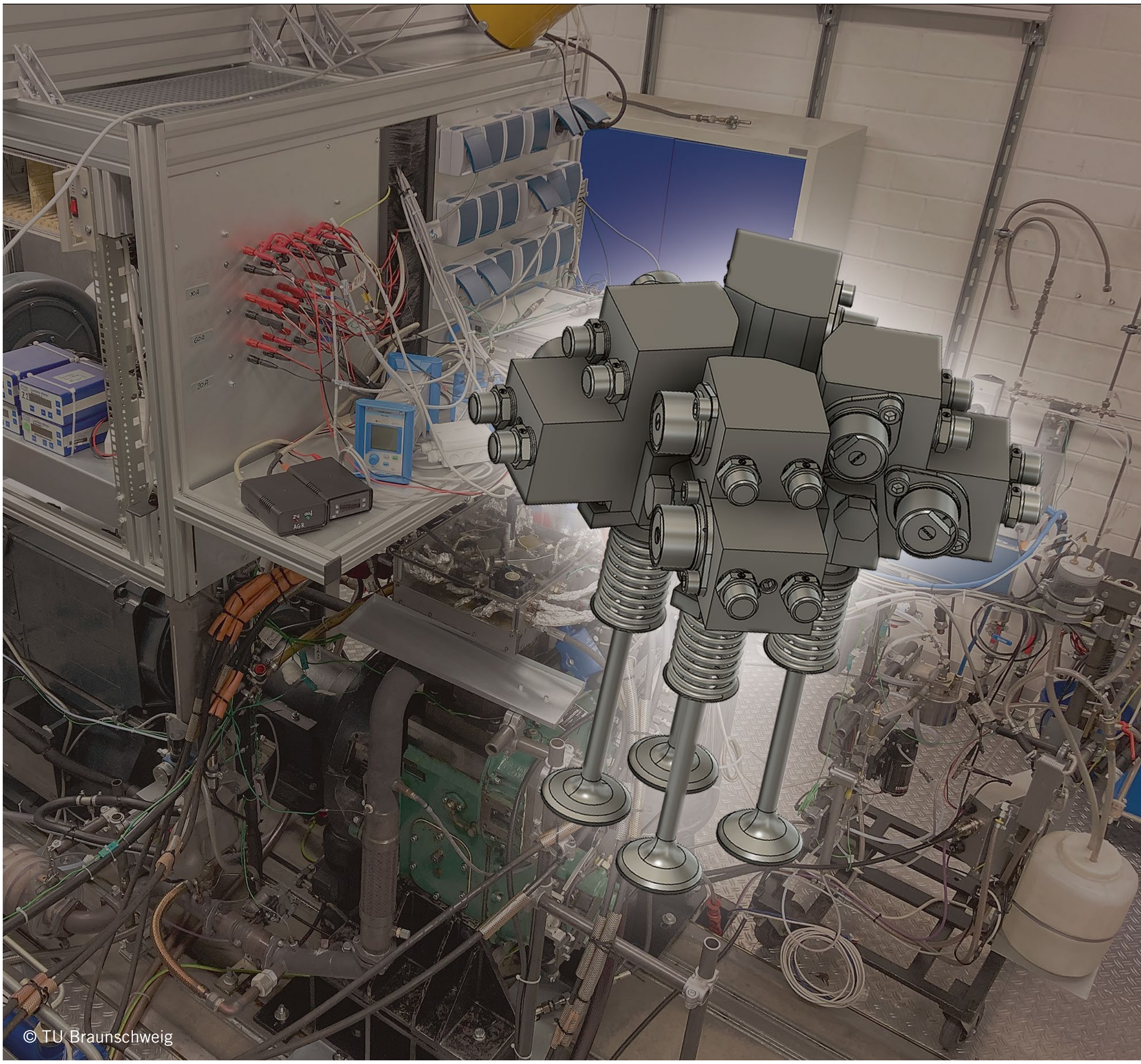
Potentials of Air Path Variabilities for Future Commercial Vehicle Gas Engines to Increase Efficiency and Reduce Emissions

Diesel engines still dominate the market for commercial vehicles. Due to its reduced carbon/hydrogen ratio, natural gas offers high potential for lowering global CO_2 emissions. There are some disadvantages with the stoichiometric combustion process, which can be countered with a suitable technology mix. In the FVV research project (No. 1346), an evaluation of the technology combinations EGR, Miller combustion process and water injection was carried out on a commercial vehicle engine at the TU Braunschweig.

