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NEW LAMBDA = 1 GASOLINE POWERTRAINS NEW TECHNOLOGIES AND THEIR INTERACTION WITH CONNECTED AND AUTONOMOUS DRIVING



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ABSTRACT

The introduction of new emission legislations in Europe (Euro 6d) and China (China 6b) increases the pressure on the automotive industry to develop new and better exhaust gas aftertreatment and combustion systems. The fulfillment of PN and NOx targets in real world driving scenarios and increasingly electrified powertrains have forced the introduction of Gasoline particulate filters (GPFs) and enlarged catalytic converters. Now on top of these major upgrades, the monitoring of CO emissions according to RDE legislation (Real Driving Emissions) puts high load fuel enrichment for component protection into focus and a ban on enrichment is widely expected. Hence, Gasoline engine technologies which enable lambda 1 operation in the entire engine map are specifically promoted. Against this background, this paper presents stoichiometric component protection technology packages and operational strategies for ultra-low CO emissions in all real driving scenarios. Solutions from base engine modification to water injection and vehicle cooling concepts to control functions are assessed. Favorable combinations are identified considering costs and realistic integration in running vehicle programs.

Additionally, connectivity and automated driving can help to achieve a reduction in real world energy consumption and therefore help mitigate potential consumption increases resulting from lambda 1

concepts. This paper will quantify the impacts of connectivity and automated driving on real world fuel consumption based on improvements in driving behavior as well as operation strategy.

1 INTRODUCTION

Since the introduction of Euro 1 in 1992, the emission limits for passenger cars with internal combustion engines have been continually tightened and have now achieved a level of below 50 % of the initial status in Europe. Additional limitations for the particle number (PN) emissions for vehicles equipped with Gasoline direct injection engines are being considered now. With the introduction of the Euro 6d-TEMP legislation, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), which represents more realistic vehicle operation in the associated cycle (WLTC), as well as adopted boundary conditions have replaced the former new European driving cycle (NEDC). Furthermore, on-road measurement and monitoring of nitrogen oxide (NOx) and carbon monoxide (CO) emissions, using portable emission measurement systems (PEMS), have been implemented with the Euro 6c limits in 2016. By introducing conformity factors (CF), the current legislation in the European Union (EU) is limiting the pollutants based on a definition of not-to-exceed conformity factors for NOx and particle number (PN) under RDE conditions, see Figure 1.

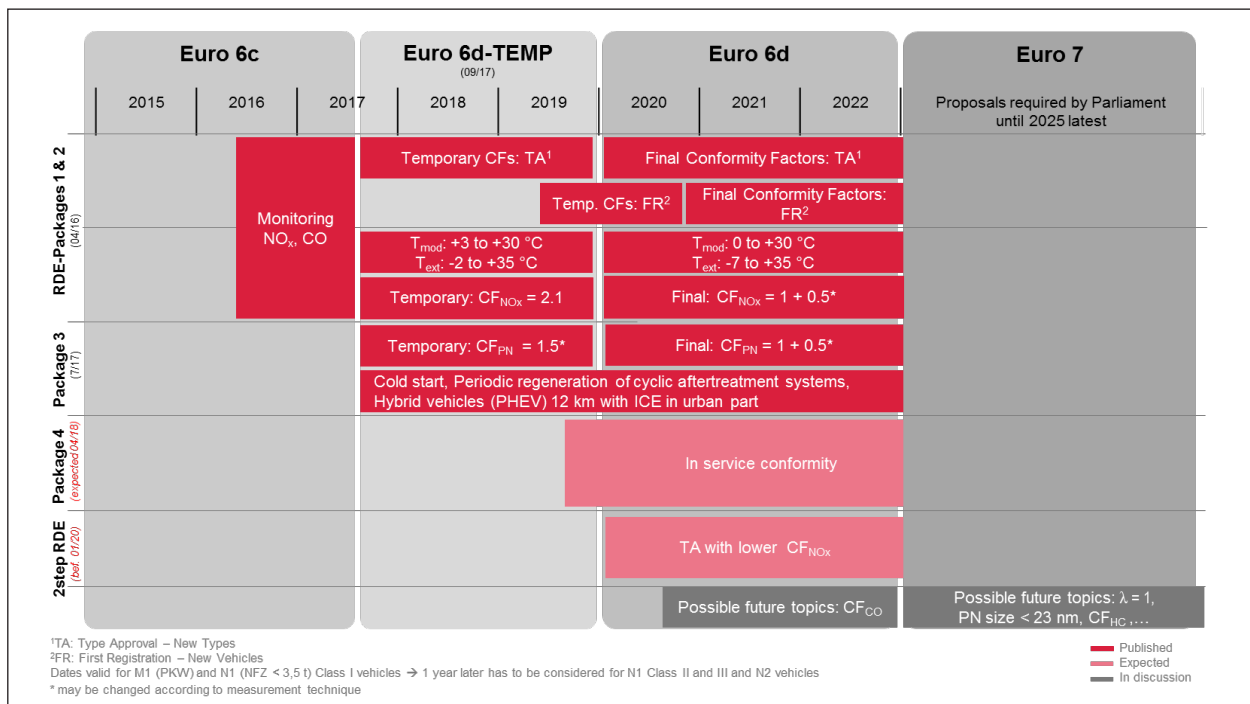


Figure 1: Real Driving Emission scenario in the European Union

With the already known road map for the reduction of the CFs for NO_x and PN in the future and the history of, at first, monitoring and later introducing strict legal limits and conformity factors for these pollutants, it is very likely that also CO emissions under RDE conditions will become the next topic for the emissions legislation.

First examples show that the acceptance policy of the authorities towards component protection by fuel enrichment as an auxiliary emission strategy (AES) seems to change. As a consequence, this is forcing the development of engines without fuel enrichment independent from the introduction of CFs for CO. Hence, a conformity check of CO under RDE conditions is mandatory.

This paper focusses on the current status of CO emission levels under various driving conditions and discusses countermeasures in order to decrease these emissions. It concludes with an analysis and recommendations for measures which will be able to comply with potential RDE CO limits.

2 CURRENT STATUS OF CO EMISSIONS UNDER RDE CONDITIONS

Although the possible introduction of a conformity factor for CO means a stricter legislation and

difficulties in complying with these targets, the on-road RDE tests of current vehicles so far tell a different story. In this context, Figure 2 displays with EMROAD post processed RDE test results of several vehicles plotted against their power-to-mass-ratio (PMR). PEMS measurement systems from two different sources were used. The grey FEV scatter band shows results of several vehicles from different OEMs, all tested on FEV's Aachen RDE track. The Aachen RDE track is compliant with the emission regulation and covers also sections in an average mountain range.

The red dots indicate monitoring results published by the ACEA (European Automobile Manufacturers' Association) [2] or the respective OEMs. In general, it can be stated that the results are in line and compliant. Single outliers can be explained by major differences between the RDE tracks or regarding exhaust system conditions as well as possible calibration take-overs from a time before RDE regulations were in place. While the aging status of the aftertreatment systems that were installed in the tested vehicles, represented by the red dots, is not known, all tests at FEV were conducted with aged catalysts and GPFs using either customer related aging methods or in-house burner rigs to age to full-useful-life (FUL) status, which means 160 000 km for EU applications.

