

Der Einfluss von 48 V auf Grundmotorreibungs- und Effizienzoptimierung – Ansatz zur Quantifizierung in zukünftigen Fahrzyklen

**(The impact of 48 V to friction
and efficiency optimization
of the base engine –
Approach for quantification
in future driving cycles)**

Dr. Wolfgang Schöffmann
Dr. Helfried Sorger
Dipl.-Ing. Andreas Ennemoser
Dr. Christoph Priestner
Dipl.-Ing. Matthias Hütter
Dipl.-Ing. Borislav Klarin

AVL List GmbH
Hans-List-Platz 1
A-8020 Graz, Österreich

Abstract

To achieve fleet fuel consumption legislation of 95g/km CO₂ in 2020, various electrification measures will be introduced, besides engine measures, to reduce the overall energy demand of the vehicle. The introduction of 48V electrical architecture provides increased electric recuperation and limited electric driving at lower cost compared to full hybrid solutions, offering considerable fuel reduction potential in the WLTC.

Current belt starter-generator systems already realise direct recuperation and torque boost functions. Additionally they can support a highly effective electrical supercharging system which is clearly superior to current multi-stage turbocharging concepts, particularly in transient response. With flywheel starter-generator concepts, additional functions open up such as purely electric driving in a limited range, or simplification of the base engine towards the goal of a beltless engine. Demand controlled, electrical auxiliaries are already in series production for the cooling-, vacuum- or air conditioning systems. Additional areas of interest are the oil system and variable elements in the valve train or crank train.

The optimum balance of electrical and mechanical functions on the base engine and its periphery requires an application dependent evaluation with the aim of minimized overall system complexity and cost as well as added customer value.

In this paper, the effects of friction and power loss of electrified components are investigated in detail for the relevant driving conditions, especially when consequently implemented into a dedicated 48V base engine with the aim of a modular functional integration.

Kurzfassung

Im Zuge der Einführung der Flottenverbrauchsvorgaben von 95g/km CO₂ in 2020 werden neben motorischen Maßnahmen zur Verbesserung des Verbrauchs auch verschiedene Elektrifizierungsmaßnahmen eingeführt werden, um den Gesamtenergiebedarf des Fahrzeuges zu senken.

Die Einführung einer 48V Architektur ermöglicht höheres elektrisches Rekuperationspotential, sowie limitiertes elektrisches Fahren bei wesentlich niedrigeren Kosten im Vergleich zu Vollhybrid Lösungen und bietet beträchtliches Kraftstoffeinsparungspotential im WLTC.

Mit aktuellen Riemen-Starter-Generator-Systemen lässt sich neben der direkten Rekuperations- und Boostfunktion ein leistungsfähiges elektrifiziertes Aufladesystem der VKM darstellen, das insbesondere im Transientverhalten aktuellen kombinierten Aufladesystemen deutlich überlegen ist. Mit Schwungrad-Starter-Generatoranordnungen bieten sich Zusatzfunktionen, die einerseits rein elektrisches Fahren im begrenzten Bereich ermöglichen, andererseits am Grundmotor eine Entfeinerung zum riemenlosen Motor erlauben. Die bedarfsgerechte, elektrische Aggregatesteuerung ist für Kühlsystem, Vakuumsystem oder Klimakompressor bereits teilweise in die Serie eingeflossen, zusätzliche Optionen bieten sich im Ölsystem und bei Variabilitäten im Ventiltrieb oder Kurbeltrieb.

Die optimale Balance der elektrischen und mechanischen Funktionen des Basismotors und seiner Peripherie erfordert eine applikationsabhängige Betrachtung mit dem Ziel niedrigster Gesamtsystemkomplexität und -Kosten sowie erhöhtem Kundennutzen.

Im vorliegenden Beitrag wird der Reibungs- und Effizienzeinfluss von elektrifizierten Komponenten in den relevanten Fahrzyklen im Detail betrachtet, insbesondere in der konsequenten Umsetzung in einem massgeschneiderten 48V-Grundmotor, mit dem Fokus auf eine modulare Funktionsintegration.

1 Introduction

In 2020, the second target of the European Union CO₂ Emissions Standard that regulates fleet averages becomes operative. The target for new passenger cars has been set at 95g/km of CO₂ (based on NEDC) which represents a reduction of 27% compared with the 2015 mandatory targets [1]. Additionally, the upcoming introduction of Worldwide harmonized Light vehicles Test Procedures (WLTP) and Real Driving Emissions (RDE) are expected to require increased levels of vehicle dynamics and engine operating load points compared to NEDC. Consequently, when assessing technology options to meet future emissions regulations it becomes important to consider all three cycles during this transition period.

In order to achieve the required improvement for 2020 legislation, future powertrain developments that reduce emissions in dynamic vehicle use, such as assisting acceleration and energy recuperation, but also increased efficiency at higher engine loads compared to NEDC become essential. Advanced internal combustion technologies are not predicted to achieve the necessary results on their own, so alternative approaches must be considered.

At present it is possible to purchase a Micro-hybrid vehicle equipped with a BSG combined with a traditional 12V architecture; these systems are predicted to increase in popularity in the near future as they enable some of the performance improvement required. However, the 12V architecture limits the amount of power and thus energy that can be recuperated effectively over the drive cycle.

One potential solution to overcome this system limitation is to increase voltage above traditional levels, enabling greater power and so energy recuperation during deceleration and braking events, increasing the power available for torque assist during acceleration and permitting the electrification of base engine pumps and drive transfers to allow optimisation of the base engine at higher load points. In this respect, a 48V

architecture should be considered as a cost effective approach to meet future emission legislation [2, 3, 4, 5, 6].

2 Powertrain Architecture Options with 48V

2.1 Importance of the application voltage level

When considering increasing the vehicle architecture voltage level from 12V it is important to understand what is the most appropriate solution. Using a 48V system maximises the system voltage without the significant cost burden associated with increased safety regulations (ECE-R 100) associated with using a voltage over 60V. A 48V system also enables e-machines with a power range of up to 20kW which offer significant energy recuperation potential.

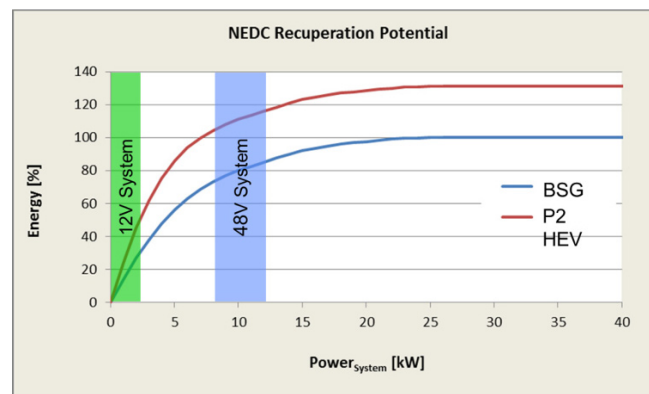


Fig. 1: Energy recuperation potential over NEDC comparing 12V and 48V solution

In previous AVL research it was shown the 12V BSG system with intelligent power supply and start/stop can reduce fuel consumption by up to 7% over the NEDC. Savings are increased by a further 2% using a 48V system due to higher recuperation potential. If torque assist is utilised with the 48V system a total saving of 11% can be achieved compared with the baseline design.

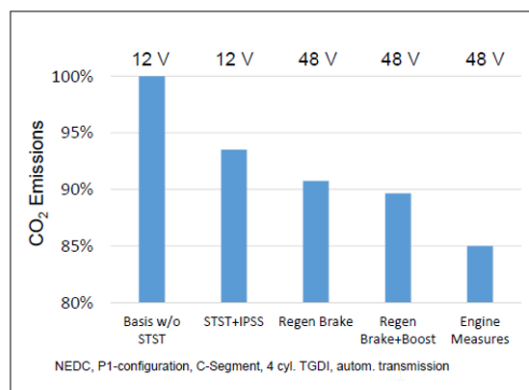


Fig. 2: CO2 potential with 48V: Impact of different functionalities [7]

Using further 'indirect benefits' permitted by the use of the 48V P1 configuration, such as further downsizing and optimisation, the vehicle is predicted to achieve an additional 4% savings.