WRITTEN BY

Marius Betz, M. Sc.
was Research Associate at the Institute for Internal Combustion Engines and Fuel Cells (ivb) at TU Braunschweig (Germany).

Prof. Dr.-Ing. Peter Eilts
is Head of the Institute for Internal Combustion Engines and Fuel Cells (ivb) at TU Braunschweig (Germany).



© TU Braunschweig

1 MOTIVATION

Stoichiometric natural gas combustion with exhaust gas aftertreatment by means of a three-way catalyst offers high potential for the targeted reduction of CO_2 emissions. On the one hand, the lower carbon/hydrogen (C/H) ratio means that less CO_2 is emitted compared to conventional fuel. On the other hand, the currently strictest NO_x legislation can be complied with it. However, this combustion process offers disadvantages, such as knock limitation and throttling losses. Well-known countermeasures include the following key technologies in particular:
– Exhaust Gas Recirculation (EGR)
– Miller valve timing (Early Intake Valve Closure, EIVC)
– Water Injection (WI).
By reducing the tendency to knock, the combustion can be advanced, and the compression ratio can be further increased in addition to the early adjustment of combustion. This contributes to a further increase in efficiency and thus enlarges the CO_2 emission reduction potential. The extended combustion durations can be reduced by potent ignition systems or improved charge motion. The resulting boost pressure requirement must be provided by a suitable turbocharging system.

2 AIM AND METHODOLOGY

The aim of the project was to evaluate the forementioned package of measures. A single-cylinder commercial vehicle diesel engine with variable valve train [1, 2] was converted into a stoichiometric commercial vehicle gas engine and equipped with High-pressure (HP) EGR, WI and a turbulence-generating piston, **TABLE 1**. At the beginning of the investigations, important operating points of a commercial vehicle engine were identified. In order to minimize the test matrix, preliminary investigations on swirl influence and different spark plugs took place. In the main tests, EGR rates, Intake Valve Closing (IVC), WI injection rate and compression ratio were varied. The tests were carried out both in isolation and in combination to work out effects and possible cross-influences.

Subsequently, the measured data were analyzed by a pressure analysis. By means of loss analysis, the thermodynamic advantages and disadvantages could be quantified. The results of the pressure analysis were also used to calibrate and validate a predictive combustion model (SI Turb) and a knock model according to Urban [3]. This allowed the combustion of the single-cylinder engine to be simulatively transferred to a full engine. MAN Truck & Bus provided a full-engine model of the MAN E18 with an in-series Turbocharging Group (TCG) for this purpose, **TABLE 1**. The procedure is shown in **FIGURE 1** and the validation of the combustion model in **FIGURE 2**.

Experimental single-cylinder engine		**Unit**
Basic engine	AVL FM520	
Configuration	MAN D20	
Number of cylinders	1	-
Bore	120	mm
Stroke	140	mm
Piston displacement/cylinder	1583	cm³
Geometric compression ratio	12.2; 13.2 ;14.2	-
Full engine		**Unit**
Configuration	MAN E18	
Number of cylinders	6	-
Bore	118	mm
Stroke	145	mm
Piston displacement/cylinder	1586	cm³
Geometric compression ratio	13	-

TABLE 1 Technical details of the investigated single-cylinder engine and the full engine [4] (© TU Braunschweig)

3 EXPERIMENTAL RESULTS

The experimental results – described in more detail in [5, 6] – reflect the findings in literature. It was found that a prechamber spark plug leads to preignition and is more suitable for low-load applications. It was also found that high swirl and intense squish flow leads to higher wall heat losses. Both EGR and variable valve