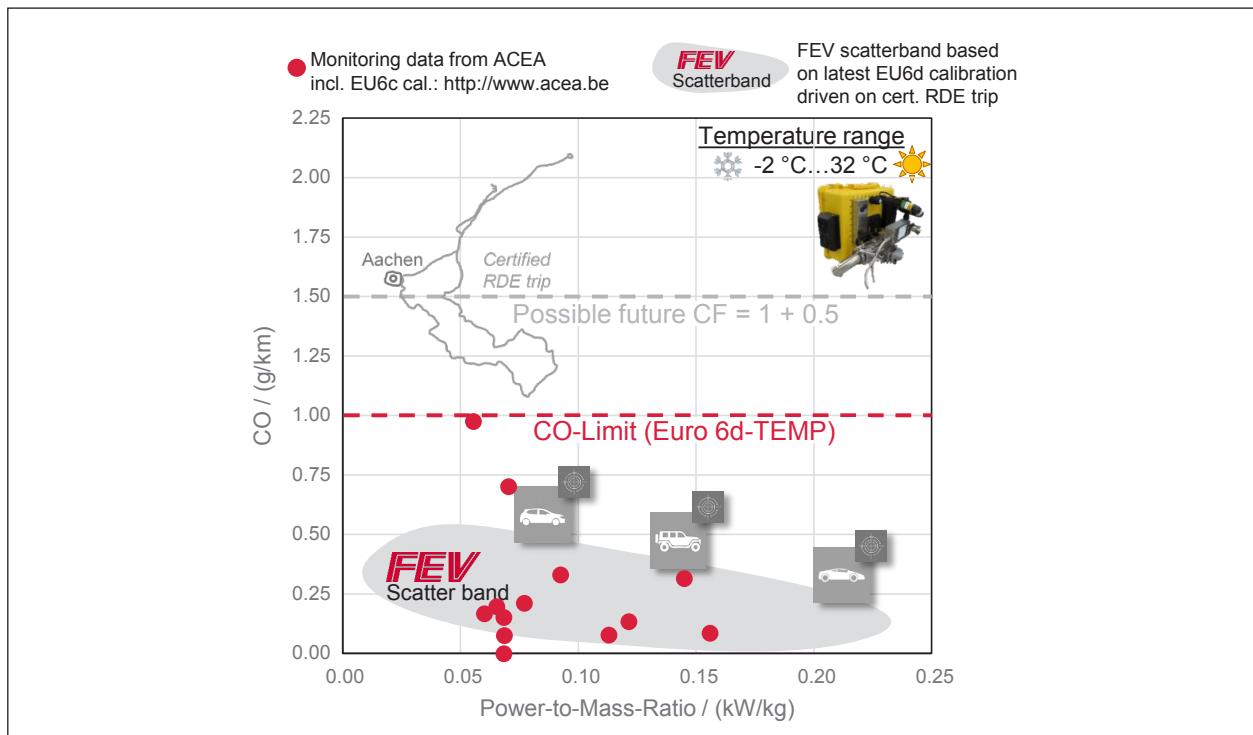


Figure 2: CO emissions during standard RDE tests

The results show a clear trend of increasing CO values with a decreasing power-to-mass-Ratio (PMR). On the left hand side of the plot, the results of vehicles with a low PMR are shown. These vehicles are mainly developed for urban driving (small A-segment city cars) or they are heavy vehicles with a small engine. For high powered vehicles (sports cars) on the right hand side of the graph, the lowest CO emissions were recorded for a similar driving profile. The higher the PMR, the less likely an engine operation in map zones with fuel enrichment occurs.

All displayed results stay below the legal limits and are compliant with the possible future CF of 1 + 0.5 measurement tolerance for nominal boundary conditions and standard driving behavior. However, the single outliers show that variation in the boundary conditions can lead to different results. As RDE testing can also include highly dynamic driving, this scenario also needs to be taken into account.

2.1 INFLUENCE OF HIGHLY DYNAMIC DRIVING ON CO EMISSIONS APPLYING WORST-CASE RDE BOUNDARY CONDITIONS

Worst-case conditions, like highly dynamic driving, extreme ambient temperatures or very low fuel quality, can lead to increasing pollutant emissions. Hence, it is reasonable to focus further on these possible influences which can adversely affect the emission behavior.

Different engine conditions and operation modes can result in very high CO emissions that cannot be handled by the three way catalyst (TWC). It is well-known that the TWC only operates efficiently at stoichiometric conditions, which requires a relative air/fuel ratio (λ) value equal to 1. Only small deviations can be accepted for short periods of time using the catalyst's oxygen storage capacity [3][4]. Very dynamic driving with many full load accelerations or driving constantly at full speed causes engine operation with enriched air/fuel ratios. The extra fuel does not participate in the combustion due to the lack of oxygen and the use of its evaporation enthalpy helps to cool down the combustion chamber and the exhaust system. The RDE legislation specifically prescribes certain boundary condition limits which need to be complied with in order to have a valid RDE test. Despite this "simplification", a combination of all

boundary conditions on the worst-case side can significantly increase the emissions.

Often, the investigation of all influencing boundary conditions for the determination of RDE values requires consideration of several cycles and driving scenarios. This leads to challenges regarding development time and costs, if a large number of different cycles need to be tested. Figure 3 shows the main RDE boundary conditions and a comparison of the WLTC chassis dyno cycle with an on-road RDE test (conducted on the FEV Aachen RDE track). In addition, a simulation-supported tailor-made worst-case RDE driving scenario, conducted on a chassis dyno is depicted. The on-road Aachen RDE test is compliant with the law and covers also sections in an average mountain range. The respective boundary conditions are normalized when compared to the legal worst-case boundary conditions. The best-case condition of each criterion is marked by the center of the diagram, whereas the worst-case conditions are marked by the outer borders – the borderline conditions.

The number of different counter influencing parameters emphasizes the necessity to use simulation supported testing to ensure that a worst case is tested. With the developed methodology, it is possible to create a specific worst-case driving scenario using simulation supported testing on a chassis dyno. For the identification of the scenarios, several input parameters are required in order to create a design-of-experiments (DoE) based model of the vehicle emissions: the vehicle and powertrain specifications including the gear shift pattern, engine out emission maps, λ values as well as the driver model and boundary conditions. The more vehicle information is available, the more accurate are the simulation results and thus the resulting driving scenarios. [5]

The v^*a_{apos} value describes the positive acceleration multiplied by the vehicle speed and is a first characteristic number to evaluate RDE driving. In combination with the positive altitude gain, the v^*a_{apos} values are of special importance for the CO emissions. For the respective cycle, with further accelerations at high v^*a_{apos} values, the legal CO emission limit could be exceeded. Thus, the cycle generator combines the stronger accelerations with high road gradients to ensure engine operation at high load points with fuel enrichment for thermal component protection applied. Additionally, a sufficient number of less dynamic accelerations

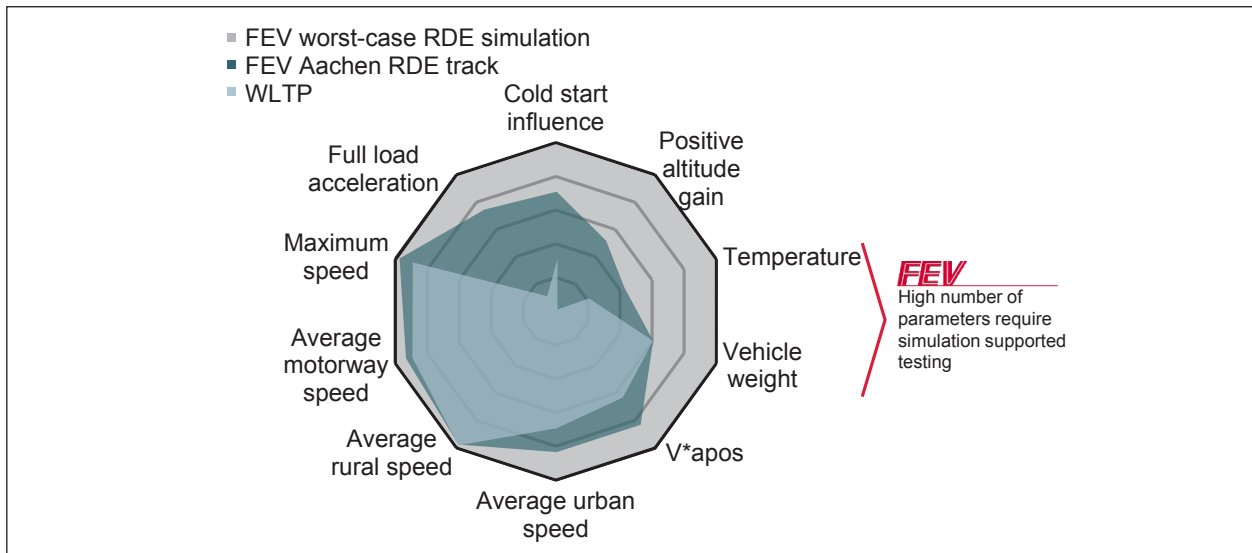


Figure 3: FEV approach: tailor-made simulation of worst case RDE cycles

can be taken into account to control or lower the v^*_{apos} value to stay within the legal cycle limits. Also, the road load coefficients, the maximum and the average speeds can be modified to gain the desired loads or exhaust gas mass flows. The cold start influence refers to the driving distance which is used to calculate the distance related emissions. For RDE purposes, the cold start emissions affect at least the minimum urban driving distance of 16 km. For the WLTC, the urban emissions are not separately evaluated.