2.2 E-Motor configurations and attributes

With increasing power levels for the e-machine it is important to assess the optimum configuration for a 48V system. Traditionally the 12V and 48V system has been situated in the front end auxiliary drive (FEAD) as it is a straightforward upgrade to an existing engine architecture with lowest impact on vehicle package, cost, production and aftersales.

The auxiliary drive considerably contributes to the total engine friction. Measures to reduce the auxiliary drive friction are on the one hand an on-demand control and the removal of belt driven accessories, on the other hand the reduction of the belt pre-tension.

For the 12V generator, intelligent control algorithms with brake energy recuperation as well as minimization of the loading in acceleration mode, have been widely introduced in series production.

To reduce the belt pretension a minimization of the axial tolerances, as well as a reduction of the number of idlers are a prerequisite for the base layout. Minimization of the tolerances is achievable by direct mounting of the auxiliaries without brackets, or the modular combination of the drive on one single bracket. Additional measures with increasing cost impact:

- Mechanical belt tensioner
- Generator overrun pulley
- Decoupled belt pulley at the TV-damper

Typical auxiliary drives are equipped with a 12 V start-stop generator and A/C compressor. The same layout is valid in principle for the 48 V BSG system (Fig. 3:).



Fig. 3: Auxiliary drive layout for 48V Belt-Starter-Generator

The friction reduction potential of the measures at the auxiliary drive overall is high.

Future applications with clean sheet designs give more flexibility in configuration. The main attributes for the e-machines have been considered [7], Fig. 4:

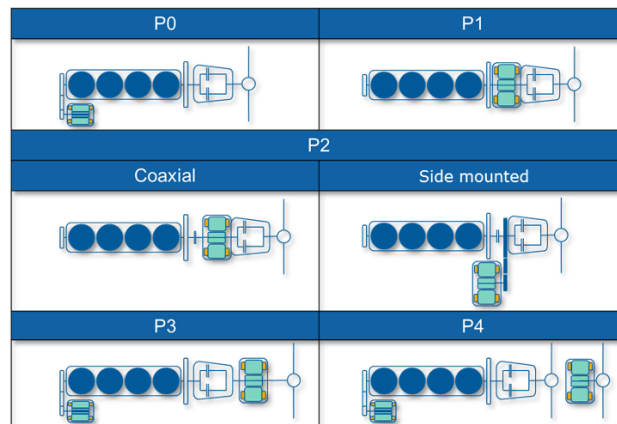


Fig. 4: 48V E-Motor system configurations

P0: The e-motor is installed in the belt drive system from the combustion engine.

- The power, torque, recuperation and hybrid function is limited. Pure e-drive is not possible.
- The package is beneficial because the combustion engine can remain in the original position.

P1: The e-motor is fixed to the crankshaft of the combustion engine.

- The diameter of the e-motor can be bigger which is beneficial for torque assist.
- The package is more challenging due to the fact that additional space between engine and transmission is required.

P2: The e-motor is installed between combustion engine and transmission. A C0 clutch can decouple engine from the powertrain.

- Electric manoeuvring and sailing possible.
- High recuperation potential and full hybrid functionality due to the additional clutch.
- The coaxial variant is often limited in powertrain length. And the system complexity increases because of additional clutch control and hybrid functionality
- The side-mounted e-motor can be driven by gear set and need less space in length, but some additional package space on the side of the powertrain
- The additional gear ratio can be used to operate the e-motor on higher speed which is beneficial

P3: The e-motor is located between transmission and differential.

- The full hybrid functionality can be realized. Due to additional gear set also a high speed e-motor is possible
- The package space is often limited and the additional gear ratio from the transmission cannot be used. The e-motor cannot be used for engine start.

P4: electrical rear axle

- The full hybrid functionality is given including the potential for four wheel drive and torque vectoring. Single or multi speed can be realized in the e-rear axle
- An additional BSG to be used for engine start and battery charging in idle [5].

Each of these configurations has some benefits and disadvantages, which are important for a future 48V architecture. Below the main characteristics are described, Fig. 5:

Configuration	P0	P1	P2		P3	P4
			Side mounted	Coaxial		
Torque assist	+	++	++	++	++	++
E-Drive/Coasting	0	0	++	++	++	++++
Recuperation potential	+	+	++	++	++	++++
Start-Stop Capability	+	+	++	++	-	-
Package	++	+	++	+	0	0
CO2 potential	+	++	++++	++++	++++	++++

0 → Basis 12V w BSG+SS

Fig. 5: Main Characteristics of 48V System configurations [13]

If we take these definitions in account, the most beneficial solution in terms of CO₂ and functionality will be P2, P3 and P4. Analysis results conclude a P2, P3 & P4 configuration can achieve a further 2% fuel economy saving compared to P1 layout as the engine can be decoupled, removing the drag loss of the engine (Fig. 6:).

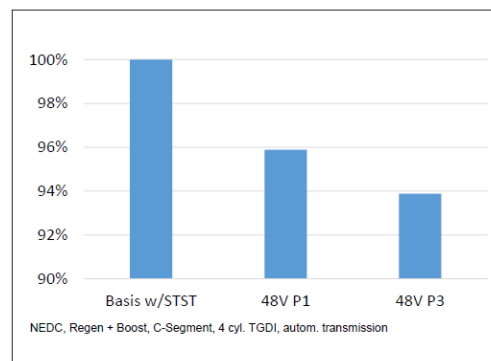


Fig. 6: CO₂ potential of different 48V-topologies [7]

The combination of significant fuel reduction savings, potential for electric driving in coasting mode and at low speed for parking/pull away, as well as using the gear ratio of the transmission and eliminating the conventional alternator, indicates the P2 configuration should be selected to reduce the base engine complexity. To avoid an increase of the powertrain length and to enable use of a high speed e-motor the parallel P2 configuration was selected for further studies.

3 Attribute comparison of 48V engine components

With the introduction of a 48V system within the vehicle, the opportunity arises to electrify further engine and powertrain components that are traditionally mechanically driven. This leads to new opportunities not only within the components themselves but also to additional benefits that can be utilised by the base engine and traditional peripherals [6]. The integration of a latest generation gasoline powertrain in the front section of a C-Class vehicle is shown in Fig. 7:.. The 1,6L-TGDI gasoline engine is combined with a 7-Speed double clutch transmission.

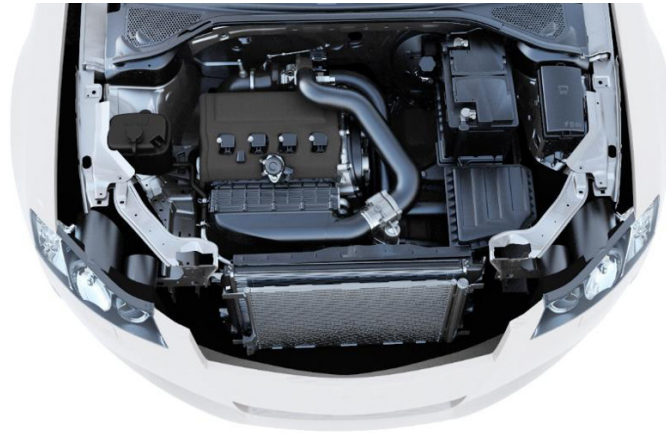


Fig. 7: Vehicle Front package – Powertrain with 48V System

Electrification options considered include the base engine, air path and charging system, vehicle auxiliary pumps and air conditioning, transmission, battery and additional advanced vehicle measures. Also considered are further opportunities for different technology control strategies, enabled by the higher voltage level architecture, in order to maximize the complete vehicle benefits. In the following section the options will be discussed and evaluated.

