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Challenges and Solutions for Modern Gasoline Engine Applications

Abstract:

Future CO2 scenarios raise the need for a systematic view on the best fitting solution for the whole drivetrain. A wide range of different technical solutions are available to suit the individual demands. Out of this large variety, short-termed this may be a direct injected downsized turbocharged gasoline engine as one of the most promising solutions to be applied in large volume production. On the other extreme there may be an electric powertrain, considered to be more long-termed. For both approaches and for all solutions in between there are challenges which have to be overcome.
This paper deals with specific challenges of named two powertrain applications and describes the technical solutions for it:

- *For the gasoline direct injected engine (GDI) the forthcoming EURO 6 emission standards, especially with respect to particulate number PN emissions, is considered to be a challenge.*
- *For electric vehicles the limited operation range due to battery weight and cost is a hard trade-off which has to be matched. So called Range Extender RE units with combustion engines may be a solution for this.*

By systematical evaluation of potential solutions and by means of appropriate development tools and methodology the challenges for development of future leading powertrain can be overcome.

Key words: Gasoline, Particulate Number, Emission Reduction, Hybrid, Electric Vehicle, Range Extender.

1. Introduction

After economic crises in 2009 the automotive industry recovered quickly and passenger car (PC) and light duty vehicles (LDV) exceeded a production volume of more than 65 Mio in 2010. What we can see when looking to global automobile production, there is an increasing diversification by different fuels and for different propulsion technologies, Figure 1.

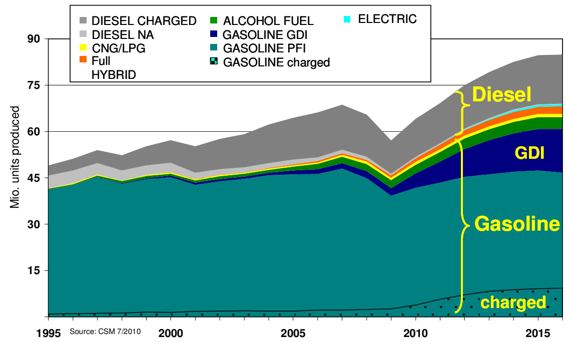


Figure 1: Global Vehicle production and share of different propulsion technologies

For modern powertrain we do not have to deal only with the internal combustion engine (ICE) and transmission any more. Further elements such as control system, the electric motors and the battery for energy storage are gaining significant importance, and each of these elements is offering certain flexibility. These elements have to be matched appropriately to achieve highest efficiency of powertrain. On the other hand, the overall flexibility carefully may only be utilized to that extent that system complexity and costs do not get overstressed. That means, a well defined flexibility profile has to be determined for the individual powertrain application. This is even better understandable, if you interpret the expression "flexibility" also as complexity, risk and cost [1,2].

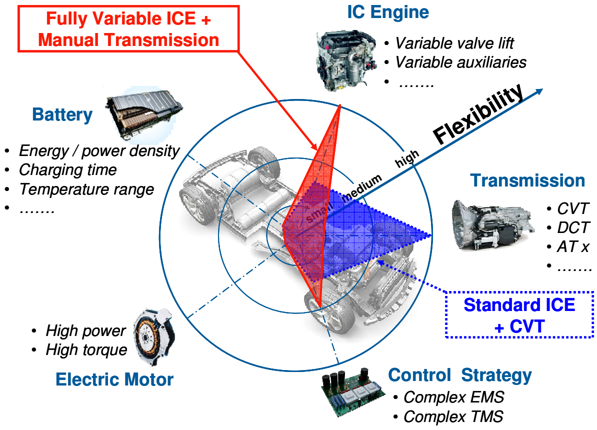


Figure 2: Application of flexibilities for „conventional powertrain"

With conventional powertrain similar results can be achieved by implementing system flexibility into the engine (e.g. variable valvetrain, improved auxiliaries, etc.), or as alternative by investing into advanced transmission (CVT, DCT), Figure 2.

As an other example we can take Hybrid concepts [3,4,5]. Thereby, an increased degree of electrification allows more flexibility to match the individual usage profiles and utilize improved fuel efficiency. The different “degrees of electrification” are reflected in the various kinds of Hybrid-concepts as already can be seen on the market or which are expected to be introduced. In the final consequence, the maximum degree of electrification is leading over to the pure battery electric vehicle (BEV), Figure 3.

