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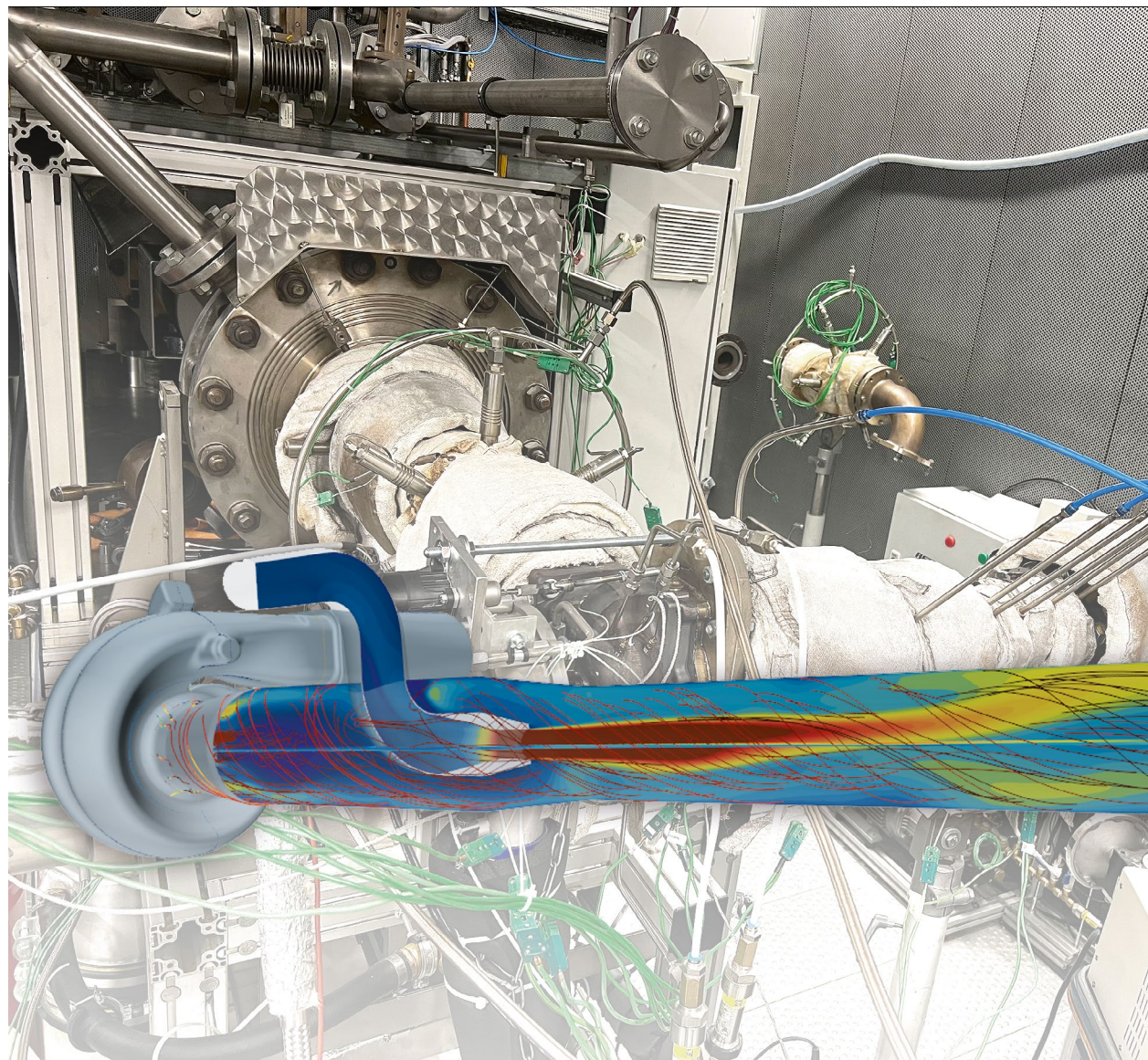
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Potential Analysis of Exhaust Gas Turbochargers with Ejector Bypass

The development of efficiency-optimized combustion engines is accompanied by increasing requirements on the turbocharging system. One potential technological component in this context is an exhaust gas turbocharger with an ejector-based bypass. This configuration can offer a robust and cost-effective substitute for variable turbine geometry while providing efficiency advantages compared to conventional wastegate turbochargers. As part of an FVV research project (no. 1450), experimental and simulation-based investigations of ejector technology as an alternative bypass strategy were conducted collaboratively by RWTH Aachen University and the Technische Universität Berlin.