3.1 Base engine pumps

Utilising electrified pumps gives the opportunity to ensure the supply of oil and coolant exactly matches the demand, as the pump has the freedom to operate without any fixed drive ratio. With this approach the energy consumption of the electrical pump is reduced compared to the mechanically driven component at higher engine speeds due to reduced friction, volumetric losses and over supply. For example, at maximum engine speed, the electric oil pump requires around half the power consumed by the fixed mechanical version. However, at high power levels the motor size also becomes significant and should be considered for packaging; although due to deletion of the mechanical drive there is inherently more flexibility in location, extra power demand at cold oil temperature and therefore high viscosity should be considered. For the cooling system an electrical controlled thermal management system can be realized to guide water on demand and therefore speed up the heating up process as well as reducing the required flow from the coolant pump. Furthermore, when electrifying the oil and water pump, pre-lubrication and after-run cooling functions can be realized permitting the advanced control strategies that reduce real world emissions.

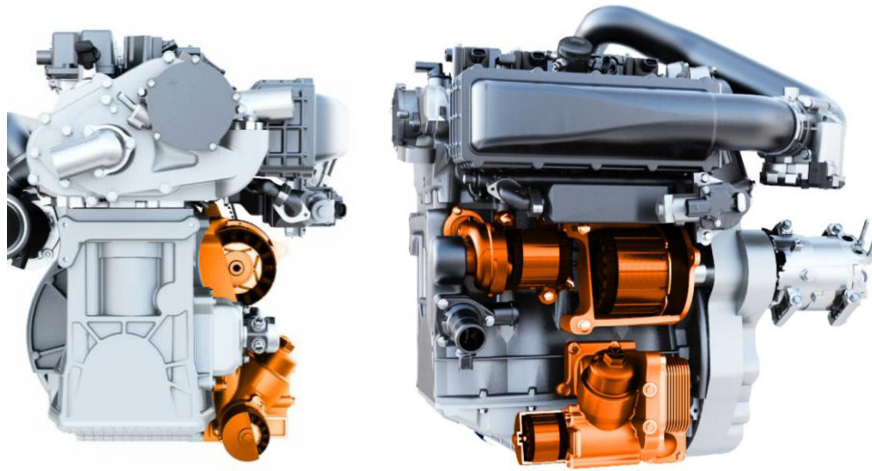


Fig. 8: Electric oil and coolant pump arrangement

One further option for the oil and water pumps is a combination of mechanical and electrical components. The mechanical components could be sized to more closely match the actual demand at high engine speed, with the electrical pump supplementing the supply at times of peak demand. This setup would perhaps give the greatest overall system performance but the cost of having two components and additional pipe work could be considerable. A fuel pump has potential for electrification however the high pressure output requires high drive torques and therefore requires a large, heavy and expensive e-machine. As the fuel pump is already a highly optimised component due to its flow controllability it is not estimated to give greater performance when electrified.

3.2 Base engine

Hydraulic variable cam timing phasers are increasingly being replaced by electrical phasers. This gives additional flexibility, for example actuation after engine stop. An additional potential in removing the hydraulic variable cam timing phasers is, reducing the peak engine oil demand, which will give an additional benefit of reducing the oil pump power demand.

A next step could be to remove the timing drive, tensioners, guides, oil lubrication jet completely and consequently avoid timing drive friction. A possible route is to electrify the valve train actuation. One approach is to drive the camshafts with electric motors. As well as the immediate friction reduction, component count and NVH benefits from removing the timing drive, the system could allow fully flexible valve timing without cam phasers, as this function is taken over by the e-motor. However the required cam driving torque and fixed valve lift are disadvantages of this system.

The thermodynamic advantage of full valve train variability is obvious although camshaft driven systems with mechanical or electro-hydraulic operation only are not on the market to date. A final approach to electrify the valve train is the application of individual electrical actuators for each valve. This approach had been intensively investigated by various manufactures in the past and is worth to be reconsidered with higher system voltage availability.

Another potential advantage of an electrically driven valve train is its ability as a cylinder deactivation system on one hand, as well as an enabler for further performance and efficiency increase of the combustion engine. However, high demand of electric power as well as considerable cost in combination with significant functional risk associated with piston to valve synchronization will remain in the system architecture.

When considering an electrically driven valve train, it may be worthwhile to investigate if the camshafts with poppet valves are still the most appropriate solution for the base engine. A valve concept with much lower peak torque requirement such as a rotary valves may become viable with electric drive; however being far from market availability such solutions are not taken into account in the present evaluation.

3.3 Charging technology options with 48V

There are a variety of configurations available when considering the electrification of the air path technology. A first step to permit additional downsizing but maintaining engine responsiveness could be to add an e-booster to the intake path.

The additional use of an electrically driven supercharger, particularly during transients and at lower speeds, permits the targeted calibration of the turbocharger for the high-speed range. On the one hand, this extends the applicable range for single-stage turbocharging technology towards higher specific power with the target of a rational total system; on the other hand, in combination with two-stage turbocharging, it enables the highest power density combined with spontaneous responsiveness as shown in Fig. 9:.

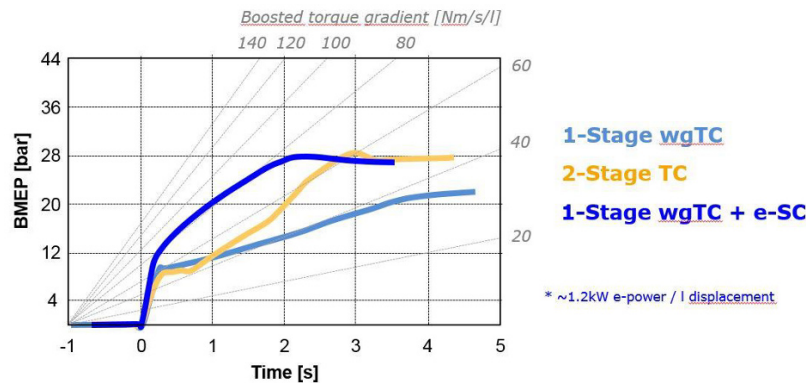


Fig. 9: Transient Response of Charging System Configurations

This has been shown to be an effective solution in both 12V and 48V applications for Gasoline as well as Diesel engine applications [8]. It can also allow the possibility of using low pressure EGR, although the compressor will need to be designed for residuals in the flow.

When considering other future 48V applications, the additional power availability for electrification could encourage use of electrically assisted turbochargers; reducing turbocharger response times to improve driveability and permitting the turbine to operate more rapidly at higher efficiency tip speed ratios. A recently presented hybrid charging system is a derivative of an electric assisted turbocharger (ea-TC). Proven components of conventional turbochargers are used for the so-called Cross-Charger® [9]. The specific novelty is the E-Motor on the cold side as an integral part of the compressor (Fig. 10:). The electric assistance by the Cross-Charger® promises to achieve a significant improvement of the mean effective pressure build-up without the additional routings and bypass as required with a separate electric charger.

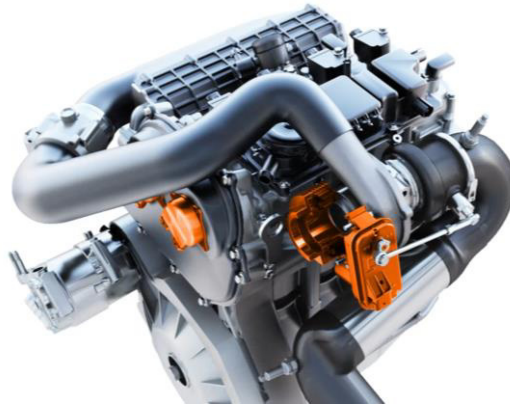


Fig. 10: Integral E-Motor with Turbocharger [9]

The final step to electrification of the intake and exhaust system is a mechanically independent compressor and turbine side, resulting in an electrically driven charging system at the intake side and a turbine-generator-unit on the exhaust side. The system complexity is moderate compared to a multi-stage turbo system. However, the energy losses in steady state operation, as well as the need for two electrical machines, limit the application range.