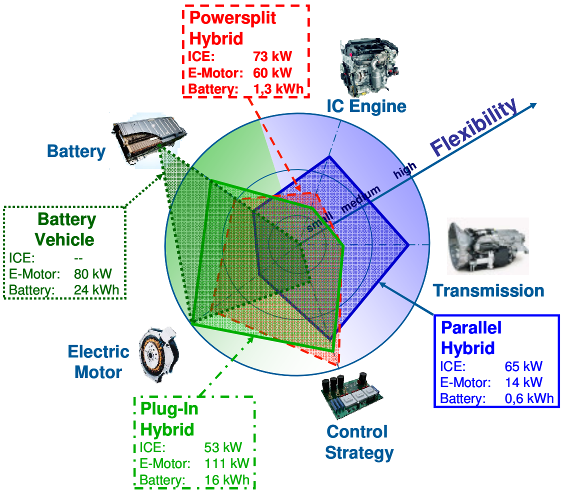


Figure 3: Flexibility-profiles for different kinds of Hybrid- and Electric-Vehicles.

As the battery for pure battery EV still is the most dominant cost factor, a battery electric vehicle (BEV) with Range Extender (RE) may be a very practical solution, Figure 4.

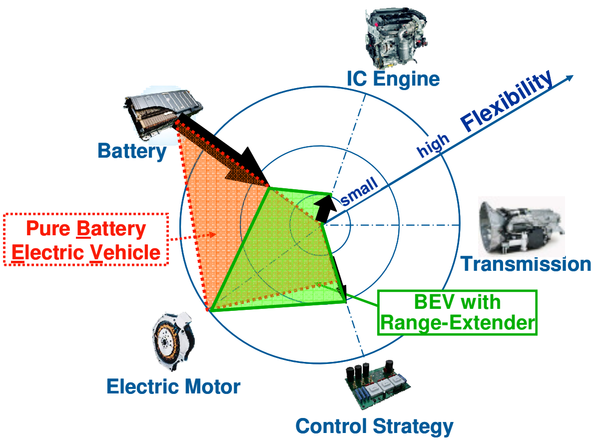


Figure 4: Flexibility profile of battery electric vehicle with/without range extender.

The advantage of Range Extender EV may be seen in the fact that more than 80% of vehicle useage the driving distance is less than 50km and the battery capacity for such short distances is required significantly smaller, saving cost and weight. For driving distances exceeding the given range, the Range Extender unit is re-charging the battery. An example of such Range Extender application is outlined in chapter 3 of this paper.

2. Challenges for Modern Gasoline Engines Development

When looking to conventional PC powertrain, we see one very dominant trend: Downsizing by means of Turbocharged Gasoline Direct Injected engines (TGDI). These kinds of engines are already in the market in millions of sold units and gain very positive customer feedback all over the world.

2.1 Performance Evolution of TGDI Engines

To utilize the advantages of these powertrain concepts, a strong focus is put upon high torque at low engine speed. A favourable low-end-torque characteristic allows long transmission gear ratios (“downspeeding”) and motivates driving at lower engine speeds, which finally results in significantly reduced fuel consumption. Current and forthcoming engines of different brands are consequently following this trend, Figure 5.

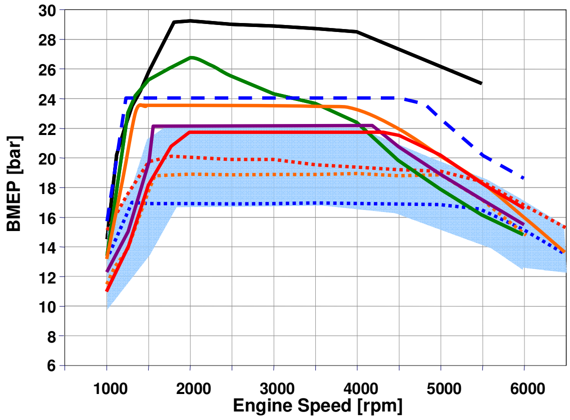
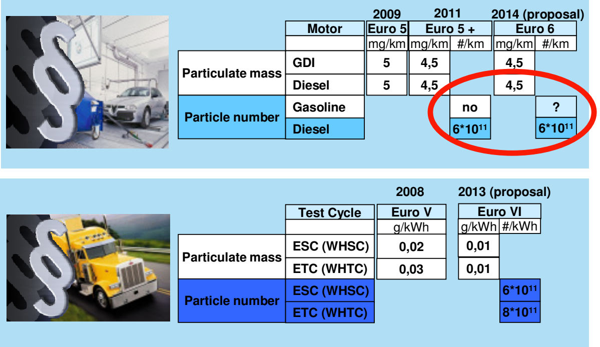


Figure 5: Benchmark of BMEP torque characteristics for current and future TGDI engines

Even these engines are demonstrating a permanent increase in specific power, the specific fuel consumption in part- and full-load permanently has been reduced. Due to permanent progress in modern engine engineering and by means of various design features, especially the mixture enrichment at full load has been eliminated to a very wide extent.