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1 MOTIVATION

In conventional exhaust gas turbochargers (TCs) with wastegate, the exhaust gas energy contained in the bypass mass flow remains unused. In contrast, the ejector bypass TC concept, illustrated in **FIGURE 1**, employs a convergent nozzle to accelerate the bypass flow. The resulting low-pressure region downstream of the nozzle outlet induces a suction effect on the exhaust flow downstream of the turbine wheel. This leads to a reduction in pressure at this position, which subsequently lowers the pressure upstream of the turbine. When integrated into an Internal Combustion Engine (ICE) system, this effect directly reduces gas exchange work (PMEP), with additional efficiency gains possible through secondary effects depending on the combustion process.

The Chair of Energy Conversion Systems (TME) at RWTH Aachen University carried out comprehensive investigations using 3-D simulations (Computational Fluid Dynamics, CFD) to analyze

the internal flow processes of the ejector and to determine key design parameters. The models were validated using measurement data from the hot gas test bench. Based on these findings, a potential analysis for various vehicle applications was carried out at the Chair of Powertrain Technologies (FZA) of the Technische Universität Berlin. For this purpose, a predictive 0-D ejector model was developed that can be used in the GT-Power simulation environment and coupled with various engine models.

2 FUNDAMENTAL INVESTIGATION

For the ejector design, different nozzle geometries were initially compared to each other (convergent versus convergent/divergent according to Laval; central versus annular gap). A convergent, centralized nozzle was used for the investigations. As part of the project, a method was developed that can be utilized to optimize the ejector design by applying a newly defined ejector efficiency metric. The ejector efficiency is characterized as the quotient of the power terms of the isentropic compression of the turbine mass flow and the isentropic expansion of the bypass mass flow. The key figure thus describes the quality of the momentum exchange. The number of optimization parameters should be kept as low as possible. Six design parameters were derived that reflect the geometric relationships of the ejector system. This enabled promising designs to be defined on the basis of around 8000 simulations. Two nozzles were manufactured, each with a diameter D_{pri} and mixing pipes with different lengths L_{mix} and diameters D_{mix} . These were tested on the hot gas test bench with and without a TC. The concept is shown in **FIGURE 2**. The pressure reduction down-

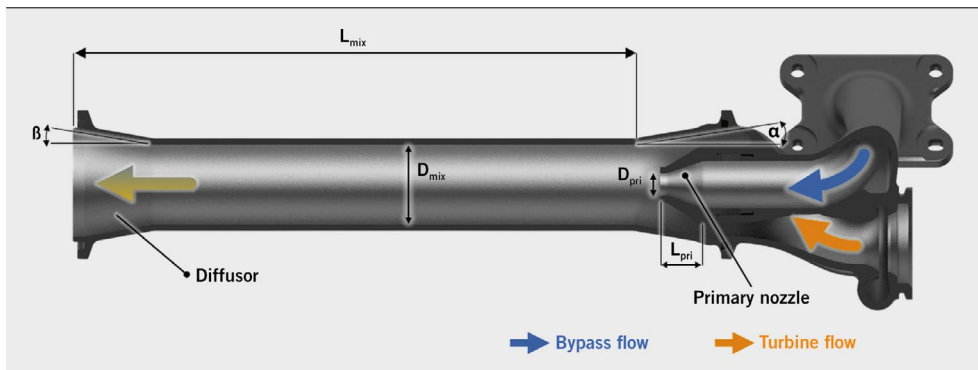


FIGURE 1 Setup of an ejector bypass TC (© TME | FZA)

