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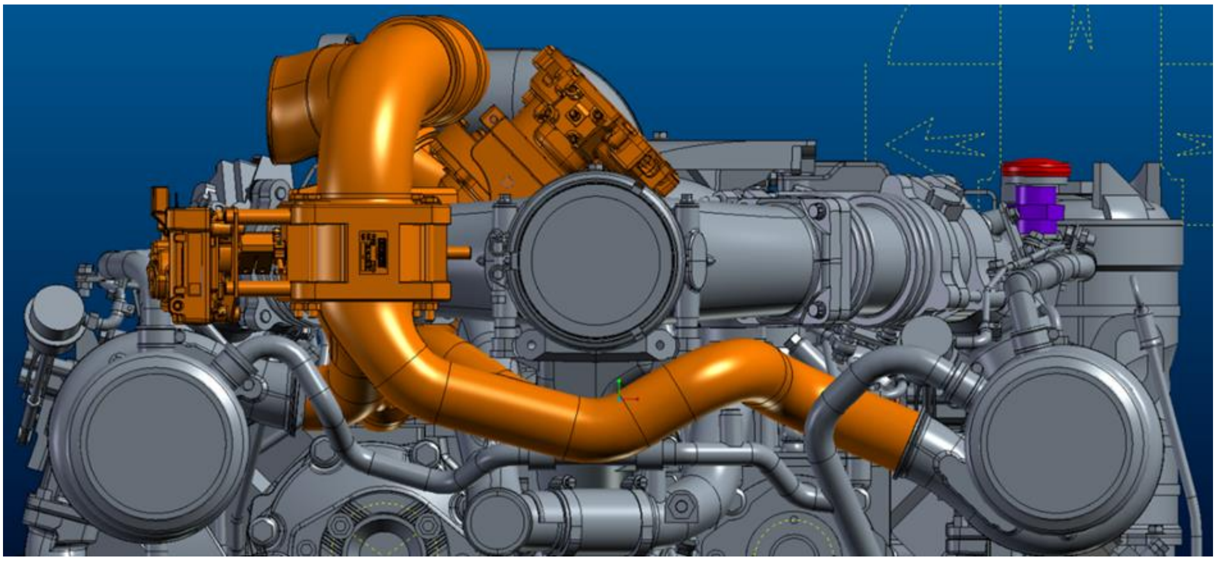
Energy Research

Final report

E-charger on Heavy Duty Engine for Off-Road Applications

Simulation, Integration, Measurements and Analysis





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Summary

Driven by the reduced emission limits, diesel engines for off-road applications have undergone significant improvements over the last decade, but recently the emission regulations are focusing more and more on transient behavior.

The aim of this project is to enhance the engine dynamic in specific phases, when the intake air pressure is low and a sudden load is requested by the machine. In order to remain within the emission limits, the injected fuel quantity is limited by the engine control unit until the turbocharger is able to deliver enough air. This problem can be solved by supplementing the conventional turbocharging system with the e-charger technology and thus eliminating the turbo lag. These improvements will be verified using 1D- and CFD simulations and by performing several tests on the internal combustion engine equipped with an e-charger.

The engine test bench measurements have shown that in the engine speed range between 600 and 1000 rpm a strong dynamic improvement can be achieved and that the e-charger is an appropriate solution for the drawbacks of doing an engine downspeeding.
For example, for a load step the 90% time response can be reached in 40% and up to 80% less time depending of the engine speed and the e-charger activation anticipation.
Above 1000rpm there is not benefit to use the e-charger.

The e-charger also leads to a reduction in fuel consumption in the range of 5-8% with low soot emissions. NOx emissions increase significantly, but can be tuned to the original value by recalibrating the injection parameters without any negative impact on soot emissions.

From an electrical point of view, the e-charger version selected for the measurements is easier to be integrated in comparison with the 48V solution because it is working with a 24V voltage, and then no dual electrical board with a higher voltage is necessary. Even so, due to the strong current necessary to speed up the e-charger the compatibility to the existing system especially regarding the vehicle other current consumer and the effect to the battery must be analysed.

As the e-charger project has been sucessful, there is currently a planning concerning the distribution of tasks between the pre-development and serial development. The next steps is to perform a vehicle test and analyse the cost for eventual serie introduction.

