WRITTEN BY

Theodoros Kossioris, M. Sc.
is Research Assistant at the Chair of Thermodynamics of Mobile Energy Conversion Systems (tme) of the RWTH Aachen University (Germany).

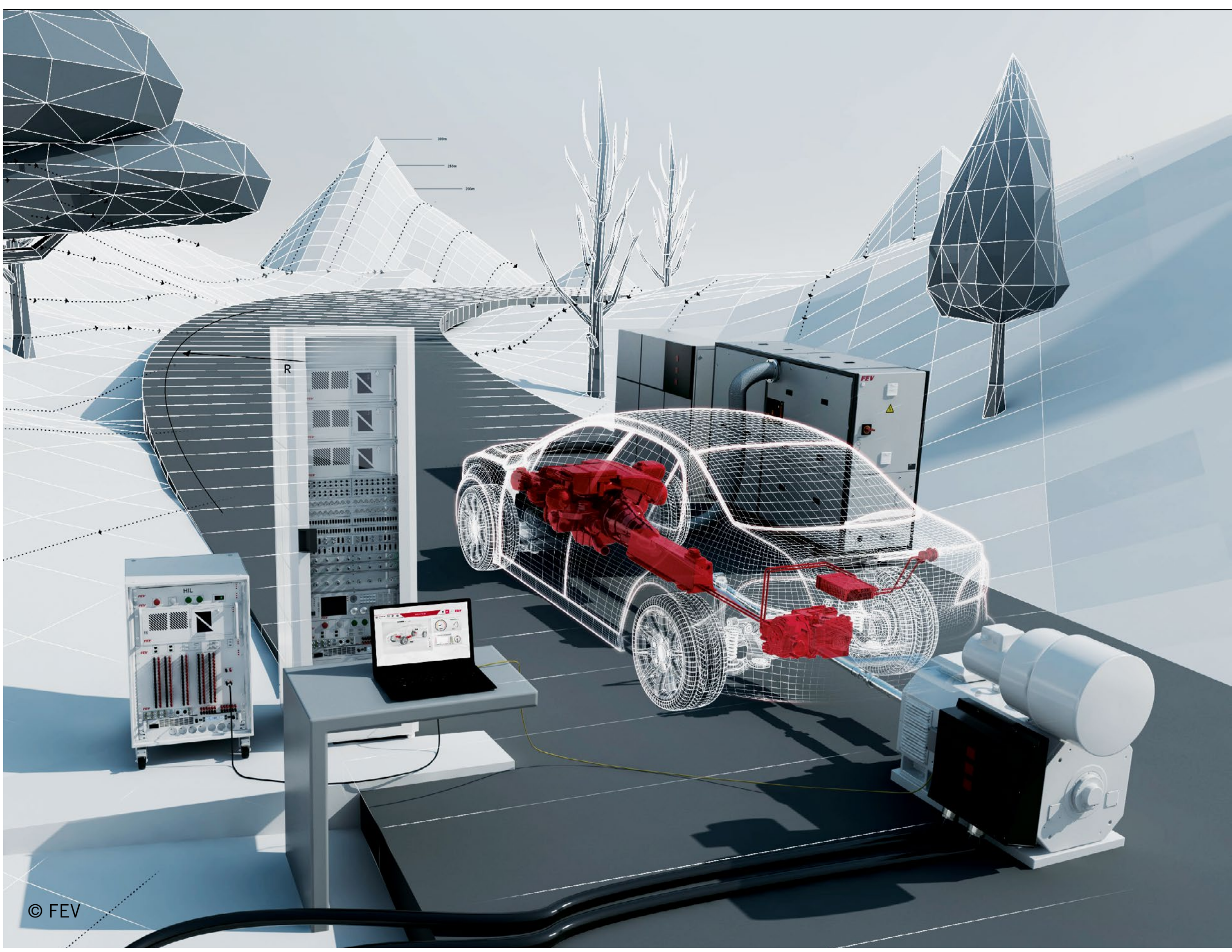
Robert Maurer, M. Sc.
was Research Assistant at the Chair of Thermodynamics of Mobile Energy Conversion Systems (tme) of the RWTH Aachen University and currently works as Project Manager at FEV Europe GmbH in Aachen (Germany).