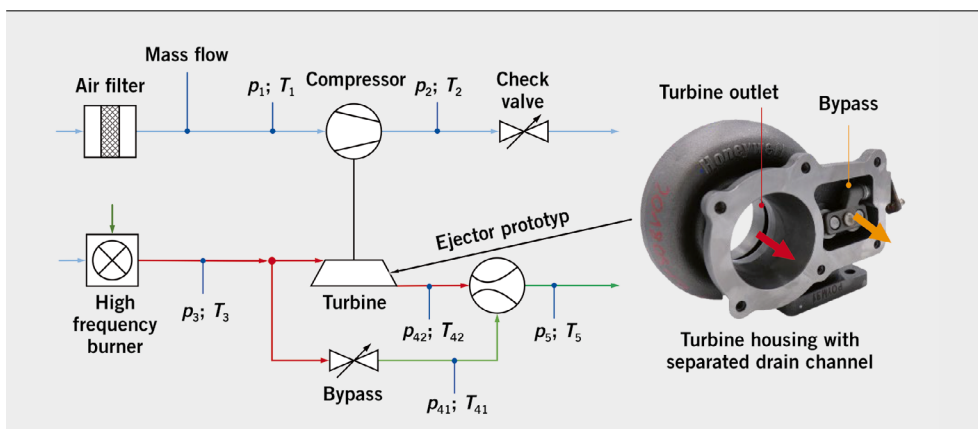


FIGURE 2 Concept of the test setup with TC and measuring points for pressure levels p_n and temperatures T_n (© TME | FZA)

stream of the turbine was analyzed to evaluate the performance of the ejector. It was found that the pressure drop increases with reducing nozzle diameter due to the stronger acceleration of the bypass mass flow. Under the given boundary conditions, however, no influence of the mixing tube length ($L_{mix} = 150$ to 300 mm) could be demonstrated. Furthermore, the pressure reduction achieved increases with an increase in the bypass rate.

Further CFD investigations showed that the intensity of the swirl caused by the turbine has also an impact on the ejector effect. **FIGURE 3** displays the percentage pressure reduction downstream of the turbine (relative to a bypass rate of 0 %) as a function of the total mass flow \dot{m}_{total} . As the swirl increases, the momentum exchange between the turbine and bypass flow increases, which has a positive influence on the ejector effect. This can be seen from the total mass flow of $\dot{m}_{total} = 0.258$ kg/s (red triangle). Here, both the turbine mass flow and the bypass rate are constant indicating turbine speed is the only variable. If the TC speed is increased from $n = 75,200$ to $100,200$ rpm at this operating point, the ejector effect increases from 4.9 to 11.3 %. This means that a higher turbine speed correlates with a higher pressure drop, which can be attributed to better mixing. Furthermore, \dot{m}_{total} has no significant influence on the ejector effect. Only the bypass rate (ratio of bypass mass flow to turbine mass flow) has an influence. This effect was also evident from the experimental results.

3 PREDICTIVE MODELING OF EJECTORS IN GT-POWER

A predictive mathematical model was developed to capture the performance of the ejector bypass TC. It was implemented in a Python function and was therefore able to be coupled with the GT-Power simulation environment. The data for the model derivation was generated by 3-D CFD simulations. With the help of statistical Design of Experiments (DoE), a simulation plan was first drawn up that considers the relevant boundary conditions to which

the ejector is subjected in conjunction with the engine and the TC. The simulation plan also includes the geometric parameters shown in **FIGURE 1**, which need to be variable for design optimization in GT-Power. The simulation model, developed at FZA, was previously successfully validated with the measurement data from TME. Based on the results of this simulation campaign, the model was derived using Gaussian process regression. To ensure applicability across various vehicle applications, the model inputs were defined in a manner that enables the geometry scaling in GT-Power. The model provides the pressure downstream of the turbine as an output variable. In the simulation environment, a pump is used to control the predicted outlet pressure. The modeling of the ejector bypass TC is based on the assumption of a variable primary nozzle whose outlet cross-section can be adjusted depending on the boost pressure demand.