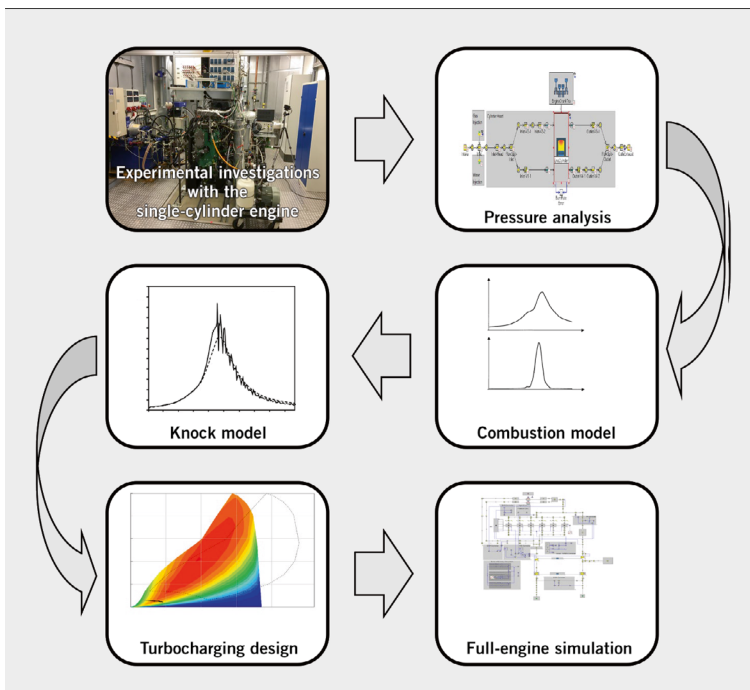


FIGURE 1 Schematical illustration of the methodology within the implemented project (© TU Braunschweig)

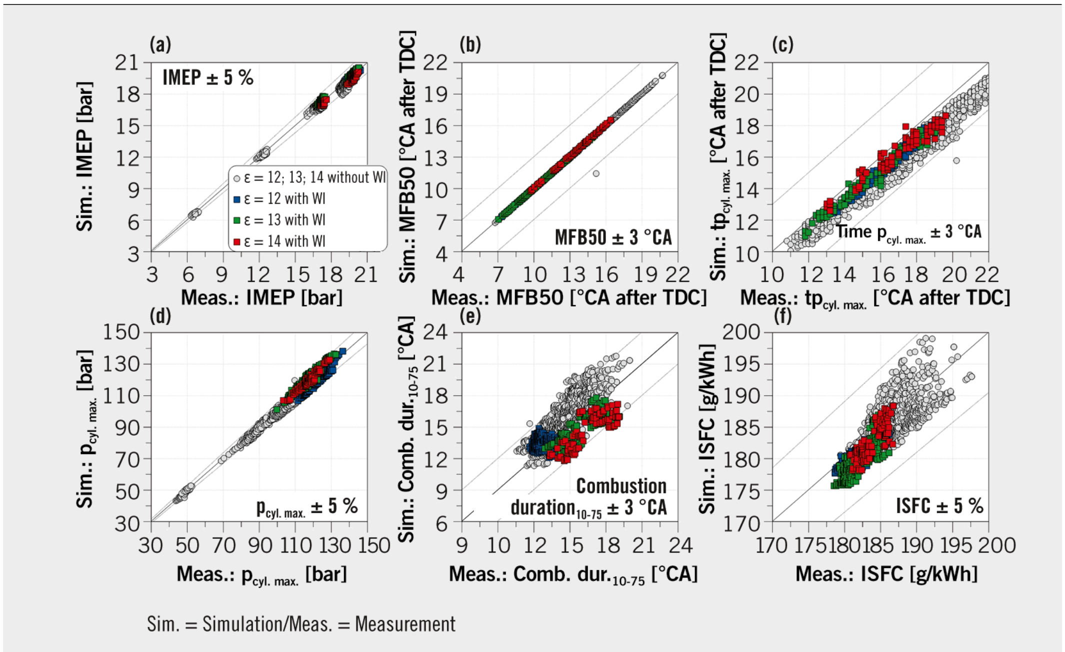


FIGURE 2 Validation of the predictive combustion model by measurement and simulation: (a) IMEP; (b) MFB50; (c) crank angle at maximum cylinder pressure ($tp_{cyl. max.}$); (d) maximum cylinder pressure ($p_{cyl. max.}$); (e) combustion duration from MFB10 to MFB75 (Comb. dur.$_{10-75}$); (f) Indicated Specific Fuel Consumption (ISFC) (© TU Braunschweig)