3.4 Electrically supported Exhaust Aftertreatment

Due to increased levels of hybridization and the opportunity to coast and boost with the 48V e-machine in the P2 configuration, the ICE is expected to be switched off during longer periods of the drive cycles. This could lead to low catalyst temperatures at engine restart conditions. One possible approach to mitigating the risk of increased emissions is the integration of an electrical heating element in the catalyst. This has been used previously at 12V, however the 48V system allows a smaller, lighter package and enables utilization of heat energy from recuperation during vehicle braking phases. Using this system, additional safety requirements should be considered as the wiring requires protection against very high temperatures. The equipment also has a very high cost and so could only be relevant for some niche products, perhaps when the e-machine grows over a certain size and is coupled with a large battery so significant time is spent at low speed in an inner city environment where engine use is minimised.

3.5 Auxiliary pumps for Vehicle systems

The increase in use of electric vacuum- and power steering pumps is expected to continue with the introduction of 48V architecture. Demand for vacuum is likely to reduce in the future, as brakes are required less often due to e-machine recuperation, and the switch from vacuum to electrical actuators such as wastegate controllers. During electrical drive the vacuum system needs to work for braking and therefore an electrically driven pump is required in hybrid systems, alternatively replacing the vacuum assist brake booster with an electrical assist version.

Another consideration for electrification is the A/C compressor. In comparison to a mechanically driven component, the electric compressor is estimated to be significantly heavier. A peak power output of up to 5kW results in a large motor requirement, however the increased speed controllability removes the need for a clutch. Full electrification of the A/C compressor, and therefore decoupling the connection to engine speed, facilitates engine switch-off during idle, coasting and braking even if there is HVAC demand without any effect on passenger comfort. It may also be pos-

sible to pre-cool a vehicle at a pre-set time or with remote activation to ensure when the passengers enter the car the temperature is immediately comfortable. This is of course highly dependent on the battery size and state of charge.

To reduce the burden of a large electrical motor specifically for the A/C compressor, the ideal configuration for the 48V motor in parallel P2 configuration, is directly located at the P2 module. This enables drive by the ICE during normal driving modes, as well as by the E-motor when the engine or vehicle is stopped. An additional feature of this configuration is the ability to mechanically drive the compressor by the wheels during recuperations mode, reducing energy conversion losses.

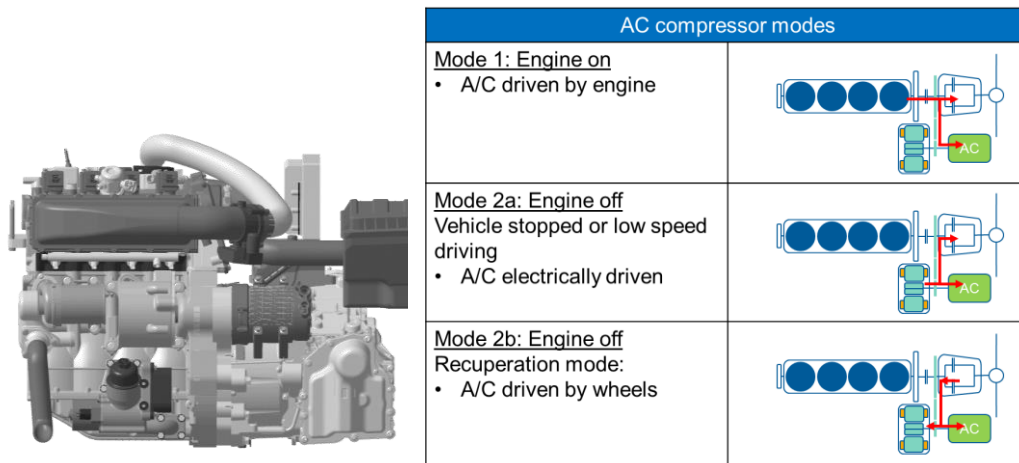


Fig. 11: Energy flow of A/C compressor configuration with 48V P2 module.

3.6 Vehicle Thermal management supported by 48V

48V enables a new engine operating strategy that has a big influence on the thermal management system. Due to stop start, e-creeping and load point shifting to sweet spots the engine thermal management system is challenged as never before. If the engine warm up phase will take longer due to switch off and e-drive support as well as the cooling down during engine off and load point shifting, there will be a big influence on the thermal behaviour of the engine. To ensure a perfect engine water temperature and therefore a high oil temperature which leads to less friction and a better engine efficiency and consequently less fuel consumption and emissions a smart thermal management needs to be chosen.

To ensure smart thermal management in the vehicle the overall cooling system needs to be taken into account. Beside an electrical coolant pump, which already has a big influence on the heating up strategy, also a radiator shutter system was introduced. The system is not new in the automotive industry but has never more beneficial than now. Due to the different engine strategy the shutter remains in the closed condition more frequently than in a standard vehicle at moderate ambient temperatures and low A/C load achieving lower aerodynamic resistance.

The second big modification that helps to improve the engine thermal strategy is a thermal engine encapsulation. A second possibility is to encapsulate the whole engine bay. The negative effect of this measure is that components which need a better cooling effect like intake and exhaust system, intake system to ensure a higher fill level of the combustion engine and exhaust system to be sure that the maximal component temperature level is not exceeded, are also thermal protected and therefore

have a higher risk of overheat. Therefore, the chosen thermal encapsulation method was direct engine part encapsulation. With this method components can be selective thermal encapsulated and therefore other components also protected because of overheating.



Fig. 12: Thermal Encapsulation of the engine

The combination of thermal encapsulation and radiator shutter gives a significant benefit but is also a challenge for the thermal management system. The balance between overheat protection of components as well as keeping a high engine temperature need a smart calibration and an intelligent software strategy behind it.

4 Efficiency and Cost Effects of electrification measures

4.1 Evaluation of component electrification potential

After identifying the different possible components which could be electrified, the most promising were included in simulations to calculate what potential exists in the electrification of the base engine. Electrically driven Coolant and oil pump were selected for further investigation as the potential of CO₂ reduction is already proven by 12V systems.

The fuel pump will remain as a mechanically driven component on the engine. This is because the leakage is already controlled on the low pressure side and therefore the efficiency is already very good. Electrification will have no significant performance benefits and actually increase the efficiency losses.

The vacuum pump needs to be electrified as soon as pure electric drive is possible to ensure braking also in engine off conditions. The A/C system has also an electric drive option for driver comfort at electric drive and engine off conditions. In the NEDC and WLTC the A/C compressor is not CO₂ relevant and without a clear definition of use case it is not possible to assess the A/C compressor CO₂ relevance.

In the air path an electric charging system will be implemented.

The deletion of the FEAD components leads to the elimination of the auxiliary drive and timing drive with all their relevant components like tensioner and idlers.

In the following chapter a simulation with the given boundaries will be presented to give an indication of the possible CO₂ reduction potential with the chosen base engine architecture.

Function	Effect on performance	Effect on FC & efficiency	Package	Customer value	Functional risk	Complexity reduction	Comment
Generator/E-machine	+	+	0	+	0	+	P2 architecture
E-Water pump	0	+	+	0	0	+	
E-Oil pump	0	+	+	0	-	+	
AC compressor	0	0	+	+	0	+	Mechanical and e-driven
PS pump	0	+	+	0	0	+	Needed for pure e-drive
Vacuum pump	0	+	+	0	0	+	Needed for pure e-drive
E-cam phaser	+	+	+	+	0	0	
E-Turbo	+	+	0	+	0	0	Highest potential in FC
E-catalyst	0	+	0	0	0	0	Heating strategy
Supporting measures							
Grill Shutter	0	+	0	0	0	0	Reduction Air-Drag
Thermal encapsulation	0	+	0	+	0	0	Faster Warm Up and Restart

0 → Basis 12V w BSG+SS

Fig. 13: Evaluation of electrified powertrain/vehicle components

The following figure shows a potential configuration of the optimum 48V engine:

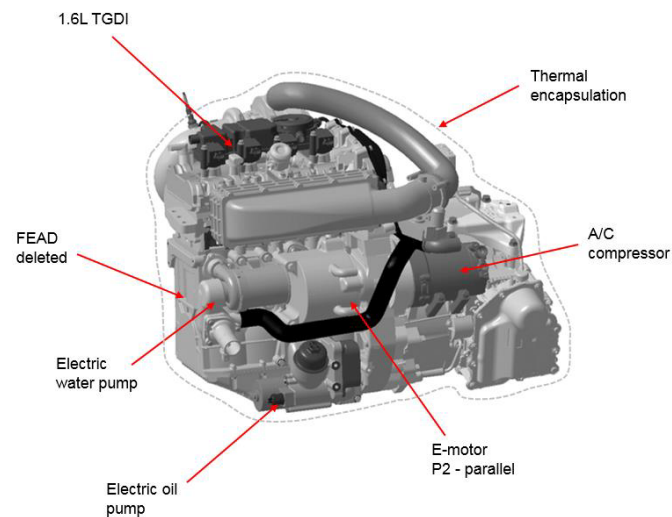


Fig. 14: Powertrain electrification Gasoline - Potential PT components

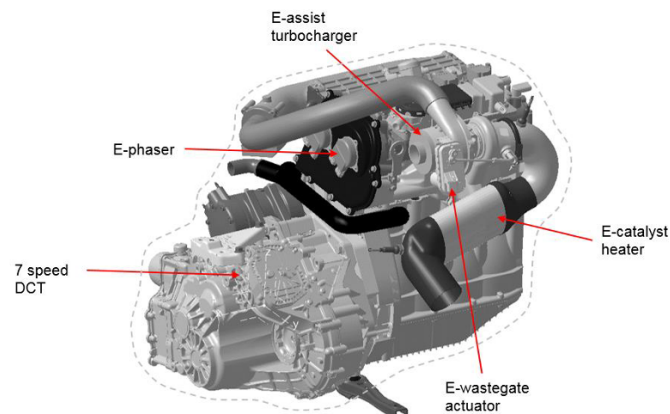


Fig. 15: Powertrain electrification - Potential PT components

In general, electrification of the engine gives the potential to delete the FEAD belt and remove the width of the oil pump drive, which could contribute to counteracting any additional length from the whole powertrain with the inclusion on additional clutches or gear/belt drives to the e-machines.

4.2 Efficiency improvement path

To investigate the effects of different vehicle/engine related changes on the CO₂ reduction in a defined driving cycle, a complete vehicle simulation approach was selected. This approach is called AVL-„Vehicle Thermal Management System (VTMS) simulation“ (Fig. 16:). It is a highly integrated system approach for identifying the effects of individual optimization measures on the total vehicle fuel consumption [10].

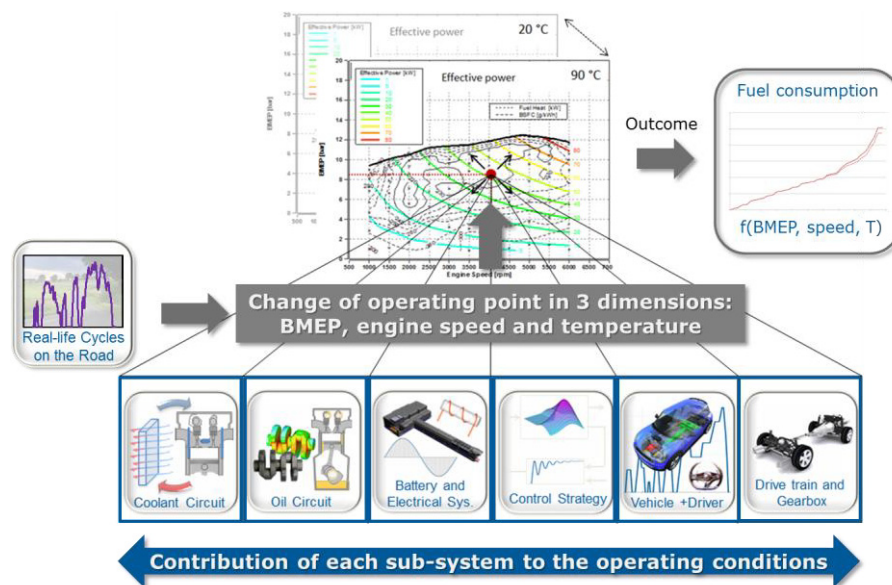


Fig. 16: VTMS Virtual Vehicle Model

Using this approach a vehicle is modelled in the AVL 1D simulation environment in such a way that the simulation model represents the behaviour of the actual vehicle and can thus be used to simulate the fuel consumption of the selected vehicle in any driving cycle (NEDC, WLTC, RDE, etc.). In the VTMS simulation also the vehicle's thermal system is modelled, therefore the comprehensive effect of changes of any vehicle subsystem (e.g. cooling system, lubrication) on the fuel consumption can be observed. For example, the effect of electrifying the coolant pump is considered on one side as a friction reduction on the engine and on the other side influences the engine warm-up. This means the fuel consumption of such change is a result of direct engine load reduction through lower friction and friction reduction caused by faster engine warm-up.

As a base for the calculation a 4-cylinder gasoline engine was chosen. In the table below the main engine data are defined:



IN LINE 4 CYL TGD BASE ENGINE			
Displacement [l]	1,6	Intake system	CAC
Rated speed [min ⁻¹]	4850	Water pump	Fixed ratio
Rated Power [kW]	120	Oil pump	Variable
Max Torque [Nm]	251	FEAD	A/C, tensioner, idler, W/P, alternator, PS pump
Start / Stop	Yes	Piston cooling	Pressure regulated

Fig. 17: Reference engine main data

As a reference vehicle for the investigations a C-segment class vehicle was chosen. The table below shows the main vehicle data:

C-SEGMENT BASE VEHICLE	
Fuel Tank Volume	50 Liter
Total Length	4250 mm
Total Width	1800 mm
Total Height	1460 mm
Wheelbase	2640 mm
Curb Weight (=dry weight)	1130 kg
Gross Weight	1450 kg

Fig. 18: Reference vehicle specifications

Based on the engine and vehicle model as above, the contribution of the individual electrification measures on the engine to the overall vehicle CO₂ improvement was simulated and summarized.

The potential in fuel reduction for a 48V hybrid vehicle for the Vehicle Thermal management System (VTMS) is influenced by two main aspects:

- Reduction of required mechanical power since most of the auxiliaries can be driven by recuperated electric energy
- Reduction of friction due to faster warm-up achieved by improved thermal control strategy

4.2.1 Impact of Emission Cycles on Efficiency Measures

As example, typical results for achievable reductions in fuel consumption for a segment B vehicle are presented on Fig. 19:. The study includes the following variants:

- Variable oil pump (Variant 1)
- Variable oil pump with reduced pressure level (Variant 5)
- Reduction of piston ring tension (Variant 3)
- Variable coolant pump (Variant 2)
- Combined measures (Variant 1, 2 and 3)

Hardware / Control strategy overview	Baseline	Variant1	Variant2	Variant3	Variant4	Variant5
Variable displacement oil pump (2÷4 bar)		✓			✓	
Variable displacement oil pump (1.5÷2.5 bar)						✓
Variable Coolant Pump			✓		✓	
Friction reduction (Piston Ring Tension)				✓	✓	

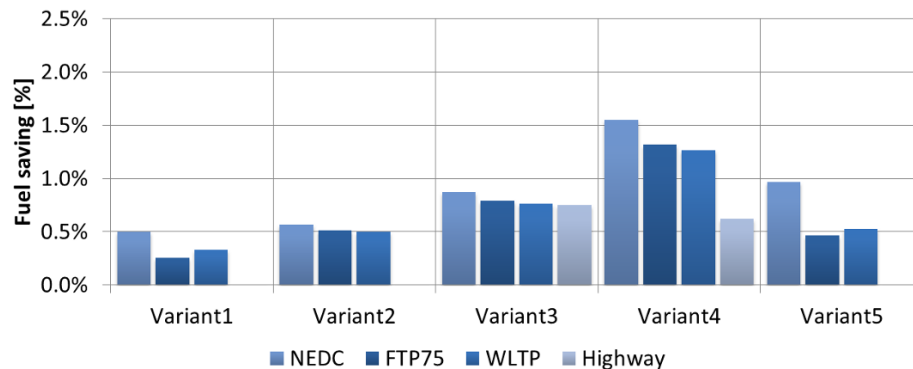


Fig. 19: FC reduction potential on different cycles using VTMS models

On the one hand, the improvement of FC reduction for variable oil pump with reduced pressure level and reduced piston ring tension is resulting from reduced FMEP maps (reduced power consumption of the oil pump and reduced friction values of the tribo-system “piston-rings-liner”) including the interaction on the warm-up characteristic in the approach of the comprehensive VTMS Model. On the other hand, the results for the variants “Variable coolant pump” and “Combined measures”, already take into the consideration the thermal effect of faster engine warm-up by reduced engine friction values by the temperature dependency of the applied FMEP maps. Analyzing the effect of single measures only, it can be seen that the variable oil pump provides the highest benefit of FC reduction. As expected, the highest FC reduction can be achieved by combining all the measures in a bundle. However, it has to be stated that the single measures certainly do not sum up in a linear way, due to the fact that they act on similar warm-up effects, which are interlinked among each other by the thermal system.