Zusammenfassung

Angetrieben durch die reduzierten Emissionsgrenzwerte wurden bei Dieselmoren für Off-Road – Anwendungen in den letzten Jahren erhebliche Verbesserungen erzielt, doch in letzter Zeit konzentrieren sich die Emissionsvorschriften mehr und mehr auf das transiente Motorverhalten.

In diesem Projekt soll die Motordynamik in Betriebspunkten verbessert werden, wenn der Ansaugluftdruck niedrig ist und ein plötzlicher Lastsprung durch die Maschine angefordert wird. Zur Einhaltung der Emissionsgrenzwerte wird die eingespritzte Kraftstoffmenge durch das Motorsteuergerät solange begrenzt, bis der Turbolader genügend Luft liefern kann. Dieses Problem kann gelöst werden, indem der konventionelle Abgasturbolader mit der E-charger-Technologie ergänzt und somit das Turboloch eliminiert wird. Diese Verbesserungen werden mit Hilfe von 1D- und CFD-

Simulationen und durch Versuchsreihen an einem mit E-charger ausgerüsteten Verbrennungsmotor verifiziert.

Prüfstandsversuche zeigen eine signifikante Dynamikverbesserung des Verbrennungsmotors mit integriertem E-charger im Bereich von 600 bis 1000 min^{-1}. Somit ist die Verwendung des E-chargers eine geeignete Maßnahme zur Beseitigung von Dynamikproblemen in Betriebspunkten mit niedriger Motordrehzahl. In Abhängigkeit des Motorbetriebspunktes und der Aktivierungsstrategie des E-chargers wird bei einem Lastsprung die Zeitdauer zum Erreichen von 90% des maximalen Motordrehmoments um 40% bis zu 80% verkürzt. Die Aktivierung des E-chargers bei Motordrehzahlen über 1000 min-1 führt zu keiner Dynamikverbesserung des Verbrennungsmotors.

Die Verwendung des E-chargers führt ebenfalls zur Reduzierung des Kraftstoffverbrauchs im Bereich von 5-8% bei gleichzeitig geringen Rußemissionen. Die NOx-Emissionen steigen deutlich an, lassen sich jedoch mittels Neukalibrierung der Einspritzparameter und ohne negativen Einfluss auf die Rußemission auf den ursprünglichen Wert bringen.

Der hier getestete E-charger arbeitet mit einer 24V Betriebsspannung und ist im Hinblick auf die Fahrzeugintegration der 48V-Variante vorzuziehen, da auf ein duales Betriebsspannungsnetz verzichtet werden kann. Aufgrund des hohen Strombedarfs zum Beschleunigen des E-chargers muss dennoch die Kompatibilität zu existierenden Systemen, besonders hinsichtlich der anderen Stromverbraucher und der Batterieeffekte im Fahrzeug, analysiert werden.

Aufgrund der guten Projektergebnisse mit dem E-charger wird derzeit die Planung für die Aufgabenverteilung zwischen Vor – und Serienentwicklung durchgeführt. Die nächsten Schritte umfassen die Durchführung eines Fahrzeugtests und die Kostenanalyse für eine eventuelle Serieneinführung.

Résumé

Poussés par la réduction des limites des émissions, les moteurs diesel pour les applications « Off-road » ont subi des améliorations significatives au cours de la dernière décennie, mais récemment, les réglementations sur les émissions se concentrent de plus en plus sur le comportement transitoire.

L'objectif de ce projet est d'améliorer la dynamique du moteur diesel dans des phases spécifiques, lorsque la pression d'air d'admission est faible et qu'une charge soudaine est demandée par la machine. Afin de rester dans les limites des normes d'émission, la quantité de carburant injectée est limitée par le calculateur moteur jusqu'à ce que le turbocompresseur soit en mesure de fournir suffisamment d'air. Ce problème peut être résolu en complétant le système de suralimentation conventionnel par la technologie du e-charger et en éliminant ainsi le décalage du turbo. Ces améliorations seront vérifiées à l'aide de la simulation 1D et CFD, ainsi qu'en réalisant plusieurs tests sur le moteur à combustion interne équipé d'un e-charger.