2.2 Particulate Emission of GDI Engines

Up to current legislation in Europe, particulate and smoke emission standards only have been applied to diesel engines, and particulate mass have been limited for GDI engines. With forthcoming emission limits for Euro 6, besides of particulate mass (gravimetric filter method), additionally particulate number limits for diesel as well as for all gasoline engines will be introduced, Figure 6.



	Motor	2009 Euro 5	2011 Euro 5 +		2014 (proposal) Euro 6	
		mg/km	mg/km	#/km	mg/km	#/km
Particulate mass	GDI	5	4,5		4,5	
	Diesel	5	4,5		4,5	
Particle number	Gasoline			no		?
	Diesel			$6*10^{11}$		$6*10^{11}$

	Test Cycle	2008 Euro V	2013 (proposal) Euro VI	
		g/kWh	g/kWh	#/kWh
Particulate mass	ESC (WHSC)	0,02	0,01	
	ETC (WHTC)	0,03	0,01	
Particle number	ESC (WHSC)			$6*10^{11}$
	ETC (WHTC)			$8*10^{11}$

Figure 6: Overview on current and forthcoming particulate emission legislation in Europe

With approriate design and calibration, modern gasoline port fuel injected (PFI) engines usually have significant lower particulate number emission than GDI engines of similar dispacement. Even the emission limits for Euro 6 are not yet fixed by the European Commission, the particulate number limits can be seen as considerable challenge for modern GDI and TGDI engines [6]. To meet the given limits for future gasoline powertrain, special measures in development and calibration of such modern GDI and TGDI engines have to be applied. All the efforts are focused on development activities to meet emission limits without applying expensive components like sophisticated injection systems or even particulate filters.

2.3 Development Tools and Procedures

To achieve the given targets for Euro 6, AVL has elaborated proven procedures, considering engine design on the one hand, as well as utilizing specific test environments and instrumentation.

One of these tools is the transparent engine, which provides optical access to combustion chamber and supports the identification of best suitable injector and charge motion parameters, Figure 7. On the engine test bed, AVL Particulate Counter and AVL Microsoot device are seen as standard instruments. In specific cases, the test bed development infrastructure is extended by further instrumentation such as AVL VisioFEM optical devices, Figure 8.

