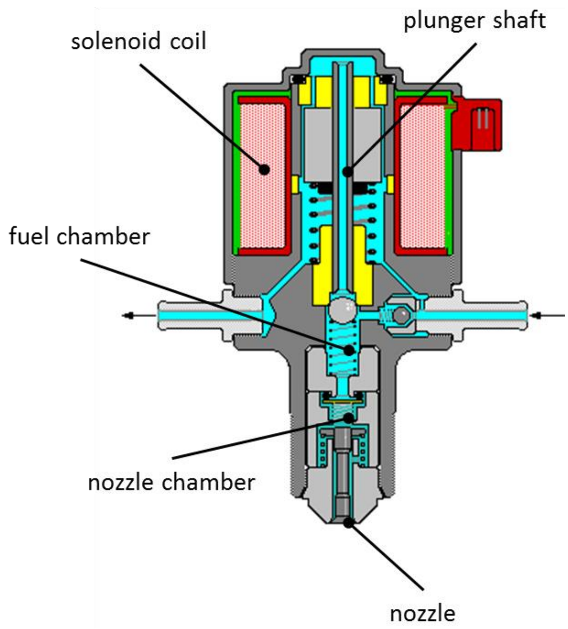


Figure 90 FICHT Injector; adapted from [92]

The fuel is supplied by a low pressure fuel pump through a fuel filter and a vapor separator to the FICHT injector (see Figure 90), which is positioned at the cylinder head and injects directly into the combustion chamber. The FICHT injector principally consists of a solenoid coil, a movable plunger, a fuel chamber with two check valves that lock in contrary direction and a pressure controlled injection valve. The plunger is accelerated by the magnetic field of the energized solenoid coil and impacts on the fuel volume in the fuel chamber and generates the high pressure by the "ram tuned" effect for the injection. The energization of the solenoid coil is controlled by the ECU. [101, pp. 43-44] [102, p. 38]

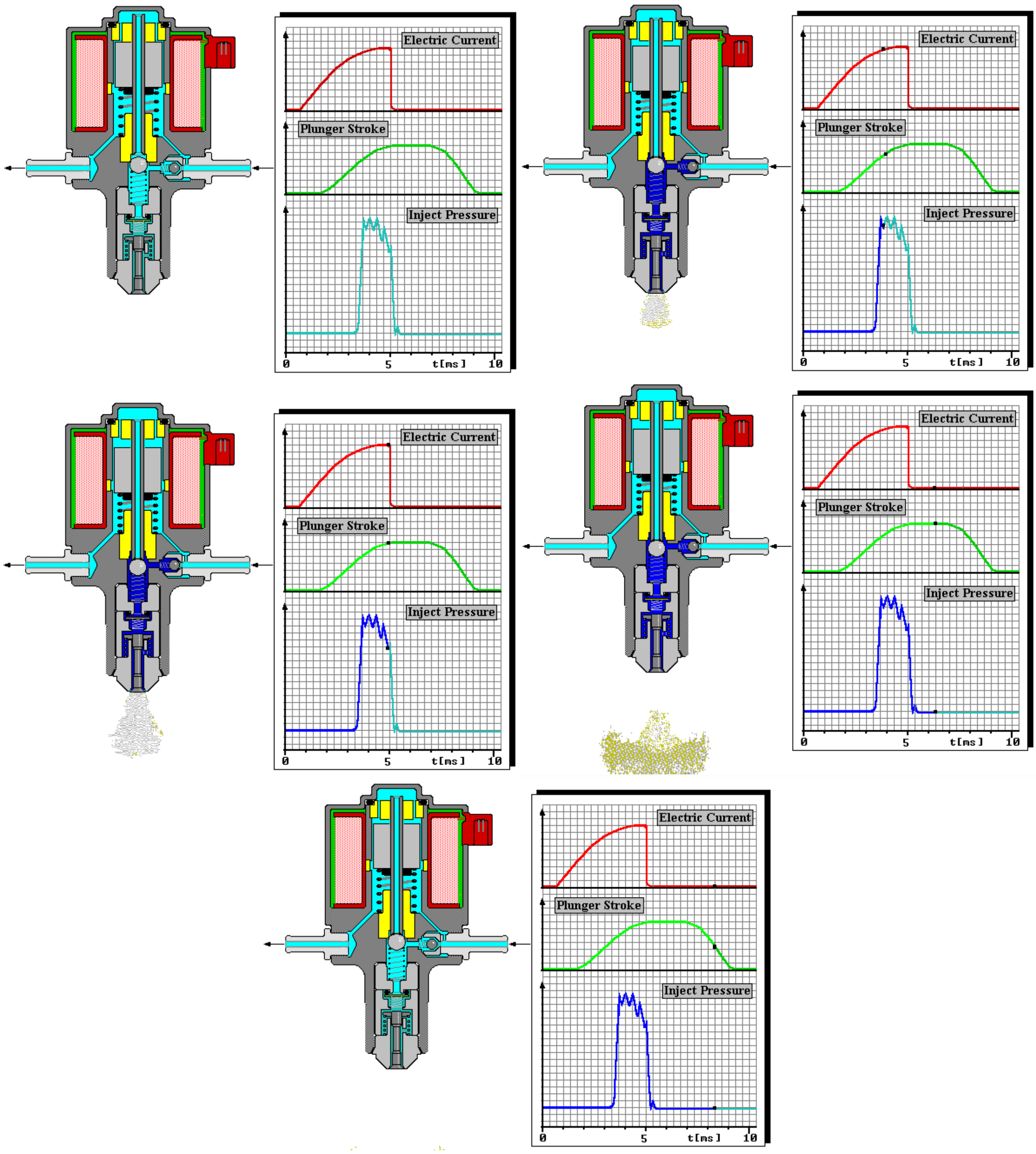


Figure 91 FICHT Fuel Injection (FFI) - injection process [92]

Figure 91 shows the FICHT injector (left) and the graphed electric current for the energization of the solenoid coil, the stroke of the plunger and the injection pressure during one injection process (right). The main advantages of the FFI are that no high-pressure pump is needed to generate high fuel pressure (≈ 40 bar) and the reduction of HC emissions. Moreover, it is the possibility to operate the engine at idle speed and low partial load ranges with stratified charge and at full load with homogeneous charge. The HC emissions are reduced, as the fuel is injected when exhaust ports are closed and, therewith, the scavenging losses are avoided. The greatest disadvantages are the required 55 V power supply for the solenoid coil actuation and the filing of the calibrating data of the FICHT injector in the appropriate ECU to compensate manufacturing tolerances, which has to be done for each injector. [101, pp. 43-44] [102, p. 38]

The E-TEC injection system is a further development of the FFI and uses also the “ram” effect to generate high pressure (≈ 50 bar). The major difference regarding FFI is the actuation of the plunger. Instead of the solenoid coil of the FFI, the E-TEC uses a so-called “voice coil”, the same principle as in loudspeakers. The FFI injector operation is based on the “either/or” principle, the injector is either completely open or closed. The voice coil of the E-TEC system permits a variable actuation of the plunger and thus the injected fuel volume can be handled better by a faster response and a higher actuation frequency. Figure 92 shows an E-TEC injector (left – closed; right – actuated) and Figure 149 presents a sectional drawing of the Rotax 850 two-cylinder two-stroke engine with E-TEC injection and 121 kW at 8000 rpm.

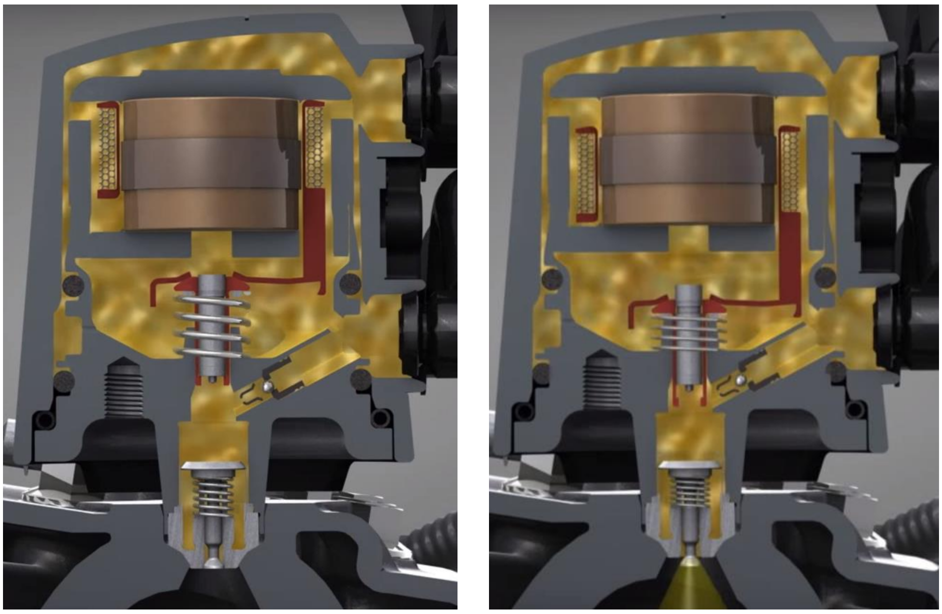


Figure 92 E-TEC injector [142]

3.1.1.1.2.5.3 Compression Wave Injection (CWI)

The Compression Wave Injection system was developed by W. Cobb (company DMS) in cooperation with John Deere for two-stroke engine applications, such as handheld garden and lawn equipment. [101, p. 50] [143] [99, p. 1]
The CWI system uses a compression wave, which is generated by the combustion, to inject a rich air-fuel mixture into the combustion chamber. The reflected compression wave is used, on the one hand, for the fuel preparation and, on the other hand, for the supply of rich air-fuel mixture to the cylinder. Figure 93 displays the main components of a two-stroke engine with CWI. The connection of CWI-tube or injector tube and cylinder is called injection port. The position of the fuel supply to the CWI tube is close to the injection port. The fuel is supplied

by a vacuum type of carburetor. In the simplest design, the CWI tube is designed as a tube that is closed at one side, which would operate well at a steady state speed. At engine start up and operating points with missing combustion, such as misfires, no air-fuel mixture reaches the combustion chamber. For that reason, the other end of the CWI tube is connected to the crankcase, the so-called charge port, instead is simply closed, to use a part of the scavenging flow to get the fuel to the cylinder. The injection port and the charge port of the CWI tube are chosen in such way that the injection begins shortly after the exhaust port is closed and simultaneously the charge port is covered by the piston skirt. [99, pp. 1-6]

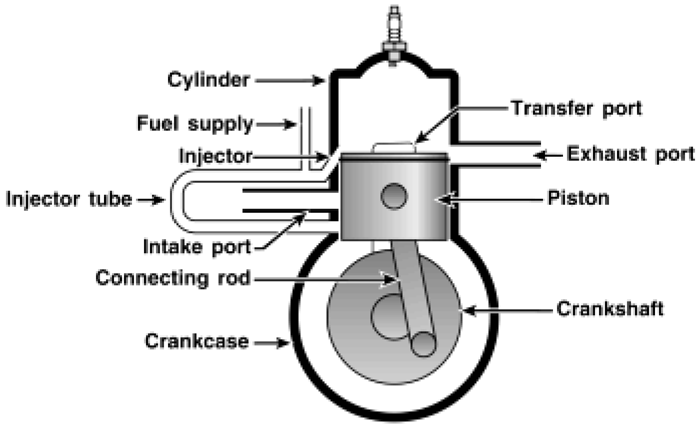


Figure 93 Main components of the CWI-technology [144]

Figure 94 illustrates the principle of CWI at one working cycle. In the compression phase, a very lean mixture is sucked into the crankcase for lubrication and simultaneously, a rich air-fuel mixture is delivered by the carburetor into the CWI tube. In the expansion phase, the lean air-fuel mixture in the crankcase and the rich mixture in the CWI tube are compressed by the downward moving piston. A check valve in the fuel supply pipe prevents a flow back to the carburetor. The piston skirt closes the charge port of the CWI tube before it opens the injection port, which is the case shortly after the exhaust port is opened. The hot gases of the combustion aid the mixture preparation and generate a pressure wave in the CWI tube, which is reflected at the end of the tube on the piston skirt. In the meantime, the combustion chamber is scavenged with the lean mixture in the crankcase. The reflected pressure wave carries the rich air-fuel mixture in the CWI tube towards the cylinder and the injection occurs with corresponding tuning after the exhaust port is closed. The engine speed range of perfect operation of the CWI system is defined by the length of the CWI tube and the control timing of injection process. [99, pp. 1-18] [80, p. 434]

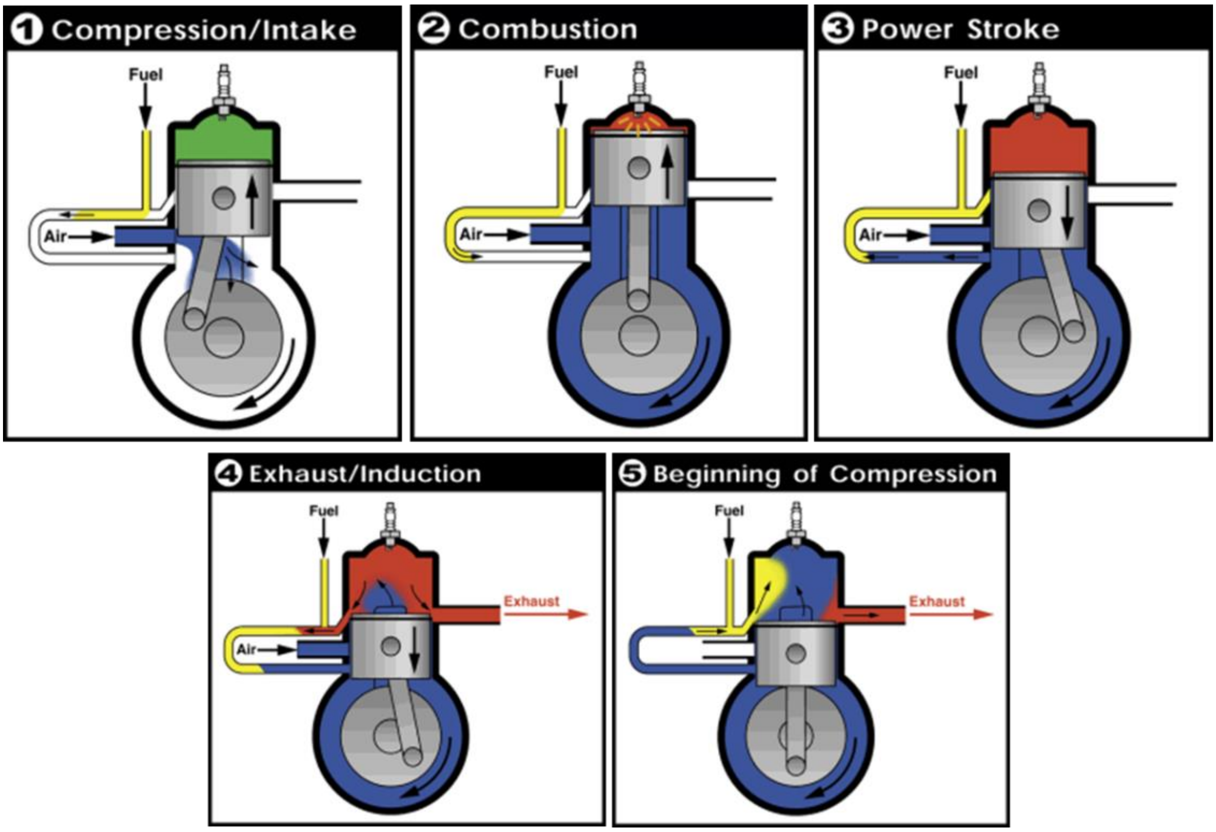


Figure 94 Principle of the Compression Wave Injection [144]

3.1.1.2 Ignition Systems

In general, the main task of the ignition systems in gasoline engines is to provide high voltage for the generation of a spark at the spark plug, which ignites the air-fuel mixture and starts the combustion process. The ignition energy can be stored in two ways, inductive – coil ignition [145] – and capacitive – Capacitor Discharge Ignition (CDI) [146]. Ignition systems are characterized by the provided high voltage, the rise time of the high voltage at the spark plug, the spark energy and the spark duration. Typical spark energy values are 25 mJ to 50 mJ for naturally aspirated engines and above of 100 mJ for turbocharged engines and DI-engines with charge stratification. In general, engines with high content of residual gas need higher ignition energy. Over time, only two approaches of the various solutions could be established on a larger scale. This is, on the one hand, the magneto ignition system and, on the other hand, the battery ignition system.

The magneto ignition system was already developed in the 19th century and today, it is mainly used in applications and vehicles wherever no or no resilient electrical system is available, such as in lawnmowers, chainsaws or other handheld equipment. In addition, it is used in some two-wheelers, where it is used in combination with a capacitive buffering of the ignition energy. The magneto ignition system (Figure 95) distinguishes between the designs with stationary magnet and rotating armature and vice versa, between rotating magnet und stationary armature. In both cases, the kinetic energy is converted into electrical energy in the primary winding by means of magnetic induction, which is transformed into a high voltage in the secondary winding. The ignition timing is done by the interruption of the current in the primary winding with a contact breaker or a transistor. A big disadvantage of the magneto ignition system is the fact that the ignition parameters, especially the peak voltage, depends on the engine speed. [77, pp. 129-133] [76, pp. 138-173] [147, pp. 362-363] [148, pp. 189-204]

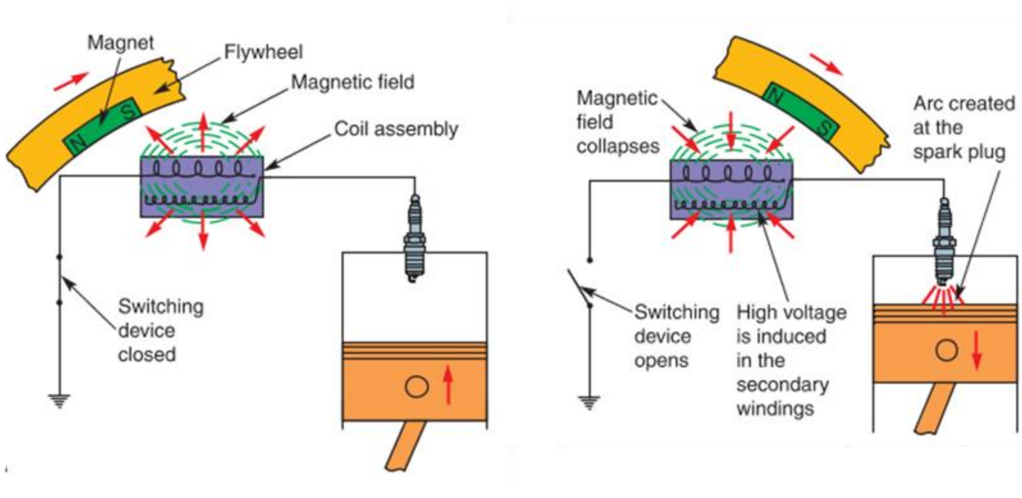


Figure 95 Schematic view of a magneto ignition system; adapted from [148, p. 190]

Nowadays, the battery ignition system is state of the art in passenger cars and is also applied in motorcycles. The coil ignition (Figure 96 – left) is most widely used and utilizes the ignition coil as transformer and as storage for the ignition energy. A timed transistor interrupts the current flow, whereby a voltage is induced in the primary and secondary winding. On the secondary circuit, the high voltage leads to the ignition spark between the electrodes at the spark plug. In the past, mechanical breaker points were used instead of the transistor. The mechanical breaker point was affected by contact erosion, which led to shifts of the ignition points.

At a later stage, transistors were used to switch the primary current, whereby the risk of contact erosion was reduced due to the lower current that is required to switch the transistor. Another step was the replacement of the mechanical breaker point by Hall pick-up or induction pick up. The next development step was the electronic ignition system. Thereby, the ignition angle is determined in dependency of the engine speed and load by maps, which are stored in the ignition control unit. In addition, the ignition control unit can also consider parameters such as engine temperature. The last development step was the distributor less semiconductor ignition system for multi-cylinder engines, which operates without mechanical ignition distributor. This distributor less ignition system usually uses one ignition coil per cylinder. The mechanical functions of inductive ignition system have been replaced step by step by electric functions.

The CDI (Figure 96 - right) stores the ignition energy of the battery in the electrical field of a capacitor in the primary circuit. The capacitor is discharged by a switching process of the thyristor, whereby the resulting current generates a voltage at the primary winding. The ratio of the transformer causes a high voltage at secondary circuit, which is necessary for the ignition spark. The spark duration is about 0.1 ms to 0.3 ms and is therefore significantly shorter than at coil ignition systems. As a result of the short spark duration, the ignition of the air-fuel mixture cannot be ensured in some cases, such as for example at charge stratification. [77, pp. 129-133] [76, pp. 138-173] [147, pp. 362-363] [148, pp. 189-204]

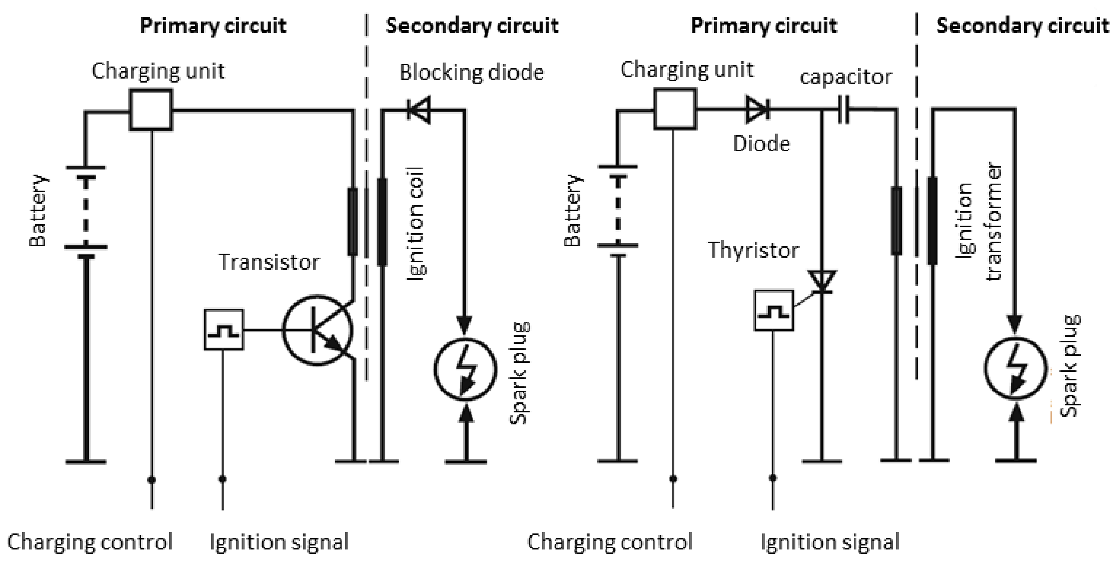


Figure 96 Schematic view of coil ignition (left) and capacitor discharge ignition (right); adapted from [77, p. 129]

3.1.1.3 Engine Management Systems

In the beginning of the 1980s, first motorcycle manufacturers started with the introduction of electronic fuel injection systems (EFI), which should replace the carburetors used heretofore. The first company was Kawasaki, which made efforts to implement EFI systems in their two-wheelers. Consequently, Kawasaki equipped the first series-produced motorcycle, the KZ1000 also called Z-1 Classic, with an EFI system, in 1980. The EFI system for Kawasaki motorcycles was based on the concept of BOSCH`s Jetronic, which was also used in the car Datsun (Nissan) 280Z in an adapted version at that time. This EFI system was manufactured by Japan Precision Electronics that owned the rights to produce BOSCH`s Jetronic system for motorcycles. The ECU of the EFI system is monitored and processed the data of the engine speed and temperature, the intake air mass flow and the intake air flow temperature, and thereof the ECU determine the trigger point of the fuel injectors. In 1981, Kawasaki fitted also the new GPz1100 with an EFI system. Due to the fact that EFI systems in the early introduction phase caused performance and reliability issues, inter alia the EFI of the GPz1100, more often customers replaced the EFI systems by carburetors, in both motorcycles and cars. [149] [150] [151, pp. 17-20]

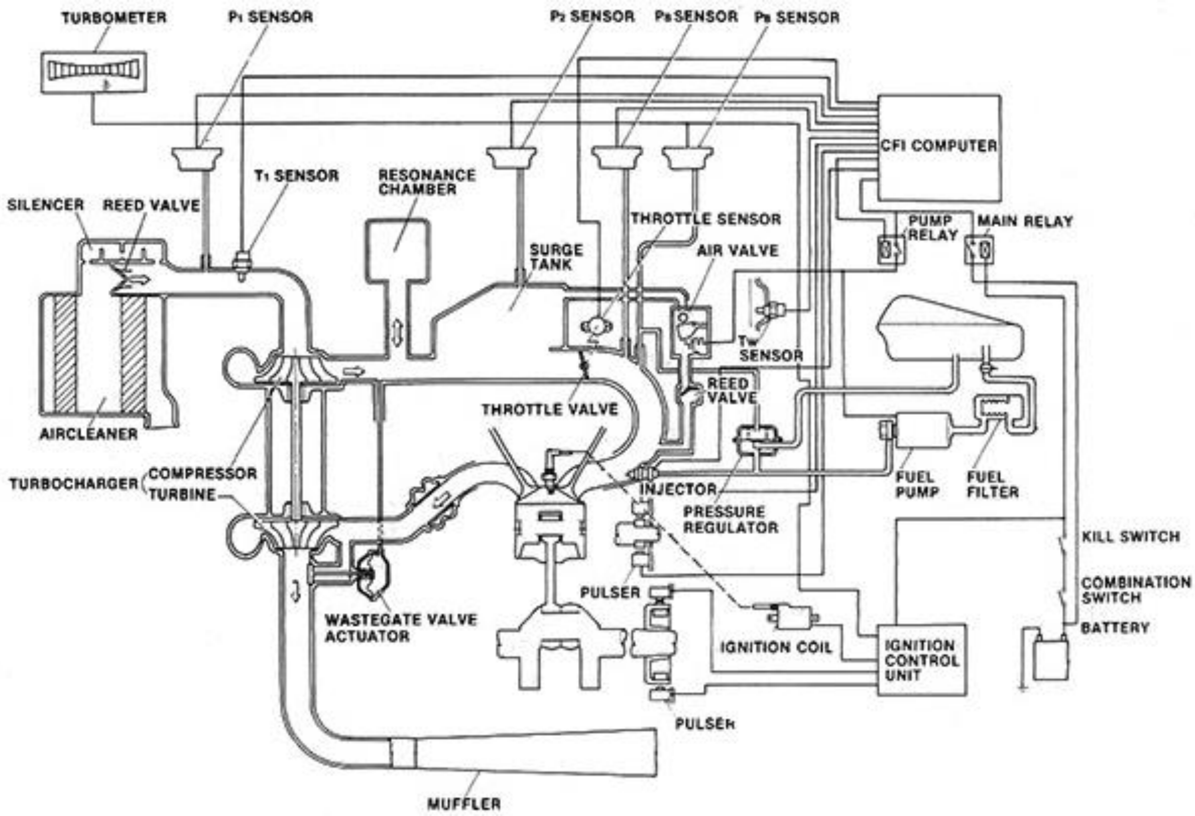


Figure 97 Honda CX500 Turbo EFI system - schematic diagram [152]

In 1982, the Honda CX500 Turbo was the first turbocharged motorcycle with was an EFI system. Due to the turbo lag and the complexity of the EFI system, which were caused by the multiple redundant fail-safe systems, the CX500 Turbo was only produced for one year. One year later, in 1983, the new model XC650 was fitted with a revised EFI system, which was far less complex than the version of the previous model. The EFI system of the XC650 formed the basis for Honda`s current Programmed Fuel Injection (PGM-FI). The PGM-FI is an n-α mapped fuel injection system, whereby the engine speed (n) and the throttle position (α) are monitored and thereof by means of control maps the basic fuel injection volume is calculated. In the next step, the basic fuel injection volume is adjusted by parameters such as intake air pressure and temperature, the engine coolant temperature and atmospheric pressure. [153] [151, pp. 17-20] [154]