Detail investigations of the temperature distribution and thermal loading in the cylinder block, pistons and piston rings considering the distribution of friction and the local heat transfer processes are studied using latest simulation methods based on coupled elasto-hydrodynamic (EHD) and multi-material thermal analysis [15].

The accuracy of VTMS model can be improved by results of the detailed investigation of the subsystem friction contribution. Here subsystems are analyzed by engine cycle simulation using multibody dynamics with flexible bodies, EHD and computed fluid dynamics (CFD) methods. The transmission efficiency investigation as shown in Fig. 20: is performed in parallel to base engine development.

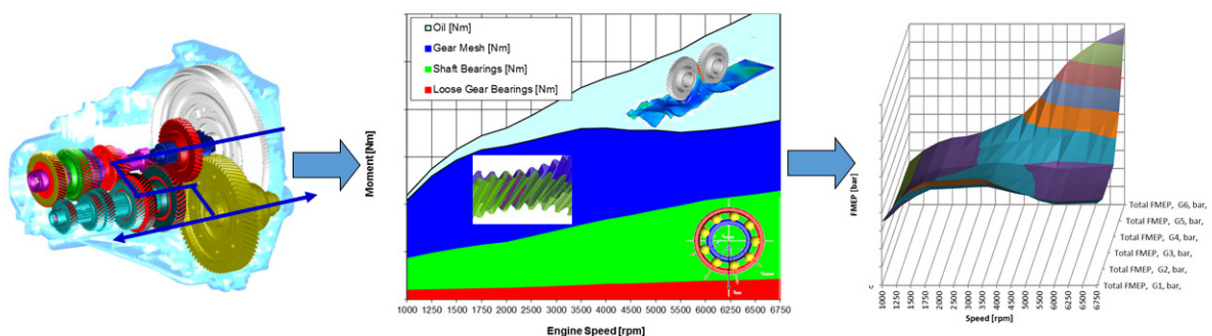


Fig. 20: Gear drive and transmission efficiency analysis

The transmission multi-body dynamic model as used for transmission durability and NVH analysis already includes detailed friction models of roller bearings and gear contacts. For the accurate prediction of gear rattle noise, oil splash losses are also precalculated using multi-phase CFD simulations considering oil and oil mist fractions. Those losses are applied as additional drag loads acting on the rotating parts. The effect of different oil types, levels and operating temperatures on lubrication, efficiency and NVH performance is also included in the simulations. The final results are extracted as friction maps and used as input for more accurate driving cycle simulations.

4.2.2 CO₂ reduction due to lower mechanical auxiliary power

To assess the potential benefits of electrified auxiliaries a simulation of energy consumption by each auxiliary over WLTC was calculated. The cumulated energy use over the cycle for each component can then be summed to reach the total energy consumption for all auxiliaries.

The coolant pump as well as the oil pump had been investigated in regard of the influence of mechanical power consumption as fixed displacement pumps as a baseline, mechanical switchable pumps and finally controlled, electrically driven.

The comparison of the results is shown in the figures below. The solid lines show the cumulated energy, whereas the dotted lines reflect the relative contribution.

For the coolant pump the required energy can be reduced by 50% when using a switchable coolant pump. For the electrically driven coolant pump the required energy is almost negligible in the cycle since the coolant flow is controlled on demand and not in operation for most of the cycle. The main benefit will be gained by enhanced warm-up of engine which is not considered in this investigation.

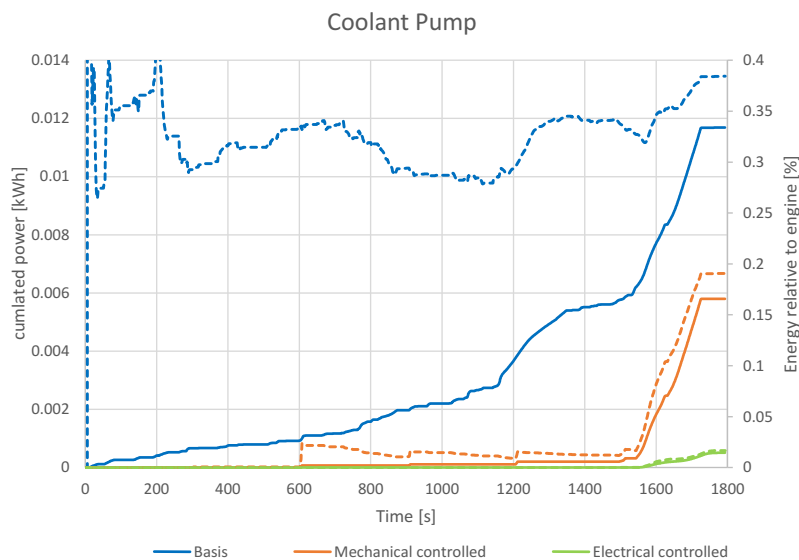


Fig. 21: Energy consumption of the engine coolant pump

The required energy of the oil pump in the comparison shows a fuel consumption reduction potential of the pressure and flow controlled pump of approximately 0,5% in the Cycle. The required energy of the electric pump is slightly higher than for the mechanically variable pump due to the electric efficiency loss, not considering any recuperation benefits.

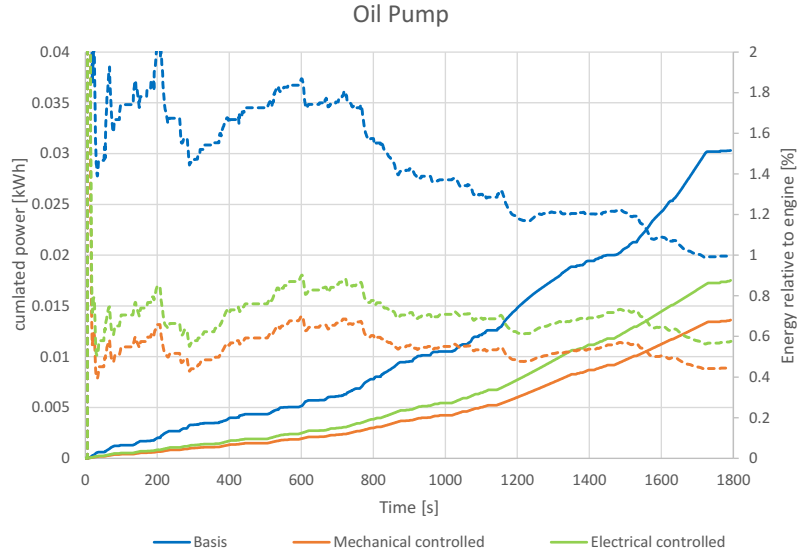


Fig. 22: Energy consumption of the engine oil pump

The cumulated energy of all auxiliaries over the cycle is shown as “auxiliary sum” in Fig. 23: and, by the end of the cycle, equates to just over 450kJ. This equates to 4.2% of the total work done by the entire engine.