Dr.-Ing. Stefan Sterlepper
is Chief Engineer at the Chair of Thermodynamics of Mobile Energy Conversion Systems (tme) of the RWTH Aachen University (Germany).

Prof. Dr.-Ing. Stefan Pischinger
is Head of the Chair of Thermodynamics of Mobile Energy Conversion Systems (tme) of the RWTH Aachen University (Germany).

Zero-Impact Emissions for All Traffic Scenarios Through Optimization of Exhaust Aftertreatment Systems

In the FVV project (no. 1412) "Zero-Impact Tailpipe Emission Powertrains", two reference vehicles with current exhaust gas aftertreatment systems were examined under demanding operating conditions at the RWTH Aachen University. It is shown that both vehicles no longer have a significant impact on air quality in most scenarios and that they fulfill the criterion of Zero-Impact Emissions. By integrating additional heating measures and increasing catalytic converter volumes, this can also be achieved in other critical scenarios.



© FEV

1 MOTIVATION

The FVV research project, which was carried out at the Chair of Thermodynamics of Mobile Energy Conversion Systems at the RWTH Aachen University, is based on the new Zero-Impact Tailpipe Emission (ZITE) approach, with which the permissible pollutant concentration in the tailpipe is deduced from the air quality. This makes it possible to observe a vehicle fleet with Internal Combustion Engines (ICEs) in real-life scenarios and thus to assess the actual environmental impact. For this purpose, a passenger car and a light commercial vehicle were forcasted for the year 2030 and the term ZITE was quantified. Nitrogen Oxide (NO_x) emissions were examined for both vehicles under various conditions in order to derive measures to comply with ZITE if necessary.

2 DESIGN LIMITATIONS

Zero-Impact Emissions (ZIE) comprise that the exhaust emissions of a vehicle fleet do not significantly affect the ambient air quality [1, 2]. In a study by Hausberger et al [2], the "zero-impact air quality contribution" was defined in such a way that the contribution of road traffic is lower than a defined "irrelevance threshold", which is 3 % of the limit value [3] for the average annual pollutant concentration in the European Union (EU) [4]. This limit value is derived from the air quality standards set by the World Health Organization (WHO) in 2006 [5]. The established legal framework enables the assessment of emissions from the transport sector in comparison to other sectors. The irrelevance threshold of 3 % described in this context originates from the Federal Immission Control Act (BImSchG 5, paragraph 1, no. 1) of the German ordinances. These guidelines specifically concern the operators of industrial plants subject to licensing.

For design limitations, particulate emissions from brake and tire abrasion must be taken into account. For particulate emissions at the tailpipe, a holistic approach using the latest filter technologies is required. In this project, the focus is on NO_X tailpipe emissions since these are evidently only caused by the engine and the exhaust gas aftertreatment system. The investigations were supported by analyses of simulation results. Data from the air quality measuring station Stuttgart am Neckator was used to calculate transfer factors between ambient air and tailpipe.

A vehicle fleet was assumed which includes passenger cars, light and heavy commercial vehicles. In order to achieve the ZITE standards at local fleet level, each individual vehicle should be limited in terms of emissions, with commercial vehicles given higher limits than passenger cars. The derived emission factors were extrapolated to include six further scenarios. This also requires the consideration of local parameters such as traffic patterns and air dispersion characteristics [1]. For this purpose, a comprehensive test matrix was developed with a total of seven different scenarios, each characterized by unique boundary conditions [6], **FIGURE 1**.