In the same year as Honda released the XC650, Suzuki and BMW also introduced electronic fuel injection systems in motorcycles for the first time. Suzuki used a Mikuni-BOSCH L-Jetronic system in the XN85 and the K100 model from BMW was also equipped with a BOSCH L-Jetronic. Most of the used EFI systems in motorcycles at that time were based on adapted EFI concepts of automobiles. The L-Jetronic was used by several manufacturers in various models until the mid-nineties. [151, pp. 17-20]

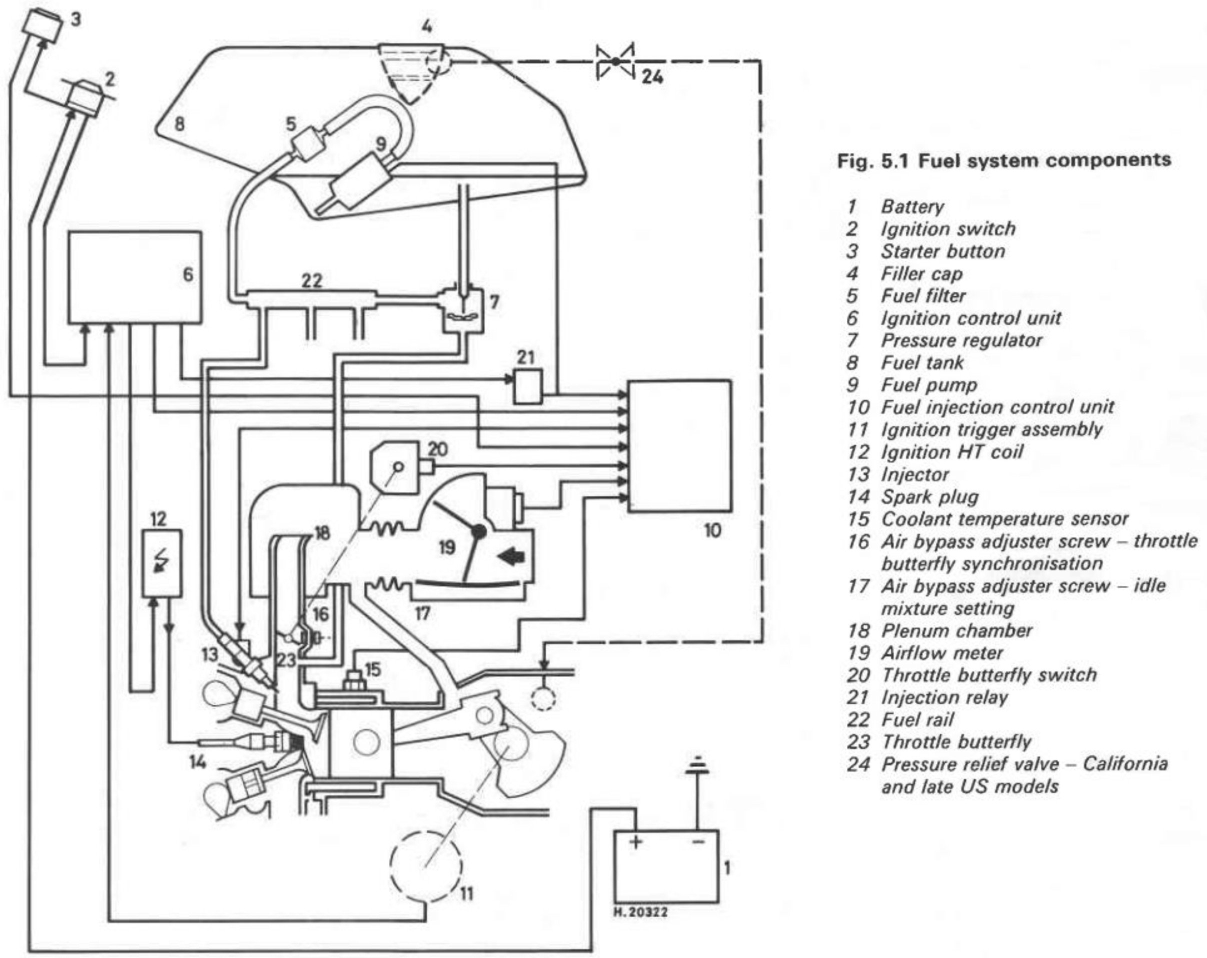


Figure 98 BOSCH LE - Jetronic - BMW K100 (1983) [155, p. 129]

The L-Jetronic processes the information of the engine speed, the intake air flow mass and temperature, the throttle valve position and the engine coolant temperature to determine in consideration of correction factors the appropriate trigger time and duration for the fuel injection. The air flow meter measures the deflection angle of the air vane via a potentiometer, which is deflected by the intake air flow. The engine speed is measured via Hall sensor at crankshaft. [78, pp. 183-184] [155, pp. 128-129]

In 1987, Ducati's first motorcycle with EFI, the Ducati 851, could be purchased. The implemented P7 EFI system was developed by Magneti Marelli and was the first "true digital" injection system. The P7 EFI system is the result of the experience from Magneti Marelli by providing fuel injections systems for Fiat and Ferrari automobiles. An advantage of the "true digital" system in comparison to the earlier analogue systems from other manufacturers is that Ducati could easily implement alternative fuel maps for EFI two-wheeler by plug in a chip into the motherboard for the first time.

In 1995, Harley Davidson started to fit their Electra Glide touring motorcycles with a "α/n-system" EFI system from Magneti Marelli. In 2002, they used an EFI system from Delphi, which additionally considered the intake manifold absolute pressure as an additional parameter for load determination. In the same year, Yamaha released their first sport bike with EFI, the YZR-R1. The hybrid design or once so-called "carbojectors" from Yamaha used a below atmospheric pressure slide, such as a constant pressure carburetor, to control the intake air flow and an ECU determined the appropriate fuel quantity for the injectors in consideration of several sensor signals. Triumph used EFI for the first time in the Triumph Speed Triple, in 1997. In 2000, the Triumph TT600 was equipped with a Sagem MC 1000 engine management system, which had already advanced functions at that time, such as automatic cold-start compensation or a self-diagnostic capability, which had not been seen on a motorcycle with EFI until then. [151, pp. 17-20]

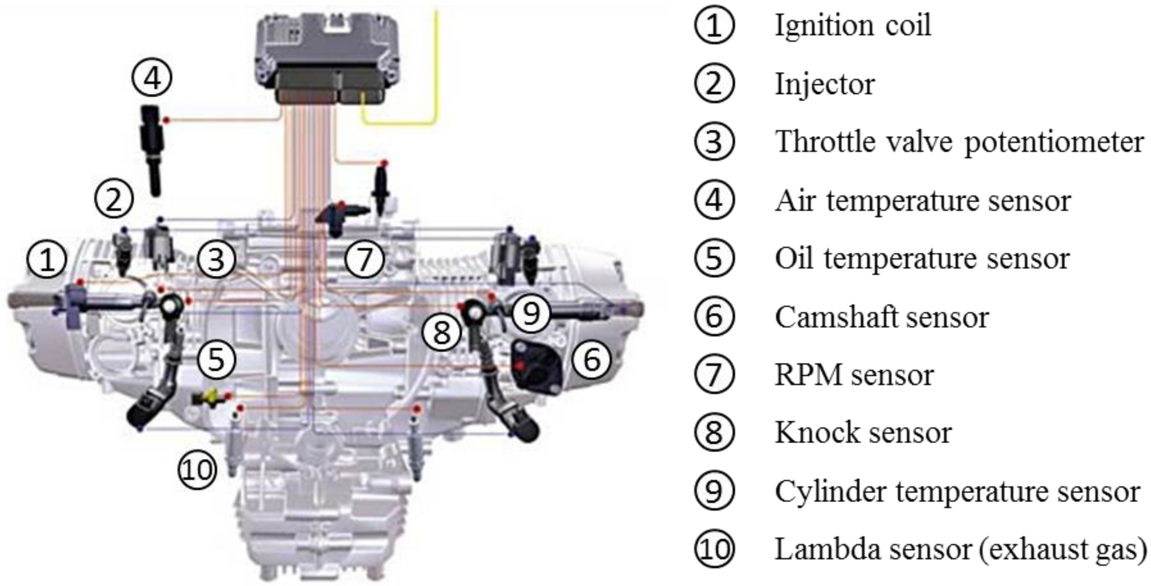


Figure 99 Digital Motor Electronics (DME) for BMW motorcycles with boxer engines as from 2004; adapted from [78, p. 187] [156]

In 1990, BMW implemented the Digital Motor Electronics (DME), also known as BOSCH`s Motronic, in their motorcycles, thus replacing the L-Jetronic, which was used until then. Figure 99 depicts the functional diagram of the further developed DME of the new boxer engine generation from BMW, which were introduced in 2004. This generation of electronic engine control allows a fully sequential fuel injection that means the injection is individually adjusted for each cylinder. Moreover, the fuel is directly injected into the combustion chamber at the moment when the intake valve is open, which is detected by a camshaft sensor. This avoids that fuel is stored upstream from the intake valve. The ECU determines indirectly the intake air flow mass via the engine speed (n), the throttle valve position (α), the intake air temperature, the engine coolant temperature, the ambient pressure and the stored maps, and calculates for each cylinder the appropriate amount of fuel and ignition time in dependency on the engine operating status and engine operating points. The warm-up and idle control allows the omission of the “Choke” – the manual mixture enrichment at cold start – by the automatic regulation of the fuel quantity and bypass channels for additional air. In addition to the adaptation of the injection time, the injection volume can be adjusted too, by a variation of the fuel pump pressure, and thereby, the fuel metering is improved. The variable pressure control of the fuel pump makes a fuel return unnecessary, as always the correct fuel amount is delivered. A knock sensor is attached on the cylinder block and if a combustion knock is detected, an ignition retard is carried out by the engine electronics as a safeguard against damages on the engine. The integrated closed lambda control ensures an optimal mixture formation (λ=1) in the relevant operating range of the engine, which is required for a three-way catalytic converter as exhaust gas after treatment. A lambda sensor detects the remaining oxygen content in the exhaust gas flow and the ECU adjusts the injection volume appropriate to the signal of the lambda sensor. [78, pp. 183-184]

Modern motorcycles use electronic engine management systems (EMS) as standard such as shown in Figure 100. The depicted system components are essential for an efficient engine operation, and furthermore, they ensure the observance of the emission legislations. The requirements to such overall systems, especially in the commuter segment on the growing markets in India or South East Asia, are low costs, a low system complexity, low maintenance and a simple repair. The cost aspect primarily complicates the introduction of such an extensive EMS in these markets and therefore a significant price reduction is necessary to be able to compete with the carburetor technology that is still widespread in these regions. [105, pp. 378-380]

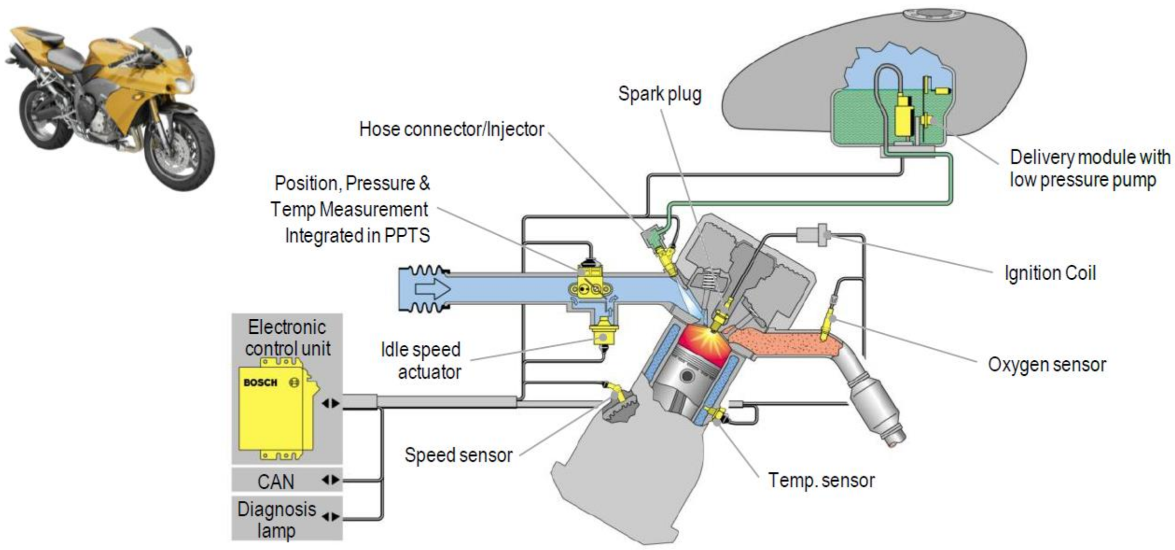


Figure 100 ICE with intake-manifold and EMS from BOSCH - scheme [105, p. 379]

3.1.1.3.1 BOSCH – "Low Cost" Electronic Engine Management System

One of the main focuses in the development of a new "low cost" EMS was the implementation of a new and significantly smaller ECU and hydraulic system – injector and fuel pump. Moreover, the aim was to implement software functions that can substitute sensors in the EMS. The new credit card-sized ECU housing was realized by the takeover of chip manufacturing technologies and the improved plug connection was derived from consumer electronics. However, the requirements to plug connections in two-wheelers are substantially greater, e.g. vibrations, temperature, humidity, etc.. In addition to the requirements of minimum fuel injection quantities and a low tolerance of injection volume, the demands with regard to injector size and noise emissions in motorcycles are significantly higher than in passenger cars. By developing, the reduction of the overall length of an already used intake manifold injector (EV14) succeeded in around 50%. The EV14 injector is already marketed for motorcycles and is based on the design of an intake manifold injector for passenger cars. Furthermore, a mechatronic approach, the Controlled Valve operation (CVO), was developed to handle the conflict of objective that comprises the achievement of the minimum fuel volume of approximately 1 mg per injection on the one hand and the minimization of the noise emission level on the other. The benefits of the CVO solution are the lower costs in comparison to a fundamental new design of the basic injector design and the low noise emissions that are significantly below the state of the art of 50 dB(A). [105, pp. 379-382]
Figure 101 shows the control impulse and the valve lift without and with the Control Valve Operation (CVO) of the injector. It can be seen that the valve lift is significantly smoother than without the new mechatronic control approach.

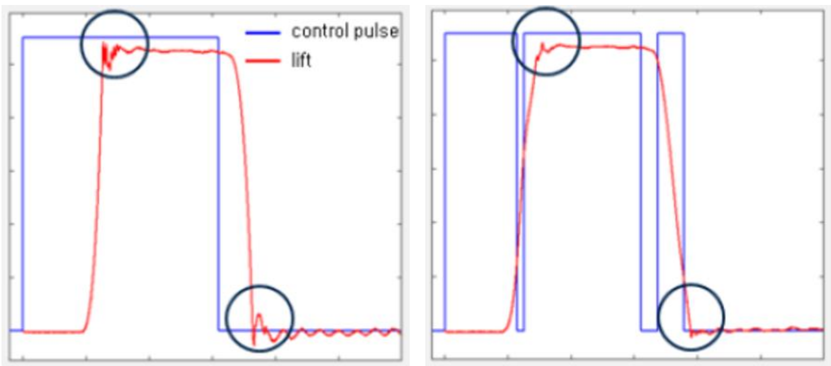


Figure 101 Valve lift (red) and impulse (blue) without (left) and with (right) Control Valve Operation [105, p. 382]

The fuel pump was designed as an in-tank piston pump and contains the pressure regulator for constant fuel pressure. The two-wheeler commuter segment as target market limits the size of the fuel pump to a delivery rate of about 5 l/h, which is derived due to the common engine displacements in this sector of 100 cm^3 to 150 cm^3. [105, p. 383]
The speed based "Nmot"-functionality enables the utilization of the engine speed of one-cylinder engines, due to the missing superposition from other cylinders, to derive information of the working process for the control algorithms. The main challenge was to achieve a sufficiently precise resolution of the engine speed with a standard speed sensor. In this case a trigger wheel with a 36-2 pitch was used. The compression phase is characterized by a speed decrease as a result of the air mass that has to be compressed and the expansion phase is

identified by a speed increase due to the carried out work on the piston. The engine speed deceleration and acceleration are depending on the engine load, the higher the engine loads the stronger the speed decelerates at compression or accelerates at expansion.
Figure 102 illustrates this for one working cycle of a one cylinder engine with various loads. As already described in literature [157], the “Nmot”-functionality uses the deceleration of the engine speed during the compression phase to estimate the relative air mass (rl) and the acceleration during the expansion phase is used to estimate the center of combustion and to determine the indicated mean effective pressure (IMEP). The estimation of the relative air mass enables the derivation of leakage and ambient pressure, whereby the intake manifold pressure sensor can be removed. The estimation of the center of combustion allows an adaptation of the ignition angle and therefore provides functions of a cylinder pressure indication. The determined IMEP permits the estimation of the air fuel ratio (λ). [105, p. 384]

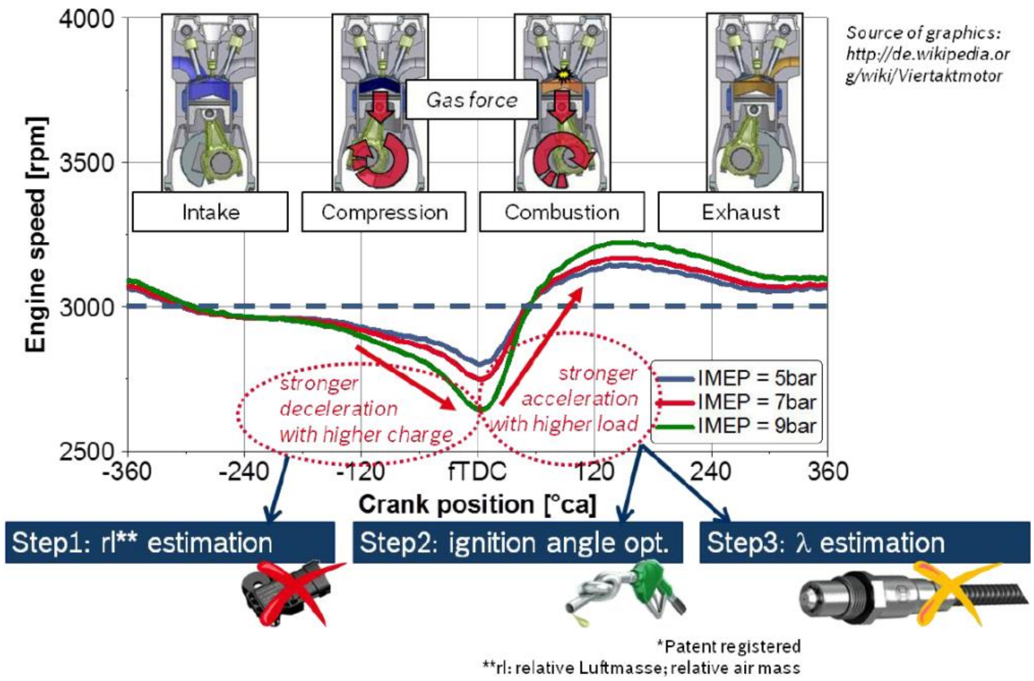


Figure 102 Engine speed curve over one working cycle for a single cylinder (BOSCH) [105, p. 385]

The ignition delay and spark duration are influenced by manufacturing tolerances, fuel quality (RON – Research Octane Number), tolerances in the ignition system, ageing and wear. As a consequence the center of combustion is shifted to a given ignition angle. The assumption of a distribution for the resulting total error enables the identification of the effect on the fuel consumption and NOx – emissions. Figure 103 shows that the impact of the resulting total error on fuel consumption and NOx highly, depends on the target combustion phasing. The resulting total error is assumed as a Gaussian distribution. The diagram on the left side illustrates an efficiency optimized combustion phasing and on the right side a late target combustion phasing is depicted, which is used in two-wheeler to reduce NOx or to rise the exhaust gas temperature at partial load. The efficiency optimized center of combustion with minimum of fuel consumption is located around 6°CA to 8°CA after TDC, however, a deviation from the optimal combustion phasing results in a fuel consumption increase. This would mean an increase of the fuel consumption of up to 4% and of the NOx emissions of up to 35%, if center of combustion is earlier. A deviation of the center of combustion from the

late target combustion phasing to early would result in an increase of the NOx emissions of up to 30% and in direction to late the fuel consumption would increases of up to 10%. [105, pp. 385-387]
Figure 104 shows the "Nmot"-functionality by means of an engine measurement. The chart above depicts the ignition angle and the imposed error to the ignition angle (offset), below the target combustion phasing (set point), the position of the center of combustion of the heat progression curve (FHR50 N/U) and the position of the reference combustion phasing of the heat progression curve (FHR50 reference) are displayed. The FHR50 U/N is estimated by the engine speed signal and the FHR50 reference is calculated by indicated cylinder pressure. [105, p. 387]

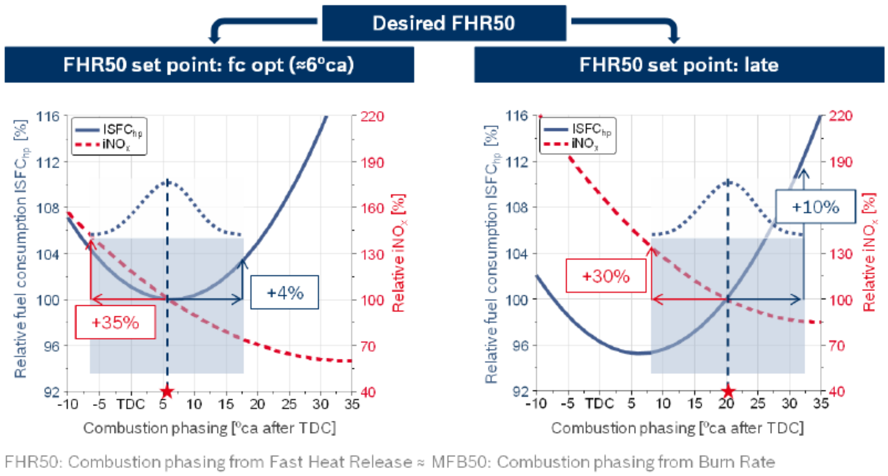


Figure 103 Consumption and emission potential with deviations of the center of combustion from the reference point (BOSCH) [105, p. 387]

The introduction of an ignition angle error leads to a shift of the center of combustion and is detected only by the engine speed signal. The applied "Nmot"-functionality enables the engine control to adjust the ignition angle so that the target combustion phasing is achieved. Due to the use of standard components for engine speed sensor, sensor wheel (36-2) and ECU the "Nmot"-functionality has a good cost benefit ratio. [105, p. 387]

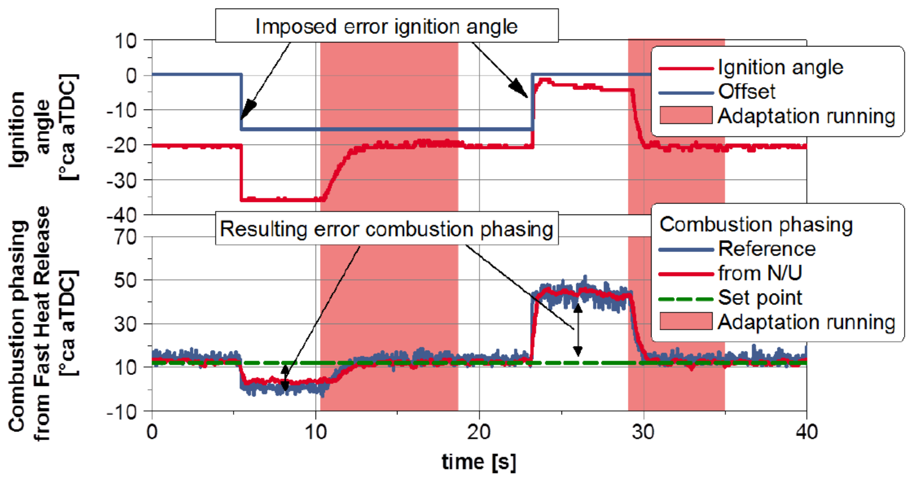


Figure 104 Results from engine measurements with adjusted ignition angle to ensure the reference location of the center of combustion by BOSCH [105, p. 388]

3.1.1.3.2 Ride-by-Wire

“Ride-by-Wire” means the replacement of the well-known accelerator cable, which is usually used for throttle linkage, by electrical sensors and actuators. The request of the driver is detected by sensors (potentiometers), which is forwarded the opening command in form of an electrical signal to the ECU. The ECU generates a set point setting for the throttle position and air-fuel ratio from the driver request and the current driving situation. The driver situation is determined by monitoring various parameters, such as for example engine speed and temperature, ambient pressure, gear selection, etc.. After the set point/actual comparison of the throttle position, the ECU controls an actuator that opens and closes the throttle corresponding to the present conditions of driver request and driving situation. The whole system has to be designed in such way that in the case of a system failure the motorcycle remains controllable or at least can be controllably stopped. The ride-by-wire technology offers benefits in regard to driving behavior and emissions. Various modes can be deposited in the ECU that differ in regard to throttle response and performance behavior of the engine. Thus, the driver gets a completely different driving experience, from “sporty” to “comfortably”, mediated from one and the same motorcycle. In addition, the emissions can be handled better, for example the cold start emissions can be reduced by means of a special programming, which results in a faster heating of the catalytic converter in the early start phase.

Yamaha has done pioneering work in the field of ride-by-wire technology. In 2006, the Yamaha YZF-R6 was introduced with the YCC-T technology (Yamaha Chip Controlled Throttle). The YCC-T system operates after the same principle as the EPT (Electronic Power Throttle) technology by KTM, which was introduced in their 690 single-cylinder generation one year later, in 2007. Both systems used the accelerator cable as connection to the throttle body, where the driver request was converted into an electrical signal. In consideration of this electrical signal and other parameters, the ECU controls the optimal throttle position and air-fuel ratio. At the EPT technology, the acceleration cable does not directly control the throttle. Nonetheless, it is used as mechanical stop for the electric actuation system. That means that in the case of closing the throttle the electrical actuation system was subordinated to the mechanical system (acceleration cable). Due to the YCC-T technology in the Yamaha YZF-R6, the ECU had to be enlarged to about the factor 5 compared to the previous model in order to provide the required processing power.