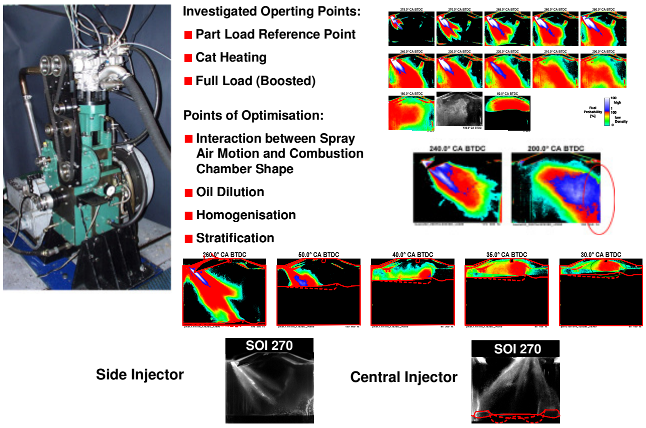


Figure 7: AVL Transparent engine as standard GDI development tool

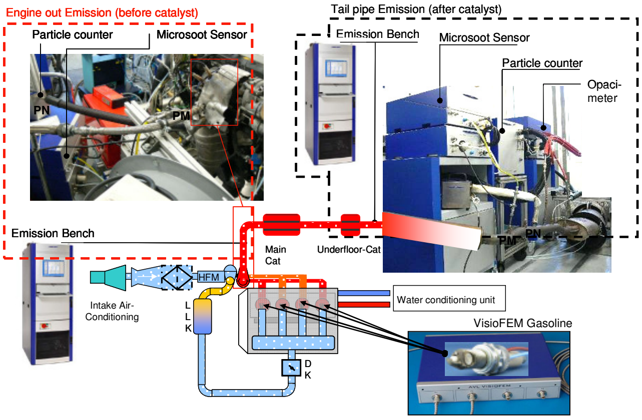


Figure 8: Instrumentation arrangement on AVL development test bed

This test bed equipment in combination with calibration and new methodology is considered to be the basis for a successful calibration. In the following development process, new ECU functionality and strategies for cold start, catalyst heating, dynamic and warm-up are implemented and optimised by means of intelligent calibration strategy.

2.4 Particulate Reduction by Calibration

As standard task for vehicle calibration, work usually is started with base series calibration (e.g. Euro 4). After initial assessment, the improvements are applied to achieve Euro 6 limits in NEDC cycle.

The main tasks for NEDC calibration improvement can be categorized into four main areas, each requiring different approaches for PN reduction from a GDI engine:

- Cold start
- Catalyst heating
- Drive-away with a cold engine
- Particulates from a warm engine

COLD START:

The engine should be capable of achieving a quick and reliable start under a wide variety of environmental conditions such as cold/hot, altitude level as well as with different fuel qualities. The cold start behavior of a gasoline engine is of primary importance during calibration. For particulate reduction, the first injection event has to be of the highest quality for mixture formation. This can be achieved by raising fuel rail pressure as high as possible (during cranking) before the first injection event and then by optimizing the injection strategy to minimize fuel impingement on the cold combustion chamber walls. To avoid excessive cranking time the fuel system hardware must be well matched and optimized for rapid pressure rise.

CATALYST HEATING

In order to meet the proposed Euro 6 PN standard, additional consideration for particulates is required during catalyst heating that was not necessary for previous emissions levels. Direct injection is able to provide a drive cycle emissions benefit over MPFI by supporting much more retarded ignition timing during catalyst heating. By targeting the fuel spray into a small piston bowl, a certain degree of stratification is achieved placing a second injection late in the compression stroke. The rich mixture thus formed at the spark plug supports stable combustion at much more retarded ignition timings than it would be possible with a homogenous mixture. In catalyst heating mode the late ignition timing causes much of the combustion energy to dissipate as heat in the exhaust, but causing the combustion chamber to heat up slowly.

DRIVE-AWAY WITH A COLD ENGINE

After cold start and catalyst heating, the next challenge for particulate reduction is to achieve rapid warm-up of the engine, in particular, the combustion chamber and piston crown have to be warmed-up. This is important, because transients in the NEDC contribute approximately 60% of the overall PN emissions, and a large proportion of that are produced during the first three hills of the test cycle, within the first 200 seconds of the test. In the subsequent hills, the PN curve flattens off significantly, which is due to the warmer combustion chamber. AVL has developed additional ‘drive-off’ functionality which provides rapid warm up of the piston crown through control and calibration changes.

PARTICULATES FROM A WARM ENGINE

In the EUDC (extra urban drive cycle of the NEDC), the engine is fully warmed-up, but vehicle speeds are higher and there are longer acceleration phases than during the city cycle, which can result in fuel impingement on the piston due to the increased fuelling requirements which lengthens injection durations. The methodologies for particulate reduction for cold engine operating conditions, can also be used to reduce steady state and transient particulates from a warmed up engine in these higher load conditions.

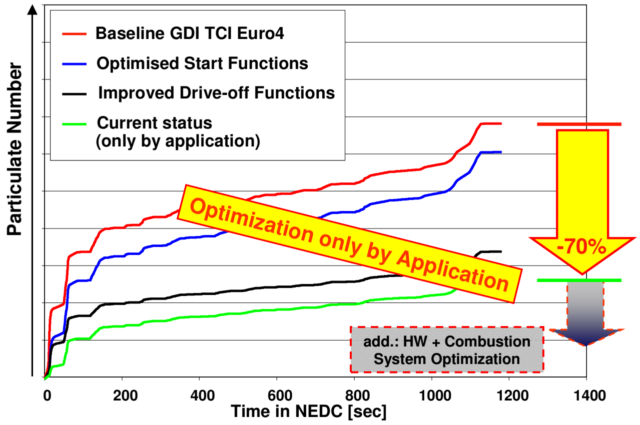


Figure 9: Reduction of particulate number emission in NEDC cycle by means of engine calibration

Finally it can be stated, that by incorporating the appropriate development tools and methodology, the particulate number emission can be brought to required levels. This has been proved in several development programs, Figure 9.