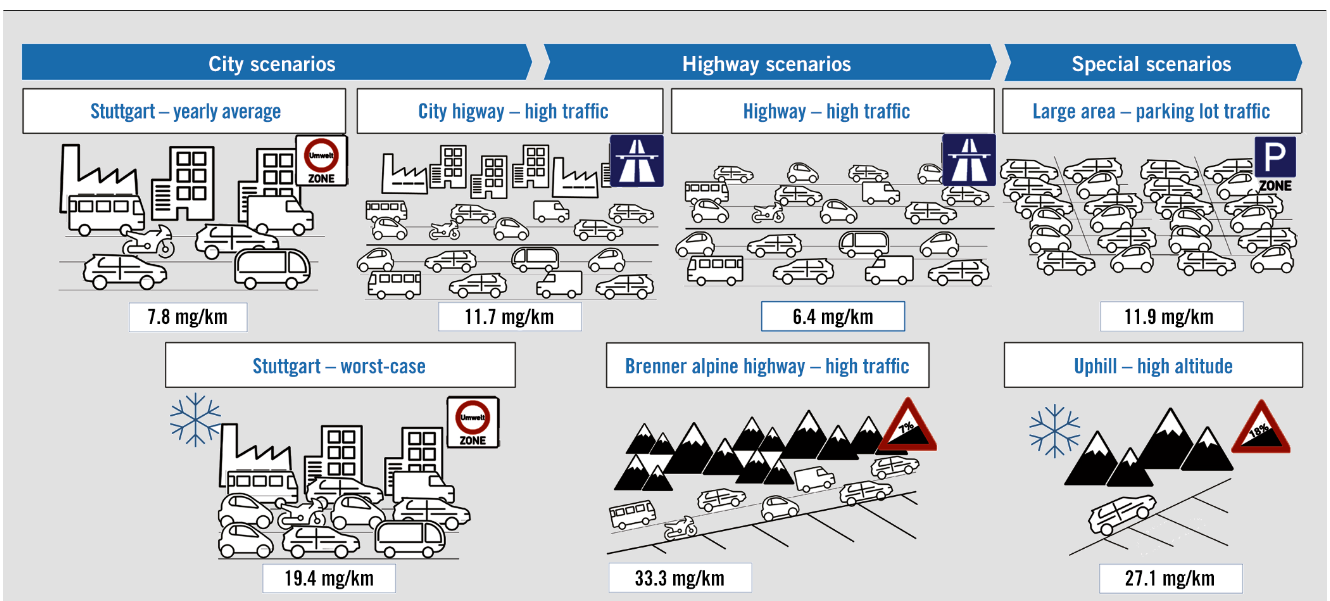


FIGURE 1 Real-world scenarios for testing ZIE compliance of vehicles (© tme)

3 REFERENCE VEHICLE

Proceeding from discussions on the new Euro 7 legislation in the EU, a base scenario for 2030 was developed in the working group together with industry representatives. The reference vehicles, which were selected on the basis of predicted emission limits, are a passenger car powered by a gasoline engine (class M1) and a light commercial vehicle with a diesel engine (class N1, group III). In both cases, they are hybridized vehicles (Hybrid Electric Vehicles, HEVs), as mild hybridization is assumed to be the standard technology for 2030. The general development trend for ZIE is predicted to be an increase in size of catalytic converters compared to the state of the art in Euro 6 vehicles and the integration of external heating measures for Exhaust Aftertreatment Systems (EATS) [1].

Components of the hybrid powertrain concepts and introduced terms can be found in **TABLE 1**. **FIGURE 2** (left) shows the initial technology package for the zero-impact design of the passenger car reference vehicle. The derived powertrain configurations for the light commercial vehicle can be found in **FIGURE 2** (right).