Figure 105 Ride-by-wire throttle body and throttle grip from KTM [158]

In 2012, KTM was the first company that has presented a gasoline motorcycle completely without accelerator cable and only with “real” ride-by-wire system, in their new 690 Duke (Figure 105). The system consists of two sensors (potentiometers) with independent power supply at the throttle grip, which record the driver request. An annular spring mediates the feeling of a conventional throttle grip. Two independent processors in the ECU are responsible for data handling of the driver request and additionally, they monitor each other. As already explained above, after the determination of the driving condition and the set point/actual comparison of the throttle position, the ECU controls the actuator of the throttle in accordance with a deviation from the set point. The angle of the throttle can be set on an accurate of 0.1°. The ride-by-wire from KTM is designed redundantly, that means all essential components such as the sensor for recording the drivers request, the throttle sensor and the processors in the ECU are available twice, to avoid a total failure. Nowadays, a variety of manufacturers offer motorcycles with drive-by-wire, such as KTM, BMW, Ducati or MV Agusta, only to name a few. [78, p. 190] [158]

3.1.1.3.3 STIHL M-Tronic

In 2006, STHIL introduced the carburetor based engine management system M-Tronic for handheld power tools, e.g. chainsaws or cut-off machines, to meet future emission regulations. The STIHL M-Tronic system expands a diaphragm carburetor by an ECU and a small solenoid valve. The solenoid valve functions as fuel metering valve that is controlled by the ECU. Figure 106 shows the scheme of the STIHL M-Tronic. A speed-based characteristic curve is stored in the ECU and manages the fuel metering. This battery-less system requires no additional load detection and sensors. The flywheel is equipped with an additional set of poles and provides both, the electrical energy for the system as well as the speed signal. The operating states are determined by the evaluation of the speed signal in the ECU. In order to determine the air fuel mixture, a specifically "lambda-fault" is introduced – an interruption of the fuel supply over a few revolutions – and the resulting change of the operating state in the form of a speed increase or decrease is detected by the ECU and allows an indirect deduction of the current lambda value. [80, pp. 436-437]

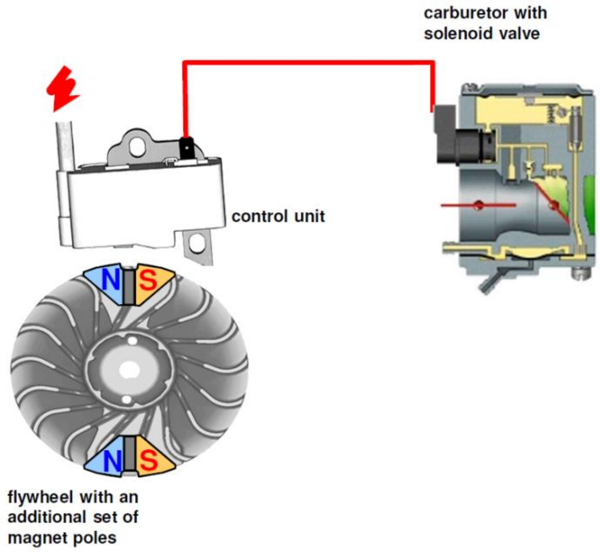


Figure 106 STIHL M-Tronic - schematic views [159, p. 8]

For example, if the solenoid inserts a “lambda-fault” and the current air fuel mixture is too rich, the speed increases due to the power increase and therewith lambda can be indirectly determined (Figure 108). [80, pp. 436-437]
Figure 107 shows the comparison of the engine management systems (EMS) of STIHL M-Tronic with a standard system of a Gasoline Direct Injection (GDI) engine. The blue marked components of the GDI EMS are replaced by software functions at STIHL M-Tronic. The orange marked components are responsible for the determination of the optimal air-fuel ratio and ignition timing, and the yellow marked parts are responsible for the provision of the fuel and the fuel metering.

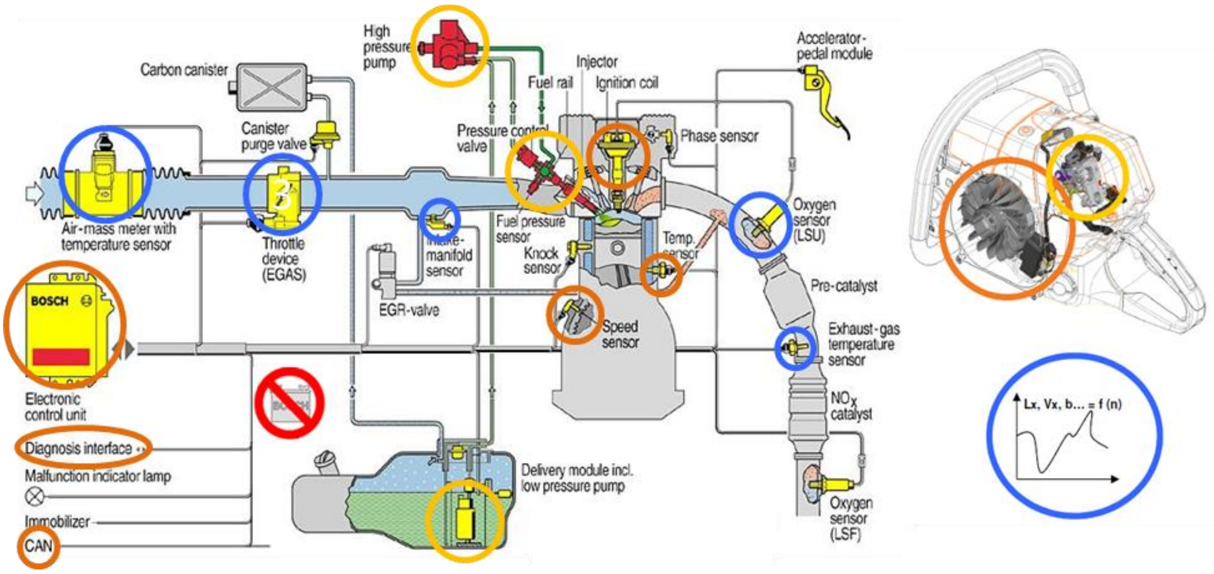


Figure 107 Engine management comparisons of STIHL M-Tronic and a standard EMS for gasoline engines with direct injection; adapted from [160, p. 30] [161]

Figure 108 (left) shows the lambda control of STIHL M-Tronic. Basically, the power will increase when a too rich air fuel mixture (λ << 1) becomes lean, since the maximum power is slightly located below λ=1. If the air-fuel mixture becomes leaner (λ > 1), the power will decrease. The insert of the “lambda-fault” either causes a significant engine speed increase (air-fuel mixture is too rich), a significant speed decrease (air-fuel mixture is too lean) or a slightly speed increase, if the engine already operates at the best point. Figure 108 (right) depicts the results of a lambda test, which indicates a correlation between engine speed and lambda (λ). [80, pp. 436-437] [160]

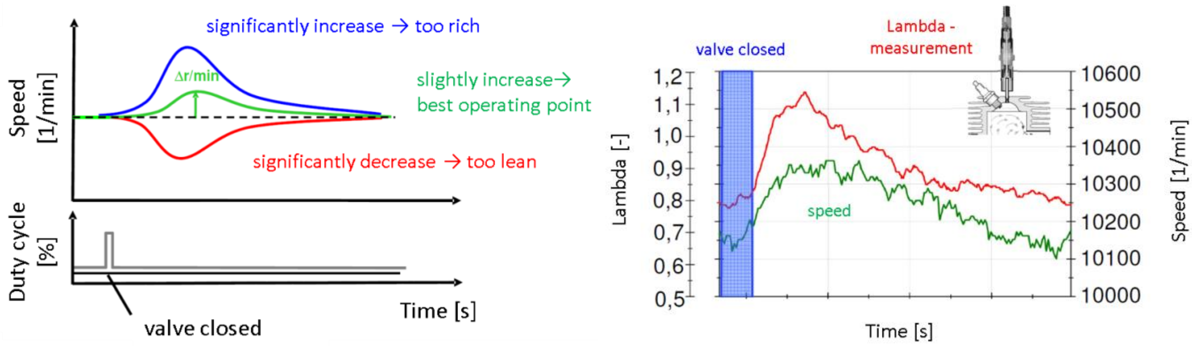


Figure 108 STIHL M-Tronic - lambda control [160, pp. 32-33]

3.1.1.4 Exhaust After-Treatment Systems

The pollutant emissions of internal combustion engines can be reduced by measures inside the engine as well as by after-treatment measures. For example, an internal exhaust gas recirculation (EGR), which can be realized with variable valve train (such as Honda V-TEC, Ducati DVT), can improve the reduction of emission. Moreover, variabilities in the valve train would allow the implementation of the Miller-cycle [162], which would have benefits with regard to NOx emissions and efficiency. In the following the main focus is on exhaust after-treatment systems. [80, pp. 404-407] [104, pp. 107-121]

Exhaust after-treatment systems are necessary to meet the more and more stringent emission limits and therefore, are standard equipment in modern two-wheelers. In motorcycles, oxidation catalysts and three-way catalytic converters are mainly used, and normally located in the front part of the exhaust muffler or in a front muffler. According to the current state of exhaust after-treatment for small engines, no SCR catalytic converters are applied in this segment.

A catalytic converter consists of a ceramic substrate or a metal substrate, which forms a fine honeycomb or cell structure. Typical cell densities for motorcycle catalysts are between 100 cpsi (cells per square inch) to 300 cpsi. Metal substrates are characterized by a faster heating and a higher temperature resistance than ceramic substrates, but they are also more expensive. The present level of development shows that only metal substrates meet the high loads and requirements in motorcycles. A ceramic substrate could be damaged due to their brittleness by the strong vibrations in motorcycles. The so-called washcoat is applied on the substrate, which leads to a surface enlargement and functions as oxygen store. In addition, the washcoat includes an atomically shaped coat consisting of a mixture of the precious metals Platinum, Palladium and Rhodium, which functions as chemical catalyst for the conversion process of the emissions. The catalytic effect is influenced by the composition of the precious metals. The catalytic converter can also be negatively affected by so-called catalyst poisons, such as lead, sulfur or phosphorus. In operation the catalytic converter needs a minimum temperature, the so-called light-off temperature, of about 250 °C to 300°C in order to start chemical reactions. [78, pp. 196-200]

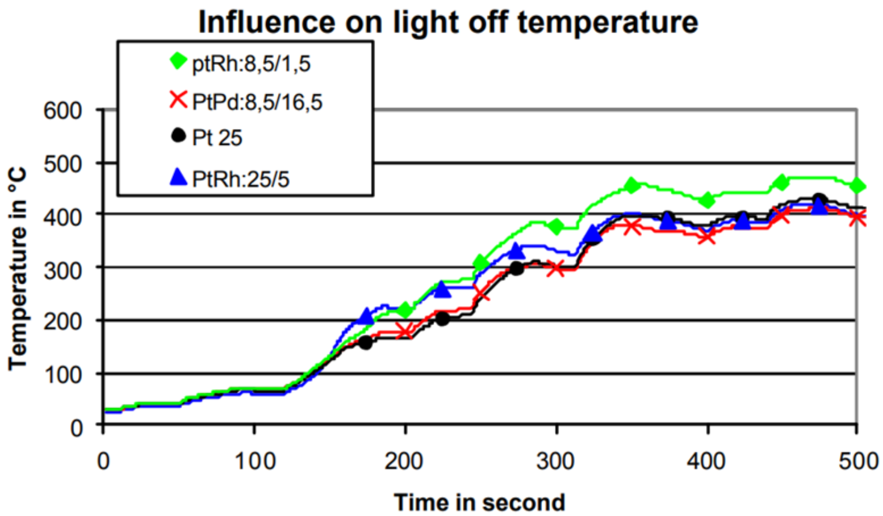


Figure 109 Influence of the precious metal load on the light-off temperature [163, p. 8]

Figure 109 shows the influence of the PGM (Platinum Group Metals) load on light-off temperature. Typical PGM loads of catalyst in two-wheeler sector are between 30 g/ft³ and 70 g/ft³ (~1.06 g/l - 2.47 g/l). The light-off behavior is essential as it affects the cold start emissions, which represent a not irrelevant proportion of the emitted emissions. The light-off time can be affected by the location of the catalytic converter – the closer the catalytic converter is positioned to the engine the faster it is heated and the shorter is the light-off time. This strategy depends on the fact, whether only a part – pre-catalyst – or the whole catalytic volume is positioned near the engine. A further alternative is an electrically heated catalyst [164]. Catalytic converters are standardly designed as a straightly tubular body, but also the flexible tube form was investigated for motorcycle catalysts [165]. The design of a catalytic converter bases on a series of target trade-offs. For example, for performance reasons the flow cross-section of the catalyst should be as large as possible, with a low wall thickness of the cell structure, to reduce throttling losses by a low flow resistance. This causes package problems and furthermore, a larger catalyst is heated slower especially in partial load range, which means higher cold start emissions. The positioning of the catalytic converter as near as possible on the engine can counteract this, however, the position of the catalyst must not negatively affect the gas dynamic, especially at two-stroke engines. At full load, the position near the engine results in an overheating problem, which can lead to permanent damage. In appropriate technical literature [166] future trends will be described. In the following section, are closer look is given on the oxidation catalyst and the three-way catalyst. [78, pp. 196-200]

3.1.1.4.1 Oxidation Catalytic Converter

The oxidation catalytic converter is used in gasoline engines with lean-burn concepts ($\lambda > 1$). In two-stroke engines oxidation catalysts are generally used for the catalytic purification of exhaust gas, due to the fact that an air-fuel ratio of $\lambda = 1$ is difficult to realize. At conventional two-stroke engines, the scavenging process is carried out with air-fuel mixture, which causes scavenging losses whereby unburned hydrocarbons reach the exhaust system. The oxidation catalytic converter oxidizes the partially burnt/unburned hydrocarbons (HC) and the partially oxidized component carbon monoxide (CO) to carbon dioxide (CO_2). This form of exhaust gas after-treatment allows no reduction of NOx emissions. As a result of the high proportion of residual gas at conventional two-stroke engines, the NOx formation is relatively low. The oxidation of carbon monoxide occurs at relatively low temperatures in comparison to the oxidation of hydrocarbons, which need higher temperatures to achieve an equal conversion rate as at carbon monoxide. The performance-oriented design of some two-stroke engines ($\lambda \sim 0.9$) makes the oxidation of CO and HC difficult owing to air deficiency. Although the conversion rate is low, the high HC emissions cause high thermal stress. For this reason, a so-called “bypass” is implanted to reduce the conversion rate and therewith the thermal stress. [89, pp. 125-129] [101, p. 30] [104, pp. 501-505]

3.1.1.4.2 Three-Way Catalytic Converter

The three-way catalytic converters are state of the art as exhaust gas after-treatment at four-stroke engines that mainly operates stoichiometric ($\lambda = 1$). The oxidation catalyst and the reduction catalytic converter are combined in a catalyst bed. The oxidation of CO and HC emissions requires an excess of oxygen, whereas the reduction of NOx emissions needs the presence of reducing elements. The conversion rate is very sensitive regarding the air-fuel ratio (see Figure 110), therefore the combustion should be done as stoichiometric as possible. The air-fuel ratio is regulated by means of a lambda oxygen sensor, which measures the oxygen content of the exhaust gas, to maintain a stoichiometric ratio. The lambda oxygen sensor detects a lean or too rich air-fuel mixture and the control adjusts the air-fuel ratio in accordance with the measurement of the lambda oxygen sensor. Thus, an air-fuel ratio of $\lambda = 1$ is reached that is only averaged over time. The oxygen storage ability of the catalytic converter is an essential part, as the resulting short phases of a lean or rich mixture have to be compensated to avoid a rise of emissions, when the air-fuel ratio slightly deviates from the optimum value ($\lambda = 1$). [77, pp. 158-172] [89, pp. 125-129] [101, p. 30] [104, pp. 501-505]

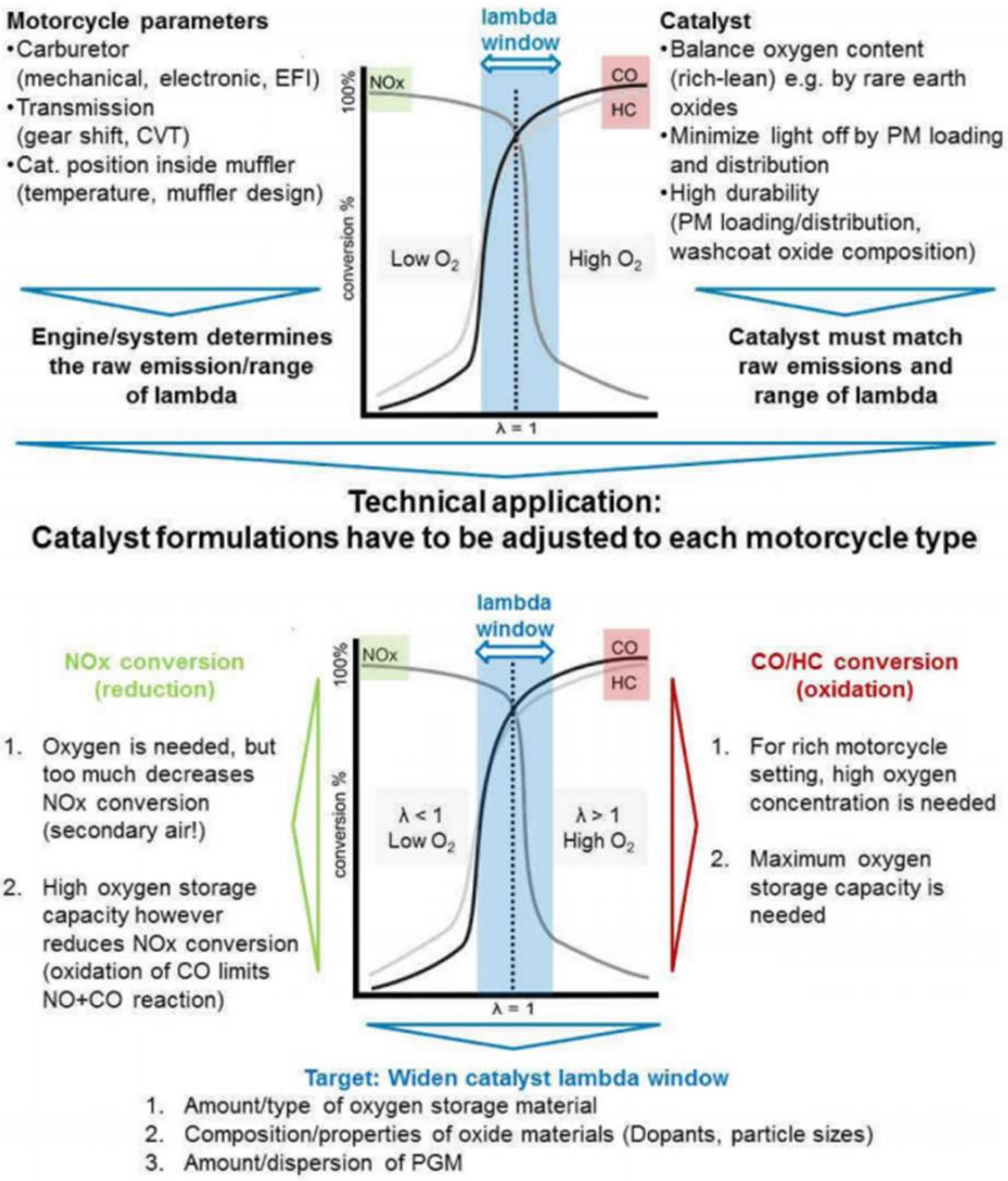


Figure 110 Challenges for a catalyst and influences on the lambda window [167, p. 3]

3.1.2 Engine Concepts

3.1.2.1 Two-Stroke

3.1.2.1.1 STHIL 2-MIX Engine

The scavenging losses are the main reason for the high HC emissions of two-stroke engines. During the scavenging process the intake and exhaust port are open at the same time whereby, unburned air-fuel mixture reaches the exhaust port which results in high HC emissions. The stratified scavenging, also called “2-MIX” technology by STIHL [168] [169], is a concept to reduce the scavenging losses of two-stroke engines and, consequently, also the high HC emissions. This stratified gas-exchange concept reduces the scavenging losses due to the fact that the scavenging process is carried out only with pure air instead with air-fuel mixture. STIHL uses the 2-MIX technology for example in hedge trimmers, chainsaws and cut-off saws with displacements from about 30 cm³ to 98 cm³ and power outputs of 0,7 kW to 5 kW. Figure 111 depicts one working cycle of a two-stroke engine with a stratified scavenging process. [80, pp. 434-435] [170, pp. 460-461] [171]

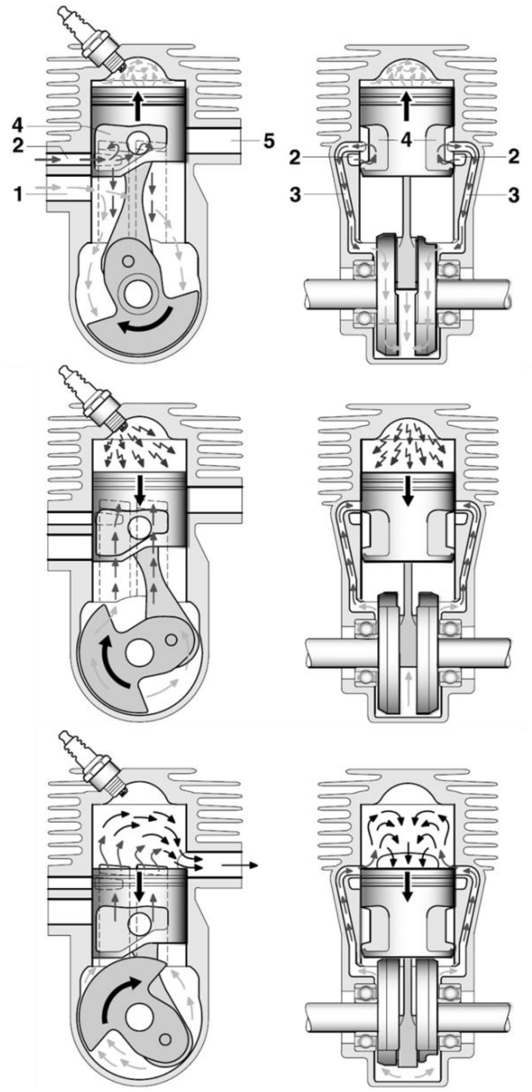


Figure 111 Two-stroke engine with stratified scavenging by STIHL [170, p. 461]

In the compression phase (Figure 111 – top), air-fuel mixture is sucked through the intake port (1) into the crankcase. At the same time, a recess in the piston (4) release enables a connection between the pure air channel (2) and the transfer passage (3). Due to the below atmospheric pressure in the crankcase and in the transfer passage (3) and the ambient pressure in the pure air channel (2) the transfer passage is filled with pure air.

In the expansion phase (Figure 111 – middle), the air-fuel mixture in the crankcase and the pure-air in the transfer passage (3) are pre-compressed. At first, the piston (4) releases the exhaust port (5), then the transfer passage (3) into the combustion chamber is opened (Figure 111 – bottom) and the combustion chamber is scavenged by pure air. The pressure in the transfer passage (3) and crankcase is greater than the pressure in the combustion chamber, as the exhaust port at the scavenging process (5) is already opened, when the transfer passage (3) is released. When the exhaust gas is scavenged out of the combustion chamber by the pure air cushion, the air-fuel mixture flows into the combustion chamber and is mixed with the residual pure air.

The carburetor plays a decisive role in such two-stroke engines with stratified scavenging, as it is responsible for the separation of pure air and the air-fuel mixture. The supply with pure air and the air-fuel mixture can be performed by a double/multi-flow carburetor or a carburetor with a split-plate. Moreover, a conventional carburetor can also be used, if the below atmospheric pressure is significantly enough pronounced to separate the pure air and the air-fuel mixture at the carburetor. This is the case at appropriate high engine displacements. [170, pp. 461, 467]

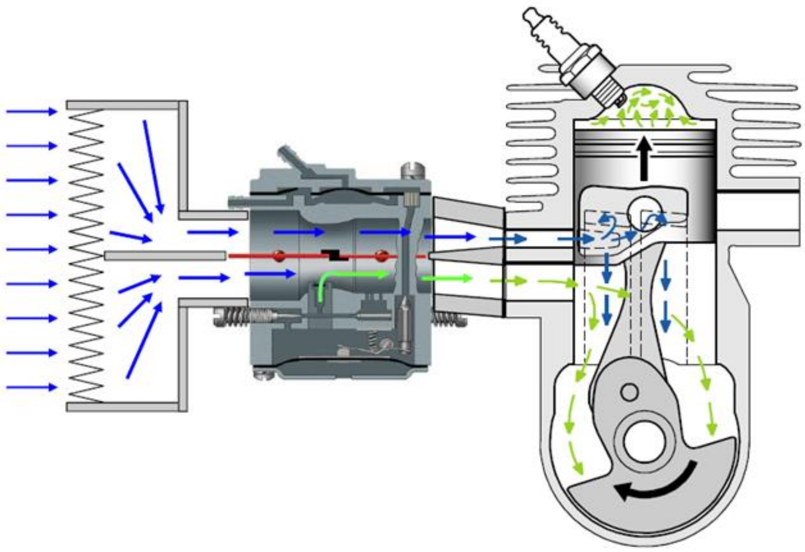


Figure 112 Two-stroke engine with carburetor by STIHL [172, p. 7]

Figure 113 illustrates the comparison of two-stroke engines with and without stratified scavenging regarding Brake Mean Effective Pressure (BMEP), HC emissions, specific power and fuel consumption. Neither the BMEP nor the specific power show deteriorations of two-stroke engines with stratified scavenging towards conventional 2-stroke engines, whereas the HC emissions and consequently also the fuel consumption demonstrate significant improvement.