It can be seen that the areas of the WLTC and the on-road RDE measurement in Figure 3 are close to each other except for the three aspects of positive altitude gain (the WLTC does not contain a road gradient), the number of full load accelerations

and the cold start influence. An example for a tailor-made worst-case RDE driving cycle is shown in Figure 4 for a vehicle with a PMR of about 0.095 kW/kg. The highly dynamic nature of the cycle with its accelerations as well as the applied road gradients (in red) are clearly visible.

An additional advantage of the presented approach is the possibility to reduce the test length to save time and costs during a vehicle calibration process. The methodology enables reducing the test duration by about 66 % without losing essential information for the post processing procedures EMROAD and CLEAR. The investigations which will be described in the following assumed a cycle of approximately 33 km length. For that purpose, single phases are systematically cut out and then

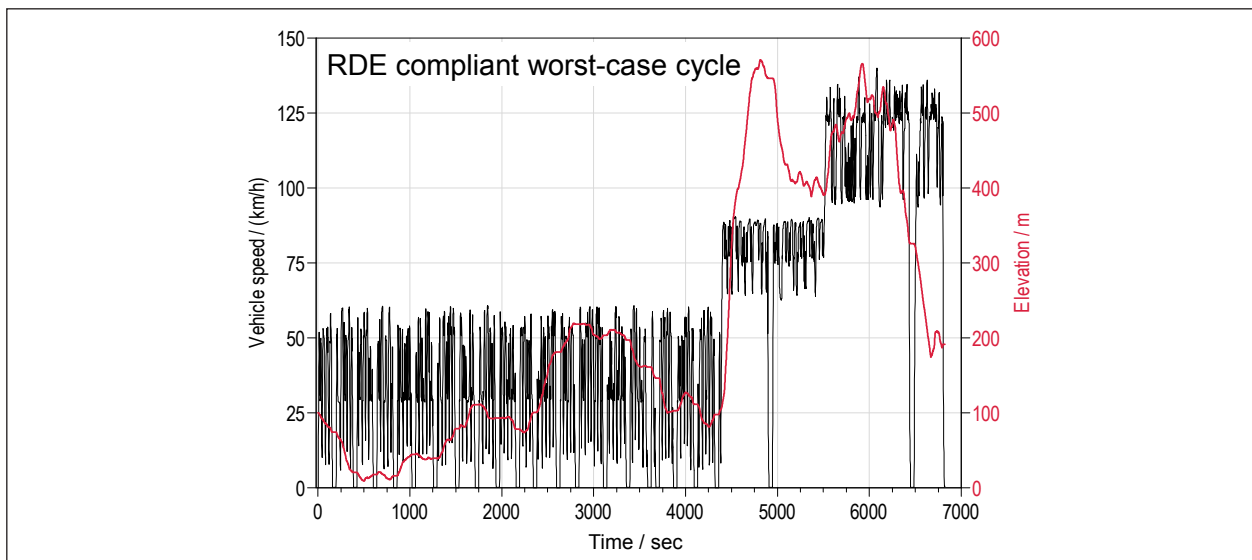


Figure 4: Example for a tailor-made worst-case RDE cycle derived from FEV's RDE simulation

reassembled into the measurement file to create a complete RDE cycle. Special post-treatment, using a self-developed software tool, is necessary to ensure the correct weighting of the cold start phase.

2.2 RESULTS OF A RDE-COMPLIANT EMISSION CYCLE WITH FUEL ENRICHMENT FOR COMPONENT PROTECTION

To show the impact of potentially aggressive driving styles on the RDE CO emission level, a C-segment vehicle with a PMR of about 0.06 kW/kg and an aged TWC/GPF combination was tested on a chassis dynamometer using the presented tailor made RDE scenario. As mentioned in the previous chapter, the shortened cycle approach was applied. The corresponding speed profile, the CO emissions as well as the indicator bit for component protection fueling are collated in Figure 5.

The detailed view on the time sequence between 1950 and 2050 seconds in the lower part of the figure depicts the CO emissions and the air fuel ratio measured upstream of the TWC.

Regarding the accumulated CO emissions, a direct relationship between the increase in emissions and the “overfueling” for component protection can be observed. The legal CO limit of 1 g/km is exceeded considerably and even the possible future CF of 1 + 0.5 cannot be met. It should be noted that this scenario represents not even the worst possible cycle as it is aimed to compare it directly with a less powerful lambda 1 variant. The detailed view on the air/fuel ratio shows that only ten seconds of rich air/fuel ratios already result in 0.5 g/km CO which is 50 % of the legal CO limit for the WLTC (lower part in Figure 5). The extensive exceedance of even the potential CF target requires the application of countermeasures like hardware changes or suitable calibration strategies.

During the phase between 1985 and 1995 seconds depicted by enlargement, a full load acceleration from 80 kph to 112 kph at engine speeds between 3400 and 4200 rpm takes place. Figure 6 shows a lambda engine map of the tested vehicle, highlighting two engine load points with their respective relative air/fuel ratios and the resulting catalyst efficiency. At steady state part load

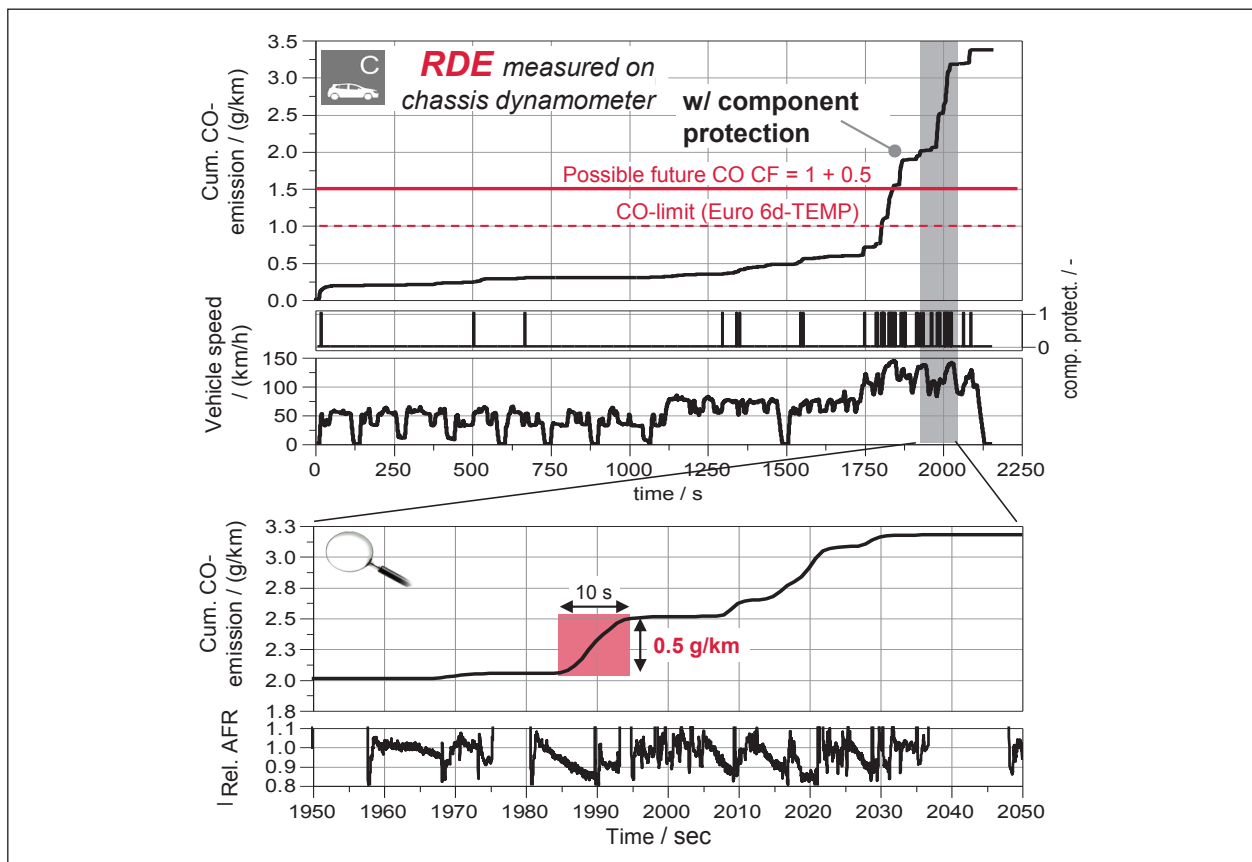


Figure 5: Tailor made dynamic RDE cycle test results showing how CO emissions can become a very critical issue