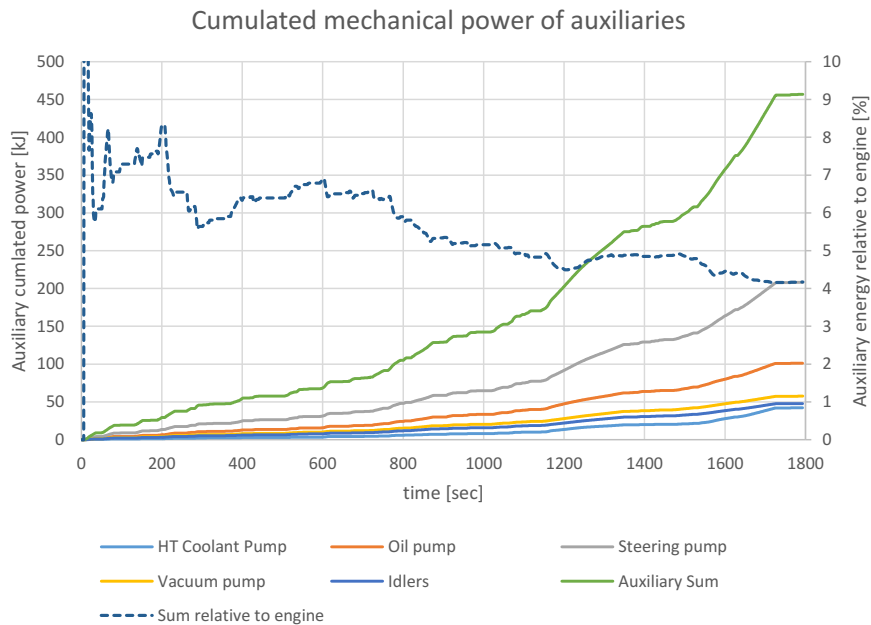


Fig. 23: Cumulated mechanical power of auxiliaries

Assuming the electrified components can be driven by recuperated electrical energy, a potential saving of 4% fuel and CO₂ reduction is predicted.

4.2.3 CO₂ reduction due to improved warm-up

To assess the effect of technology combinations and their impact on vehicle emissions, three scenarios were simulated in VTMS. The scenarios can be seen in Fig. 24: and include a baseline, pump electrification with active shutters and, pump elec-

trification, active shutters and thermal encapsulation. These technologies were considered most influential on improving the engine warm-up times.

	Basis	VTMS_1	VTMS_2
Coolant pump	Mechanical	Electrical	Electrical
Oil pump	Mechanical	Electrical	Electrical
Grill Shutter	No	Yes	Yes
Thermal encapsulation	No	No	Yes

Fig. 24: VTMS simulation scenarios

Considering the three VTMS scenarios, warm-up times of various significant powertrain temperatures were calculated with results shown in Fig. 25: The results highlight the electric coolant pump has the greatest influence on liner temperature. Whereas, the greatest influence on the oil and transmission temperature is thermal encapsulation.

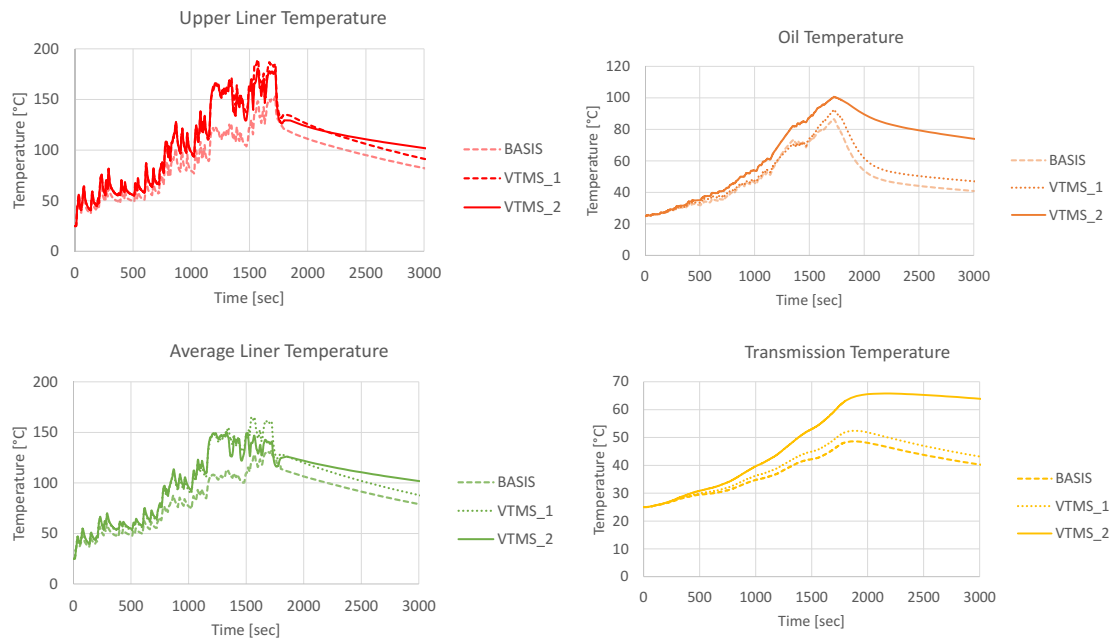


Fig. 25: Powertrain warm-up times for three vehicle configurations

4.2.4 CO₂ reduction due to 48V e-motor architecture

As discussed previously, the most significant opportunity to reduce CO₂ emissions is achieved from the integration of a high power 48V electric motor, allowing significant e-Drive capability and energy recuperation. An illustration of the utilisation of the e-motor during the WLTC is given in Fig. 26:

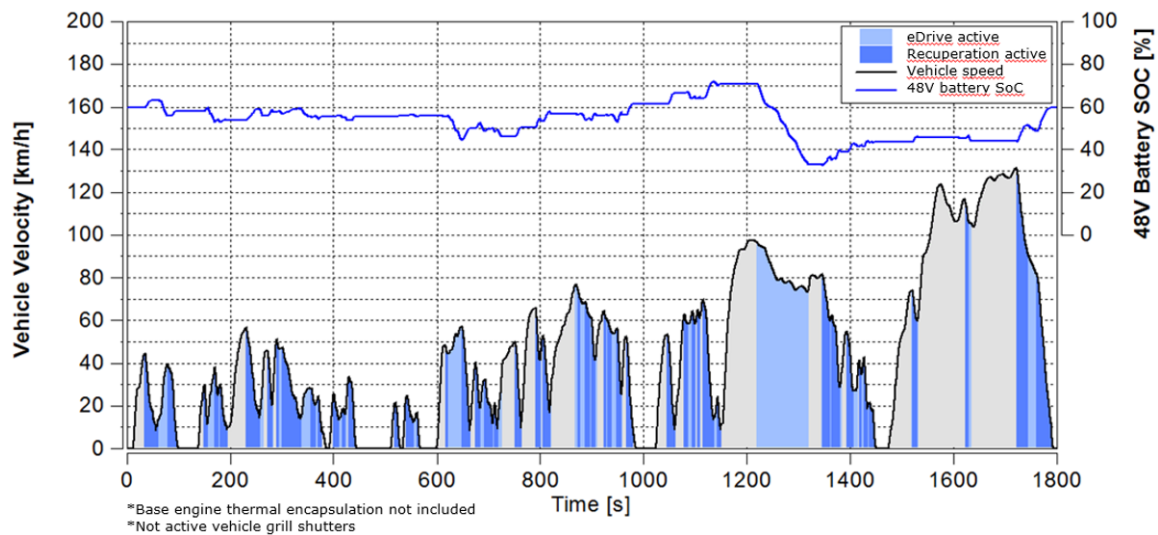


Fig. 26: Hybrid functionality in WLTC

4.2.5 CO₂ Improvement Summary

To get an understanding of the comparative benefits for each technology choice, the results have been included on one chart. The CO₂ improvement walk from the baseline vehicle is shown in the following figure:

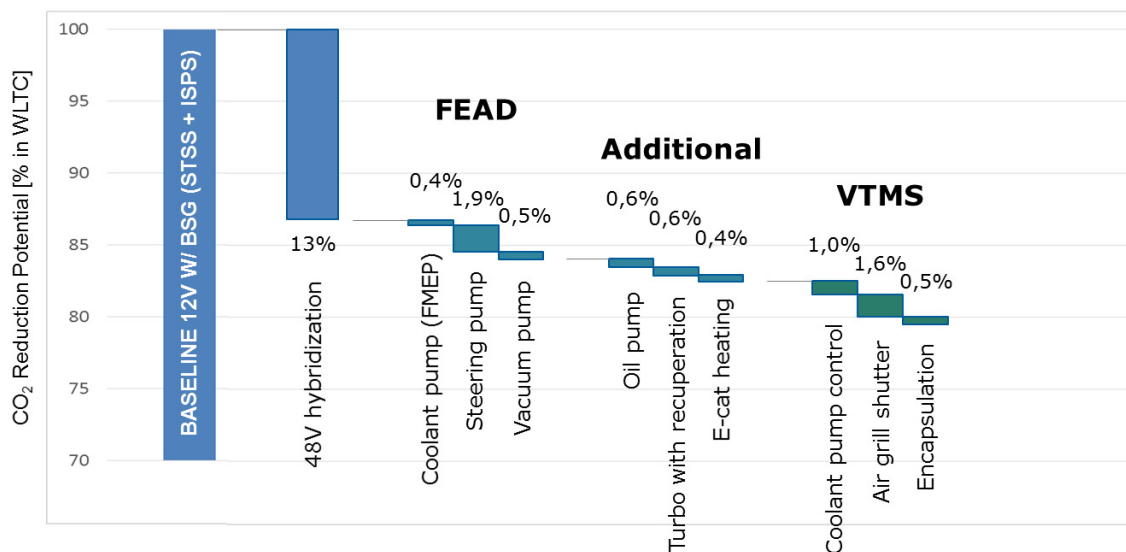


Fig. 27: Predicted emissions reduction by electrifying component

In comparison to the baseline powertrain, the simulation shows the AVL 48V concept has a significant WLTC CO₂ reduction potential of up to 20.5%. This is achieved by a 13% CO₂ reduction for the 48V hybridization and a further 7.5% CO₂ reduction due to the additional measures as shown in Fig. 27:

In a second step the combination for different systems as well as the comparison of additional cost to CO₂ reduction potential need to be considered to find a good balance. It should be stated that not all of the optimization potentials can be summed up and most of them are dependent on each other. One example is the effect of an electrical coolant pump not only through cooling on demand but also by reducing the

warmup time of the engine. Also, the oil pump and the reduced oil volume has partly an effect on the warm up. Therefore, the components cannot be considered independently and the interaction effects need to be understood.

4.3 Effect on Cost

Fig. 28: shows the trade-off between add-on cost and CO₂ savings for the electrified auxiliaries water pump, oil pump, vacuum pump, power steering pump and turbo charger with recuperation as well as for the improvements on the vehicle, like active air grill shutters and engine encapsulation. Also, the 48 Volt hybridization as a basis for these measures is shown in the diagram. The major assemblies are the e-machine, the 48 Volt battery and the DC/DC converter. Costs for additional wiring and control units have been considered as well.

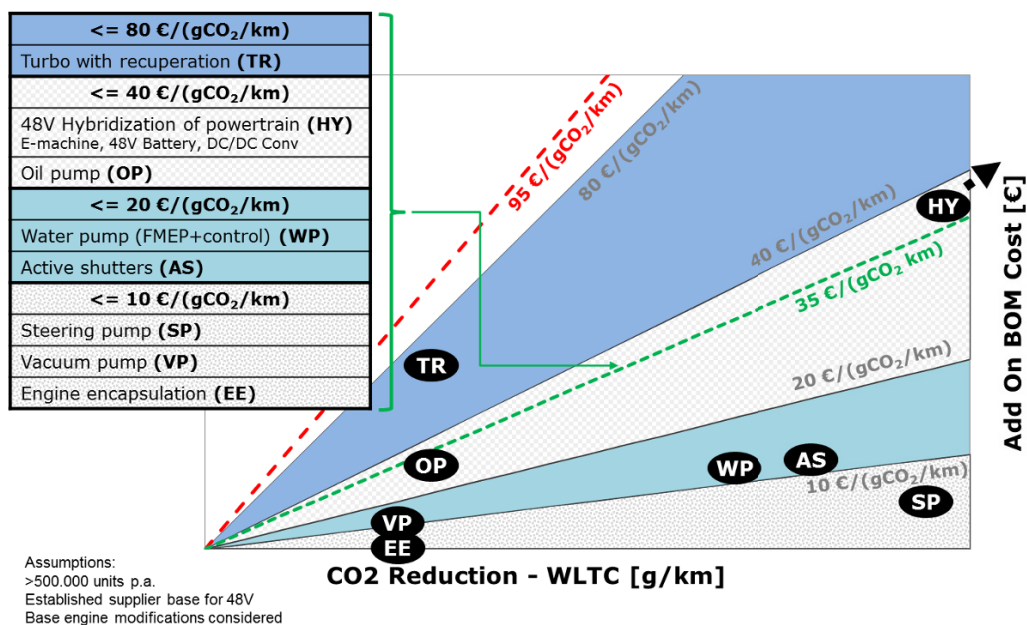


Fig. 28: Estimated reduction in CO₂ (WLTC) associated with component cost increase on bill of material (BOM) basis

Boundaries for this evaluation are:

- The concept of a base engine with belt drive provides the basis for add-on cost calculation for the different assemblies plotted.
- Changes to conventional engine architecture like belt drive (belt, tensioners, pulleys, idlers), covers and sealings are considered in the delta cost calculation.
- The presented cost data is calculated on bill of material basis.
- Cost changes are calculated based upon a hypothesis of ≥ 500.000 units per year produced in 2025 with several suppliers competing on the market. (48 Volt system established in series production).

For each component, costs versus gCO₂/km (WLTC) benefit have been considered. The EU proposed penalty of 95 €/g CO₂/km (NEDC) that will come into effect around 2020 has also been included on the chart. Although the benefits calculated over NEDC and WLTC are not strictly equal, previous results have shown that any benefit

shown on WLTC would be increased during an NEDC simulation so the penalty line can still giving a useful guide to assess if a technology solution is cost effective.

Result show that all options considered, for a vehicle of this size and performance, fall below the proposed penalty line and so become potential options to meet future legislation targets. However, the final selection of the most appropriate technology combinations for each particular OEM would perhaps also need to consider a range of powertrain options and vehicle lines. For example, it should be noted that if a different vehicle and engine combination are assessed, the cost-to-benefit chart could change; and therefore change the optimal choice to achieve the desired results over an entire fleet.

5 Summary and outlook

The introduction of 48V electrical architecture provides increased levels of power supply and energy recuperation at lower cost compared to full hybrid solutions.

Dependent on the specific application opportunities open up for the electrification of the internal combustion engine (ICE) and its auxiliaries.

Range of current powertrains already provides direct recuperation and boost function as well as powerful electrified charging of the ICE.

Electrified Turbochargers with additional recuperation function are in early advanced development as a promising next step.

Flywheel starter generator concepts, allowing temporary deactivation of the ICE and electric driving in a limited range.

On the base engine, electrification of the auxiliaries allows simplification for a beltless engine. Demand controlled, electrical auxiliaries are already partially in volume production for the cooling system, vacuum system or air conditioning.

Additional options such as electric oil pump and partial or full electrification of the valve train have been evaluated.

The optimum balance of electrical and mechanical functions on the base engine and its periphery requires an application dependent evaluation with the aim of minimized overall system complexity and cost as well as added customer value.

The extended approach is the integration of the “ideal” 48V powertrain including the optimized engine. Additional opportunities are opened up in regard of function and package by increased flexibility in the position of auxiliaries as well as function integration. Optimized vehicle thermomanagement including partial encapsulation and controlled cooling air shutters allow further efficiency improvement.

Key is the overall system approach of the 48V powertrain integration considering energy demand, cost, thermal management, aerodynamics and acoustics which is evaluated with the AVL Vehicle Attribute Engineering process to assess the balance between technology options and vehicle attributes.

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