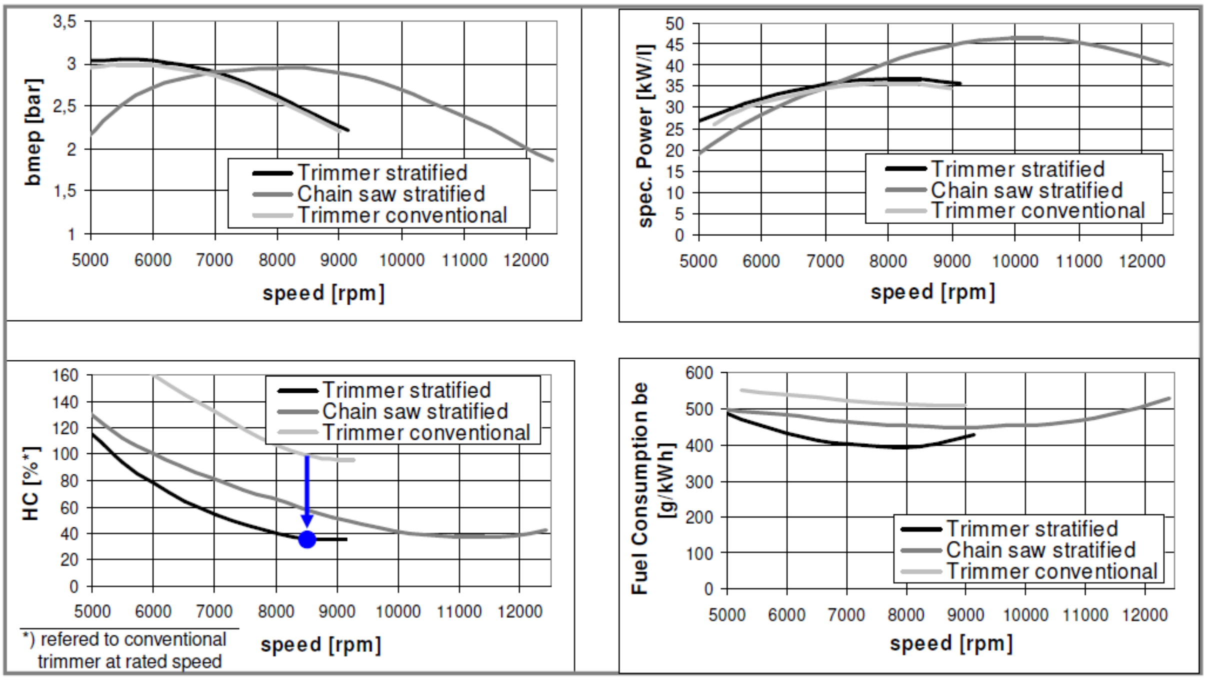


Figure 113 Comparison of two-stroke engines with and without stratified scavenging in respect to BEMP, HC-emissions, specific power and fuel consumption [172, p. 12]

3.1.2.1.2 STIHL Injection Engine

STIHL uses the battery-less, electronically controlled injection system in two-stoke handheld power tools. Figure 114 shows the system components of the low-pressure crankcase injection system including the electronic control unit (ECU) with integrated ignition coil as key component. The ECU controls the injection and the ignition. The entire injection system is supplied with energy by a generator positioned on the crankshaft, which already provides the necessary energy in less than one crankshaft rotation (see Figure 116 – start sequence). [80, p. 437] [108, pp. 674-679] [109] [110, pp. 1-2]

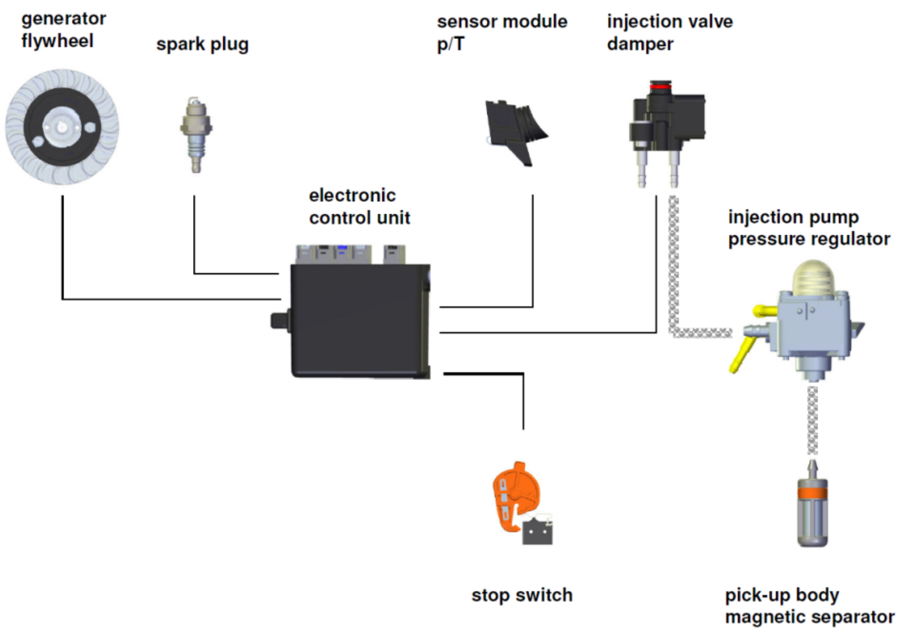


Figure 114 STIHL Injection system components for handheld power tools [110, p. 2]

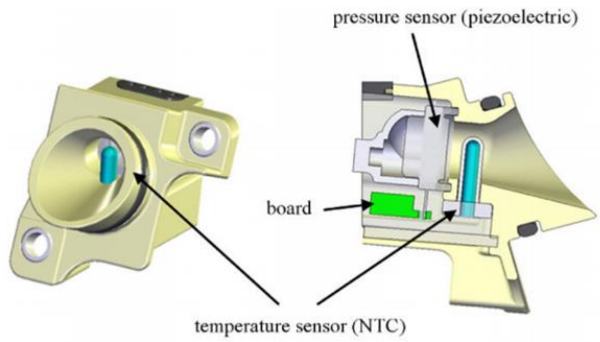


Figure 115 STIHL Injection system - temperature and pressure sensor module [110, p. 2]

The generator generates an output voltage from 0 V to 42 V_{RMS} (Root Mean Square) via the whole operating range. The required crank angle is determined via the inductive voltage profile of the generator signal, thus, an additional crank angle sensor or TDC-sensor (Top Dead Center) becomes unnecessary. The sensor module (see Figure 115), consisting of a piezo-resistive absolute pressure sensor and an NTC temperature sensor (Negative Temperature Coefficient), in combination with the analysis algorithms is used to determine the operating point of the engine by the air mass. The air mass is calculated by the ideal law of gas and the measured temperature and pressure in the crankcase. The engine management derives the optimal ignition timing, injection angle and volume from the engine speed, the air mass and the stored characteristic maps in the ECU. In addition, changing operating conditions, such as geodetic altitude, wear or changing fuel quality, are also taken into account with appropriate controller settings in the ECU. The injection process is described in chapter 3.1.1.1.2.2.1. [80, p. 437] [108, pp. 674-679] [109] [110, pp. 2-4]

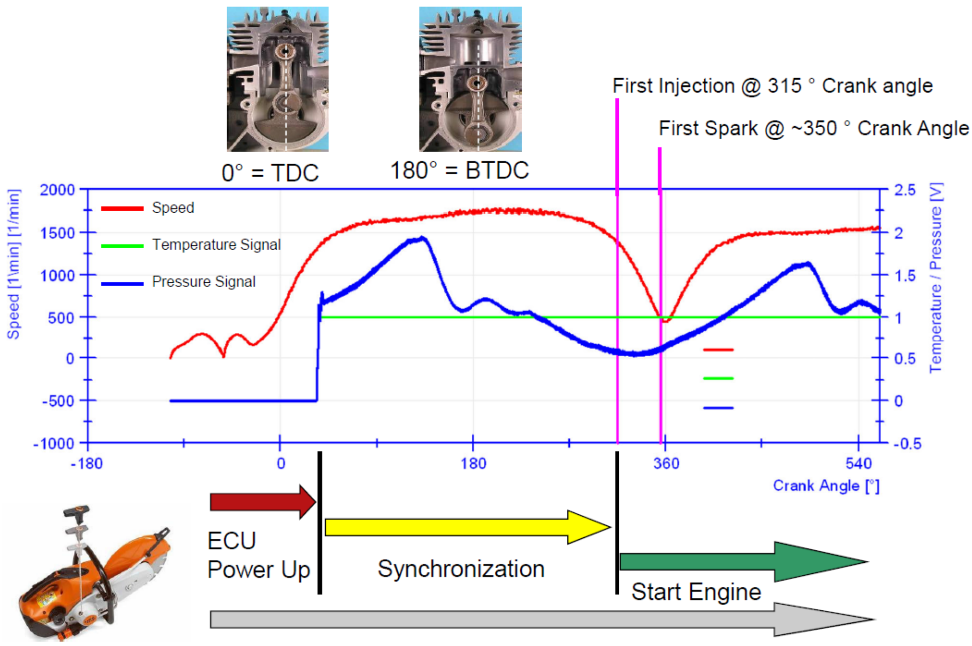


Figure 116 STIHL Injection start sequence [110, p. 5]

Figure 116 depicts the start sequence of the STIHL Injection system for two-stroke engines. After a certain speed threshold is achieved by pulling the starter rope, the power up phase begins and the ECU verifies the input signals (engine speed, temperature, pressure) on plausibility. If the plausibility test became positively finished, the synchronization of the crank angle and the generator signal is started. This synchronization phase is finished at 315°CA at the latest and the ECU can begin with the synchronized functions of injection and ignition. The injection is carried out cycle-synchronous once per revolution, i.e. one working cycle into the crankcase with a system pressure of 100 mbar. [80, p. 437] [108, pp. 674 - 679] [109] [110]

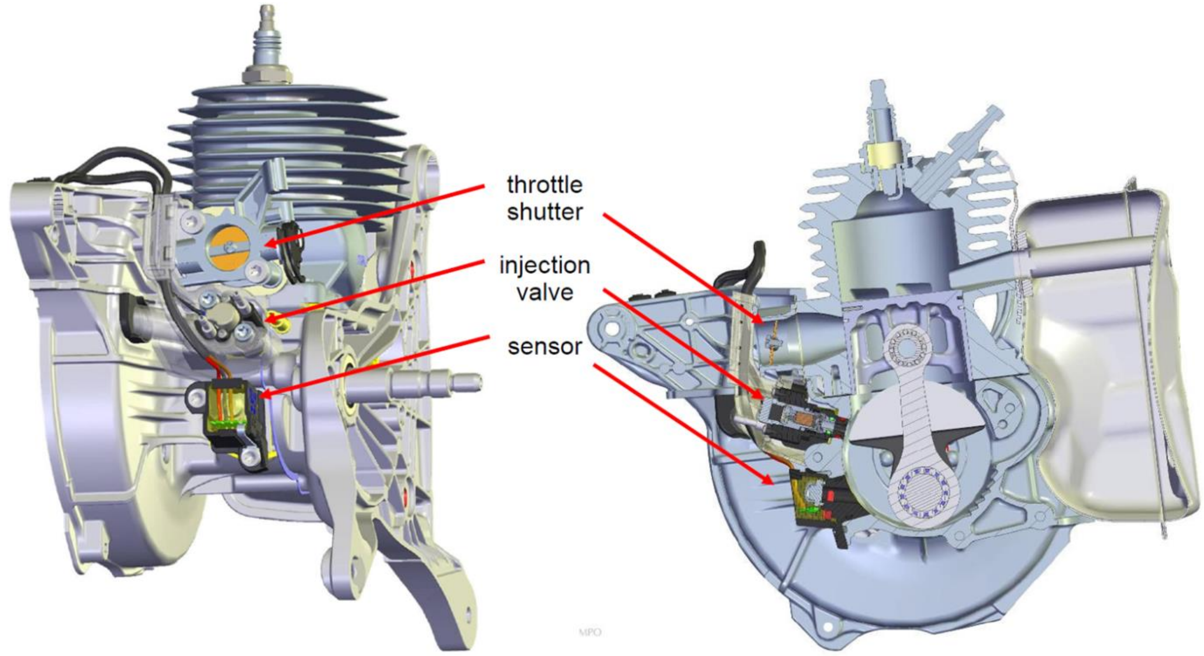


Figure 117 STIHL Injection system integration of the STIHL TS 500i cut-off handheld machine [110, p. 10]

Figure 117 pictures the integration of the pressure/temperature sensor module and the metering valve on the crankcase at the two-stroke engine of a STIHL handheld cut-off machine. Table 29 shows the comparison of different STIHL cut-off machines and their performance data. It can be seen that the TS 500i compared with the TS 420 A has a better power/weight ratio at nearly the same dimensions. This is, on the one hand, the result of the greater displacement and, on the other hand, of used injection system. [110, pp. 8-10]

Table 29 Comparison of different STIHL cut-off machines [110, p. 9]

	TS 420 A	**TS 500i**	TS 700
Carburation system	Carburetor	**Injection**	Carburetor
Engine technology	2-MIX	**2-MIX**	2-MIX
Water control	Electronic	**Electronic**	Manual
Weight [kg]	10.1	**10.2**	11.6
Length [mm]	729	**730**	840
Displacement [cm³]	66.7	**72.2**	98.5
Power [kW] / at [rpm]	3.2 / 9000	**3.9 / 9500**	5 / 9300
Specific power [kW/l]	48	**54**	51
Specific fuel consumption [g/kWh]	500	**420**	450
HC+NOx Certification level [g/kWh] (Limit 72 g/kWh)	48	**51**	51

3.1.2.1.3 Orbital Combustion Process Engine

Aprilia developed an air-assisted low pressure direct injection system, the so-called "DITECH" system (Direct Injection Technology), for a liquid cooled 50 cm³ two-stroke scooter engine. The DITECH system [95] [96] is based on the Orbital Combustion Process (OCP) and is used in the Aprilia SR 50. This system is distinguished from the OPC by another fuel metering system. The development was done in cooperation with Synerject, which functioned as system supplier. Figure 118 represents the schematic view of the DITECH system, which consists of an air compressor, a fuel pump and fuel injector, an air/fuel rail including pressure regulator, a direct injector valve and an ECU. The air compressor is directly driven via the crankshaft and provides the compressed air for the air/fuel rail, which enters into the pre-mixing chamber without a metering valve. The fuel injector from automotive sector is supplied with fuel by the electronically controlled fuel pump, which is controlled by the ECU, and injects the fuel into the pre-mixing chamber of the air/fuel rail. A pressure regulator ensures a constant fuel pressure. The direct injector, which is controlled by the ECU, directly injects the pre-mixed air-fuel mixture in the combustion chamber. The injection process into the combustion chamber is only carried out when the exhaust port is closed, whereby an improvement of emissions and fuel consumption is achieved. [95, pp. 4-7] [96, p. 5]

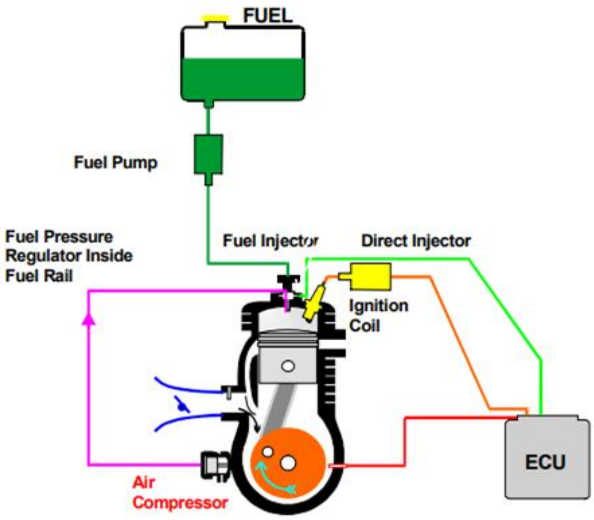


Figure 118 Schematic view of the Aprilia DITECH system [96, p. 5]

The 50 cm³ DITECH engine is based on a two-stroke engine with a bore diameter of 41 mm and a stroke of 37.4 mm by Aprilia. The geometric compression ratio is 12.5:1. The assemblies of piston/con rod and water pump as well as the components cylinder barrel, small and big end bearings, CVT and gears are identical for both engines. The air compressor was positioned in such way that the scooter could be equipped with a 16-inch wheel and the air compressor could be operated over a large crank angle. Figure 119 shows a sectional drawing of the 50 cm³ Aprilia DITECH engine including air/fuel rail at the cylinder head and the air compressor in the crankcase. [95, pp. 4-7] [96, p. 5]

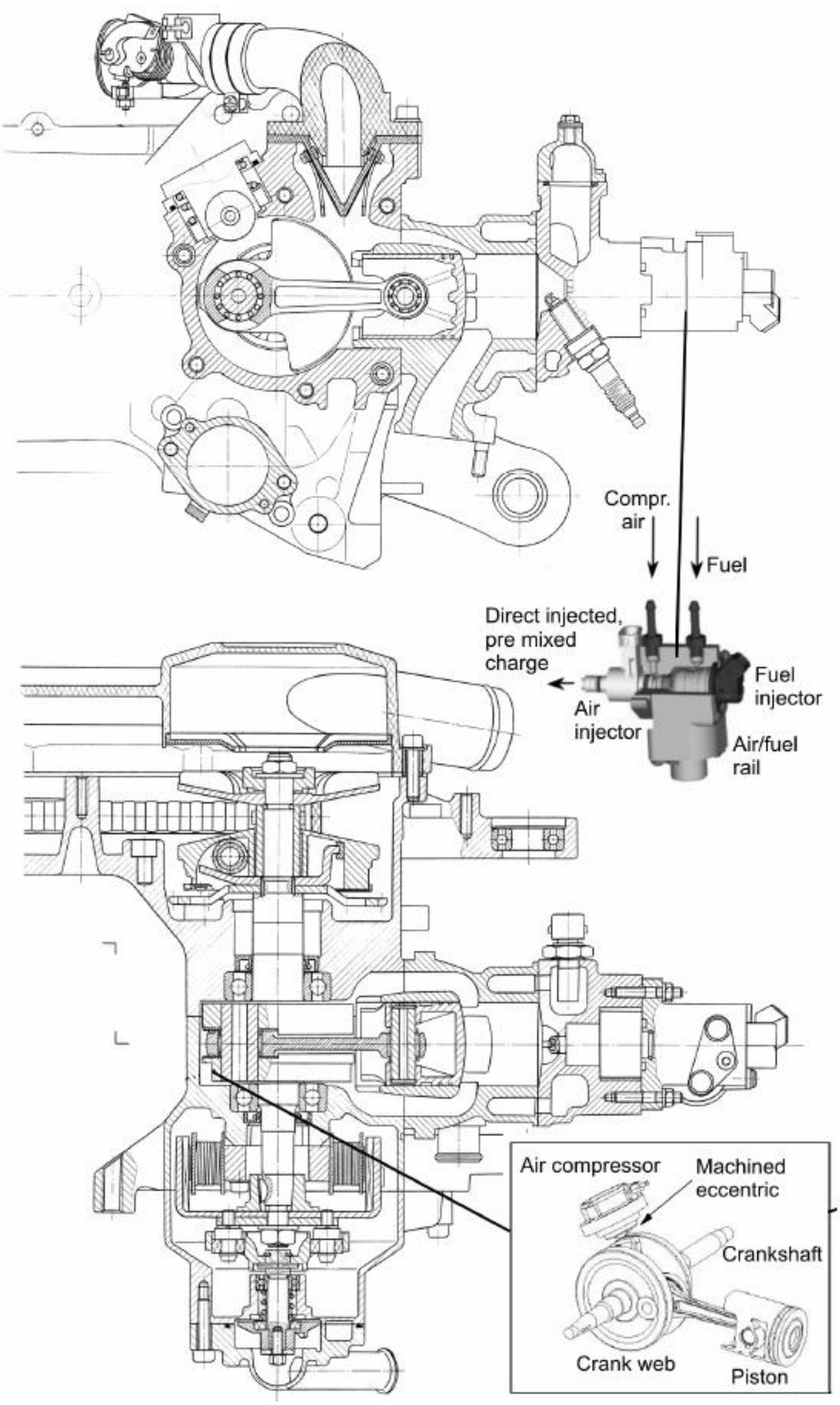


Figure 119 Sectional drawing of the 50 cm³ Aprilia DITECH [88, p. 432]

The mass balancing of the crankshaft was modified to reach mass-forcing-ellipse of the initial engine. Thus, both engine concepts can be used in the same vehicles. The lubrication system uses an electronic oil pump, which is controlled by the ECU, to spray the oil into the intake air. The ECU regulates the amount of oil depending on speed and load, which leads to a significant improvement of oil consumption. [95, pp. 4-7] [96, p. 5]

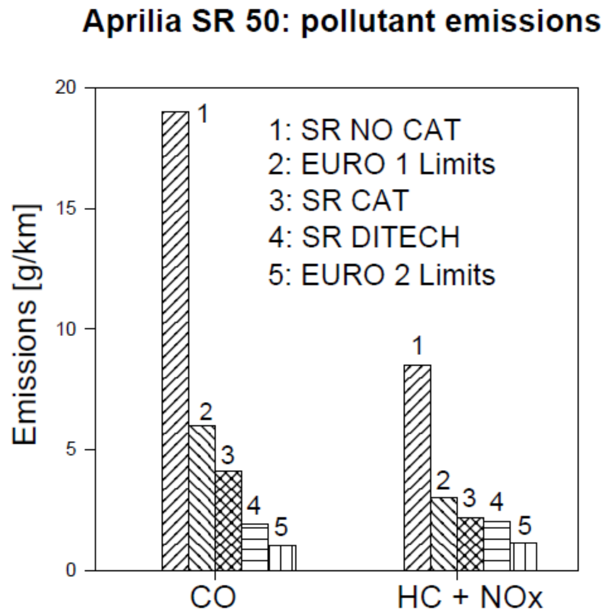


Figure 120 Emission results of the Aprilia SR 50 scooter with DITECH for the ECE R47 test cycle [96, p. 11]

Figure 120 presents the CO and HC+NOx emission results of three different scooter concepts for the ECE R47 driving cycle. The first scooter is equipped with a carbureted engine without catalytic converter (1), the second also uses a carbureted engine, however, with catalytic converter and the third is fitted with the DITECH system. In addition, the emission limits for EURO 1 and EURO 2 are depicted. The CO emissions of the DITECH engine are half that of the carbureted engine with catalytic converter and approximately one third of the EURO 1 limit, whereas the HC+NOx emissions are nearly the same. None of these concepts complied with the EURO 2 emission limits. [96, p. 11]

3.1.2.1.4 DOLCE Air-assisted Direct Injection Engine

In the course of the DOLCE project (**D**evelopment **O**f innovative **L**ow pollutant, low noise, low fuel **C**onsumption two-stroke spark ignition **E**ngines for future vehicles for individual urban mobility), a 125 cm³ two-stroke scooter engine was equipped with an electronic low-pressure fuel injection system which reached the project target emission limits of 3 g/km for CO and 1 g/km for HC+NOx at the ECE 40 Driving Cycle.
The DOLCE injection system was adapted from the already existing Piaggio FAST – Fully Atomized Stratified Turbulence – injection system [90] [91]. The Piaggio FAST technology was already used in 50 cm³ two-stroke engines, with which, inter alia, the Vespa ET2 was equipped, and which was produced in small series of approximately 6000 pieces. [89, pp. 8-9] [121, pp. 417-420] [122]

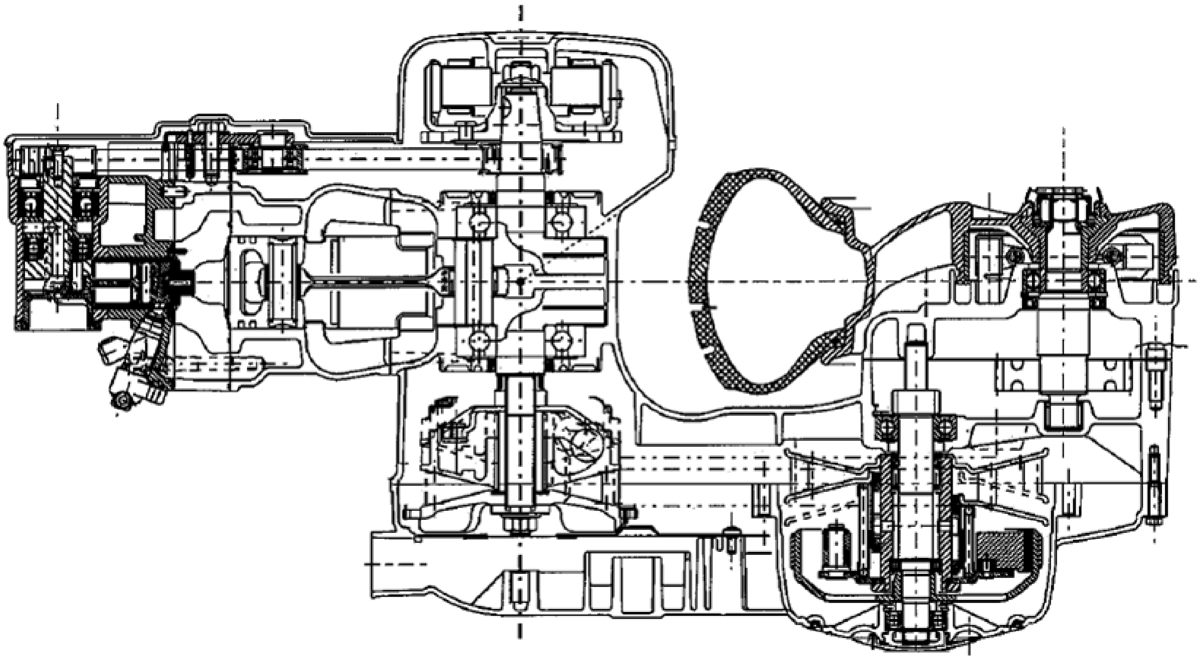


Figure 121 DOLCE engine layout with CVT, centrifugal clutch and three-axis gearbox [173, p. 5]

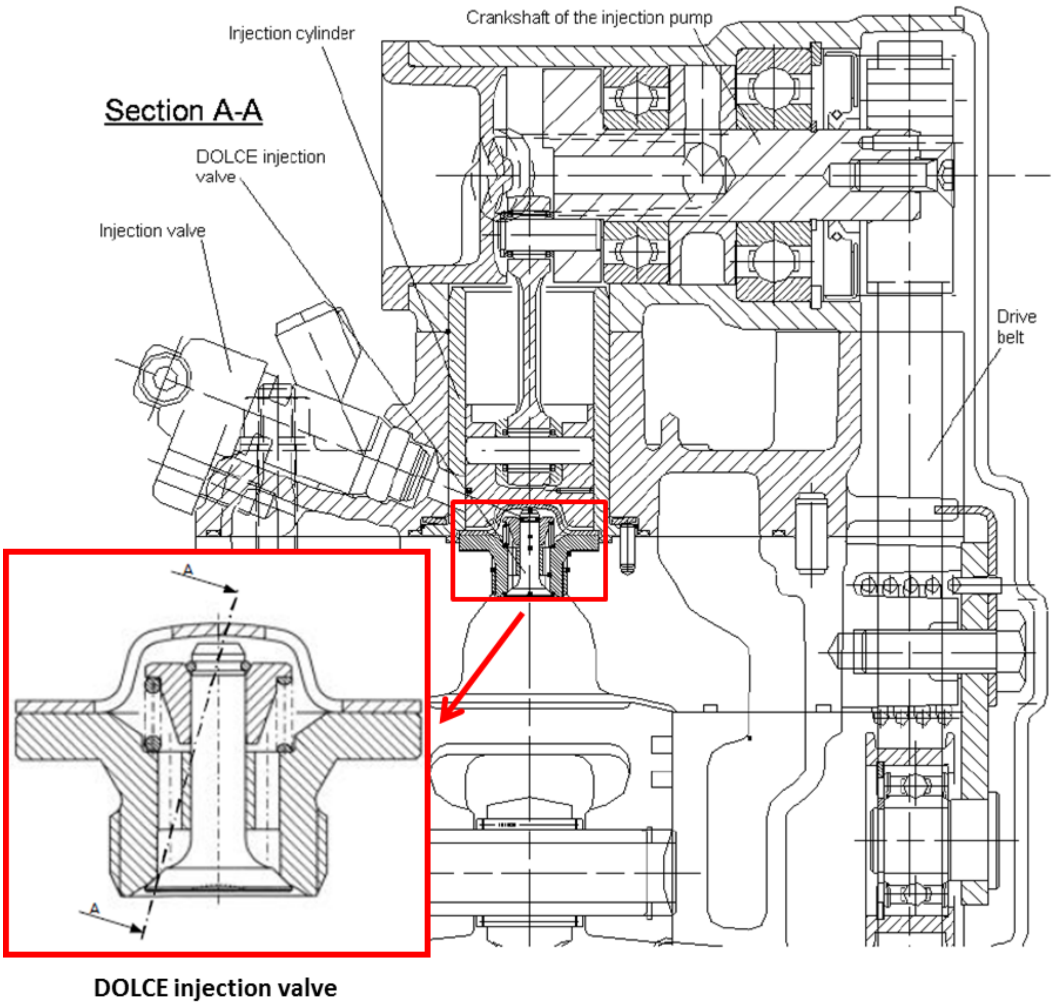


Figure 122 Cross section of the DOLCE cylinder head including DOLCE injection valve; adapted from [89, p. 19; 75]

The principle of the air-assisted direct injection system DOLCE was already described in a chapter bevor that (see Chapter 3.1.1.1.2.4.2). The DOLCE concept was designed for a 125 cm³ two-stroke spark ignition engine with loop scavenging and oxidation catalyst. Figure 121 shows the DOLCE engine layout with Continuously Variable Transmission (CVT) system and Figure 122 depicts the cylinder head as core element of the concept with the standard low-pressure single-jet injector (MMAR Pico Injector), the DOLCE injection valve, the injection cylinder of the 10 cm³ piston compressor and the drive of the piston compressor via drive belt. [89, pp. 172-173]

The control timings of the DOLCE injection system are shown in Figure 123. At 52°CA after TDC of the master cylinder, the transfer passages in the cylinder of the piston compressor are opened (Figure 123 – yellow) and the air-oil mixture flows into the “pre-compression chamber”. This occurs from 124°CA to 236°CA after TDC, referred to TDC of the piston compressor. The offset between TDC piston compressor and TDC master cylinder is 72°C. The fuel injection by the low-pressure injector into the pre-compression chamber is carried out approximately at the same control timing area (green). The exhaust ports opens at 93°CA after TDC of the master cylinder (red). The scavenging process with the air-oil mixture starts after a pressure reduction in the combustion chamber at 123°CA after TDC of the master cylinder (blue). The injection of the pre-mixed air-fuel-oil mixture into the combustion chamber is possible, when the BDC of the master cylinder is reached. The main part of the fuel-air-oil mixture is injected between 237°CA – transfer passages of the master cylinder closed – and 267°CA – exhaust ports closed – after TDC of the master cylinder (blue shaded). After the end of the injection process at TDC of the piston compressor – corresponds to 288°CA after TDC of the master cylinder – and a certain time for mixture formation, the ignition starts shortly before the TDC of the master cylinder. [89, p. 36]