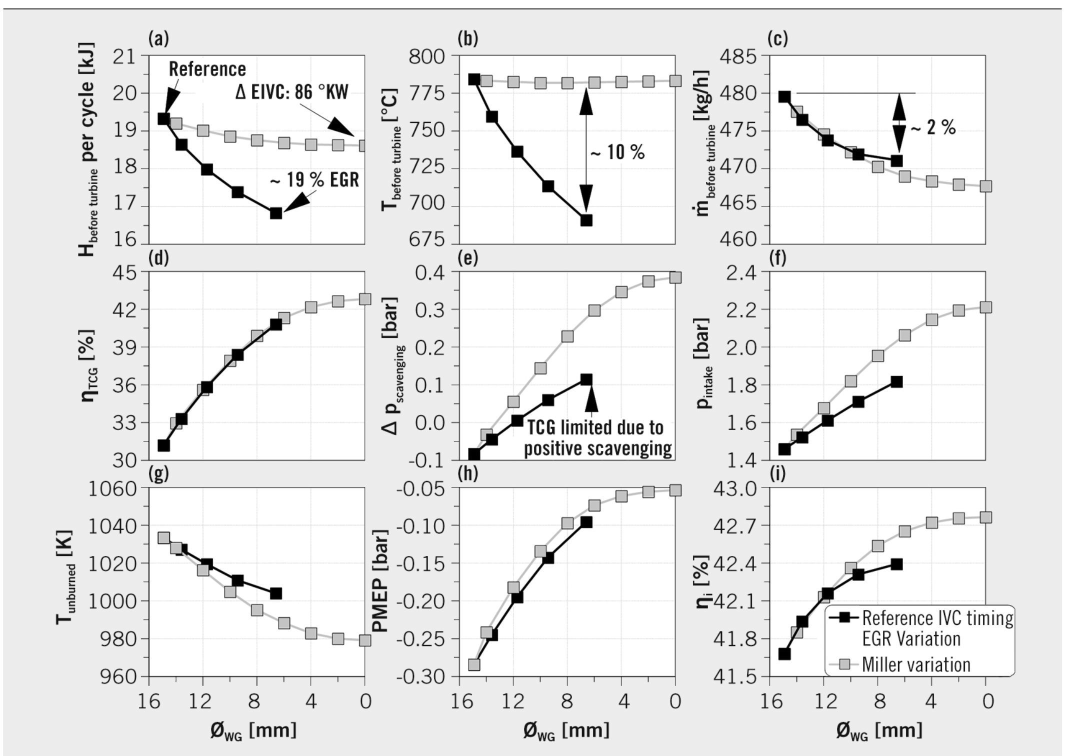


FIGURE 3 Simulative variation of the external HP EGR (reference valve timing) and Miller valve timing (EIVC) with standard turbocharging at 1200 rpm; IMEP = 16 bar; ε = 13; λ = 1; (a) enthalpy (H), EIVC and EGR variation; (b) temperature before turbine ($T_{before turbine}$); (c) mass flow before turbine ($\dot{m}_{before turbine}$); (d) total turbocharging efficiency (η_{TCG}); (e) scavenging pressure drop (Δ $p_{scavenging}$); (f) intake manifold pressure (p_{intake}); (g) temperature unburned zone ($T_{unburned}$); (h) charge exchange work (Pumping Mean Effective Pressure, PMEP); (i) indicated efficiency (η_i) (© TU Braunschweig)

timing are necessary to achieve complete de-throttling in the frequented highway point (with Indicated Mean Effective Pressure IMEP ~6 bar). EGR has a slight advantage here in terms of efficiency due to its improved fluid properties and lower wall heat losses but has higher hydrocarbon emissions. Miller valve timing instead hasn't got a great influence on the exhaust gas temperature and emissions and is therefore presumably of interest with regard to future legislation, especially for cold starts.

In the upper load range, both EGR, the Miller cycle and WI improved the combustion positions. This enabled an increase in the compression ratio. Here, the WI was shown to have the greatest influence on the combustion phasing but the lowest additional boost pressure requirements. The Miller cycle also shows an advantage in shifting the knock limit compared to EGR. This can be attributed to lower unburned temperatures. EGR shows improved fluid properties, lower wall heat losses, and lower NO_x emissions.