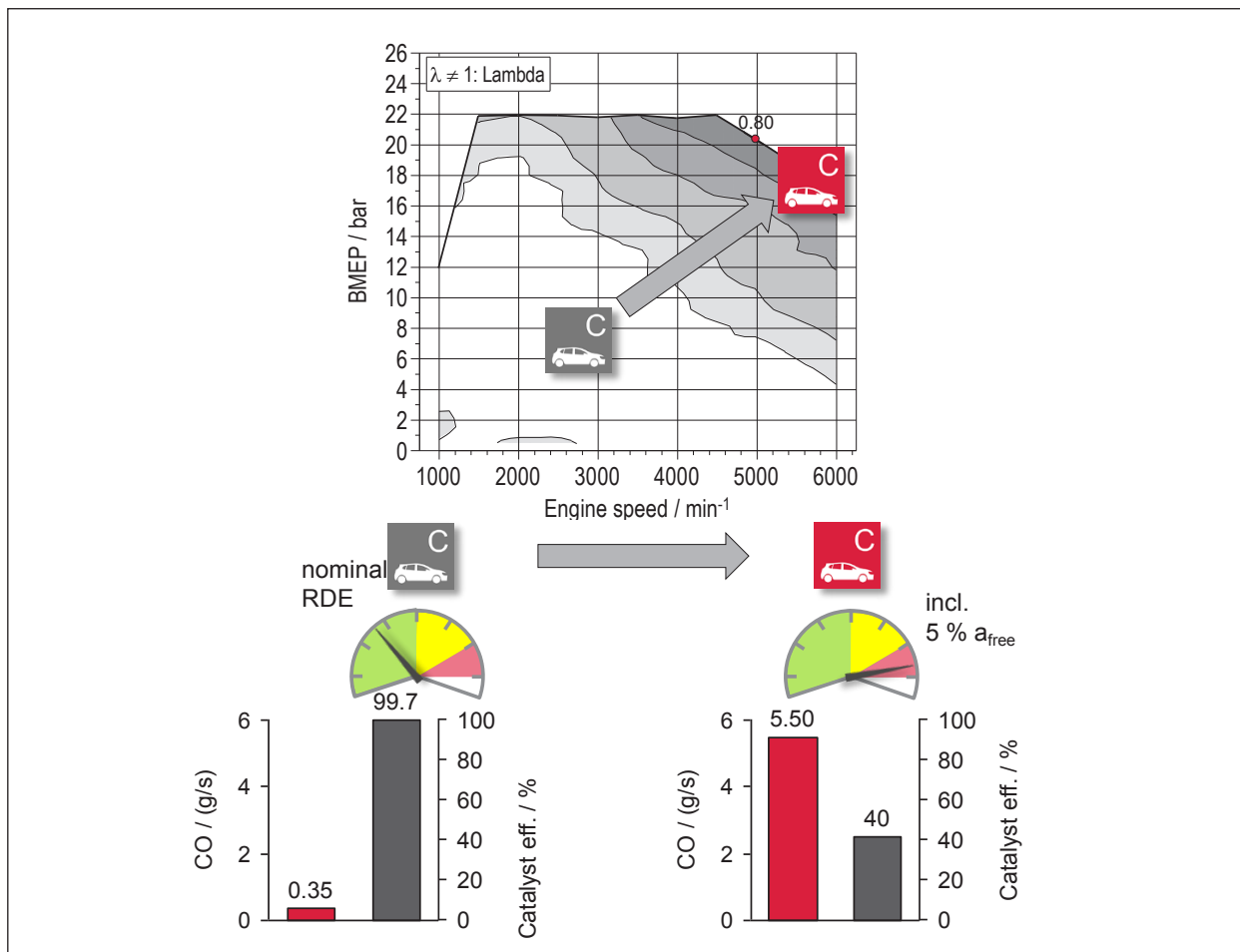


Figure 6: Air fuel ratio engine map and RDE CO emission results depending on usage on "5 % free acceleration"

operation with lambda 1 (colored in grey), the CO removal efficiency of the TWC is very close to 100 %, while during full load acceleration (colored in red), the engine operates with a lambda value of 0.8, which reduces the TWC efficiency to only 40 %.

Nominal driving without the allowed 5 % free acceleration leads to CO emissions way below the legal limits. However, exceedance of the legally allowed free acceleration by only 5 % (5 % a_{free}) leads to at least 8 g/km of CO for this specific variant, when applying the worst-case cycle.

To enable the back-to-back comparison with a less powerful engine without fuel enrichment for component protection in the same vehicle, a worst-case cycle for that vehicle variant with a PMR ~ 0.46 kW/kg was measured in addition. To safeguard components like the turbocharger from damage at exhaust gas temperatures exceeding 980 °C, the engine needs to be modified to allow completely stoichiometric operation. This typically requires a reduction of the full load performance

especially at high engine speeds which results in a rated power reduction.

Figure 7 compares the CO emission results of the C-class vehicle with the stoichiometric (dark blue) and the conventional operation with full load fuel enrichment (black).

The CO emission results for these two operation strategies in the given high-dynamic RDE cycle in comparison to RDE road tests are shown in Figure 8, which summarizes the effects of different ambient boundary conditions, driving behaviors and calibration influences on the emissions. The yellow dots represent the emission results for the given C-class vehicle weighted with EMROAD. The CO value measured with the conventional calibration (worst case, $\lambda \neq 1$) exceeds the possible future CF by far. On the x-axis, it does not correspond to the other yellow dots because of the 30 % higher rated power and the resulting different power to mass ratio. When considering the result of the all lambda 1 vehicles for the same

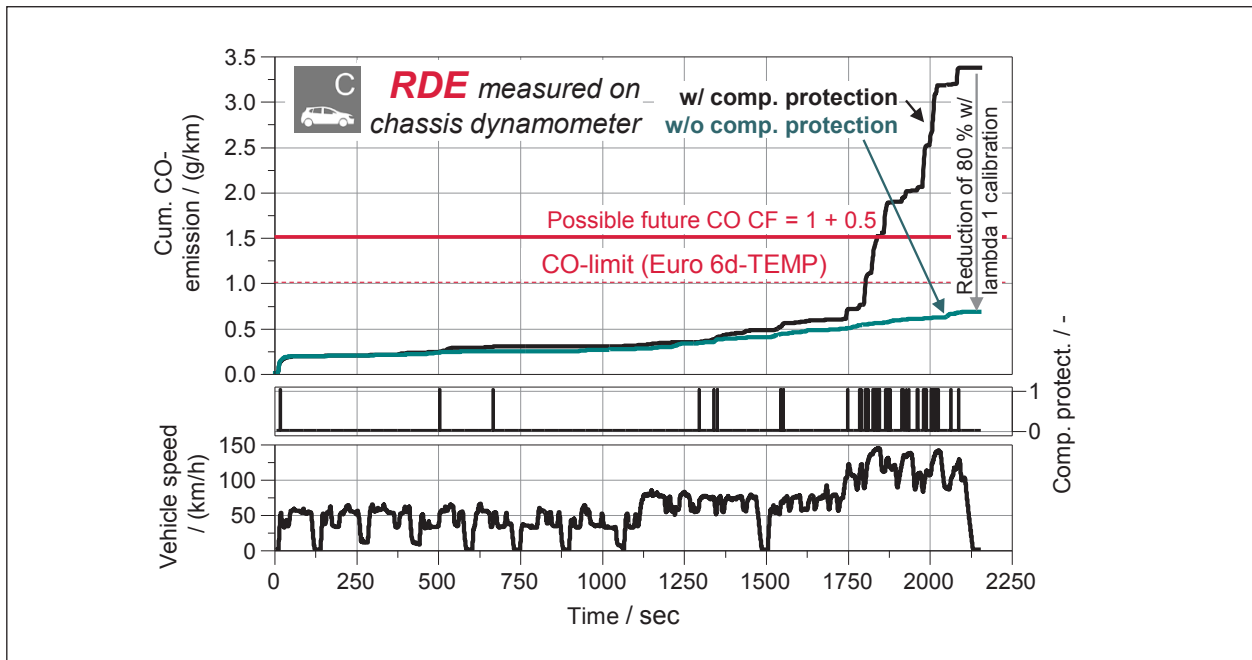


Figure 7: Comparison of worst case RDE CO emissions for conventional calibration and lambda 1 concept