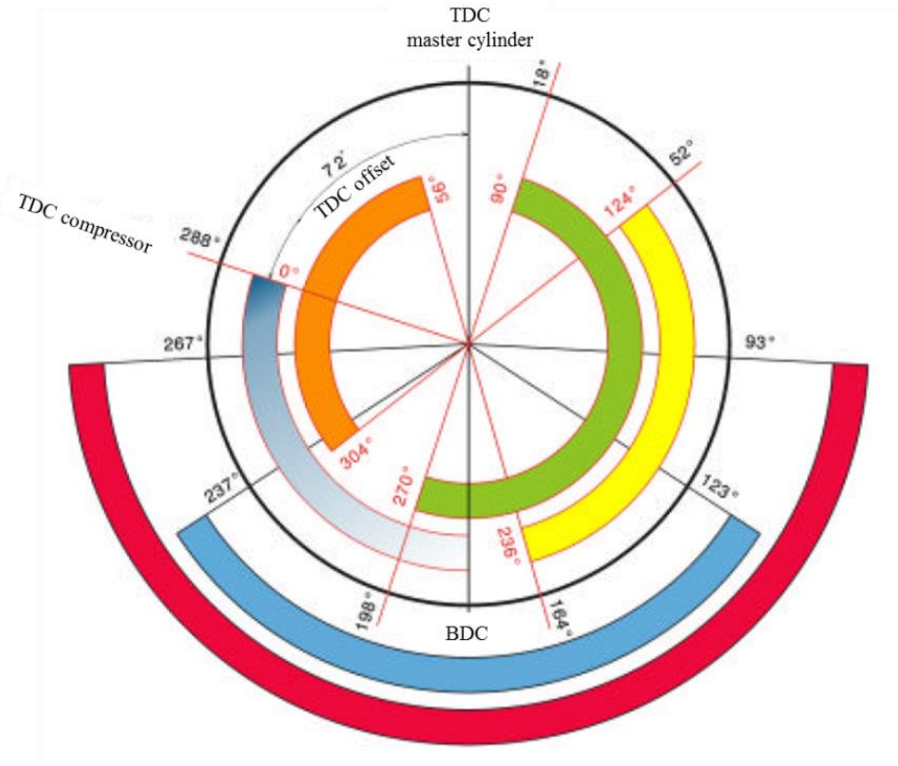


Figure 123 DOLCE injection system - control timing; adapted from [89, p. 36]

The piston compressor crankcase is recharged via the slot-control in the compressor crankshaft at the control timings 304°CA to 56°CA referred to the TDC of the piston compressor (orange). The right choice of the injection timing into the combustion chamber is essential for a good balance between low scavenging losses and sufficient time for mixture formation to reach low emissions and a good efficiency. [89, p. 36]

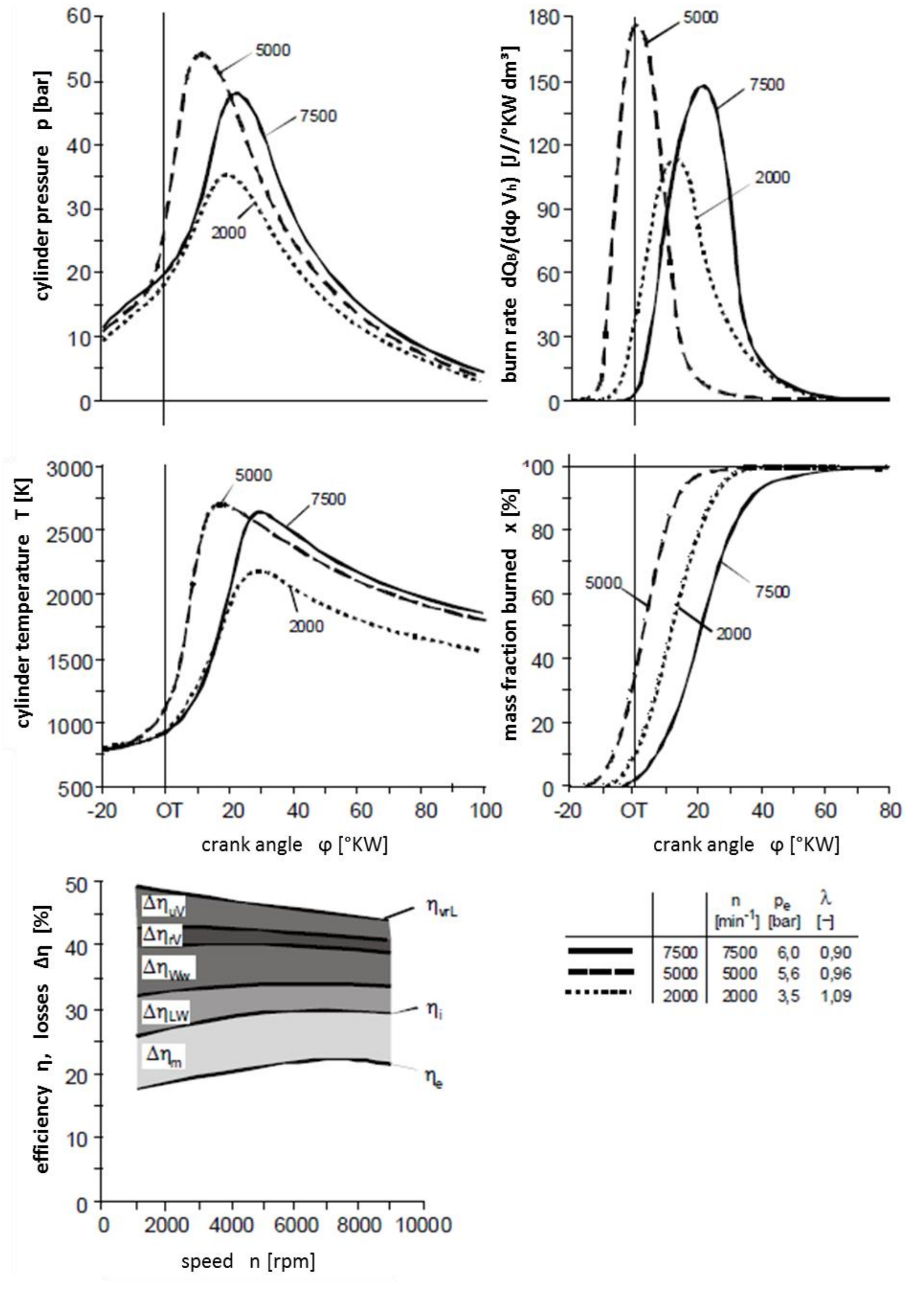


Figure 124 Loss analysis of the 125 cm³ two-stroke DOLCE engine [89, p. 96]

Figure 124 presents a loss analysis of the 125 cm³ two-stroke DOLCE engine at 2000 rpm, 5000 rpm and 7500 rpm. In the compression phase, the cylinder pressure and temperature

vary widely, since, on the one hand, the volumetric efficiency is different and, on the other hand, the ignition timing is adjusted to the engine operation points. At 5000 rpm, the ignition timing is set in such a way to limit the maximum IMEP and at 7000 rpm the ignition timing is set towards late to limit the thermal stress. As a result, the peak pressure and temperature are reduced, but the torque decreases as well. At 2000 rpm, the ignition timing was also set late, as the engine would run unstable because of the high residual gas content in the combustion chamber. Moreover, the cylinder temperatures achieve high values during combustion, due to the low air ratio (λ). The combustion comprises only a small °CA owing to the high grade of turbulence. The efficiency of the perfect engine with real charge decreases with increasing speed due to the decreasing air ratio (λ). In general, the loss shares are hardly changing with increasing speed only the losses of imperfect combustion are significant. [89, p. 96]
A further central point at the development of the DOLCE system was the EMS. Magneti Marelli has specially developed for this project an ECU and, additionally, the sensors and actuators of the EMS was tuned in such way that the electrical energy provided by the alternator/battery is sufficient to supply the electrical components with this energy. In particular, at small two-wheel engines, such as is the case at this 125 cm³ engine, is the right dimension of the electrical power unit a critical point. [173, pp. 5-6]

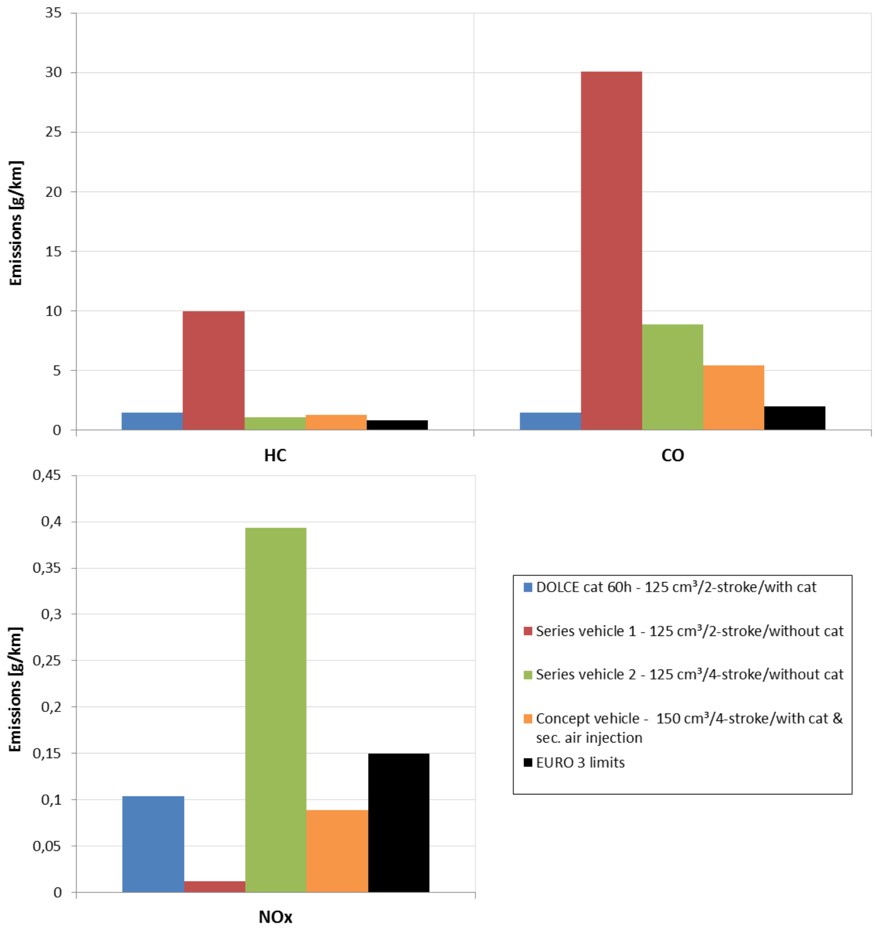


Figure 125 Emission at the ECE 40 Driving Cycle of the DOLCE engine in comparison to other series and prototype vehicles; based on [89, p. 152]

The project target with regard to emission regulation EURO 2 was reached with the developed DOLCE engine and furthermore, the EURO 3 emission limits could be also met, with the exception of HC emissions. HC emissions can be further reduced by an adaptation of the mixture formation in areas of high HC emission. Figure 125 illustrates the HC, CO and NOx emissions of the 125 cm³ two-stroke DOLCE engine with catalytic converter (blue), of a 125 cm³ two-stroke series engine without cat (red), of a 125 cm³ four-stroke series engine without cat (green), a 150 cm³ four-stroke concept engine with cat and secondary air injection (orange) and the EURO 3 emission limits (black). [89, pp. 152-153]

3.1.2.1.5 Crankcase Compressed Air-assisted Injection (IAPAC/SCIP) Engine

In 1993, IFP and Piaggio already demonstrated the benefits of the IAPAC (Injection Assistée Par Air Comprimé – crankcase compressed air-assisted direct injection) system with a 125 cm³ two-stroke single cylinder scooter engine concept [174], which is shown in Figure 126. On the basis of this proof of concept, the Italian marine outboard manufacturer SELVA in cooperation with IFP developed a prototype of a 50 HP (~37 kW) two-stroke twin-cylinder outboard engine. Starting point of the development was an already available two-stroke engine with carburetor. The principle function of the IAPAC is described in chapter 3.1.1.1.2.4.3. [126, pp. 102-106] [123, pp. 3-5]

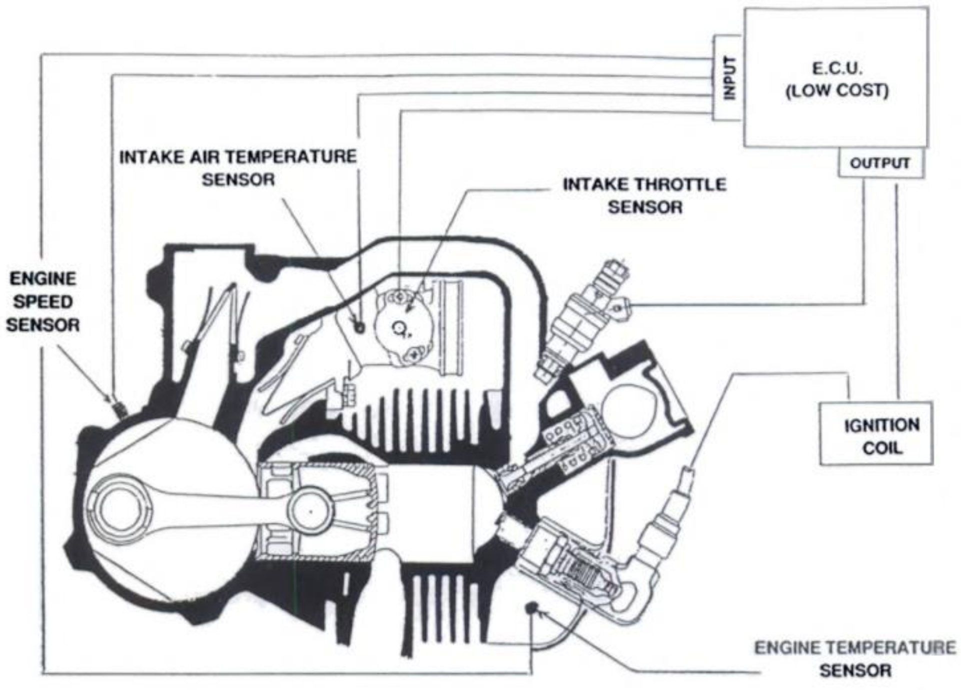


Figure 126 IAPAC two-stroke single cylinder scooter engine by IFP and Piaggio [126, p. 106]

The modification of the cylinder head was an essential part of the development. The cylinder head consists mainly of a camshaft, two inlet valves and two fuel injectors – one each cylinder. The camshaft controls the valves and is driven by the crankshaft. An adjustment of the combustion chamber design ensures that a sufficient amount of rich mixture reaches the spark plug and the short-circuit losses are minimized. Furthermore, the cylinder head has a separate lubrication circuit to provide the relevant components of the valve train with oil and the oil pump is also driven by the crankshaft. Instead of the carburetors a single throttle body with position sensor was used.

The EMS and the EFI have been developed as low cost solution in assistance with a component supplier. By the fact that the mixture preparation is carried out by the IAPAC system in the cylinder head, a conventional electronic low pressure fuel injector from the automotive sector could be used, which additionally served costs. The EMS has particularly been designed for small engines and uses a throttle position sensor, an air intake temperature sensor, engine coolant temperature sensor, a crankshaft sensor, an air pressure sensor and a neutral position sensor to manage the fuel supply and the ignition timing via the fuel injectors and the ignition coil. Figure 127 depicts a schematically view of the EMS. [123, pp. 3-10]

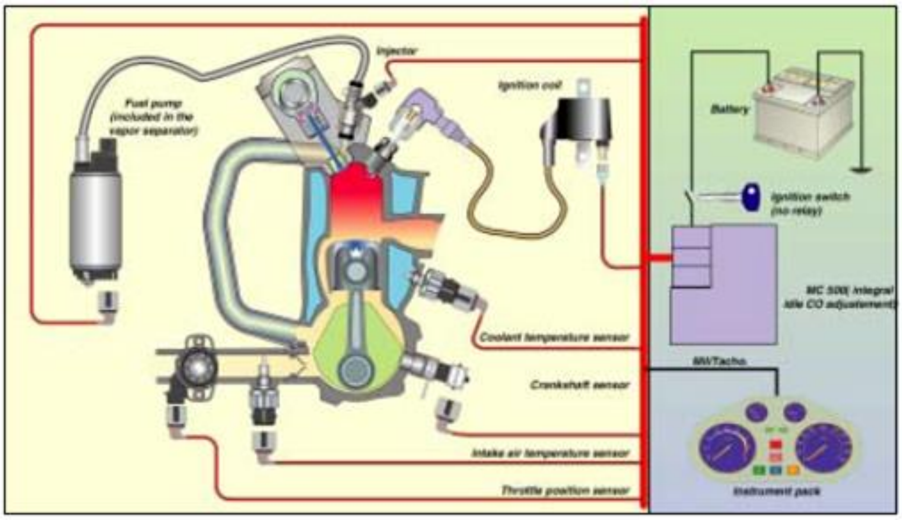


Figure 127 Schematic view of the outboard engine with EMS [123, p. 10]

Figure 128 demonstrates the comparison of the initial standard carbureted engine and the IAPAC engine. The BSFC of the IAPAC engine does not exceed the value of 350 g/kWh at WOT, with the result that the fuel consumption has been reduced at least by 30% compared to the carbureted engine. Furthermore, the HC emissions was also reduced over the entire engine speed range at WOT by about 80%. [123, pp. 6-7]

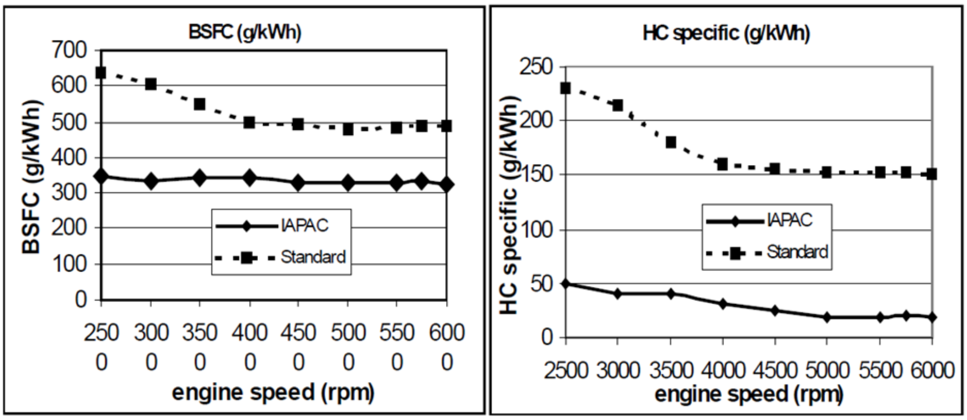


Figure 128 Comparison of standard carbureted engine and IAPAC engine regarding BSFC and HC emissions at WOT [123, p. 7]

The SCIP – Simplified Camless IAPAC – system is a modification of the IAPAC system [128] [127] [129]. Instead of a camshaft, the SCIP uses a diaphragm that is controlled by the existing pressure conditions of the engine and actuates the valve mechanically. The main components of air-assisted injection system, such as the injector, the valve and their actuation are assembled to a so-called SCIP unit, which is fitted on the cylinder head. The company

SAGEM developed and provided a low cost EMS including low pressure EFI components, the MC 500 especially for small engines.

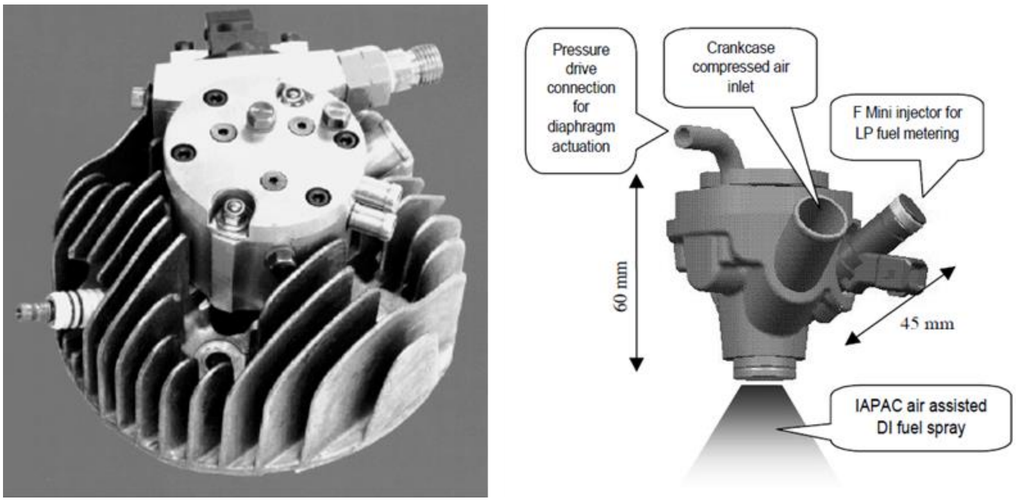


Figure 129 Standard cylinder head with SCIP unit of a 125 cm³ scooter engine and CAD view of the SCIP unit with SAGEM injector [128, p. 5; 6]

Based on the results of the IAPAC prototype engines – 50 HP two-cylinder two-stroke marine outboard engine, 125 cm³ and 50 cm³ two-stroke scooter engines –different engines were equipped with a SCIP system. First, the 125 cm³ two-stroke scooter engine with IAPAC system was modified in that way that a SCIP unit could be fitted on the cylinder head (see Figure 129). This engine served as reference engine for first investigations. In a second step, two prototypes, a 50 cm³ scooter engine and a 6 HP marine outboard engine from SELVA, were equipped with a SCIP system. Vehicle tests with the 50 cm³ scooter were carried out, using the SCIP unit of the 125 cm³ scooter engine owing to the limited resources. [128, pp. 1-6]

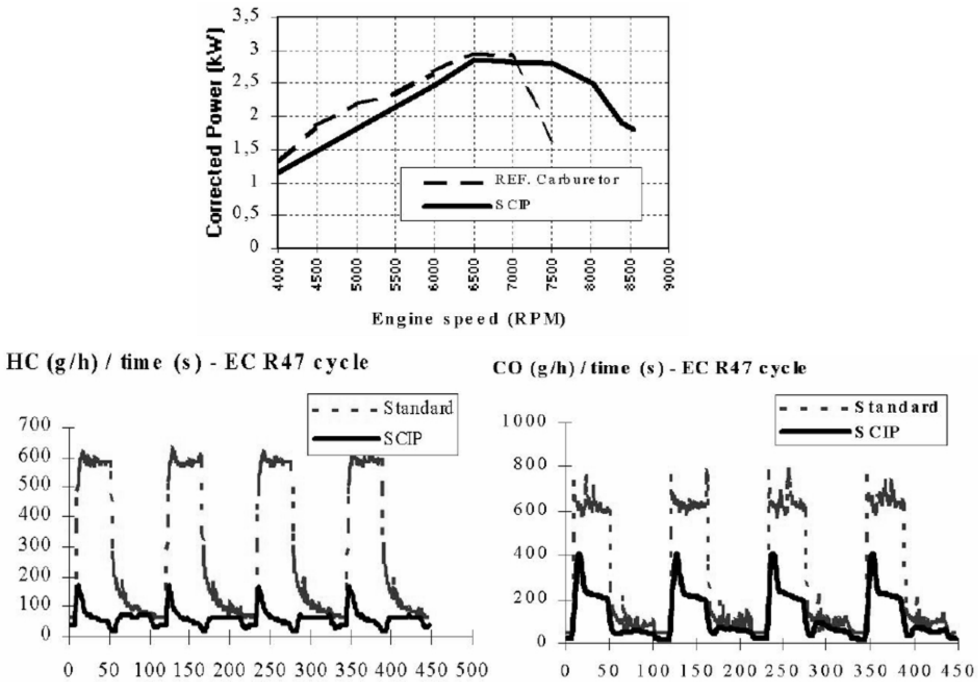


Figure 130 Comparison of standard carbureted engine and SCIP engine regarding power, HC and CO emissions [128, p. 6]

The 50 cm³ SCIP scooter engine was tested with the EC R47 driving cycle with a maximum vehicle speed limit of 45 km/h. Figure 130 shows the power, the HC and CO emissions of the 50 cm³ SCIP scooter engine compared to the standard engine with carburetor. The tests have been done without catalytic converter. The improvement of HC emissions and CO emissions are clearly recognizable. The 50 cm³ SCIP engine without catalytic converter met the EURO 1 regulation – with catalyst EURO 2 is met. [128, pp. 1-6]

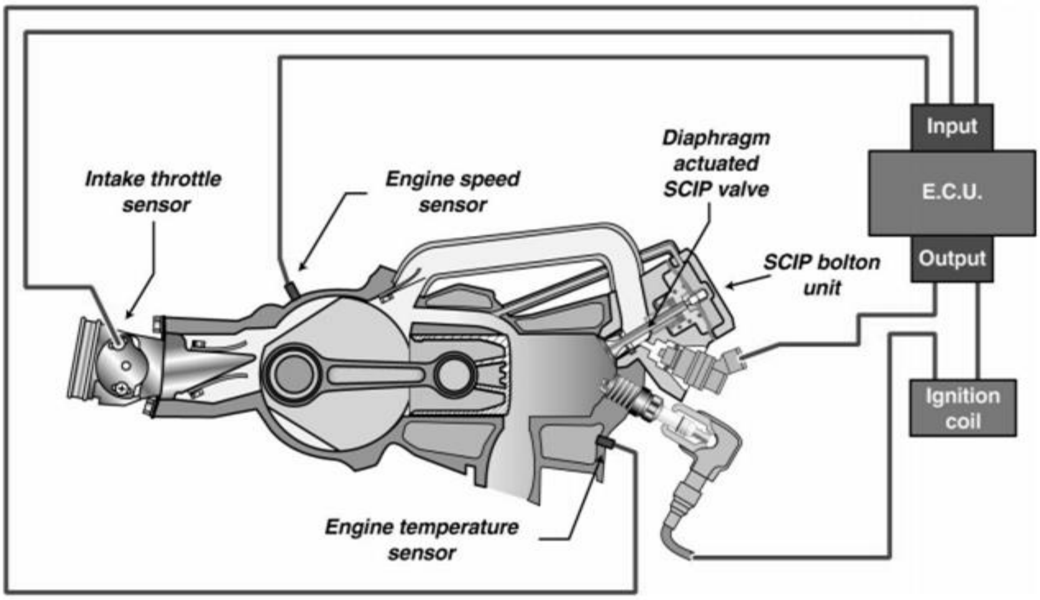


Figure 131 SELVA 6 HP portable marine outboard engine with SCIP system [128, p. 6]

Figure 131 shows the schematic view of the portable SCIP SELVA 6 HP (~4.5 kW) outboard two-stroke engine prototype. In contrast to the SCIP system of the 50 cm³ scooter engine, this SCIP system only requires one connection to the crankcase for valve actuation. In the 50 cm³ scooter engine the chamber above the diaphragm was applied with the pressure of the crankcase and the chamber below was applied with the cylinder pressure. The fuel consumption benefit of the SCIP SELVA 6HP is shown in Figure 132 compared to the standard outboard engine. [128, pp. 6-8]