Component/Measure	Term
Exhaust Burner	ExB
Electrically Heated Disk	EHD
Preheating	PreH
Power Limitation	Lim
Integrated Starter Generator	ISG
Vehicle Speed Reduction	SpdRed
Catalyst Volume	CatVol
Three Way Catalyst	TWC
Coated Gasoline Particulate Filter	cGPF
Closed-coupled Diesel Oxidation Catalyst	ccDOC
Close-coupled Coated Diesel Particulate Filter	ccSDPF
Underfloor Selective Catalytic Reduction	ufSCR
Ammonia Slip Catalyst	ASC
Permanent Magnet Synchronous Motor	PMSM

TABLE 1 Components of the ZITE drive concepts and introduced terms (© tme)

4 RESULTS AND DERIVED MEASURES

FIGURE 3 shows the simulation results for the NO_X emissions of the passenger car with gasoline engine. An average annual payload of 13 % was assumed for the calculation. Depending on the technology combination, the NO_X ZITE target values are either reached or exceeded. The combination of electric preheating and a power limitation of the ICE is below the limit for ZIE in all scenarios, except for the scenario large area – parking lot traffic. Here, the preheating time of 15 s is not sufficient to achieve the ZIE level. This is primarily due to the 100 % cold started vehicle fleet. By extending the preheating time to 20 s, ZIE conformity can be achieved. Alternatively, the burner in the exhaust gas tract proves to be a very effective tool. In combination with a short preheating phase, ZIE can be achieved in all scenarios. Even though the burner emits additional gaseous emissions, its higher thermal power output improves the overall emission performance compared to electric auxiliary heating. A power limitation is no longer necessary in this case.

FIGURE 4 lists the simulation results for the NO_X emissions of the light commercial vehicle with diesel engine. For the calculations, an average annual payload of 25 % is assumed. As shown, the specified powertrain concept for the year 2030+ achieves ZITE in all scenarios, with the exception of the scenario Stuttgart – worst-case and highway – high traffic, **FIGURE 4** (left). To ensure ZITE in the first case, faster heating of the EATS is necessary. Similar to the gasoline passenger car, an electric preheater and a powertrain concept based on an exhaust tract burner were examined as ZITE solutions for this scenario. To investigate the most difficult conditions for ZITE compliance, unfavorable initial NH_3 loading conditions in the two $deNO_x$ catalytic converters were assumed in the simulations.

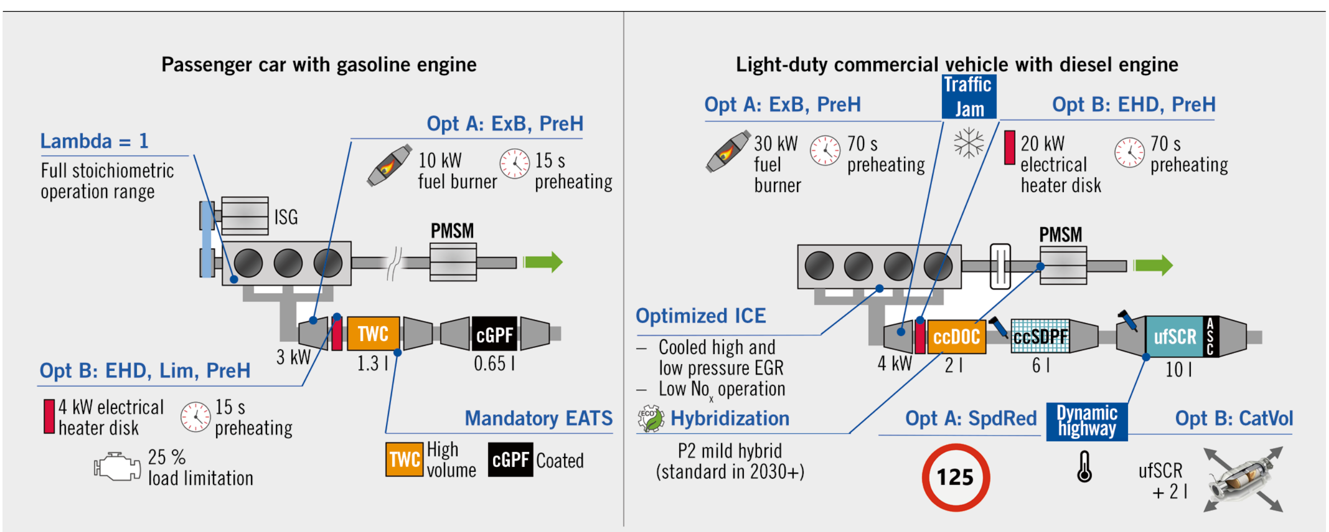


FIGURE 2 ZITE powertrain concepts for passenger cars (left) and light commercial vehicles (right) for compliance with the NO_X emission limits for road traffic (© tme)