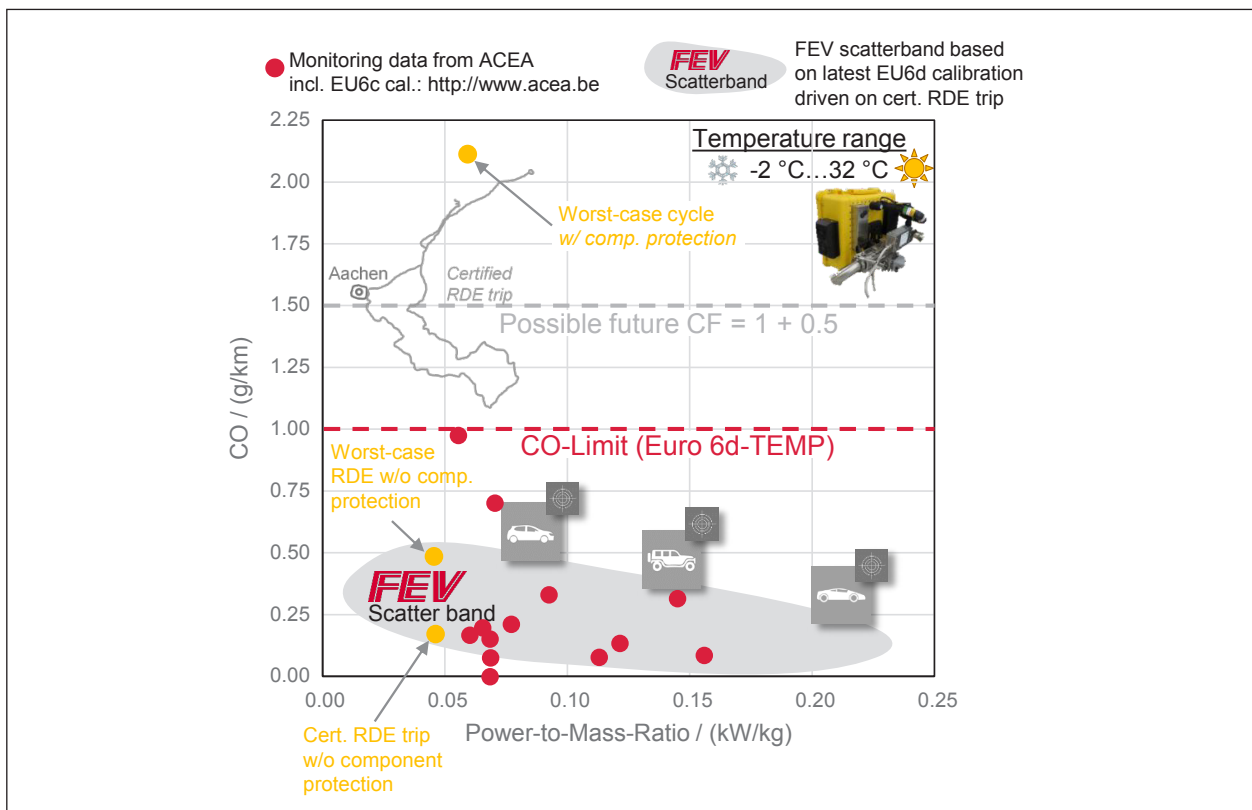


Figure 8: Classification of RDE CO emission results for different calibration concepts

cycle, a strong decrease in CO emissions becomes obvious. Even in the worst-case cycle, the CO emissions stay inside the scatter band for nominal RDE PEMS measurements conducted on road. The

third yellow dot marks an on-road RDE test. The result is situated at the lower bound, but inside the scatter band.

RDE testing can also contain very dynamic driving and application of full load accelerations at various boundary conditions. This may result in CO emissions far above the potential future conformity factor of $1 + 0.5 \text{ g/km}$. FEV has developed an efficient DoE based methodology to identify worst-case scenarios in an early development stage, even before the powertrain hardware is available. The support of the subsequent powertrain development stages by virtual testing and calibration encompasses a major potential to save development time and effort. Applying this approach, a robust solution can be developed which ensures emission levels below the legal limits under all possible RDE boundary conditions.

3 MEASURES TO ACHIEVE AN ALL LAMBDA 1 ENGINE MAP

As shown before, an entirely stoichiometric combustion can avoid CO breakthroughs and significantly reduce the emission results even for worst-case conditions. However, the need to eliminate component protection by fuel enrichment may result in a reduction of specific engine power. In compensation, a larger engine displacement might be required which however is counterproductive regarding CO₂ emissions of the vehicle fleet. These conditions bring new limitations to engine downsizing, but have also become a technology driver for the application of alternative concepts, such as e. g. water injection, usage of new materials, exhaust gas cooling solutions, variable compression ratio (VCR) and powertrain hybridization. Appropriate concepts will be discussed and evaluated below.

Basically, there are two different options to avoid fuel enrichment for component protection purposes, see Figure 9. Either more advanced and cost intensive materials, e.g. for the turbocharger turbine, the exhaust valves or the exhaust manifold are used, allowing exhaust gas temperatures (EGT) of e.g. up to 1050 °C (red arrow "Material"), or the exhaust gas temperature (EGT) needs to be limited to 980 °C by the introduction of additional technologies (blue arrow "Cooling").

The effectiveness of four different technologies will be analyzed in more detail:

- Turbocharger technology which allows to expand the exhaust gas temperature limit to 1050 °C,
- Water injection, using the high enthalpy of vaporization (factor 5.5 higher compared RON95

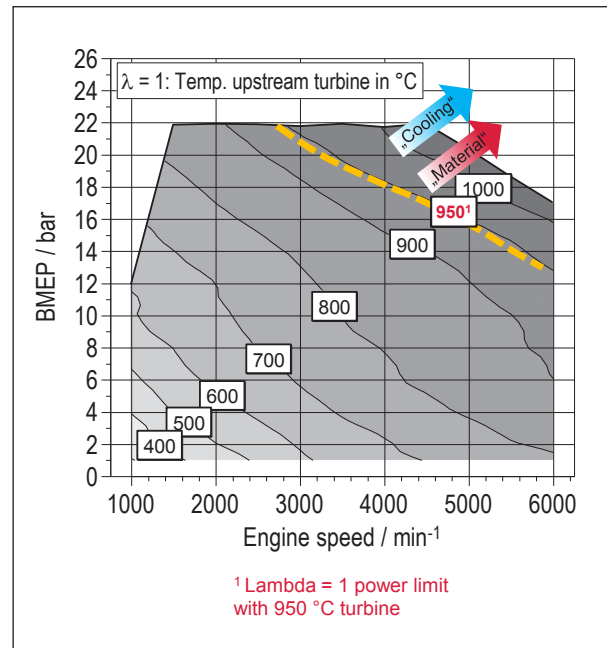


Figure 9: Exemplary $\lambda = 1$ exhaust gas temperature map

- fuel) to cool the cylinder charge, thus reducing knock tendency and exhaust gas temperature,
- Variable compression ratio with a lower compression for high load and power, so that the spark timing can be advanced for rated power (reduces exhaust gas temperature),
- Matching a turbocharger with larger turbine size and additional electrical assist (eTC) in order reduce the exhaust gas backpressure and residual gas fraction at high engine load (reduces exhaust gas temperature).

The analyses have been carried out for two base engines with specific power outputs of 110 kW/l and 90 kW/l. Both specific power values are typical for the current Gasoline engine market. Base engine A is a high power variant with a rather large turbocharger (TC) and an integrated exhaust manifold (IEM) in the cylinder head, which has been considered for base engine B as well. To reach the specific power of 110 kW/l, a strong fuel enrichment (approximately $\lambda = 0.7$) is necessary. In contrast, with a smaller TC, a higher compression ratio and less fuel enrichment for component protection (approximately $\lambda = 0.8$), base engine B only reaches 90 kW/l.