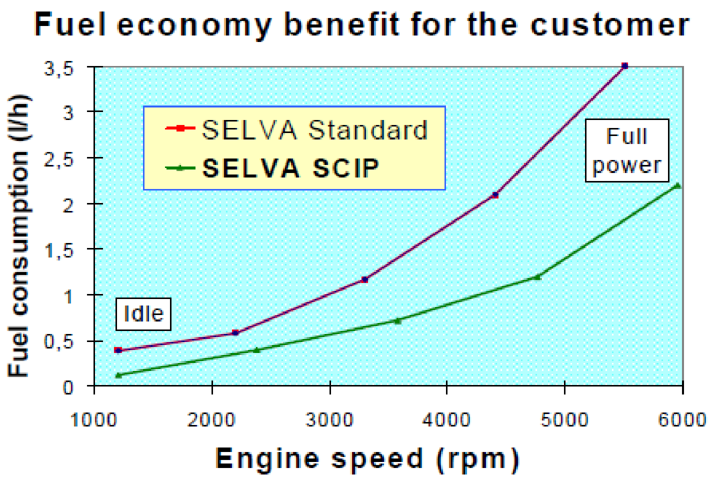


Figure 132 Comparison of the SELVA 6 HP standard and SCIP engines with regard to fuel consumption [128, p. 7]

3.1.2.1.6 2-Phase Injection Engine

Initially, the LPDI concept was developed for a 50 cm³ two-stroke scooter engine and was later adapted to a newly developed 300 cm³ single cylinder Enduro engine (see Figure 133). The carburation is done by an electronic low pressure direct injection system. The oil feed into the crankcase is controlled electronically. In addition, a 1st order balancer for mass compensation is used. The injection system and process is described in Chapter 3.1.1.1.2.3.1. [88, pp. 438-439] [111, p. 3] [114]

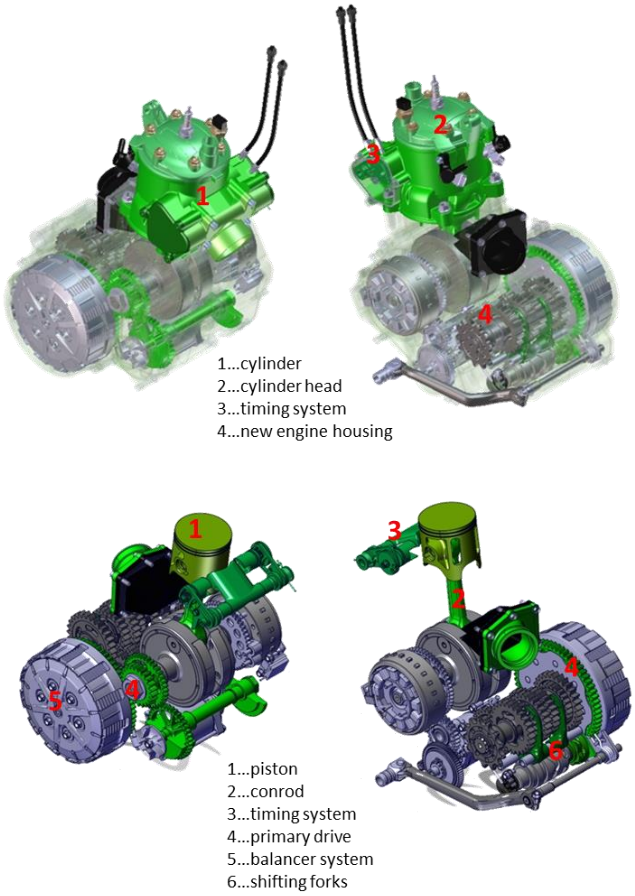


Figure 133 Isometric views of the 300 cm³ two-stroke Enduro prototype engine [114, p. 5]

The main difference between the 50 cm³ scooter/moped engine and the 300 cm³ engine with LPDI are the two fuel injectors of the Enduro engine. This is necessary to achieve the required fuel flow on the entire operating range. Figure 134 shows the two injector positions at the direct injection (left) and at the stratified mode (right). [114, p. 2]

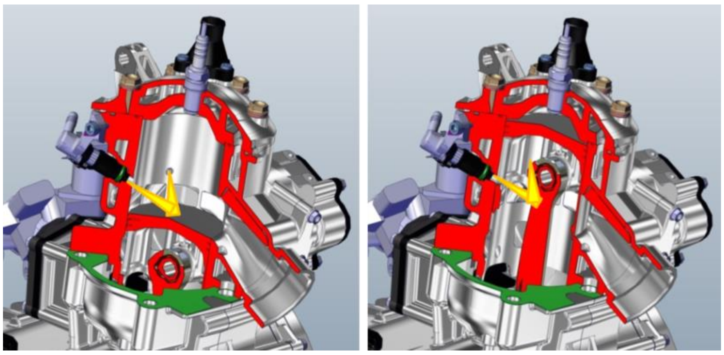


Figure 134 Injection timing for direct injection (left) and stratified mode (right) of the 300 cm³ engine [113, p. 2]

Figure 135 shows the control timing for the stratified (purple) and direct injection mode (green), as well as the scavenging process (blue) and exhaust port (red). It can be seen, that the control timings of exhaust port and scavenge port are symmetric to the BDC. The exhaust ports opening (EPO) is at 102°CA and the scavenge port opening (SPO) is at 126°CA. [111, pp. 3-4;]

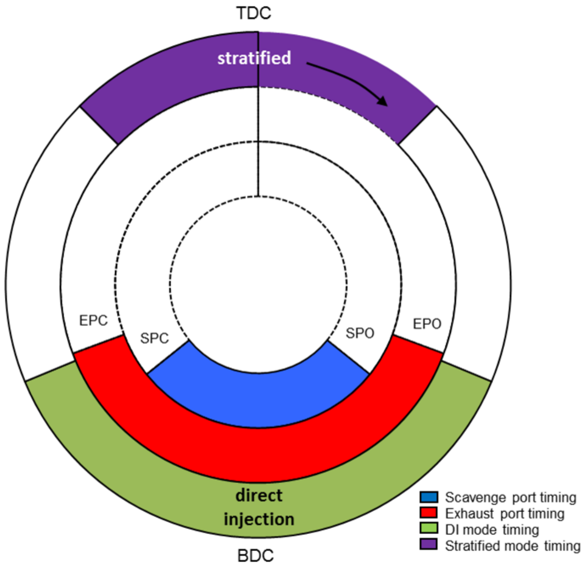


Figure 135 Port and injection control timing of the liquid-cooled 50 cm³ engine [111, p. 4]

A main part of the development was the technical design of the low pressure injection system using a low pressure standard injector from the automotive sector, respectively. The importance of the right injector tuning is shown in Figure 136. Both diagrams present untreated HC emissions. The left diagram compares it of a 4 bar two-hole injector and a 7 bar three-hole injector with that from a carbureted reference engine, and the right diagram compares the HC emissions of a carbureted engine with an LPDI equipped engine at direct injection mode and at stratified mode. The benefit of the 7 bar injector is obvious at high speed. The final injection system in the liquid-cooled 50 cm³ engines used a fuel pressure of 5 bar. [111, pp. 6-7]

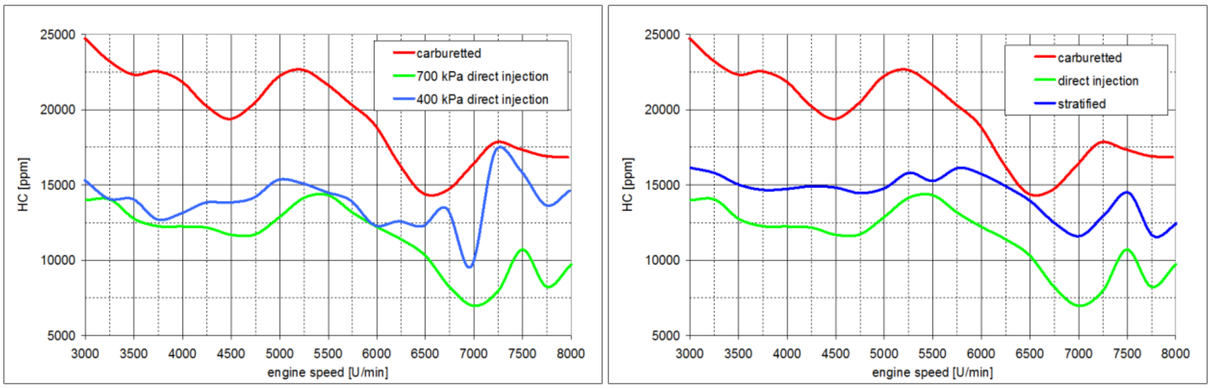


Figure 136 Comparison of untreated HC emissions of a 4 bar and 7 bar injector with a carbureted engine (left) and untreated HC emission at WOT in direction injection and stratified mode compared with a carburetor (right) [111, pp. 5-6]

In a further step, the LPDI technology was implemented in a low cost, air-cooled 50 cm³ two-stroke scooter engine to meet the emission stage EURO 4. For this, a conventional two-stroke engine with carburetor was converted to a two-stroke engine with LPDI. Figure 137 shows the implementation of the LPDI injector on the air-cooled cylinder. The conversion of the engine involved, inter alia, the following modified parts, the target wheel, the generator, the catalyst and the cylinder. New parts were the throttle body with integrated ECU, the fuel injector including ceramic insert and the fuel pump. In turn, the carburetor, the secondary air system and the CDI (capacitor discharge ignition) of the original engine could be omitted. The adjustment of the target wheel and the generator was necessary, in order to fulfil the ECU requirements. As a consequence of the air-cooled engine, the ceramic insert was a necessity, as the temperatures in such engines are higher than in liquid-cooled engines. The fuel injector is protected by the ceramic insert from the high temperatures in the mounting position. The ceramic insert reduces the injector temperature to about 100°C, which is below the resistance limit of 125°C. The sufficient oxygen level in the lean exhaust gas, caused by the LPDI, does not require a secondary air system.

On the basis of this 50 cm³ two-stroke engine with LPDI, the EURO 4 limits could be met with a conventional exhaust system, which is commonly used to comply with the EURO 2 emission standard. In addition, the costs could be reduced further by the use of a catalytic converter with 100 cpsi instead of the widespread 200 cpsi, in consideration that the EURO 4 is still met with the LPDI system. Hence, the LPDI system costs are equal or even below the system costs of engines, which fulfil earlier emission standards. [113, pp. 1, 5]

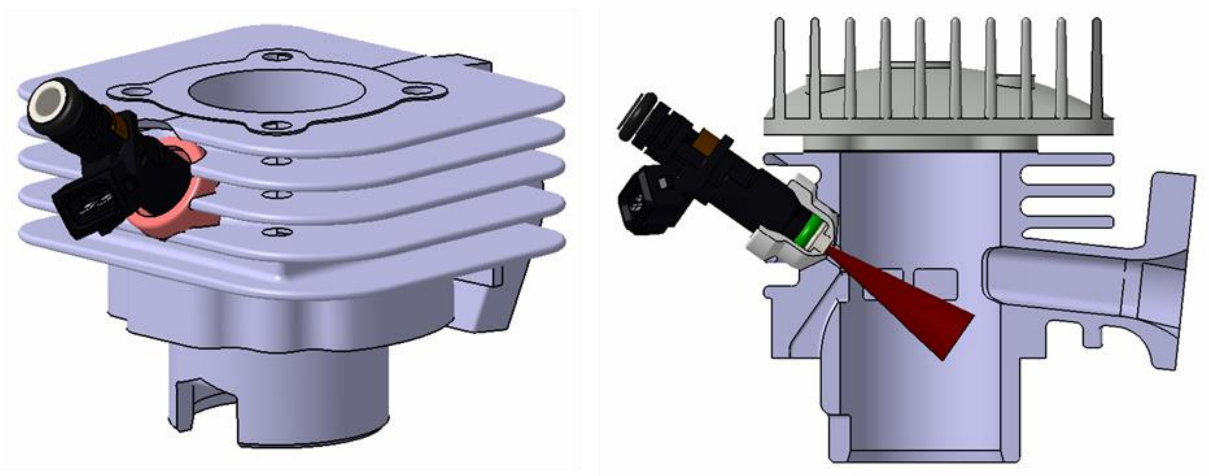


Figure 137 Implementation of the LPDI injector at the air-cooled 50 cm³ two-stroke engine; adapted from [113, p. 4]

The transient and accumulated HC-, CO- and NOx-emissions of both 50 cm³ two-stroke engines with LPDI (left – initial configuration with liquid cooling; right – EURO 4 application with air cooling) in the ECE R47 driving cycle are shown in Figure 138 to Figure 140. The most HC emissions occur in the cold start phase and thereby they raise the resulting HC level of the entire test cycle. The CO peak at the beginning of the driving cycle can be attributed the catalyst light-off. The high NOx emissions at transient conditions are derived from the high temperature – see on contrary the low NOx emissions at the beginning of the cold start.

In the first 60 s of the start process, the EURO 4 application uses a revised setup to reduce the CO and HC emissions. The setup was chosen in such way that the engine operates as lean as possible in the first 60 s but without misfiring in full load. Figure 141 to Figure 143 show the transient and accumulated HC-, CO- and NOx-emissions for the liquid-cooled 50 cm³ engine with LPDI in the ECE R40 driving cycle, which is commonly used for motorcycles with displacements ≤ 150 cm³. [111, pp. 8-9] [113, pp. 3-4]

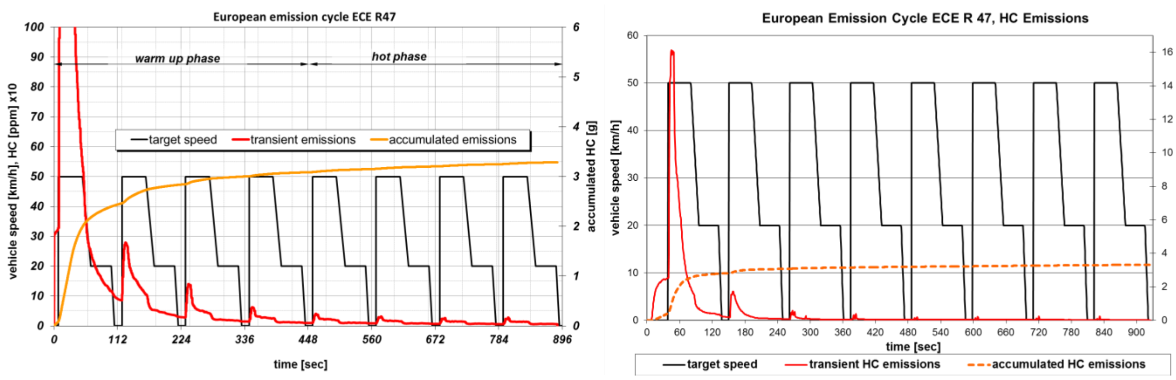


Figure 138 HC emissions during the ECE R47 driving cycle of the LPDI 50 cm³ two-stroke engine – initial configuration with liquid cooling (left) and EURO 4 application with air cooling (right) [111, p. 8] [113, p. 3]

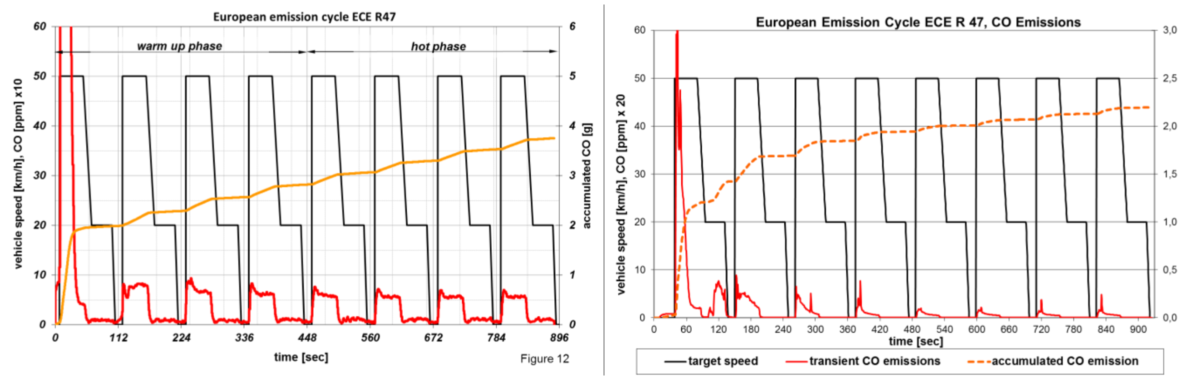


Figure 139 CO emissions during the ECE R47 driving cycle of the LPDI 50 cm³ two-stroke engine – initial configuration with liquid cooling (left) and EURO 4 application with air cooling [111, p. 8] [113, p. 4]

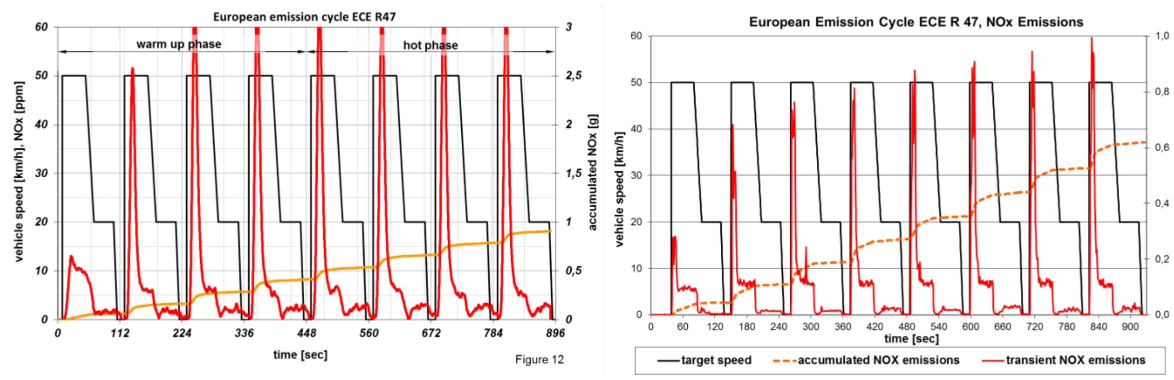


Figure 140 NOx emissions during the ECE R47 driving cycle of the LPDI 50 cm³ two-stroke engine – initial configuration with liquid cooling (left) and EURO 4 application with air cooling [111, p. 8] [113, p. 4]

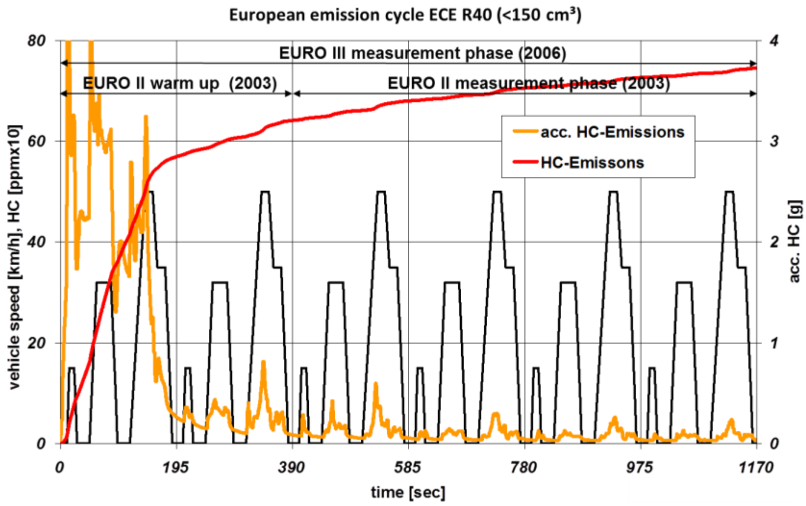


Figure 141 HC emissions during the ECE R40 driving cycle of a vehicle equipped with LPDI [111, p. 9]

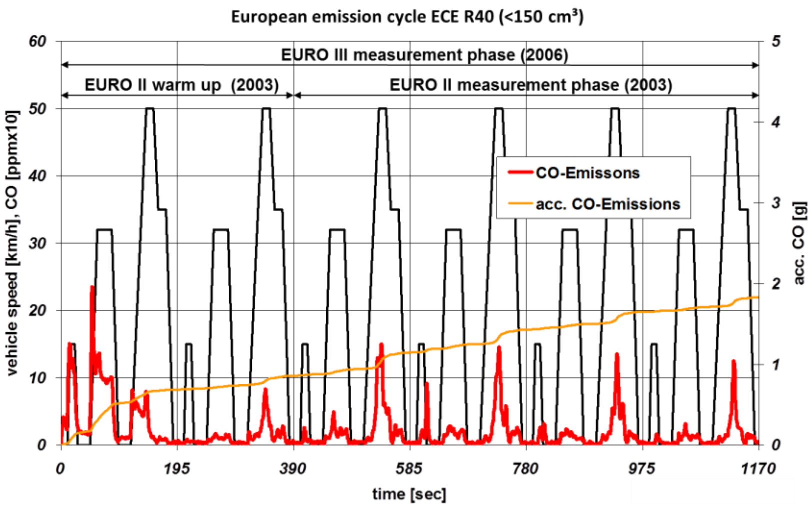


Figure 142 CO emissions during the ECE R40 driving cycle of a vehicle equipped with LPDI [111, p. 9]

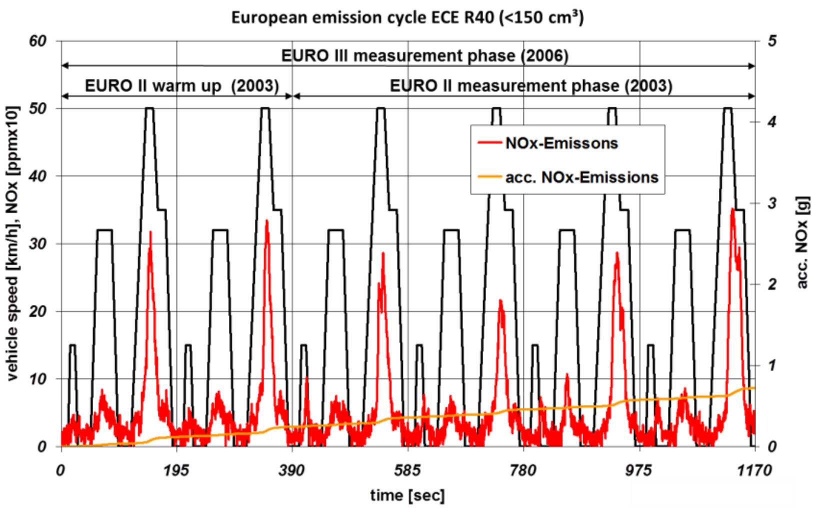


Figure 143 NOx emissions during the ECE R40 driving cycle of a vehicle equipped with LPDI [111, p. 9]

3.1.2.1.7 "Ram Tuned" Direct Injection Engine

In 1998, a series hybrid car concept for a small passenger car, the Citroen Saxo Dynavolt, was already released at the International Car Exhibition of Paris (see also [175]). This concept used a two-cylinder two-stroke engine with direct injection system as range extender to recharge the battery. The two-stroke engine had been chosen due to the power-to-weight ratio of two-stroke engines. The adverse fuel consumption and emissions of two-stroke engines were compensated by a direct injection system, the "Ram Tuned" injection system by C. Stan. Figure 144 shows the Citroen Saxo Dynavolt with the system configuration of the function and hybrid modules. [135, pp. 1-2]

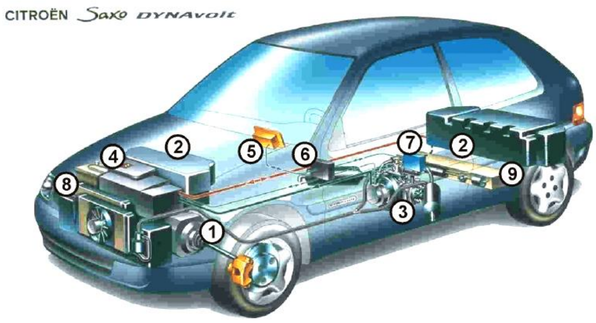


Figure 144 Citroen Saxo Dynavolt with hybrid modules [135, p. 3]

This hybrid concept car was developed on the basis of the electric car Citroen Saxo Electrique. The two-stroke engine with direct injection is included in the APU (Auxiliary Power Unit) with the alternator and weighs 8 kg without oil, coolant and fuel. Moreover, the two-stroke engine was designed very compactly with the dimension of 0.3 m x 0.3 m x 0.25 m (length x width x height). The two cylinders of the water-cooled 200 cm³ engine are oppositely positioned (see Figure 145) and provide an effective mechanical power out of 10 kW with an engine speed limit of 7000 rpm. In consideration of the inertial forces, the engine uses a simultaneous ignition in both cylinders. Hence, the crankcase can function as pump for the scavenging process as at conventional two-stroke engines. As a result of the compact engine dimension the bore-to-stroke ratio is low with about 0.655 and, therefore, the engine speed has been increased to reach an appropriate output power. Moreover, the low bore-to-stroke ratio leads to friction conditions of conventional two-stroke engines in spite of a high engine speed, due to the moderate piston speed. [135, pp. 2-5]

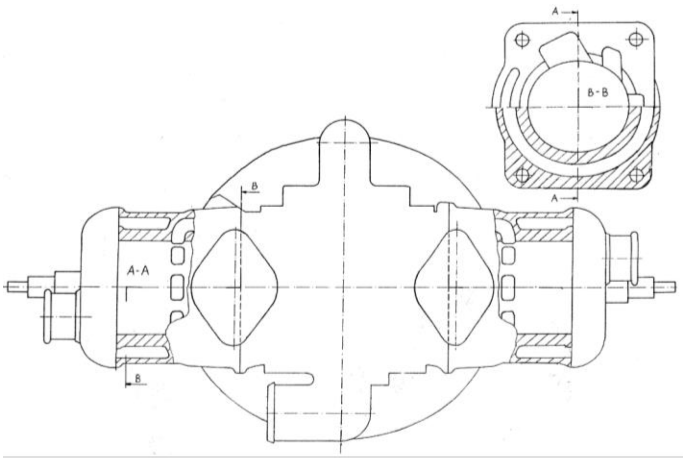


Figure 145 Design of the basic carbureted engine [135, p. 3]

The main requirements for the injection system were a significant short spray length of the injected fuel owing to the compact combustion chamber, a compact high pressure injector module, a low energy consumption that should not exceed a limit of 150 W (approximately 2% of the effective engine power) and an acceptable price behavior. In addition, a main problem is the extremely short time for fuel injection and mixture formation generally in two-stroke engines especially at this high-speed two-stroke engine. Figure 146 depicts the schematic view of the used “Ram Tuned” injection system (left) and the high pressure module (right). The “Ram Tuned” injection system has already been explained in chapter 3.1.1.1.2.5.1. The high pressure fuel injection module contains the injector, the solenoid valve, the pressure pipes and the wave damper. [135, pp. 2-5]

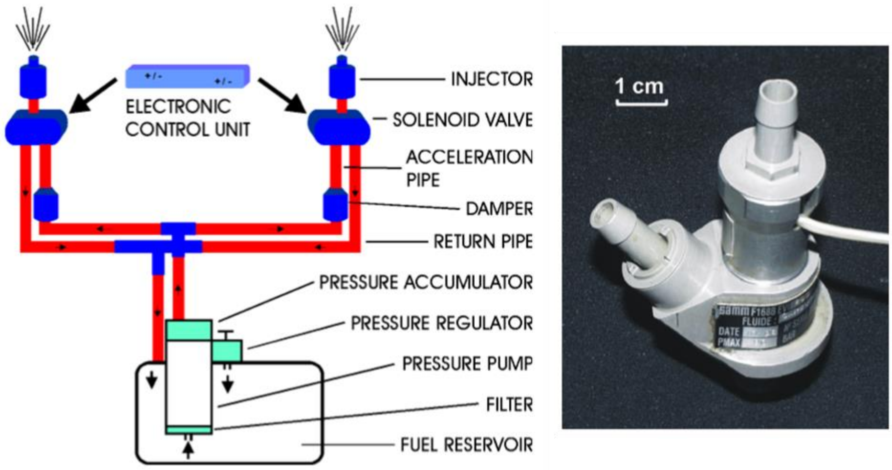


Figure 146 Schematic view of the "Ram Tuned" injection system (left) and high pressure injection module (right) [135, p. 5]