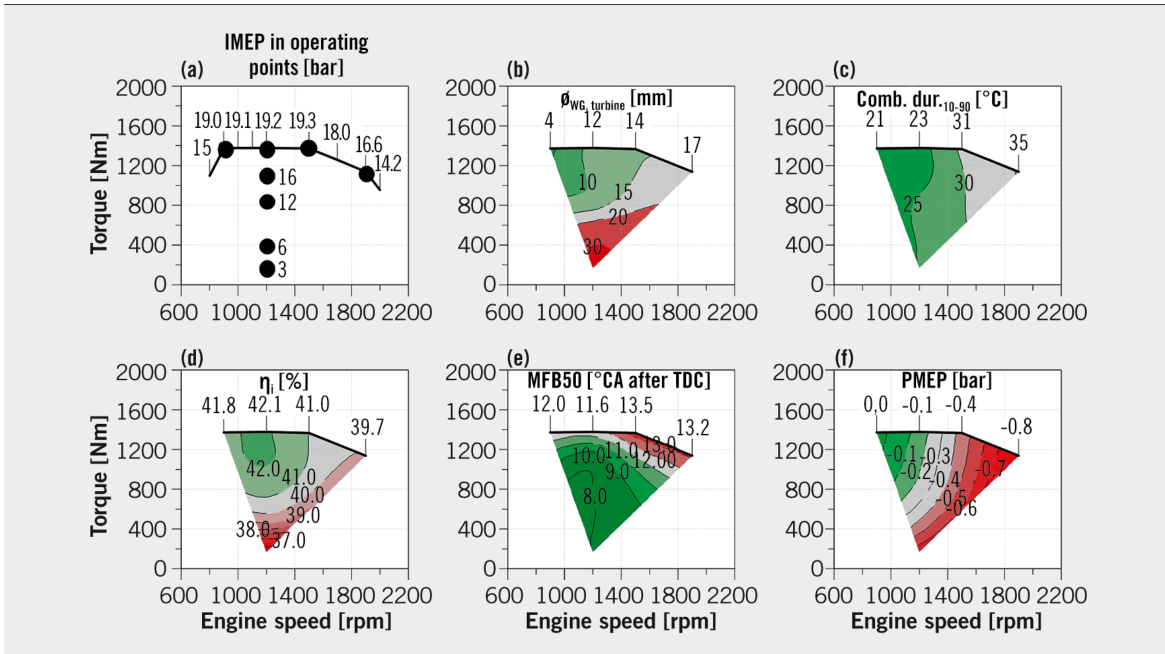


FIGURE 4 Simulative results of the base configuration (ε = 13) with reference IVC timing at 550 °CA after TDC and standard turbocharging: (a) IMEP in the operating points; (b) WG diameter; (c) combustion duration from MFB10 to MFB90 (Comb. dur.$_{10\text{-}90}$); (d) indicated efficiency (η_i); (e) MFB50; (f) charge exchange work (PMEP) (© TU Braunschweig)

4 INFLUENCE OF MILLER AND EGR

The influence of EGR and Miller valve timing on the TCG was also investigated simulatively on the full engine configuration. The boost pressure must be increased in each case. This is done by closing the Wastegate (WG), which is used for load control in the basic configuration. It can be seen that the exhaust enthalpy at the turbine decreases with increasing EGR rate due to the decreasing exhaust gas temperature, **FIGURE 3** (a). Accordingly, less enthalpy is available for boost pressure buildup compared to the Miller cycle.

By closing the WG, the turbine efficiency and thus the overall efficiency of the turbocharging increases, **FIGURE 3** (d). This results in lower exhaust backpressure, which in turn leads to reduced charge exchange losses. The scavenging pressure drop thus becomes positive in large parts of the engine map with closing the WG, so that external High Pressure (HP) EGR is no longer possible, **FIGURE 3** (e). This is the case at 19 % EGR or 6 mm WG opening. In the case of Miller valve timing, on the other hand, the WG can be completely closed. Compared to EGR, this leads to a higher positive scavenging drop, **FIGURE 3** (e), and thus to lower charge exchange losses, but also to lower temperatures in the unburned mass, **FIGURE 3** (g). This, in turn, can have a positive effect on the knocking tendency. It is therefore advantageous to transfer the load control from the WG to the inlet valve closing.

5 OPTIMIZED APPLICATION

The basic configuration, **FIGURE 4**, was optimized in terms of EGR, Miller valve timing and compression ratio. For standard turbocharging, the compression ratio could be increased by two units to 15 by reducing the knock tendency with the aid of the Miller process. Here it was found that there is a limit in the low-end torque (LET) because there are not enough boost pressure reserves available for the Miller process. The result is a retarded combustion, so that the only option here is to use a WI (which is not shown here).