For both engines, Figure 10 depicts specific power values for exemplary technology packages enabling $\lambda = 1$ operation in the entire engine map. Starting with the base configuration using conventional full load enrichment (dark grey bar),

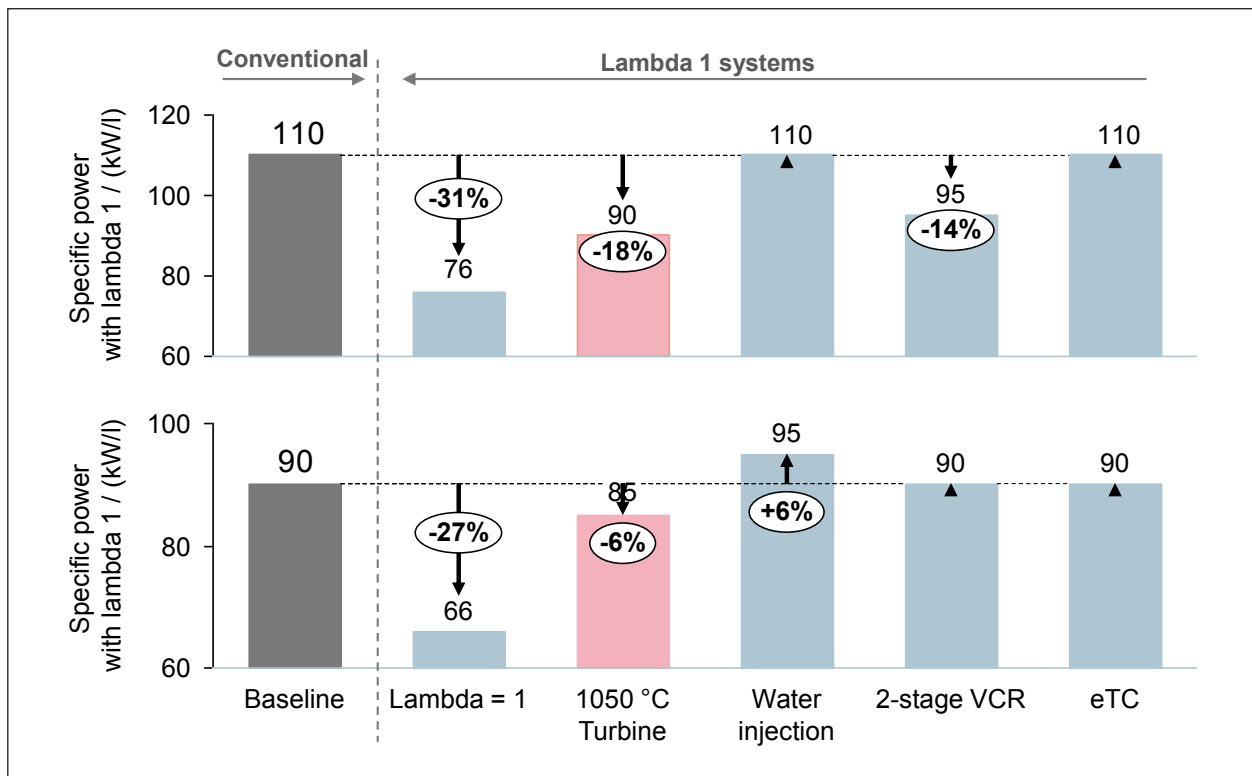


Figure 10: Quantification of $\lambda = 1$ rated power technology packages for two different base engines

the following bars from left to right show the specific power values which can be achieved with:

- An exhaust gas temperature limit of 980 °C without hardware changes compared to the base engine configurations,
- 1050 °C turbocharger turbine technology,
- Direct water injection,
- Variable compression ratio (2-stage VCR),
- A larger turbine size in combination with electrical assisted TC (eTC).

For both engines, a significant reduction of specific engine power occurs if the EGT of 980 °C has to be adhered without additional technologies being introduced. In case of engine A, a stronger power reduction of 31 % can be observed which is due to the higher requirement for enrichment of the high performance engine compared to engine B. If this derating would only be compensated only by upsizing of the engine displacement a significant disadvantage of e.g. about 10% in case of engine B would occur. Thus, alternative solutions have to be introduced which partly or fully compensate not only the engine derating itself but - in some cases - offering an additional benefit for further efficiency increase as discussed in this paper.

The usage of a turbine material with a 1050 °C EGT limit represents moderate technical effort

and offers a significant potential to gain back engine performance. But for both base engine specifications, this technology alone is not sufficient to fully compensate the losses in performance. Still a lack of 6 % respectively 18 % remains compared to the baseline engine configurations with fuel enrichment. Nevertheless, evaluating its potential, cost and availability, the 1050 °C turbine technology appears to be an attractive step towards $\lambda = 1$ full load operation with justifiable additional expenses.

Direct water injection is able to completely avoid power losses (in case of engine A) or even increase the performance as shown for engine B [7]. Currently, this complex technology is not yet ready for series application. However, intake port water injection has already been introduced for niche applications [8]. Ongoing projects at FEV have demonstrated that also with intake port water injection the specific power at lambda 1 can be increased by up to 30 kW/l.

A variable compression ratio ("2-stage VCR") is able to completely overcome a loss in performance for engine B and also comes with additional benefits with respect to fuel consumption (FC) reduction. Regarding engine A, the rated power loss can be limited to only 14% with a VCR system, while enabling $\lambda = 1$ operation. Next to water injection,

VCR is a most promising solution to combine high specific power and fuel consumption reduction with the requirement of stoichiometric air/fuel operation in the entire engine map.

The matching of a significantly increased turbine size allows to gain back the full load performance of both base engines. A larger turbine reduces the exhaust gas backpressure and thus the residual gas fraction in the cylinder. This allows to elevate the boost pressure capability to enable Miller cycle valve timings. In order to avoid a disadvantage in low end torque caused by the larger turbine, additional measures such as two stage boosting [9] or electrically assisted turbocharger technology (eTC) are required. This has been considered for the far right bar in Figure 10.

As a single technology, water injection shows the highest potential with respect to specific power at $\lambda = 1$ operation in the whole engine map. However, it requires a large extent of adaptations for the engine itself, but also for the vehicle and the calibration. Its significant potential results from the high enthalpy of vaporization of water compared to conventional RON95 fuel, which can be seen in Figure 11. Water substantially increases the cooling effect for the same mass of liquid injected. Nevertheless, the amount of water consumption at frequent high load operation represents a major challenge. Moreover, this technology requires involvement of the vehicle operator in frequently refilling the water tank.

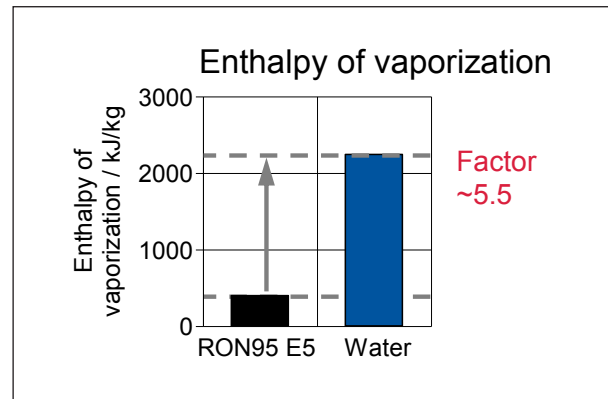


Figure 11: Enthalpy of vaporization for water and RON95 fuel

This is one of the reasons why approaches such as the combination of VCR, 1050 °C materials for the turbine and advanced boosting concepts are a promising alternative.

As shown before, an application of a large turbine offers the opportunity to gain back the specific engine power losses for both engine concepts. In order to avoid a drawback in low-end-torque (LET) performance, countermeasures, such as application of a 2-stage boosting system or an electrically assisted TC, have to be considered. Figure 12 shows a powertrain layout with an eTC in combination and a 48 V mild hybrid (MHEV) system with belt-starter-generator (BSG) on the left side and the corresponding fuel consumption reduction potential in the entire engine map on the right side.