The initial pressure of the injection system for this concept is about 0.45 MPa to 0.55 MPa. This injection system configuration is designed with a high pressure fuel injector module for each cylinder, which are supplied with one and the same initial pressure. Thus, the high pressure occurs only in the acceleration pipe in the high pressure module and the residual system is only applied with initial pressure. The injector opens at a pressure of about 1.8 MPa to 2.5 MPa. The pressure increase as a consequence of the closing solenoid valve and the resulting pressure wave is approximately 5 MPa to 8 MPa with duration of about 0.5 ms to 0.8 ms. [135, pp. 4-5]

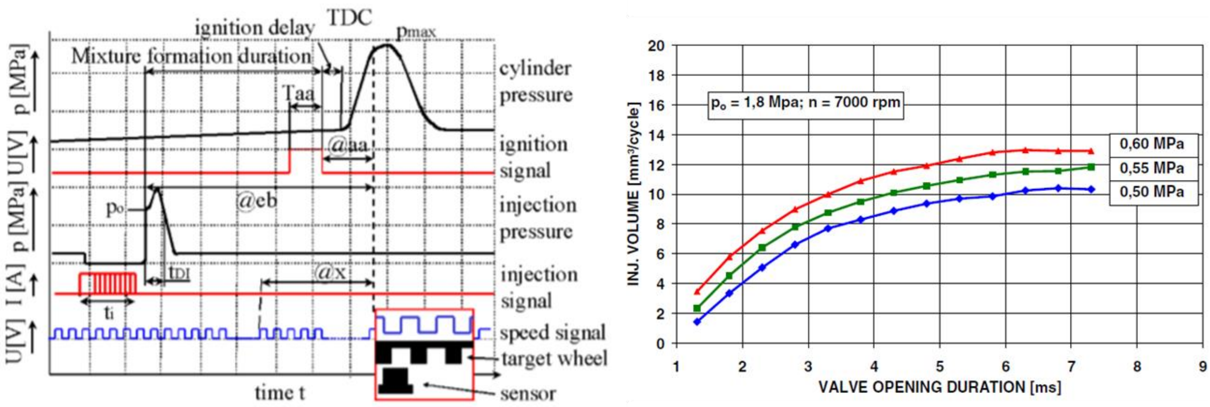


Figure 147 Injection and ignition timing in cylinder of the DI two-stroke engine (left) and measured injection volume as in dependence of the solenoid valve opening duration and initial pressure (right) [135, p. 6]

The duration depends on the acceleration pipe length and the valve closing time. Due to the opening pressure of the injector, the duration of injection is approximately 60% to 80% of the duration of the resulting pressure wave. The amount of injected fuel is adjusted by the ECU. In dependence of the flow velocity of the fuel in the pipes the injected fuel volume can be adjusted between 0.4 mm³ to 18 mm³. [135, pp. 4-5]

Figure 147 depicts the injection and ignition timing depending on the engine speed and the crank angle. The speed signal, the signal of the crank angle and the throttle position are processed in the ECU, which derives the current for activating the solenoid valve depending on engine speed and load. The duration of current is equal to the opening time of the solenoid valve. The flow velocity of the fuel rises with the increasing duration of solenoid valve opening and is limited by the difference of initial pressure and pressure in the reservoir. The pressure wave for the fuel injection is initiated when the solenoid valve is closed again by the ECU. In consideration of the operating point, the ECU determines the ignition timing. [135, pp. 5-6]

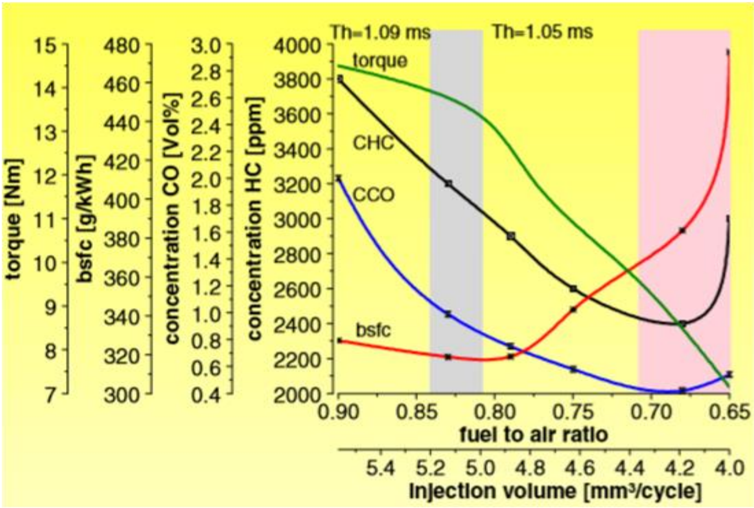


Figure 148 Torque, BSFC, CO- and HC-emissions of the DI two-stroke engine at load range of 75% - 100%

Due to the control of the quality instead of the quantity of the air-fuel mixture and the fact that a series hybrid concept is only operated in idle and full load, a throttling of the air is unnecessary. The charge stratification is only adjusted by the fuel injection system. Figure 148 depicts the results of torque, BSFC, CO- and HC emissions in the load range of 75% to 100%. [135, p. 8]

3.1.2.1.8 E-TEC Direct Injection Engine

The BRP Rotax 850 E-TEC engine is designed for the utilization in snowmobiles. The 850 cm³ two-cylinder two-stroke engine delivers 121 kW at 8000 rpm with a bore diameter of 82 mm and a stroke of 80.4 mm (see Figure 149). This engine uses the second generation of the E-TEC direct injection system. The E-TEC injectors, which are also known as “voice coil” injectors, are explained in chapter 3.1.1.1.2.5.2. In addition to the two E-TEC injectors, two “boost” injectors are positioned behind the throttle bodies. These boost injectors are activated at the mid- and high speed range and injects an air-fuel mix, when the driver opens the throttle abruptly to improve the response of the engine. The throttle bodies have a diameter of 55 mm and are located close to the cylinders. Eleven compartments in the intake system ensure an improvement regarding intake air flow as well as noise emission. [51] [176] [177] [178]

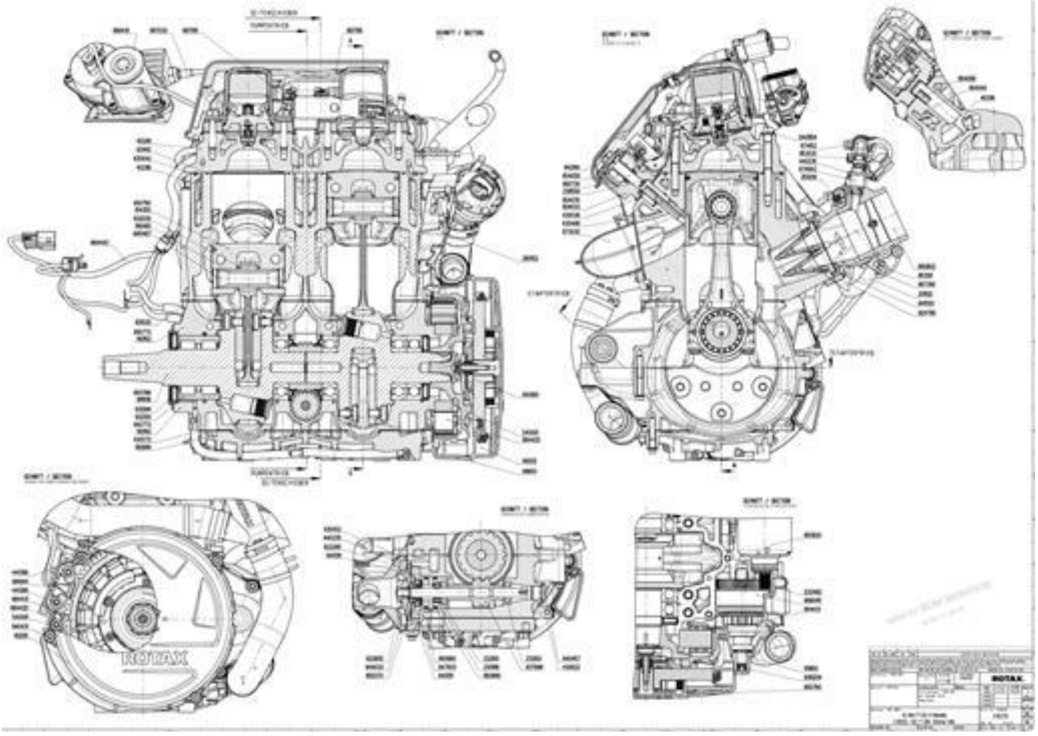


Figure 149 Rotax 850 E-TEC engine - sectional drawing

Even designs and technologies from four-stroke and diesel engines are implemented in the 850 E-TEC engine. The piston ring is held by a new cast iron piston ring carrier, which is derived from diesel technologies, that improves the internal micro movement behavior as well as the thermal expansion. The plasma coating on the aluminum cylinders reduces the friction, due to their porous condition the oil is "slightly absorbed", such as at a sponge, with the result that more oil locally remains on the cylinder wall. The crankshaft design of two-pieces forged crankshaft was derived from four-stroke engines. The bearings and other components are directly lubricated instead of the "splash and spray" lubrication concept of previous engine versions, whereby the oil consumption is reduced significantly. [176] [177] [178]

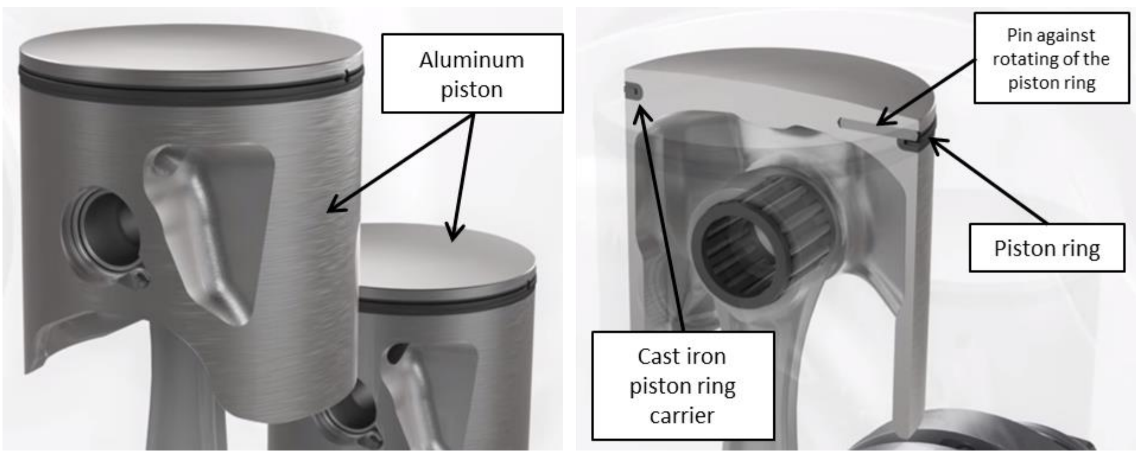


Figure 150 Aluminum piston with cast iron piston ring carrier of the BRP Rotax 850 E-TEC engine; adapted from [176]

The BRP Rotax 850 E-TEC engine uses the 3-D RAVE (Rotax Automatic Variable Exhaust) exhaust valve technology (see Figure 151). These electronically controlled exhaust valves adjust the exhaust port size in accordance with a 3-D mapping that is stored in the electronic control module. The exhaust valves have three given positions that are adjusted by the crankcase pressure. The connection to the crankcase is controlled by the electronic control module. The exhaust valves consist of a primary and a secondary valve. The secondary valve is sucked in their closing position – means not a complete closing of the exhaust port – by the below atmospheric pressure in the crankcase at idle and low engine speeds. At mid-range speeds, the neutral position of the exhaust valves is reached – the second valve is opened while the primary is already closed – by means of releasing the below atmospheric pressure by the electronic control module. At high engines speeds, the primary exhaust valve is pushed open by the crankcase pressure. This process is also initiated by the electronic control module. The RAVE technology offers benefits with regard to torque, fuel consumption and performance. [176] [177] [178]

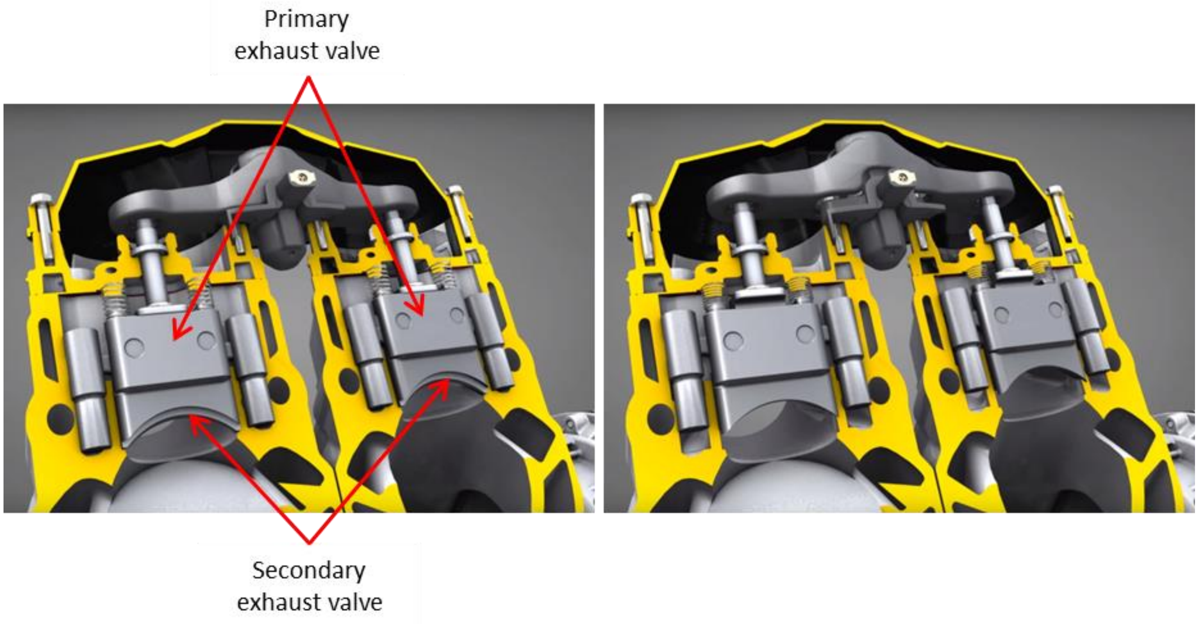


Figure 151 RAVE technology by BRP Rotax – RAVE closed (left) and open (right) position; adapted from [179]

3.1.2.1.9 Compression Wave Injection Engine

The Compression Wave Injection (CWI) system [99] is used in several applications, such as in trimmers or UAV. Moreover, there exist some engine concepts that use the CWI in a modified form, such as the "MuLS" (Multi-Layer Stratification) two-stroke engine [180], for example. The CWI concept is described in chapter 3.1.1.1.2.5.3.
Initially, the CWI was used in a 25 cm³ engine for handheld lawn and garden equipment. Figure 152 shows the CWI engine concept of this 25 cm³ engine including the CWI engine components. [99, p. 7]

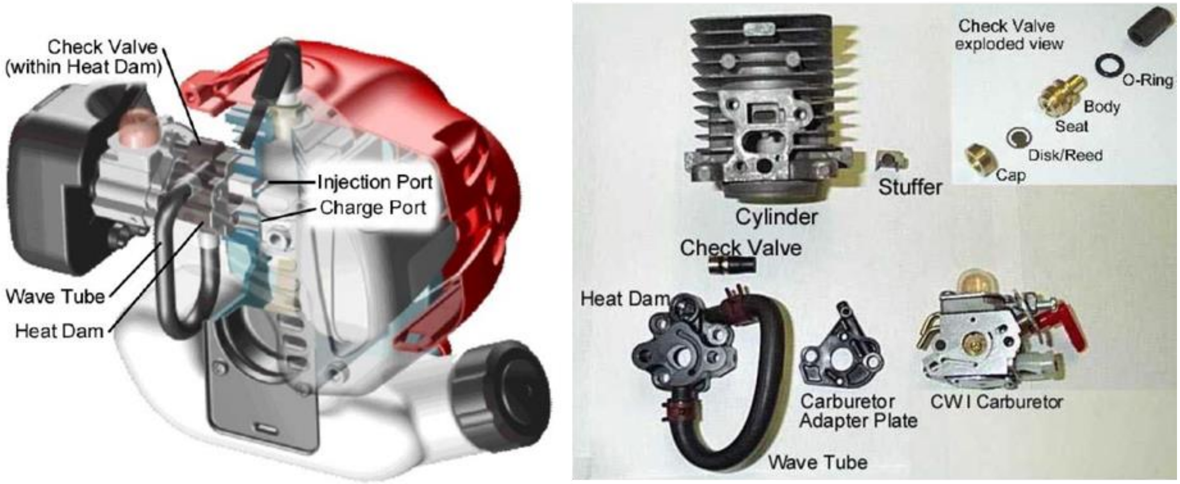


Figure 152 CWI Trimmer power head (left) and CWI engine components (right) [99, p. 8; 10]

Due to the pressure die-casting manufacturing of the engine cylinder, the modifications were reduced to a minimum for the CWI engine in comparison to the initial cylinder, to minimize the costs for new tools. The cylinder has two transfer ports, an injector port and a charge port. A groove in the piston skirt was necessary to adjust the charge port timing, as the charge port could not be changed owing to crankcase design. The piston pin was secured against rotation. The ignition system, the cooling fan and the crankcase remained the same. The CWI wave tube is connected with the engine ports by a "head dam" manifold, which serves as thermal shield for the carburetor and contains the fuel check valve. The fuel system is based on a low cost "cube" type carburetor, which is connected by an additional adapter plate with the heat dam manifold and the fuel check valve. The lubrication system is identical to the lubrication concept of the initial two-stroke engine and is done with an oil-fuel mixture.

The "cube" type carburetor works according to [99] as follows:
"The carburetor is fitted with a second parallel venturi that is used to meter the fuel to the CWI system. This venturi has a throat of approximately 1.5 mm diameter. The fuel for the high-speed metering circuit is fed to the small venturi from the atmospheric metering chamber through a high-speed adjusting needle. The flow through the CWI induction path is throttled with a hole through the shaft that carries the butterfly valve in the main carburetor throat. In this way, the path to the CWI system and the main air induction path are simultaneously throttled. Separate idle-fuel metering is also provided to the CWI induction path, the design of which is dependent on the manufacturer of the carburetor"

Figure 153 Hirth cylinder head and engine with iPower [50]

Another engine application that uses the CWI system is shown in Figure 153. The company Hirth Motoren offers the "iPower" (CWI) technology as an option for their engines. These engines are used, inter alia, in ultralights and ultralight-helicopter or unmanned aerial vehicles with displacements from 30 cm³ to 313 cm³.

3.1.2.1.10 High-Pressure Direct Injection Engine

Within the scope of the doctoral thesis by S. Schmidt [101] and the consequently resulting publications [181] [182] [183], a high pressure direct injection system for a 500 cm³ two-stroke engine was developed and released in late 2004.

The challenge of the project was to combine the advantages of two-stroke engines – high power-to-weight ratio, low package space and low maintenance – and four-stroke engines – low emissions and low fuel consumption. For this purpose, the working process for a two-stroke high pressure direct injection (HPDI) system should be investigated and designed on the BRP Rotax 955 SDI two-cylinder two-stroke engine. The basic engine was converted into a one cylinder engine for the investigation. The fact that the available time for mixture formation is significantly shorter and the speeds are typically higher at two-stroke engines changes the requirements to a direct injection system for two-stroke engines compared to that for a four-stroke engine. Hence, a standard high pressure direct injection system with electromagnetic hallow cone swirl atomizer and a maximum injection pressure of about 120 bar from the four-stroke automatic sector, which was adapted for the 360°CA working process, was used to meet the requirements regarding mixture formation at two-stroke engines. Two approaches for fuel injection timing meet the conditions of high power and low emissions as well as the utilization of a standard injection system from the automotive sector: the first is to start the injection after the exhaust port has closed to reduce the scavenging losses – late injection - and the second is to inject during the load exchange and to use the interaction with the flow field to reduce the scavenging losses – early injection. The first approach requires a late injection phase and the second approach enables two variants, either early or late injection phasing, whereby the position of the injector is different. [101, pp. 56-59, 81] [181, pp. 3-4]

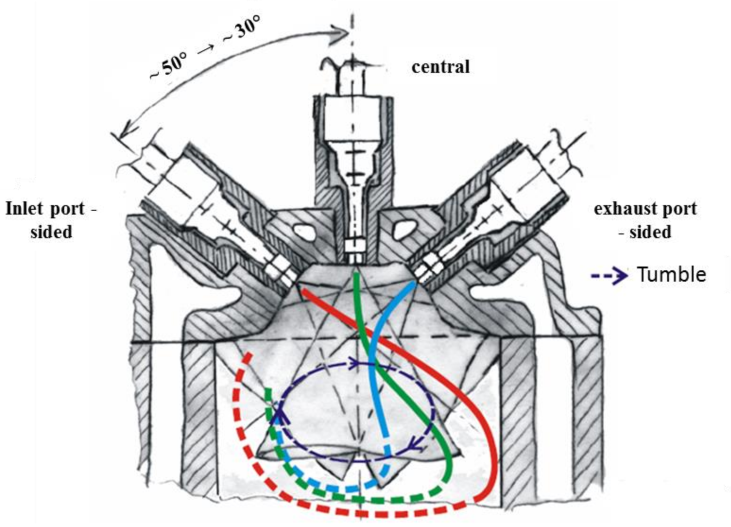


Figure 154 Sketch of possible injection positions and the interaction of the spray with tumble and combustion chamber walls [101, p. 85]

Figure 154 shows a first draft of investigated injection positions. From the demands regarding early and late injection phase and the port timing diagram (see Figure 155) a very short available time for fuel injection at the two-stroke engine is derived. The available injection time at two-stroke engines for early injection is about 2-3 ms and for late injection it is approximately 1 ms at 8000 rpm WOT, and as a consequence a high static flow rate of up to 20 g/s for the injector is necessary to meet the requirements. In contrast, the available injection time at four-stroke engines for a homogeneous charge is approximately 8-10 ms. [101, pp. 58-59] [181, pp. 4-5]

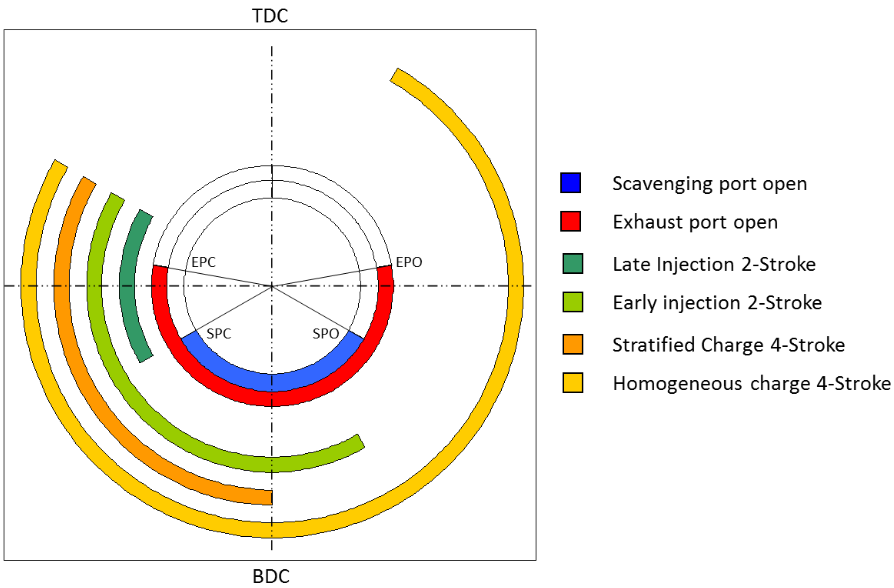


Figure 155 Port timing diagram with possible injection phases; adapted from [101, p. 59]

Figure 156 presents the results of a CFD calculation for the distribution of Equivalence Ratio (EQR) in the combustion chamber for three different injector positions at 340°CA, which is equal to the ignition time. The central injector position with an angle of 10° has a rich mixture area at the crushing gap on the side of the intake port. The 50° lateral positioned injector shows the same, but on the exhaust port side. All further investigations have been carried out with lateral injection angles of 28° and 40°. [101, pp. 89-90] [181, pp. 5-6]

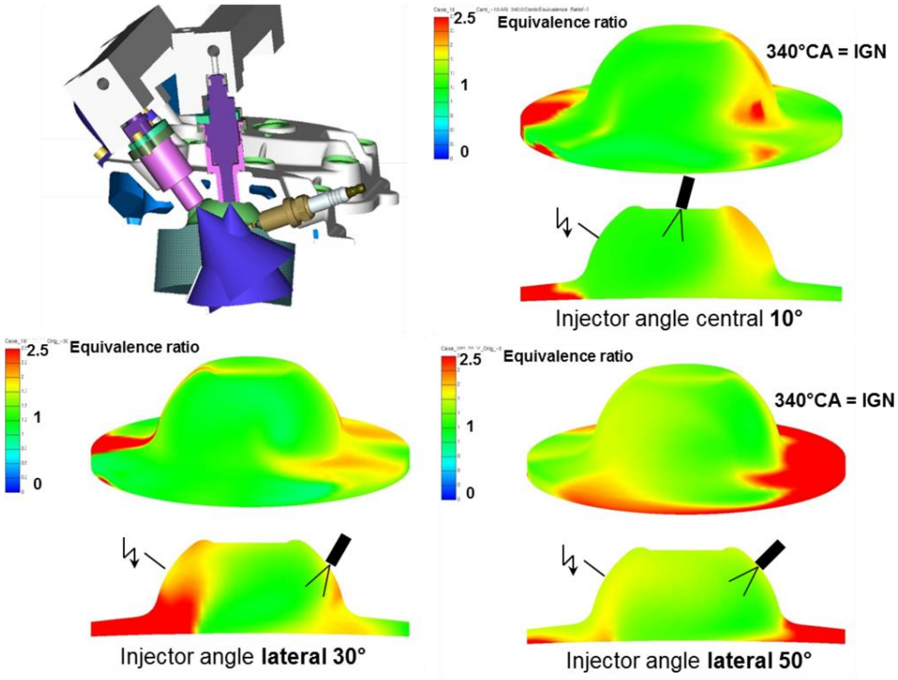


Figure 156 Distribution of Equivalence Ratio by different injection positions at 340°CA after TDC [101, pp. 90, 109]

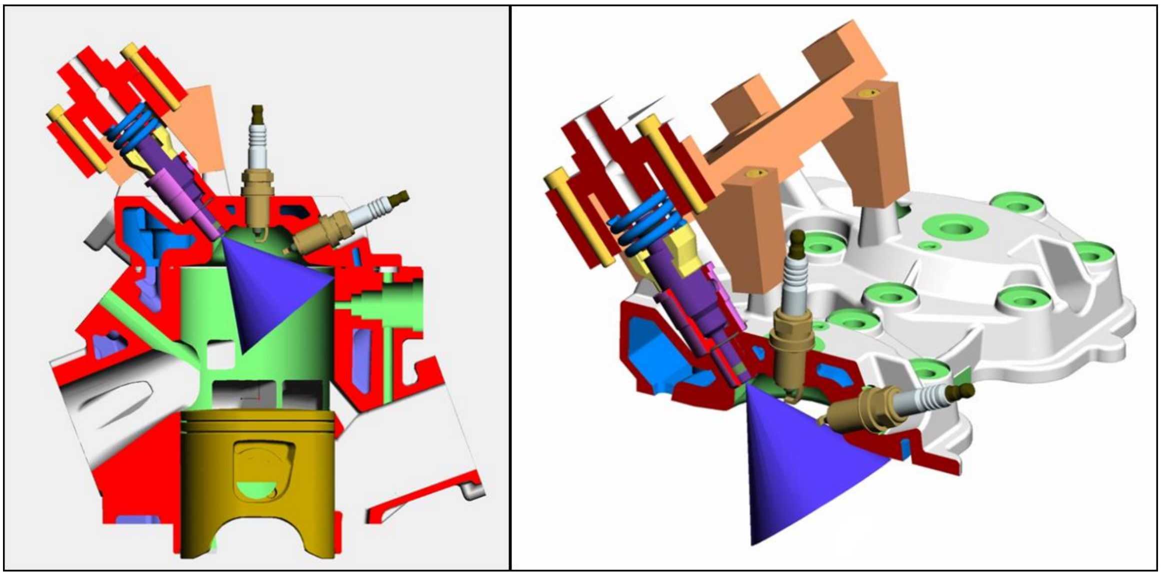


Figure 157 Sectional view of cylinder head and injection system [101, p. 92] [182, p. 6]