4 POTENTIAL ANALYSIS FOR VARIOUS VEHICLE APPLICATIONS

A GT-Power model of a 4-cylinder engine with a rated power of 110 kW and 1.4 l displacement was employed to investigate the application potential of ejector bypass technology for passenger car engines. In this study, the conventional single-stage wastegate TC was replaced by the ejector bypass TC model. Initial efforts focused on optimizing the ejector geometry at an operating point near rated power, where the highest bypass rates and thus the greatest potential for optimization are expected. To manage the spatial constraints and mitigate negative effects on exhaust gas aftertreatment associated with increased heat losses at low loads, the length of the ejector mixing section was limited to 200 mm. The optimized geometry was then used to conduct a full engine map analysis.

FIGURE 4 presents differential engine maps comparing the ejector bypass TC system with the baseline wastegate TC design. The effective efficiency map ($\eta_{effective}$), **FIGURE 4** (left), reveals a general

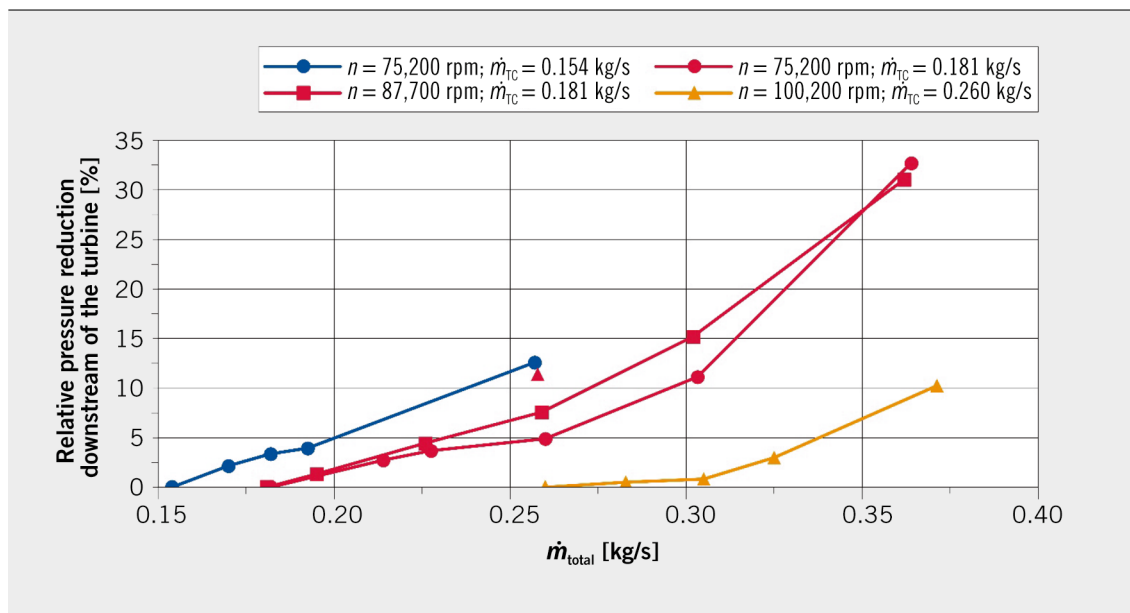


FIGURE 3 Relative pressure reduction downstream of the turbine as a function of \dot{m}_{total} for different speeds and bypass rates of different turbine mass flows (\dot{m}_{TC}) (© TME | FZA)