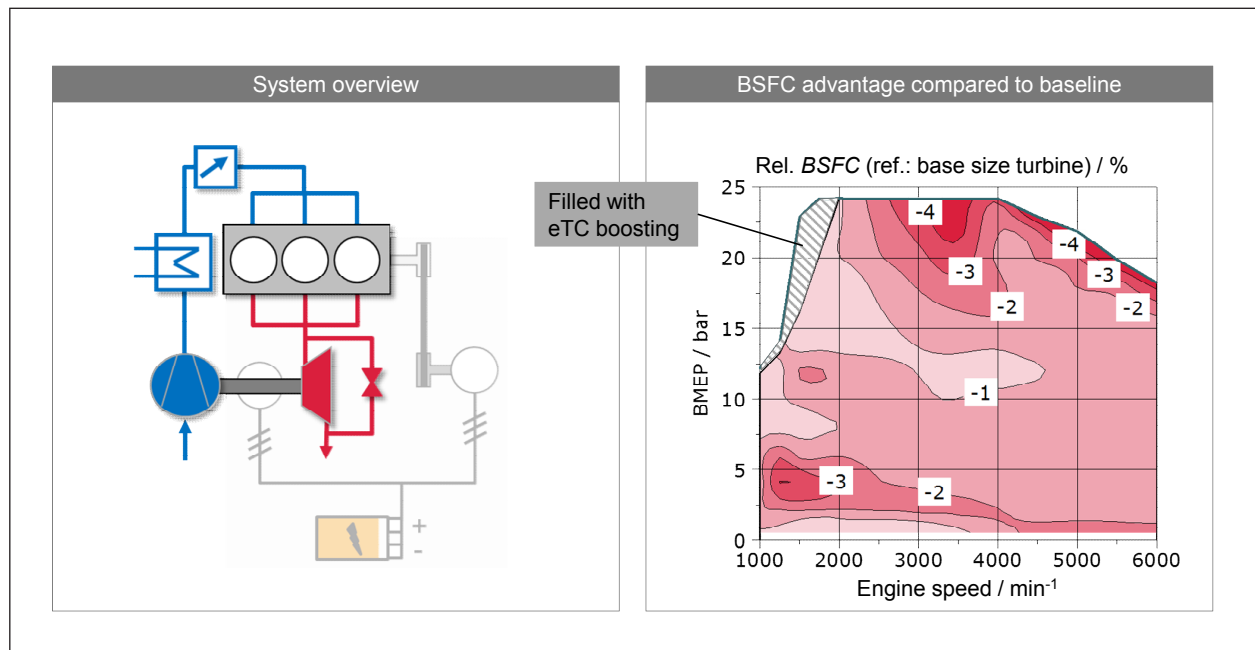


Figure 12: Potential of a large turbine layout combined with e-boosting for FC reduction

There are major FC advantages at high load in general, but also at part load, the efficiency of the ICE is improved by up to 3 %. The reason for this advantage is a difference in waste-gate (WG) operation strategy. With the baseline configuration, the waste-gate was used to provide a sufficient transient performance of the ICE. In case of the electrically supported TC, the WG can be opened further at part load providing substantial advantages in efficiency.

In addition to the beneficial effects mentioned before, the portion of the excessive energy of the TC can be used for exhaust energy recovery via the electric machines of the TC and the BSG. The benefit of this effect is pronounced at high engine loads and moderate engine speeds.

5 IMPACT OF CONNECTIVITY AND AUTOMATED DRIVING ON ENERGY EFFICIENCY

The rise of automated driving as well as the increasing degree of connectivity in vehicles hold additional potential to increase the energy efficiency of vehicles especially under real world conditions. Hence, potential negative effects of lambda 1 concepts on energy consumption can be offset by a connected and automated vehicle (CAV). Integrated V2X connectivity enables prediction of future driving situations (horizon) while the automated driving functionality minimizes the uncertainty attached to driver specific

behavior. Therefore the entire vehicle behavior can be predicted with a minimal uncertainty. The consumption benefits resulting from this prediction are calculated based on two main effects (so-called impact factors):

- Driving profile: Based on prediction the driving profile of a CAV can be optimized for efficiency, e.g. smoother driving or reduced stops
- Operation strategy: Prediction enables an optimized operation of the powertrain and auxiliary components, e.g. predictive battery management, predictive costing or intelligent climate control

It should be noted that additional efficiency benefits apart from the aforementioned effects can be achieved by vehicle modifications resulting from different consumer demands towards a CAV in comparison to a conventional vehicle, e.g. reduction in required peak power because the human is not involved in the driving task anymore [11]. These vehicle modifications effects were not considered in this paper. All three potential impact factors are also displayed in Figure 13.

The quantification of the energy efficiency improvement potential is executed for a CAV in the midsize care segment equipped with an extended V2X connectivity package. It also offers automated driving functionalities equivalent to SAE level 4 which is assumed to fulfill the entire dynamic driving task in a specific geofenced area or operational design domain (ODD) where

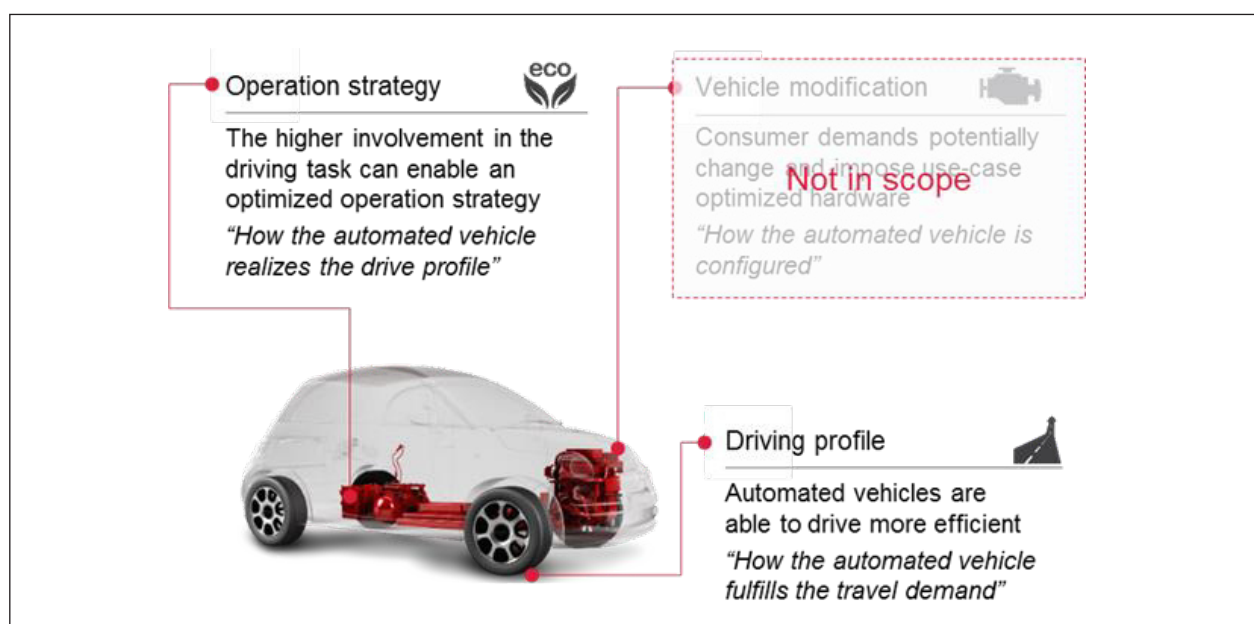


Figure 13: Impact factors of connectivity and automated driving on energy efficiency

the vehicle exclusively operates. This includes highways and city roads.

The calculation of efficiency benefits is based on a statistical analysis of 12,000 real-world cycles recorded from consumers in California during their everyday life. Representative cycles were identified and modified to approximate the average driving behavior of a CAV. This simulation was based on the following basic premises for the behavior of CAVs [12]:

1. Reduction in stops
2. Reduction in peak acceleration and speeds
3. Smoothing of the speed profile

The transformation of one of the representative driving profiles to approximate SAE level 4 CAV behavior can be found in Figure 14.

All of the aforementioned effects can be clearly observed in this transformation profile: Certain stops are removed from the profile and particularly oscillating sections are smoothed. Moreover, peak accelerations and top speeds are reduced. As a consequence technologies which benefit from low transients and engine load might be promoted which is in opposite compared to the transition between NEDC and WLTC. Besides the potential energy efficiency benefit the reduction in stops also decreases the total travel time of the cycle.

The resulting calculated fuel consumption benefits for a micro hybrid (stop/start) and a full hybrid powertrain concept are displayed in Figure 15. It should be noted that benefits from the phlegmatization of the driving profile can be exploited as well for emission reduction [13], but are not discussed in this paper.