Les essais avec le moteur à combustion, en utilisant la technologie « e-charger », ont montré une nette amélioration de la dynamique dans les régimes moteur de 600 tr /min à 1000 tr/ min. Cette technologie de e-charger est la solution adéquate pour améliorer la dynamique des moteurs à combustion dans les bas-régimes qui est l'inconvénient principale de « downspeeding ». Par exemple, lors des essais de saut de charge, la réponse dynamique, « temps de réaction du couple à 90% de la

référence », est raccourcie de 40 % voire 80% dépendant des régimes moteur. L'activation du e-charger au-delà de 1000 min^{-1} n'apporte pas d'amélioration de la dynamique du moteur à combustion.

L'utilisation du e-charger permet également de réduire la consommation de carburant de l'ordre de 5 à 8%, tout en réduisant les émissions de suie. Les émissions de NOx augmentent considérablement, mais elles peuvent être ramenées à leur valeur d'origine en recalibrant les paramètres d'injection, sans affecter les émissions de suie.

La version « 24V » du e-charger utilisée lors de cette compagne d'essai est facile à intégrer dans le moteur, comparée à la version « 48V ». Grâce à son niveau de tension plus faible qui ne nécessite pas une architecture duale. L'analyse complète de l'intégration du e-charger dans un véhicule est nécessaire, notamment à cause sa forte consommation de courant lors des sauts de charge.

Le projet « e-charger » ayant été un succès, il existe actuellement une planification concernant la répartition des tâches entre le pré-développement et le développement en série. Les prochaines étapes consistent à effectuer des essais sur un véhicule et à analyser le coût de l'introduction éventuelle de ce système pour la série.

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Contents

Abbreviations

1D	One dimension
AC	Alternating Current
BLDC	Brushless Direct Current
BMEP	Break Mean Effective Pressure [bar]
BSFC	Break Specific Fuel Consumption [g/kWh]
CA	Crank Angle [°]
CFD	Computational Fluid Dynamics
DC	Direct Current
E-booster	e-charger
E-charger	Electrical charger
ECU	Engine Control Unit
E-Turbocharger	Electrical Turbocharger
FM_EC	Supplier brand 1_e-charger
FU_m_CYL	Injected fuel quantity [mg/stroke]
HIL	Hardware in the Loop
ICE	Internal Combustion Engine
IMEP	Indicated Mean Effective Pressure [bar]
LMB	Liebherr Machines Bulle
NOx	Nitrogen Oxide ($NO + NO_2$)
RPM	Rotation per Minute [1/min]
SIL	Software in the Loop
SOI	Start of Injection [°CA]
TB	Test bench
w/o	without
WP	Work package

1 Introduction

1.1 Purpose of the project

Driven by the reduced emission limits, diesel engines for off-road applications have undergone significant development over the last decade. Due to high development progress and intensive research, cleaner diesel engines were developed without impairing the efficiency and the fuel consumption. Furthermore, the emission regulations are focusing more and more on transient behavior.

The aim of this project is to enhance the dynamic of the diesel engine in specific phases, when the intake air pressure is low and a sudden load is requested by the machine. In this case due to exhaust gas emission regulation and lack of air for a proper combustion, the injected fuel quantity is limited by the engine control unit (ECU) until the turbocharger is able to deliver enough air. This could take up to 2-5 seconds to reach the maximum engine power depending of the inertia, friction of the turbocharger and of the engine combustion. The phenomenon is commonly known as 'turbolag'.
The electrical charger (e-charger) supplements conventional turbocharging system. It improves the boost pressure and thus the transient engine response especially at low engine speeds by eliminating the turbo lag.
The main purpose of the project is to rate the improvement in the diesel engine dynamic and to show the overall potential of this technology. The results will be used as a basis for vehicle integration and testing, cost analysis and eventual series introduction.

1.2 Objectives

In this project, the goal is to achieve the following improvements integrating the e-charger technology on the diesel engine:

- Dynamic improvement ($\geq$ 40 %)
- Emission reduction (such as opacity < 10 %)
- Efficiency of the engine (2 % in certain working conditions)

These improvements will be verified using 1D simulation, CFD simulation (for volumetric efficiency) and by performing several tests on the internal combustion engine (ICE) equipped with an e-charger. Furthermore, the goal is to investigate and find a better solution to boost the ICE and mostly to improve the energy management and the engine efficiency. Another important benefit would be the emission reduction in terms of soot and therefore gas opacity.