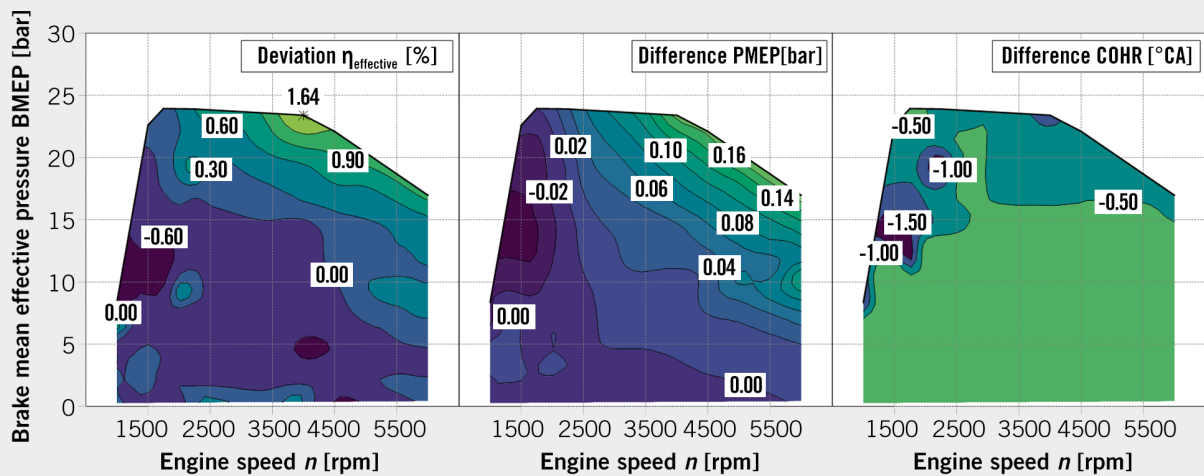


FIGURE 4 Differential maps (ejector design - wastegate design) of the passenger car gasoline engine with ejector bypass TC (© TME | FZA)

trend of increasing efficiency with rising engine power, driven by the enhanced ejector effect at higher exhaust gas mass flows and bypass rates. A maximum map-wide efficiency improvement of 1.64 % was observed. This improvement is primarily attributed to the reduction in P_{MEP}, FIGURE 4 (center), resulting from decreased exhaust pressure upstream of the turbine. As expected, no significant efficiency gains were noted in the low-end torque range and naturally aspirated regions of the map, where no bypass flow or boost pressure demand are present. The reduction in exhaust backpressure also leads to a decrease in residual gas content, thereby reducing the required boost pressure. This allows combustion to occur without irregular combustion phenomena at ear-

lier Center Of Heat Release (COHR), that means, approximately 1 °CA earlier in the range of rated power, FIGURE 4 (right).

These effects support the suitability of ejector technology for pairing with smaller turbines to enhance transient response. The corresponding increase in exhaust backpressure associated with reduced turbine size can be partially offset by the ejector effect. To illustrate this potential, the turbine inlet diameter in the model was reduced by 1 mm. The resulting decrease in rotor assembly mass moment of inertia was estimated using a simplified CAD model. The impact of this configuration in comparison to the wastegate TC is shown in FIGURE 5. The maximum efficiency benefit of the ejector design after turbine scaling reached 0.8 %,