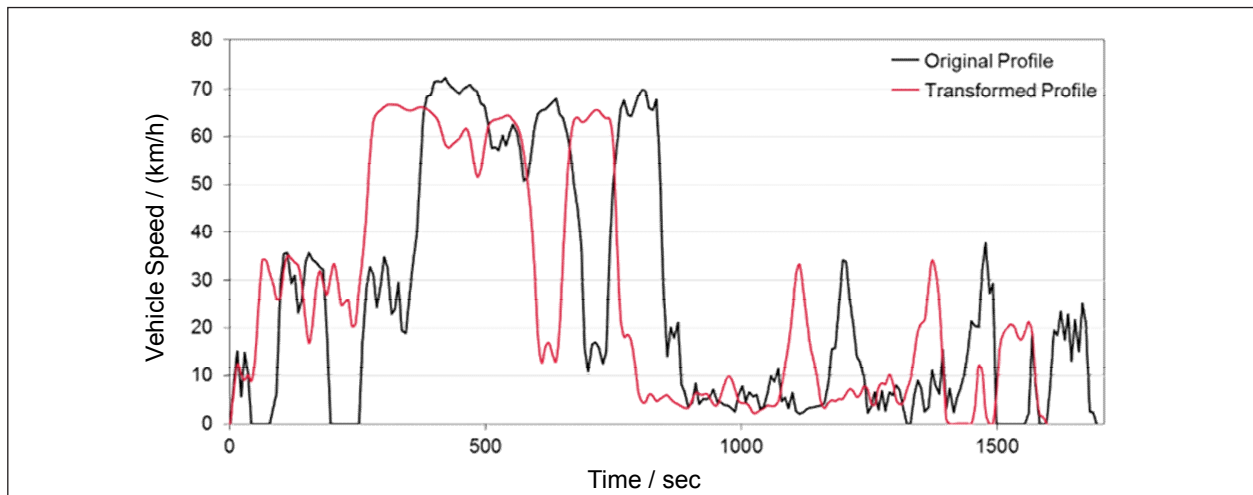


Figure 14: Example driving profile transformation for a SAE level 4 CAV

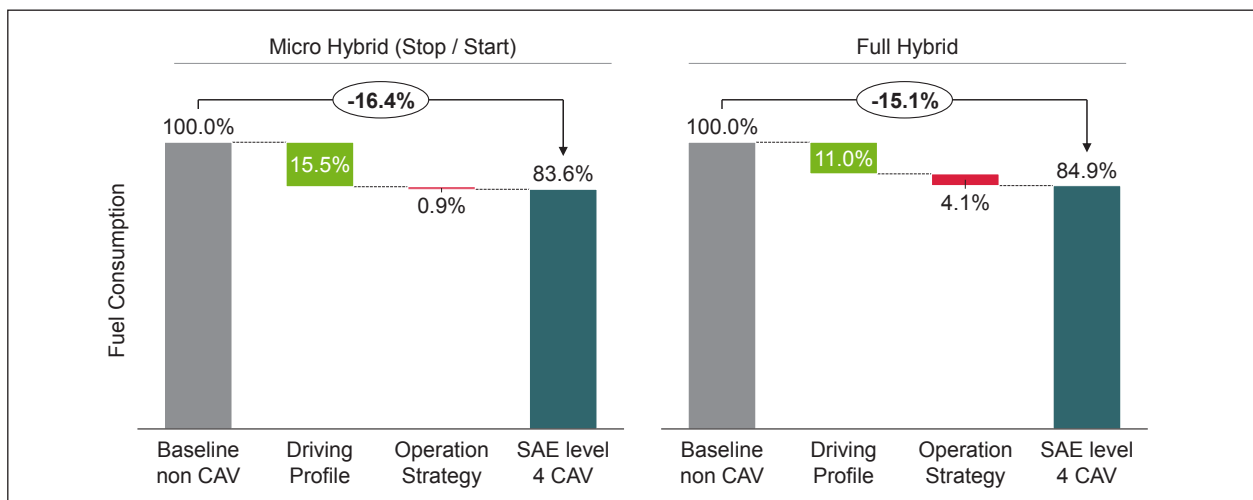


Figure 15: Fuel consumption benefits resulting from connected and automated driving (SAE level 4) for a midsize car with micro hybrid (left) and full hybrid (right) powertrain configuration

It can be found that the fuel consumption saving potential of CAVs is significant under real world conditions and also applies to highly electrified powertrains. While the micro hybrid experiences slightly more fuel consumption reduction the order of magnitude is similar between the micro and full hybrid concept.

The distribution between the two different impact factors however is significantly different between the different powertrain types. While the micro hybrid benefits almost exclusively from the driving profile, the full hybrid also has considerable efficiency gains from the operation strategy optimization. Looking at the underlying effects it can be found that the modification of the driving profile (as displayed in Figure 14) cannibalizes some of the recuperation potential available to the full hybrid and therefore reduces the consumption benefits associated with the driving profile transformation. Recuperation potential for hybrids is generally available in braking / deceleration situations which are partly eliminated from the driving profile by reducing stops and smoothing the profile. In comparison, this cannibalization effect is not prevalent with the micro hybrid and therefore the efficiency benefit based on driving profile transformation is more distinct. The significantly higher operation strategy efficiency benefit of the full hybrid is found to originate from the comparably higher degrees of freedom in power delivery in this powertrain configuration, i.e. a full hybrid can utilize prediction for multiple purposes such as optimized load shifting and battery management which are not available to micro hybrid powertrains.

SUMMARY

The restriction of CO emissions under real world driving conditions will be a next challenge the automotive industry has to address.

Although FEV's in-house and publicly accessible RDE data of on-road CO measurements paint a promising picture with typical CO results being significantly below the legal limits, worst-case driving conditions within the RDE tolerances can lead to a severe exceedance of the CO limits by a factor of up to eight. This is the main driver for a potential future broad ban on high load fuel enrichment to limit exhaust gas temperatures and protect components such as the turbines of turbochargers.

In order to avoid losing up to 30 % of the maximum power when applying lambda 1 air/fuel ratios in the entire engine map, the application of alternative technologies is required.

There are two options to overcome this power loss: Either a decrease of the exhaust temperature or the usage of enhanced materials which can cope with increased exhaust temperatures. The choice of options is dependent on cost aspects as well as on the boundary conditions of the vehicle, like the size of the engine, the maximum specific power requirement or the capability to provide additional cooling power depending on the front-end topology of the vehicle.

Engines having six or less cylinders and a moderate specific power of approx. 90 kW/l may avoid the implementation of intrusive hardware solutions like a cooled exhaust manifold due to their package situation and rather use an optimized turbocharger turbine material which enables up to 1050 °C exhaust gas temperatures limiting the power reduction to about 6 % with lambda 1. A 2-stage VCR system could completely avoid power losses, while still enabling lambda 1 operation in the entire engine map combined with additional CO₂ benefits on top. The application of water injection would not only allow the lambda 1 operation, but additionally lead to a power increase of up to 6 %. For a higher specific power level of 110 kW/l, water injection is a favorable solution to fulfill the lambda 1 requirements without a power loss because of its high cooling potential in the combustion chamber. This is getting all the more important for even higher specific power levels or use cases where package restrictions hinder "simple" solutions like

installation of a more capable cooling system in the vehicle.

The adaptation of advanced boosting systems offers a considerable potential to maintain high specific engine power values without fuel enrichment. For both base engine examples, the power of the base configuration could be achieved by a significantly increased turbine size in combination with measures to compensate a lack in low-end-torque. The combination of electrical assisted turbocharging and a mild hybridization with a 48V belt-starter-generator offers additional potential to reduce the fuel consumption not only at high loads, but at part load as well.

Combining a variable compression ratio system, like a 2-stage-VCR, with a 1050 °C turbine, also avoids power reduction for the 110 kW/l variant, while still enabling a lambda 1 operation in the entire engine map.

As the trend towards a lambda 1 calibration for Euro 6d is already ongoing, it is strongly recommended to thoroughly check current calibrations using the simulation-supported worst-case RDE cycles and potentially to consider hardware changes to timely secure future emission compliances of any engine-vehicle combination.

Connectivity in combination with automated driving is found to have a significant real world driving fuel consumption reduction potential which can help to offset potential negative effects from lambda 1 measures. For a SAE level 4 midsize segment vehicle equipped with a micro hybrid (stop/start) powertrain the potential fuel consumption benefit was calculated to be 16.4% while a full hybrid concept reached a 15.1% reduction. It was found that a micro hybrid benefits almost exclusively from a driving profile transformation while the full hybrid also experiences a significant benefit from an operation strategy optimization. This examples illustrates that powertrain technologies benefit in general from the phlegmatisation of the driving profiles by the introduction of connected and automated vehicles in real life conditions, but with different pronunciation of specific powertrain technologies.

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