NO_x [mg/km]	Cold start	ZIE-target	HEV	+ EHD	+ EHD, Lim	+ EHD, PreH	+ EHD, Lim, PreH	+ ExB	+ ExB, Lim	+ ExB, PreH	+ ExB, Lim, PreH
Stuttgart – yearly average	2 %	6.9	12.1	9.1	3.3	7.1	2.7	5.4	2.7	2.1	2.1
Stuttgart – worst-case	17 %	16.9	82.0	33.3	19.1	22.2	14.8	15.1	8.2	3.8	2.4
City highway – high traffic	2 %	7.9	10.9	3.5	3.3	3.2	2.8	2.9	2.8	2.0	2.0
Highway – high traffic	0.2 %	2.7	2.9	2.3	2.1	2.2	2.1	2.1	2.1	2.0	2.0
Alpine highway – high traffic	0.2 %	5.5	4.2	4.2	2.8	3.7	2.6	3.9	2.6	3.0	2.1
Large area – parking lot traffic	100 %	32.4	938.1	51.2	51.2	35.1	35.1	34.1	34.1	3.0	3.0
Uphill – high altitude	2 %	25.7	11.7	10.6	3.9	8.6	3.2	7.6	2.9	2.7	2.4

ZIE not achieved ZIE achieved P_{EHD} = 4 kW P_{ExB} = 10 kW P_{Lim} = 18 kW P_{PreH} = 15 s

FIGURE 3 Comparison of measures for a passenger car with gasoline engines to achieve NO_x ZITE (© tme)

After 70 s of preheating with a 20-kW electric heater or a 30-kW burner, the ZITE target can be achieved, **FIGURE 4** (top right). In this case, the emissions of the exhaust gas tract burner are slightly higher due to the additional emission formation during the preheating phase. However, it is easier to achieve such thermal power outputs with a burner, as the outputs of an electric heater are limited by the voltage level of the hybridization and the resulting currents. With 48-V technologies, maximum heating outputs of 6 kW

2030+ NO_x [mg/km]	ZIE target [mg/km]	Cold start share	2030+ ZITE result
Stuttgart – yearly average	11.6	2 %	✓
Stuttgart – worst-case	22.8	17 %	+ 100 %
City highway – high traffic	19.8	2 %	✓
Highway – high traffic	7.1	0.2 %	+ 40 %
Alpine highway – high traffic	16.3	0.2 %	✓
Uphill – high altitude	53.6	2 %	✓