3. Electrification of Powertrain

According to general expectations, the demand for different kinds of Hybrid powertrains and electric drives will increase significantly. The main technology route is not yet clear, but there will be a wide spectrum of implementation through all vehicle classes, depending on the proposed usage profile and the brand strategies of the OEMs.

The usage profile may be focused more to longer distances driven with ICE, which will lead to certain kinds of Plug-In Hybrids. Such Plug-In Hybrid Vehicles basically use downsized combustion engines at current technology level, probably in parallel installation with mechanical connection to the drivetrain. For main use in urban areas, electric vehicles with integrated Range Extender (RE) may be the appropriate solution. These Range Extenders preferably shall be applied purely serial w/o mechanical connection to the drivetrain, dedicated to provide electric energy only. Depending on level of electrification, we will see very different combinations and different kinds of ICE arrangements, Figure 10.

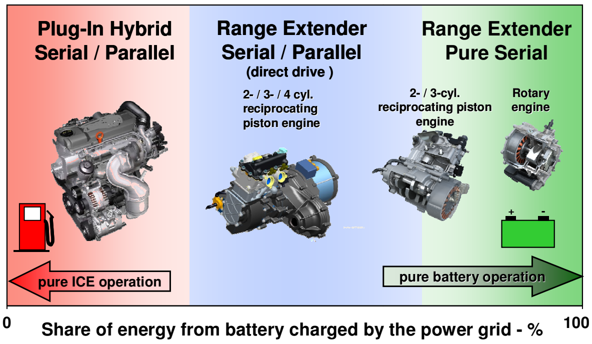
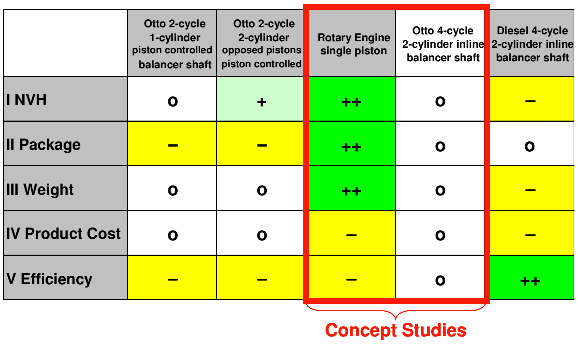


Figure 10: Powertrain configurations for different extent of battery-powered operation

3.1 Range Extender Concepts

At AVL, various engine concepts have been investigated and evaluated with respect to the key criteria for a Range Extender application. The priorities for such combustion engine are completely different as for conventional powertrain. NVH and comfort requirements are derived from the pure electric operation and thus ranked with highest priority. Also weight and packaging have to comply with the high demands for ease of integration into an electric vehicle. As the vehicle is operated most of the time as pure electric vehicle, the efficiency of the combustion engine has just minor impact on the total energy consumption of the vehicle and thus is of minor importance, Figure 11.



	Otto 2-cycle 1-cylinder piston controlled balancer shaft	Otto 2-cycle 2-cylinder opposed pistons piston controlled	Rotary Engine single piston	Otto 4-cycle 2-cylinder inline balancer shaft	Diesel 4-cycle 2-cylinder inline balancer shaft
I NVH	o	+	++	o	–
II Package	–	–	++	o	o
III Weight	o	o	++	o	–
IV Product Cost	o	o	–	o	–
V Efficiency	–	–	–	o	++

Figure 11: Decision matrix to identify most suitable engine concept for range extender

A Wankel rotary engine concept as well as an inline 2 cylinder gasoline 4 stroke engine turned out to be most promising routes, Figure 12. Finally, the single rotor Wankel rotary engine was chosen for the Range Extender concept of AVL's prototype vehicle, because of its extremely compact packaging and excellent NVH behavior. This AVL-Pure Range Extender solution offers the most consequent integration of ICE and electric machine resulting in minimum weight, package dimensions and overall system cost.