Based on the in-series TCG, a two-stage charging system was designed using a Low-pressure (LP) EGR and similarity principles according to Beineke [7]. The HP and LP stages were reduced and increased by 14 %, respectively, compared to the original. In particular, the smaller HP stage made it possible to achieve an early adjustment in Miller valve timing of > 81 °CA, which removed the limitation of the Miller combustion process in the LET, **FIGURE 5** (a). The geometric compression ratio could thus be increased to 15.6. In the entire engine map range, optimum combustion positions of 8 °CA after TDC were achieved with conventional natural gas (methane number ~ 81.5), **FIGURE 5** (e). The charge exchange losses could be reduced compared to the baseline configuration by increasing the TCG efficiency, **FIGURE 5** (f).

By increasing the compression ratio and advancing the combustion positions, a non-critical exhaust gas temperature for the turbine is achieved in the high-end torque even without EGR, **FIGURE 5** (i). Particularly at high engine speeds, the EGR rate could thus be reduced at an optimum MFB50. Compared to the baseline configuration, this has a positive influence on the combustion durations and thus on the efficiency, **FIGURE 5** (c and d). The distribution of HP EGR and LP EGR is noticeable, **FIGURE 5** (g and h). In the upper engine map the cooler LP-EGR improves the TCG efficiency by shifting the operating point in the compressor map, which has a positive effect on the fluid properties and wall heat losses. The hotter HP EGR in the lower map range contributes to thermal throttling. Efficiency can thus be increased by up to 4.8 percentage points compared to the basic configuration. This corresponds to a relative improvement of 12 %. However, in the frequented highway point, an improvement of almost 7 % was also observed.

6 SUMMARY

Through the results collected, it could be shown that the application of EGR, Miller valve timing and WI in combination is possible,