ZIE achieved ZIE not achieved

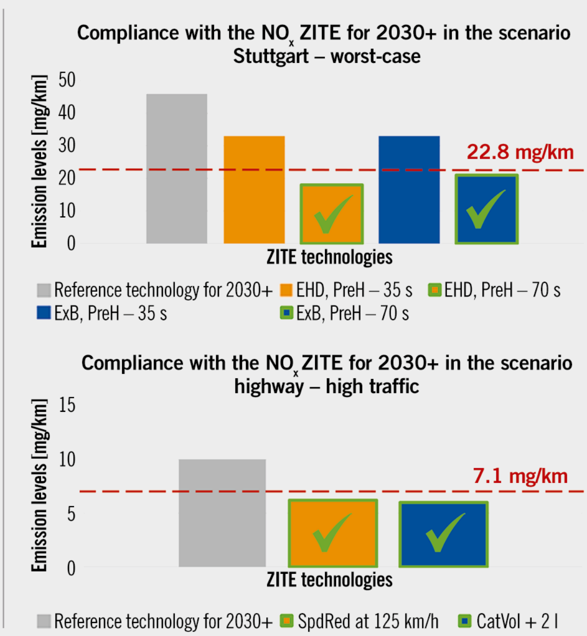


FIGURE 4 Comparison of a light commercial vehicle with a diesel engine to achieve NO_x ZITE; target values and results for individual scenarios (left), measures compared to the reference technology for 2023+ for the scenario Stuttgart – worst-case (top right) and the scenario highway – high traffic (bottom right) (© tme)

have been prevalent to date. In the scenario highway – high traffic, compliance with the ZITE specifications requires either a further reduction in the raw emissions of the combustion engine or an increase in the deNO$_X$ capability of the EATS. As shown, the defined ZITE target can be achieved by either reducing the maximum vehicle speed to 125 km/h for this specific scenario or by increasing the total underfloor SCR volume by 2 liters, **FIGURE 4** (bottom right).

4 CONCLUSION AND OUTLOOK

In this study, ZITE powertrain concepts for a gasoline passenger car and a light-duty diesel commercial vehicle were examined, focusing on NO$_X$ emissions. The ZIE fleet is defined as the fleet that emits less than 3 % of the limit value of the average annual NO_2 pollutant concentration in the EU. A ZITE test matrix was developed, consisting of seven real-world driving scenarios combining critical aspects of vehicle emissions and air quality. The standard gasoline passenger car expected for 2030+ is ZITE-compliant with minor adjustments to the hardware control system. The light commercial vehicle with the reference powertrain for 2030+ is ZITE-compliant in 70 % of the scenarios.

Through external preheating technologies, the reduction of the maximum vehicle speed or an increase of the size of the catalytic converters, the predicted vehicles can achieve ZITE in all scenarios considered. Future research and further analyses are planned in order to quantify the annual frequency of occurrence of critical situations in practice, such as those in the developed ZITE test matrix.

REFERENCES

[1] Maurer, R.; Kossioris, T.; Hausberger, S.; Toenges-Schuller, N.; Sterlepper, S.; Günther, M.; Pischinger, S.: How to define and achieve Zero-Impact Emissions in road transport? In: Transportation Research Part D: Transport and Environment, no. 116 (2023), article 103619

[2] Hausberger, S.; Uhrner, U.; Toenges-Schuller, N.; Stadlhofer, W.; Schneider, C.: Zero Impact Vehicle Emissions (Conceptual Study). Final report, FVV project no. 1407, 2022

[3] Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) (ed.): Neufassung der Ersten Allgemeinen Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz: Technischen Anleitung zur Reinhaltung der Luft (TA Luft), 2021

[4] German Federal Ministry of Justice (BfJ) (ed.): Neununddreißigste Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes - Verordnung über Luftqualitätsstandards und Emissionshöchstmengen: 39. BImSchV, 2010

[5] World Health Organization (WHO) (ed.): Air quality guidelines global update 2005. Online: https://www.who.int/publications/i/item/WHO-SDE-PHE-OEH-06.02, access: Dezember 2, 2024

[6] Maurer, R; Kossioris, T.; Sterlepper, S.; Günther, M.; Pischinger, S.: Achieving Zero-Impact Emissions with a Gasoline Passenger Car. In: Atmosphere 14 (2023), no. 2, pp. 313

THANKS

The research project (FVV no. 1412) was performed by the Chair of Thermodynamics of Mobile Energy Conversion Systems (tme) at the RWTH Aachen University under the direction of Prof. Dr.-Ing. Stefan Pischinger. It was self-financed by the FVV e. V. and conducted by an expert group led by Dr.-Ing. Frank Bunar (IAV GmbH). The authors gratefully acknowledge the support received from the funding organizations, from the FVV and from all those involved in the project. Special thanks go to Dr.-Ing. Marco Günther (RWTH Aachen) for his contribution to this work.