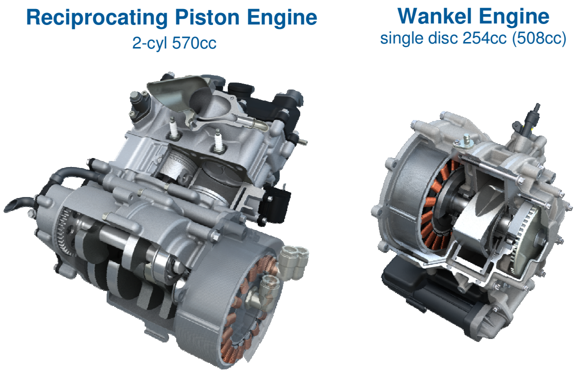


Figure 12: Variants of AVL pure range extender assemblies with combustion engine and generator

The rotary engine and the generator are applied on one common axle within common housing utilizing also a common cooling system. The range extender is packaged in an encapsulation for low noise and little vibration. That encapsulation for 1st generation included the range extender module, the intake and exhaust silencers, the power electronics and measures to avoid orifice noise. Even tests with 1st generation module showed very good results, in a 2nd generation evolution of that package further NVH improvements have been gained by enlarging the intake and exhaust silencers, Figure 13. As one positive result of that modification, the ventilator power requirement for sufficient heat removal from the module was reduced due to exhaust arrangement outside of encapsulation.

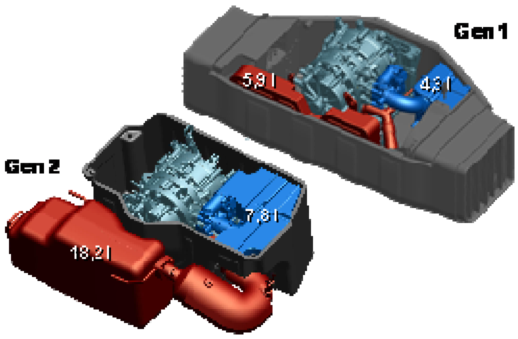


Figure 13: Module Concepts of AVL-Pure Range Extender 1st und 2nd Generation

3.2 Electric Vehicle with Range Extender in Real World Operation

The range extender is packaged in the AVL electric vehicle behind the rear axle. The vehicle is driven by a 75 kW electric motor in the vehicle front. The energy store is a Li-Ion battery packaged in front of the rear axle and in the mid tunnel, Figure 14.

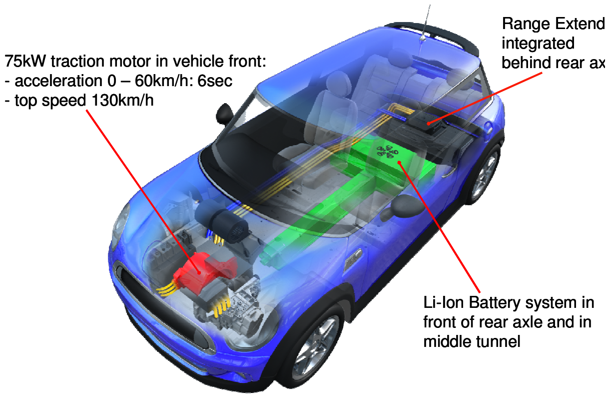


Figure 14: Base configuration of AVL Electric Vehicle with Range Extender (EVARE)

The fuel and electric energy consumption not only has been tested in NEDC cycle, but also on the road in real world operation on public roads and at different driving conditions. For the evaluation of this real life effect AVL utilises a defined fuel consumption test lap, Figure 15. Test drivers operate the vehicle for investigation on this test round with 55km length, consisting of a city part (50% time share), a country road part (28% time share) and a highway part (22% time share). The maximum speed is 130 km/h, the average speed 50 km/h. The test rounds are run 3 times. Fuel as well as electric energy is measured after each test round.

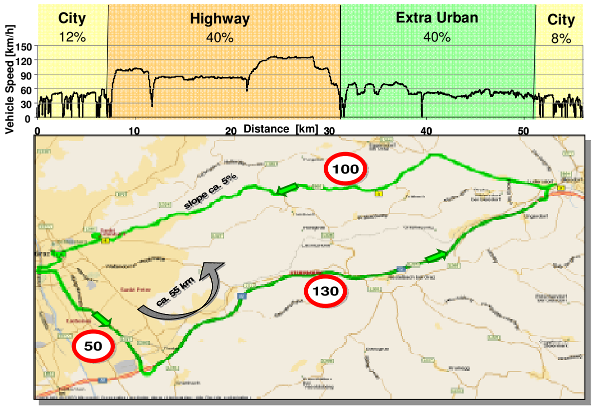


Figure 15: AVL's Fuel Consumption Lap

For the different operation modes, the CO2 emission was taken as base. For comparison to conventional ICE, tests with standard Mini Cooper model were performed in parallel. The original Mini Cooper was calculated to emit 135 g CO2/km. As an extreme kind of operation, the EV was started with empty battery and the RE was utilized to generate all the required electric energy during driving. This operation mode could be seen as "misuse" of the RE, because the vehicle is aimed to be operated purely electric only.