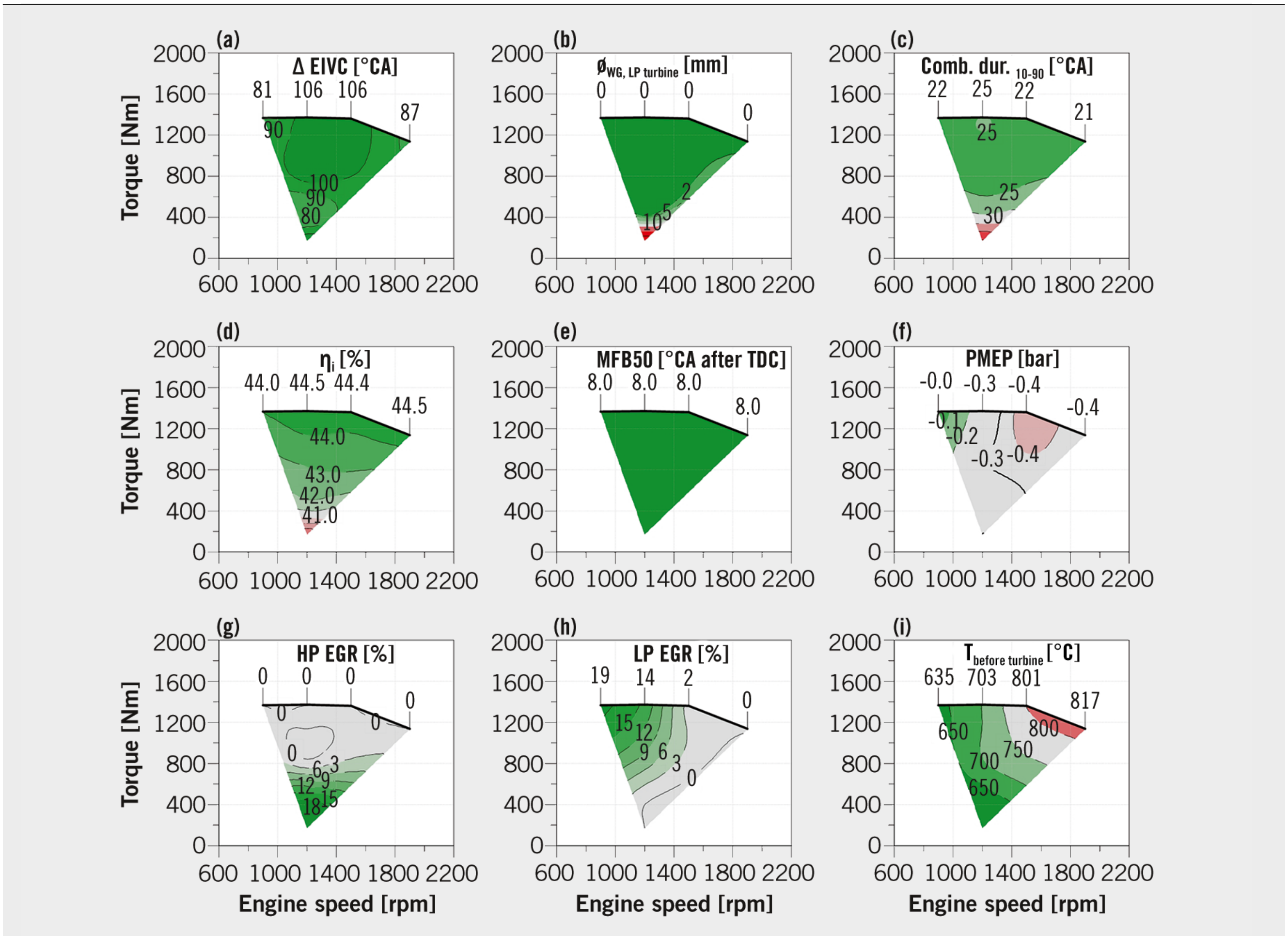


FIGURE 5 Simulative results of the optimized configuration (ε = 15.6) with Miller valve timing, HP and LP EGR and dual-stage turbocharging: (a) adjustment of EIVC (compared to reference); (b) opening of WG of LP turbine; (c) combustion duration from MFB10 to MFB90 (Comb. dur.$_{10\text{-}90}$); (d) indicated efficiency (η_i); (e) MFB50; (f) charge exchange work (PMEP); (g) HP EGR; (h) LP EGR; (i) temperature before turbine (© TU Braunschweig)

and thus the efficiency of stoichiometrically operated commercial vehicle gas engines can be significantly increased. Even single-stage turbocharging offers good potential for increasing efficiency with Miller valve timing. This can be further increased with regulated two-stage turbocharging. It has been shown that, depending on the engine map range, the technologies partly complement each other. A combination of measures is therefore quite necessary. A variable and a fast as possible valve train can help to work out the operating point-dependent compromises of fluid properties, wall heat losses, combustion positions and charge exchange losses.

REFERENCES

[1] Eilts, P. (ed.): Berichte aus dem ivb. Vol. 5. Gehrke, S.: Beitrag zum gaspfadseitigen Abgasmanagement an Nutzfahrzeugmotoren. Braunschweig, Technical University, dissertation, Düren: Shaker Verlag, 2015

[2] Kovács, D.; Eilts, P.: Potentials of the Miller Cycle on HD Diesel Engines Regarding Performance Increase and Reduction of Emissions. SAE Technical Paper no. 2015-24-2440, 2015

[3] Urban, L.; Grill, M.; Hann, S.; Bargende, M.: Simulation of Autoignition, Knock and Combustion for Methane-Based Fuels. SAE Technical Paper no. 2017-01-2186, 2017

[4] Steinert, R.; Köllner, O.; Weidner, M.; Karg, J.; Schallenberg, M.: The New Man Euro VI Gas Engine For City Buses. 13th Conference Gas Vehicles FKFS, Stuttgart, 2019

[5] Betz, M.; Höweling, N.; Kühne, U.; Eilts, P.: Effects of EGR, Variable Valve Timing, High Turbulence and Water Injection on Efficiency and Emissions of a HD Stoichiometric Natural Gas Engine. SAE Technical Paper no. 2021-24-0048, 2021

[6] Betz, M.; Eilts, P.: Potenziale von Luftpfadvariabilitäten am Nfz-Gas-Motor. Final report no. 1306, FVV e. V., Frankfurt am Main, 2022

[7] Beineke, E.: Rechnerische Untersuchung der ein- und zweistufigen Abgasturboaufladung mittelschnellaufender Viertaktdieselotoren. Braunschweig, Technical University, dissertation, 1975

THANKS

The research project (FVV project no. 1346) was carried out at the Institute of Internal Combustion Engines (ivb) of the Technical University of Braunschweig under the direction of Prof. Dr.-Ing. Peter Eilts. It was funded by the FVV e. V. and supported by a working group led by Dipl.-Ing. Dirk Weberskirch (MAN Truck & Bus). The authors would like to thank the FVV and all parties involved in the project for the received support. Further thanks go to MAN Truck & Bus for providing the simulation model and the cylinder heads. Mahle, Motortech and IAV also deserve a great thanks for providing test bench hardware and software (pistons, ignition system, knocking algorithm).