A sectional view of the cylinder head, the injector with a lateral axis angle of 40° and the high pressure rail and is shown in Figure 157. The high pressure rail has been implemented for the investigation, which permits an easier switch of the injector position. Figure 158 demonstrates the potential of the HPDI system for 2-stroke engines by a comparison of HC emissions and fuel consumption at idle and rated speed/full load with other injection systems. The advantage of the HPDI concerning HC emissions is clearly evident. [101, pp. 91-92] [181, pp. 8-9] [182, p. 6]

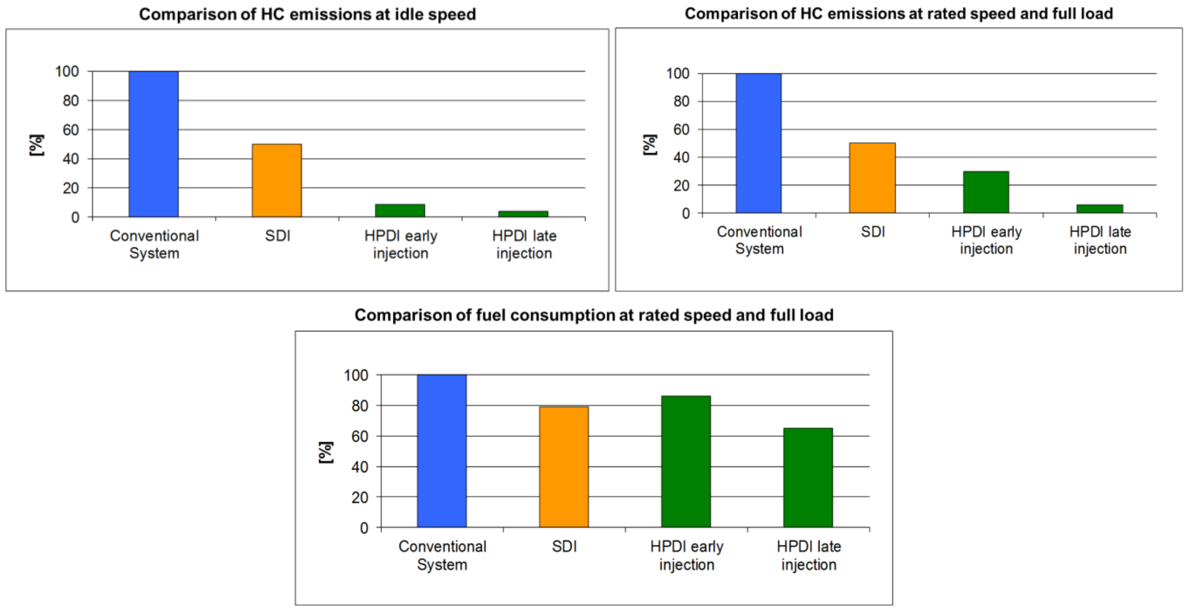


Figure 158 Comparison of HC emissions and fuel consumption for different injections systems at idle speed / rated speed and full load [181, p. 9]

This HPDI concept for two-stroke engines with the early and late injection phasing reduces HC emissions and improves the fuel consumption without a significant decline in performance. For comparative purposes a second HPDI concept for this two-stroke engine has been investigated. This second HPDI concept uses the FICHT injection system and injects the fuel by a central injector position into the combustion chamber (see Figure 159). Figure 160 to Figure 162 illustrate the comparison of BSFC, HC- and NOx-emissions for both 500 cm³ two-stroke HPDI systems and a modern 3 liter four-stroke engine with intake manifold fuel injection. The high HC emissions of the two-stroke engines are caused by the early injection strategy at higher BMEPs and, therefore, increase the scavenging losses. Due to the high residual gas share in the cylinder, the NOx emissions of these two-stroke engines are lower. The BSFC benefit of two-stroke engines can be explained by the reduced scavenging losses at partial loads. [101, p. 146] [182, p. 14]

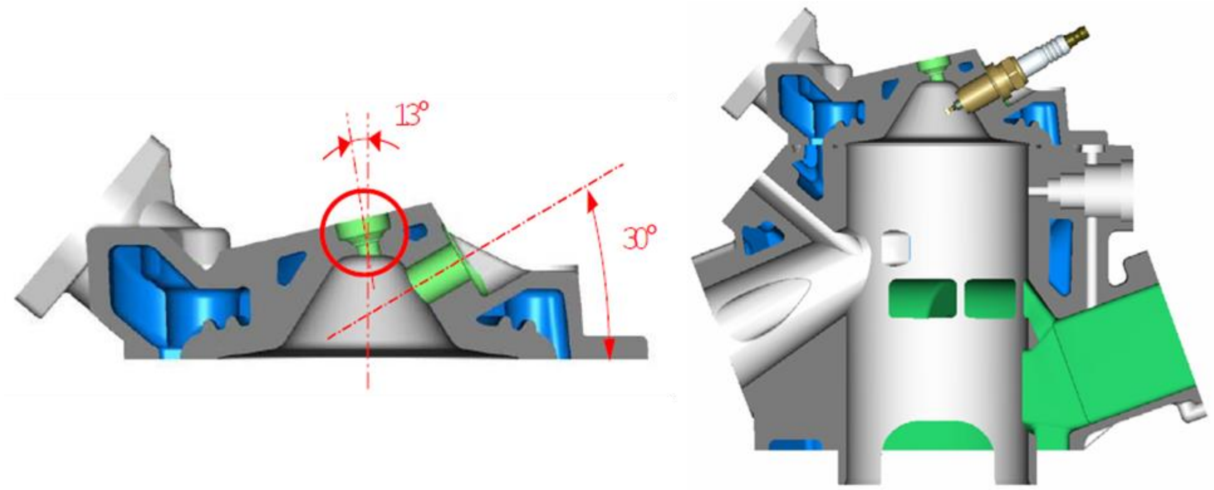


Figure 159 HPDI concept with FICHT injection - schematic view of the cylinder head with injector and spark plug position [101, p. 123]

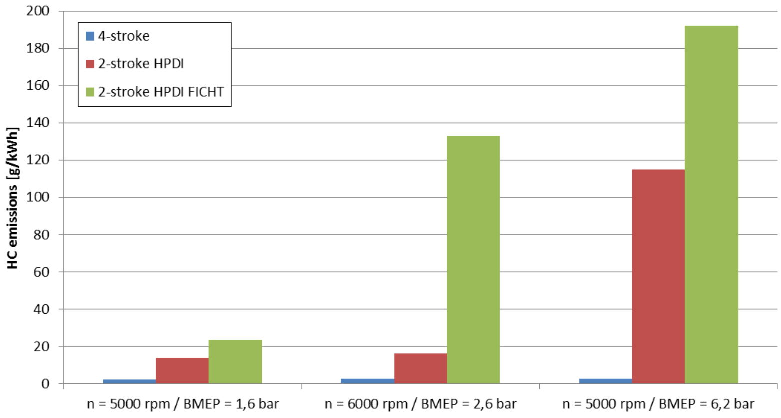


Figure 160 Comparison of HC emissions for 2-stroke and 4-stroke working processes [101, p. 146]

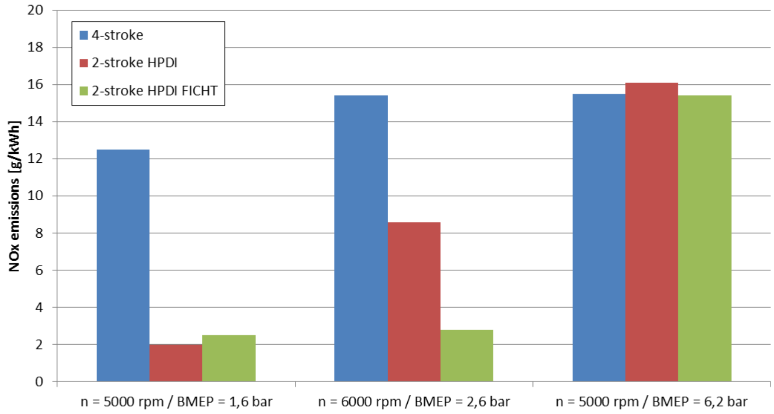


Figure 161 Comparison of NOx emissions for 2-storke and 4-stroke working processes [101, p. 146]

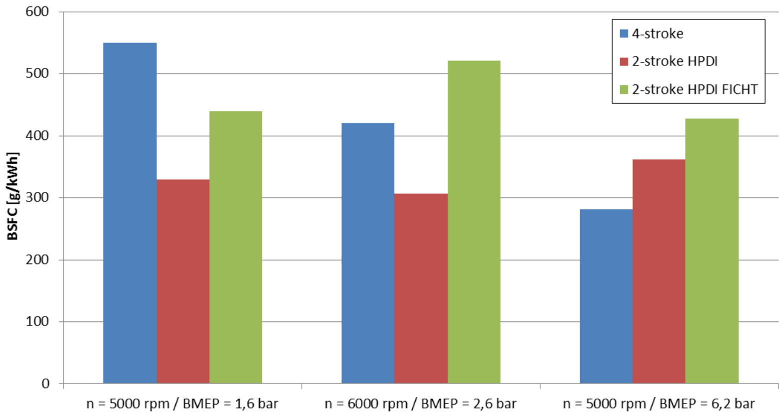


Figure 162 Comparison of BSFC for 2-stroke and 4-stroke working processes [101, p. 146]

Piaggio also investigated a high pressure direct injection concept [184] [185]. This concept used a piston pump, which was directly driven by the crankshaft, to generate a high-pressure of about 33 bar. The fuel metering was done via a coupling of the pump unit and the throttle valve. The spring-loaded injection valve is actuated by means of pressure wave.
The investigated prototype of a high-pressure injection system from Dell'Orto [186] consisted of an electrically driven high pressure pump, which could reach an injection pressure of 100 bar, and electrically controlled high pressure injectors that inject directly into the

combustion chamber. The ECU controls the injection process depending on engine load and speed, air- and cooling water temperature and ambient pressure. [101, pp. 45-46] [186, pp. 3-4]

3.1.2.1.11 Yamaha High-Pressure Direct Injection Engine

At the end of 1999, Yamaha also released a two-stroke high pressure direct injection system [100] for use in outboard engines. In contrast to engines with FICHT fuel injection and Orbital air-assisted injection systems, this non air-assisted HPDI system operates over the entire engine speed range with a homogeneous air-fuel mixture. [100, pp. 3-6; 11-12]

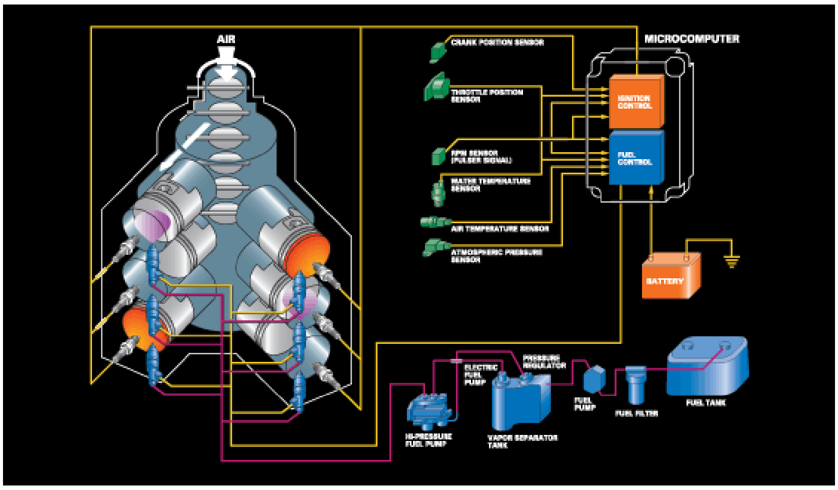


Figure 163 Schematic view of the Yamaha V6-two-stroke engine with HPDI [100, p. 6]

The V6 two-stroke engine with 2596 cm³ provides 200 HP (~150 kW) at 5000 rpm. The compression ratio is about 6.1 – 6.4 at a bore diameter of 90 mm and a stroke of 68 mm. Figure 163 shows the components of the HPDI system. A low pressure pump supplies a high pressure pump with fuel. The high pressure pump is driven by the crankshaft by means of a belt and provides the injection pressure of 50 bar, which gets through the rail to the six electronically controlled fuel injectors. The fuel is injected into scavenging flow in the combustion chamber before the exhaust port closes. The correct air-fuel ratio for the homogeneous mixture combustion is controlled by an oxygen sensor. A full transistor ignition system is used due to the longer spark duration. Figure 164 shows the accumulated HC+NOx emissions of the ICOMIA 5 mode test, also known as the ISO 8178 – E4 test cycle, for three different injection systems. [100, pp. 3-6; 11-12] [88, pp. 433-434]

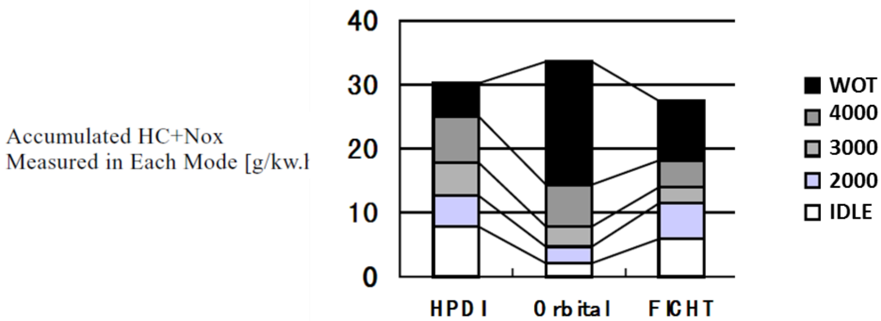


Figure 164 Accumulated HC+NOx emissions of the HPDI, Orbital and FICHT system based on the ICOMIA 5-mode test (ISO 8178 - E4 test cycle) [100, p. 12]

3.1.2.2 Four-Stroke

3.1.2.2.1 STIHL 4-MIX Engine

Due to the compact design, the easy maintainability and the well power to weight ratio two-stroke engines are widespread in hand-held applications, such as in chainsaws, trimmers or blowers. New concepts are developed as consequence of the high HC emissions of conventional two-stroke engines caused by the scavenging losses to meet the emission standards. An approach is a four-stroke engine with mixture lubrication, which is also called “4-MIX” technology by STIHL. The advantages of four-stroke engines, such as reduced HC emissions and better fuel consumption, are also countered by some disadvantages compared to two-stroke engines, such as higher costs and weight which is caused by additional parts for the valve control and a higher maintenance, e.g. valve clearance checks. STIHL uses the 4-MIX technology in their brush cutters with an engine displacement of 31.4 cm³ to 37.7 cm³ and a power out of 1.4 kW to 1.7 kW. [80, pp. 432-433] [187] [188]

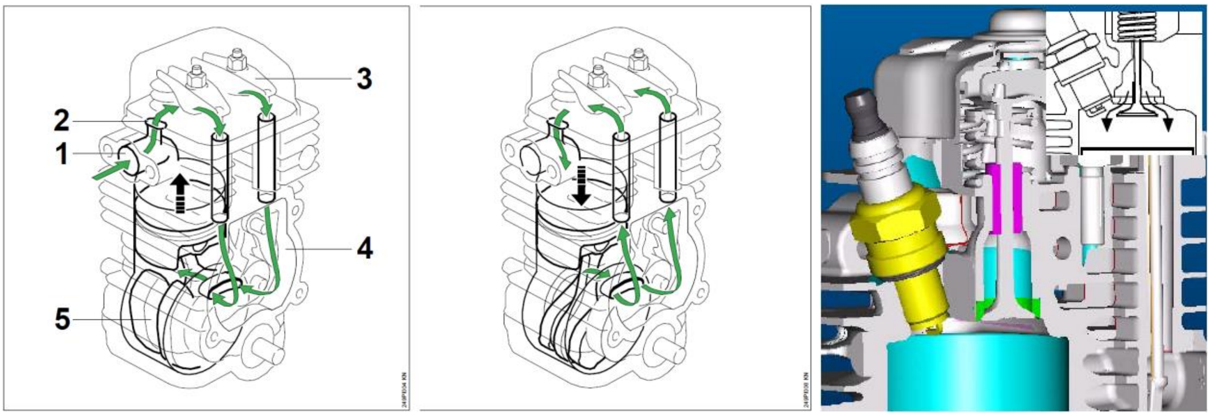


Figure 165 STIHL 4-MIX engine – lubrication system (left) and cross section of cylinder head and combustion chamber (right) [187, p. 5; 7]

Figure 165 represents the lubrication system of the 4-MIX engine by STIHL. The precisely adjusted bore (2) that is positioned downstream of the carburetor positioned connects the intake pipe (1) with the space of the valve guide (3) in the cylinder head. The valve guide space (3) and the crankcase (5) are connected through the push rod guides of the OHV-valve drive and the cam space (4). The below atmospheric pressure in the crankcase during the compression phase sucks the fresh air-fuel-oil mixture via the connection bore (2), the valve guide space (3) and the cam space (4) into the crankcase (Figure 165 – picture in the middle). In the expansion phase, the mixture is returned into the intake pipe (1) by the downward moving piston, in the same way as before in the compression phase (Figure 165 – right picture).

This lubrication system permits the elimination of the oil sump, the oil filter and the oil pump as well as the oil changes and oil level checks. Hence, the weight of this 4-MIX four-stroke engine is insignificantly higher than an equivalent two-stroke engine. In areas of application with a speed limit of 10000 rpm the 4-MIX four-stroke engine is a good alternative to two-stroke engines. At speeds above of 12000 rom, the lift-off of the vales becomes a problem. Figure 166 illustrates one working cycle of an STIHL 4-MIX engine (left above – intake;

right above – compression; left below – combustion; right below – exhaust). [80, pp. 432-433] [187, p. 5]

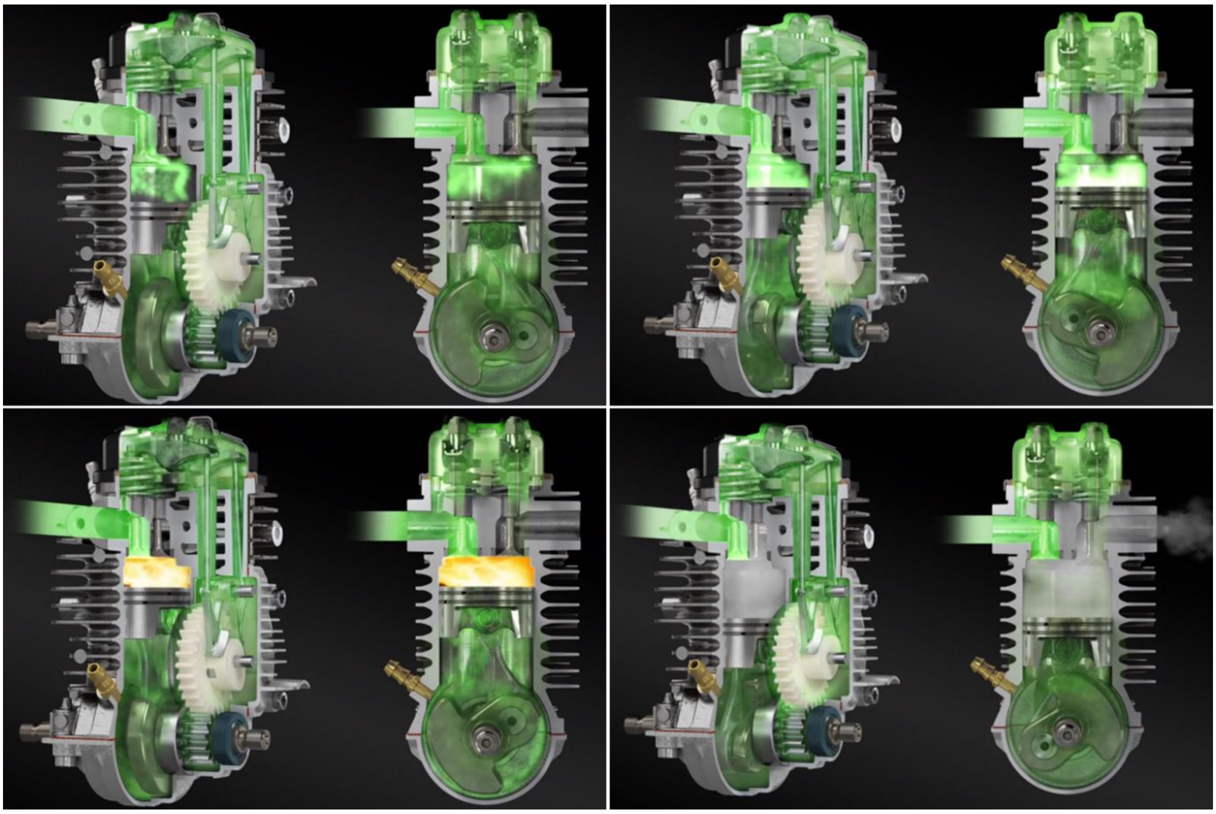


Figure 166 STIHL 4-MIX engine - one working cycle [188]

The mixture formation is taken by a carburetor. The fuel pump in the carburetor is controlled by the crankcase pressure. The crankcase pressure conditions in a 4-MIX engine differs clearly from that in a conventional two-stroke engine and therefore, the fuel pump design had to be modified. Figure 167 depicts the crankcase pressure condition of the 4-MIX four-stroke engine at Wide Open Throttle (WOT) (left diagram) and at idle (right diagram). At WOT, the revised fuel pump works as a conventional diaphragm carburetor fuel pump. At idle, an additional spring in the pump prevents a deflection of the diaphragm towards the housing, thus fuel can be delivered. [187, pp. 5-6]

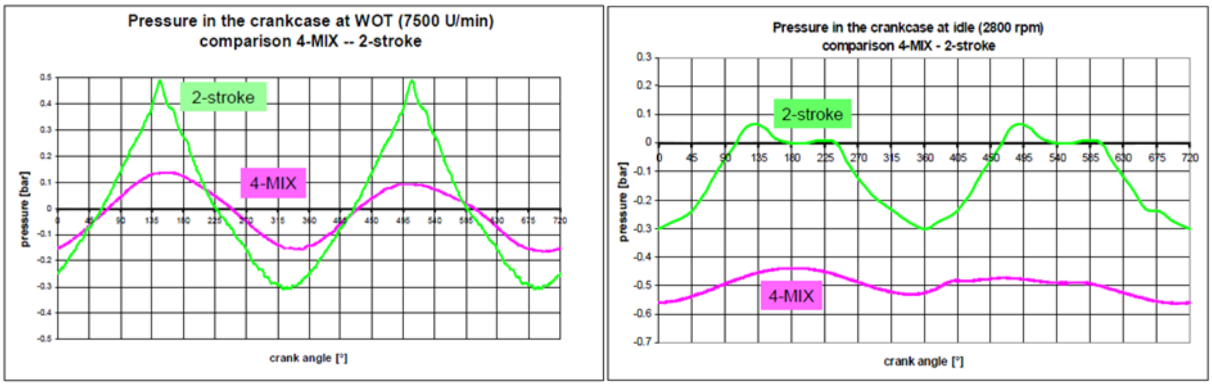


Figure 167 Pressure conditions in the crankcase at WOT (right) and idle (left) [187, pp. 5-6]

The design of the valve train was a challenge, owing to, on the one side, the weight of the whole system should be minimized and, on the other side, the valve train should withstand speeds higher than 11000 rpm. STIHL succeeded to fulfill these requirements by a simple push-rod design and single plastic cam. Figure 168 shows the STIHL 4-MIX four-stroke engine compared to the STIHL FS85 two-stroke engine and displays power, HC+NOx emissions and specific fuel consumption. The benefits of the 4-MIX engine in the area of HC+NOx emissions and fuel consumption are clearly evident. [187, p. 6; 8]

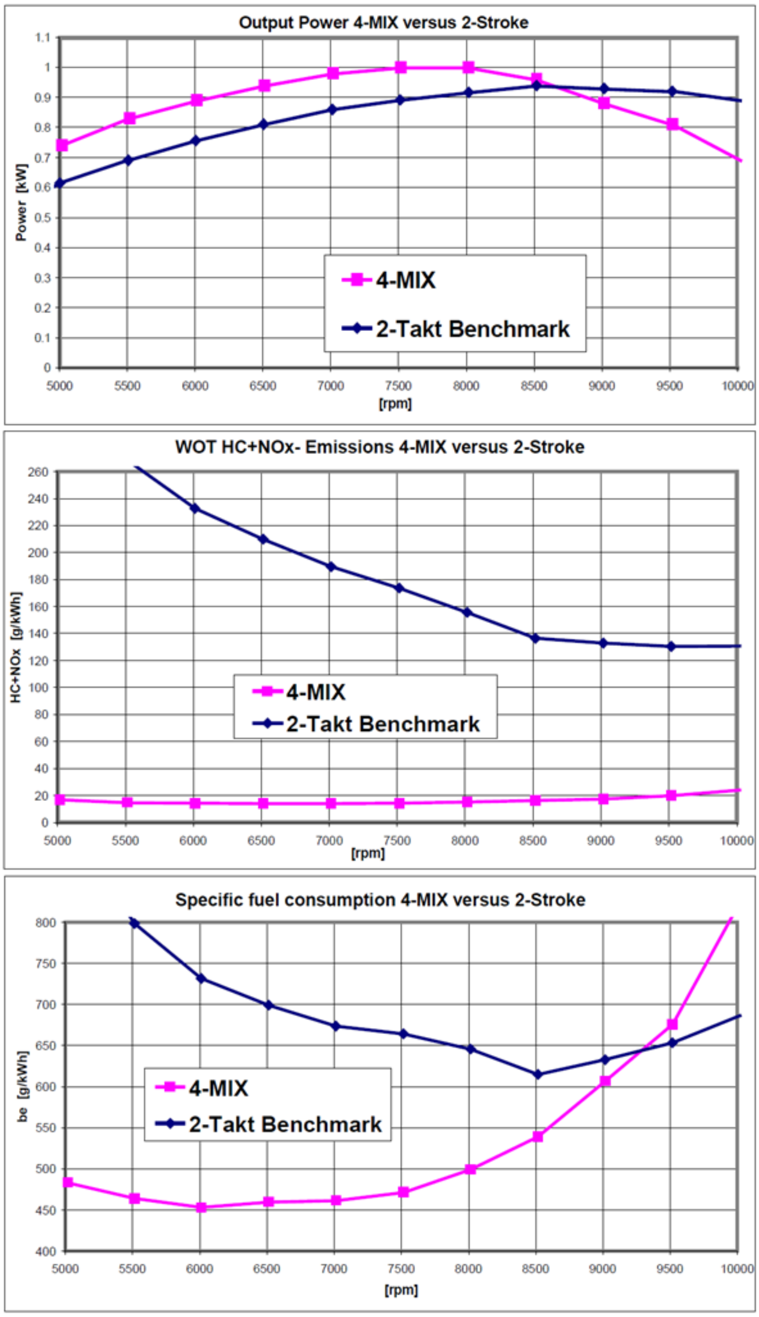


Figure 168 Comparison of STIHL 4-MIX four-stroke engine and STIHL FS85 two-stroke engine regarding power, HC+NOx emissions and specific fuel consumption [187, p. 8]

3.2 List of Figures

3.3 List of Tables

3.4 References

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