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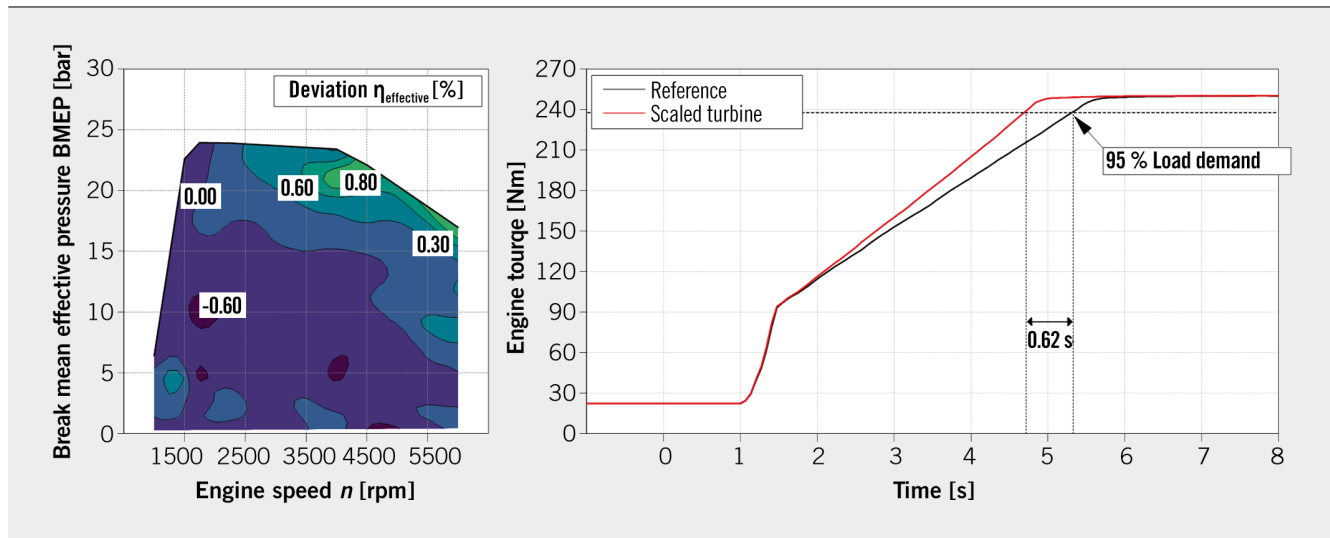


FIGURE 5 Differential map (ejector design - wastegate design) of the passenger car gasoline engine with ejector bypass TC and scaled turbine (left); engine response at a load step from BMEP = 2 bar to 22.5 bar at $n = 1750$ rpm (right) (© TME | FZA)

FIGURE 5 (left), while the rest of the engine map exhibited no significant efficiency penalties. At the same time, the dynamic performance during the load step shown in **FIGURE 5** (right) improved significantly, with the time to reach 95 % of target torque reduced by 0.62 s.

However, further analysis revealed that implementing the ejector bypass TC without accompanying compensatory measures (insulation of the exhaust pipes, modification of the engine application) can result in substantial drawbacks regarding thermal management for exhaust gas aftertreatment. The additional exhaust gas components increase the heat transfer to the environment and the thermal inertia of the system.

In addition to the gasoline application, the ejector bypass TC concept was evaluated on a 12-l, 400 kW commercial vehicle diesel engine. Owing to the diesel combustion process and the typically lean operating conditions, the benefits of the ejector system in this context were largely limited to reductions in gas exchange work. Due to consistently low bypass ratios across most of the engine map, efficiency improvements were confined to a narrow operating range near rated power. In this configuration, a maximum efficiency gain of 0.6 % was achieved.

5 SUMMARY AND OUTLOOK

As part of the fundamental investigations, it was shown that the nozzle cross-section and the bypass rate have the greatest influence on the pressure reduction downstream of the turbine. The method for optimizing the design of an ejector system was based on a newly defined ejector efficiency as the target value. A validated CFD model was used to analyze the influence of the TC on the flow field and the influence of the flow field on the ejector effect. The swirl causes a significant improvement in the momentum exchange between the turbine and nozzle flow, which can increase the ejector effect.

As part of the evaluation of ejector technology for engine applications, a predictive model was developed to enable geometric optimization and facilitate transferability across various vehicle

applications. Simulation-based analyses demonstrated that an appropriately applied ejector bypass TC system can reduce gas exchange work and residual gas content in the rated power range, thereby enhancing combustion engine efficiency. The optimization potential was found to be greater for the investigated passenger car gasoline engine compared to the commercial vehicle diesel engine, primarily due to differences in combustion processes.

However, the implementation of the ejector bypass TC system entails increased spatial requirements and a reduction in available exhaust gas energy prior to the exhaust aftertreatment system. A potential focus for subsequent research could be the conceptual development of an actuator for a variable primary nozzle, with particular emphasis on meeting the high demands for robustness and sealing capacity. Building on this, a comprehensive functional and economic comparison with variable turbine geometry turbocharging systems could be conducted.

THANKS

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