Anyway, even under this condition the vehicle performs without any power deficits. Due to electric conversion losses, the CO2 emission is slightly higher than the standard ICE vehicle, Figure 16. But, on the other hand it must not be forgotten that pure electric operation is not free of CO2-emission. Taking the German powerplant mix into consideration, the effective CO2-emission of the EV still is approx. 100 g/km taking the charging electricity from the mains. For Austria, having a high degree of electricity from water power plants, the CO2 emission for production of elctricity is significantly lower.

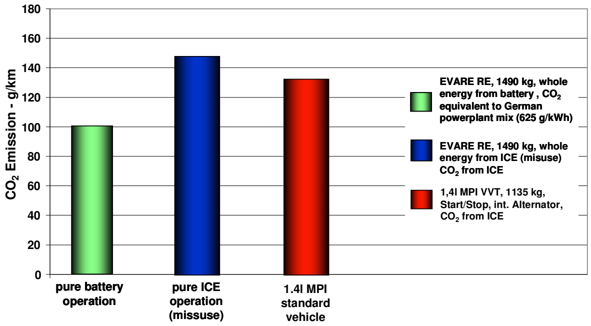


Figure 16: CO2 emission for different vehicles and operation conditions

When assessing such vehicles from an acoustic standpoint, it is known that EVs of course are not completely free of noise, but still very silent. This has to be considered when operating a RE under real world conditions. The consequence is, not to run the RE at standstill of the vehicle, and starting the RE at reduced power after exceeding a certain vehicle speed. Due to perfect NVH characteristics of the RE unit, full charging power can be delivered at vehicle speed over 50 km/h. This has been proved with many test driving candidates, that over vehicle speed of 50 km/h the operation of the RE is not more recognizable during driving, Figure 17.

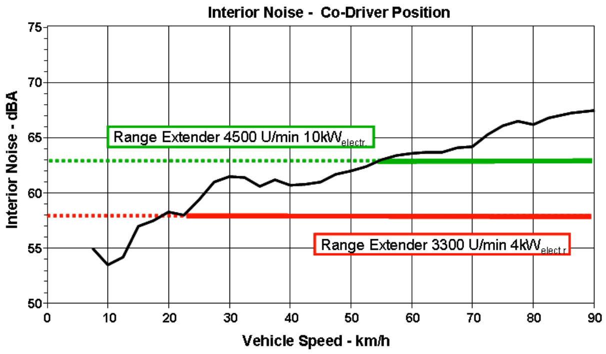


Figure 17: Interior noise of the EVARE-vehicle in pure battery operation versus interior noise generated by the "AVL Pure Range Extender" (Gen.1)

Nomenclature

APC	AVL Particulate Counter Measurement Instrument
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CNG	Compressed natural Gas
CVT	Continuous Variable Transmission
DCT	Dual Clutch Transmission
DOI	Duration of Injection
DVCP	Double Variable Cam Phaser
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EU6	European Union Emission Limit Stage 6 (Euro 6)
EUDC	Extra Urban Driving Cycle
EV	Electric Vehicle
FE	Fuel Economy
FTP	Federal Test Procedure (USA)
GDI	Gasoline Direct Injection
Gen.1	Generation 1 (first development stage of engine technology)
HCCI	Homogeneous Charge Compression Ignition
HSDI	High Speed Direct Injected (Diesel)
ICE	Internal Combustion Engine
LDV	Light Duty Vehicle
LPG	Liquified Petrol Gas
PFI	Port Fuel Injection
MY	Model Year
NA	Naturally Aspirated
NEDC	New European Driving Cycle
PC	Passenger Car
PF	Particulate Filter
ROW	Rest of the World
SOC	State of Charge (Battery)
TGDI	Turbo Charged Gasoline Direct Injection
TWC	3-Way Catalyst
VVL	Variable Valve Lift
VVT	Variable Valve Timing

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