2 Challenges and approach

2.1 Challenges

The current e-charger systems on the market are only designed and specified for car applications and thus have very different mission profiles and energy demands compared to heavy-duty off-road applications with high power engines operating at low speed.
In order to achieve the goals, innovation is required in following fields:

- The control strategy for Liebherr applications: several methods have to be developed and tested in SIL-System in order to be able to control the e-charger, depending on the different engine operating points. The available signals of Liebherr vehicles, which are also different depending on the applications, will be intensively analyzed in order to establish an appropriate common system control strategy.

- The electrical architecture of the system (battery + converter + e-charger) has to be defined with a systemic approach and energy management simulations.

- The new architecture should allow integrating of an energy recovery system on the combustion engine at a competitive cost, as battery and converter would already be available. Today such systems are difficult to emerge due to increased engine cost vs efficiency benefit.

- Electrical power need for Liebherr vehicles: required peak power will be of 13 kW for low speed range, going up to 20kW for very low engine speed. Currently available e-charger systems achieve peak power of maximum 7kW (Audi SQ7).

- DC/DC converter (24 Volt /48 Volt). Current systems have 12V/48V converters.

Furthermore, the requirement regarding the emission regulations is different compared to the passenger car industry. The new developed system should also fulfill the requirement in terms of Liebherr vehicle environment:

- Shock and vibration resistance
- Working temperature
- Acoustics level
- Lubrication of the system
- Sealing requirements
- Electrical architecture and current consumption
- Altitude requirements

2.2 Approach

WP1: Simulation and pre-design of the e- charger

The first phase of the project will be the 1D-simulation, predesign and selection of the e-charger. The matching of the compressor need to be done according to LMB diesel engines. Some engines candidates have been selected according to their field applications.

The results of WP1 will be the definition of the e-charger requirements in terms of electrical power consumption, pressure ratio, air mass flow and efficiency.

WP2: Compressor design, selection of the compressor wheel and several simulations

In the second phase, the focus will be set on the compressor design, selection of the compressor wheel and performing of several simulations such as:

- CFD simulations of the air mass flow in the compressor wheel and in the engine intake
- FEM analysis of the compressor wheel

The tasks will we performed in collaboration with suppliers of the e-charger, as they do not want do provide detailed e-charger information due to confidentiality.

WP3: Controller development and automation of the e-charger

The third phase will investigate the controller development using several Simulink and AMESim simulations. This phase is important and necessary in order to achieve the following results:

- Waste gate post calibration of the original charger
- Activation strategy and the sequences of e-charger / bypass, as this task has significant effects on the fuel consumption and dynamic.
- Safety limits of the boost pressure

WP4: Engine integration, testing and measurement analysis

The fourth phase will be the integration of the e-charger on the Liebherr engine and the test with the ICE to verify the engine improvements in terms of transient behavior, volumetric efficiency, fuel consumption and emission reduction.

3 Basics and boundary conditions

3.1 Liebherr Diesel engine

The Liebherr Diesel engine D9508 A7-05 will be used as a test engine in order to analyze different e-chargers and will be equipped with the best e-charger solution for final measurements and analysis. The main engine characteristics are summarized in figure 1.

Configuration	V-engine
Number of cylinders	8
Flywheel housing	SAE 1
Bore	128 mm
Stroke	157 mm
Displacement	16.2 l
Rated power	350 – 505 kW
Rated speed	1500 – 1900 rpm
Max. torque	3125 Nm
Dimensions (L/W/H)	1692 / 1112 / 1350 mm
Dry weight	1600 kg
Auxiliary outputs (PTO)	2
Emissions standards	EPA Tier 0 (Fuel consumption optimized) / EPA Tier 4f / EU Stage IIIA / EU Stage IV / EU Stage V / IMO III

Figure 1: Main characteristics of the Liebherr Diesel engine D9508 A7-05

Figure 2 shows the reference torque and power of the engine at full load:

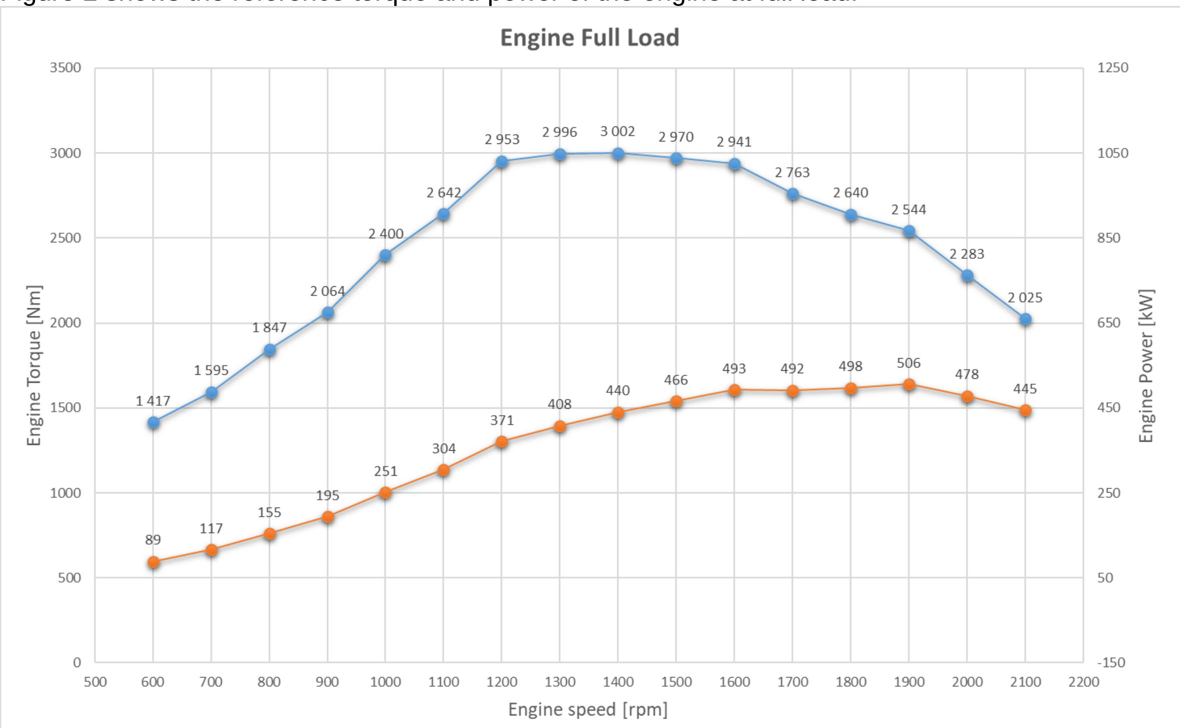


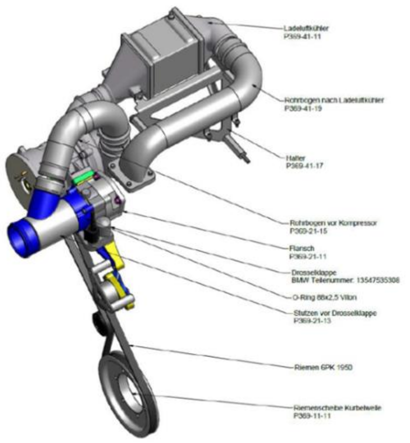
Figure 2: Reference power and torque of the Liebherr Diesel engine D9508 A7-05

3.2 Comparison of charging systems

There are several charging solutions which generally can be used, either in combination with the classic turbocharger or as a single solution, in order to improve the engine dynamics. In the following, three typical charging solutions are briefly described.

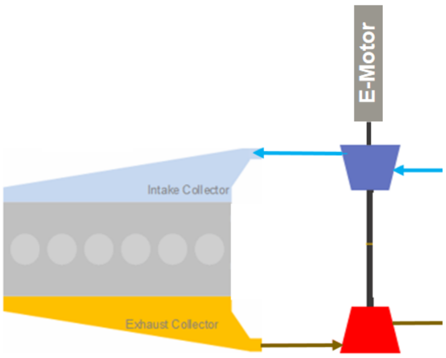
Mechanical compressor

The mechanical compressor is similar in many points to the electric compressor, except that it need to be connected directly to the engine using a mechanical connection as belt or gearing. It offers less flexibility than the e-charger, but current solutions allow more power for the air compression.



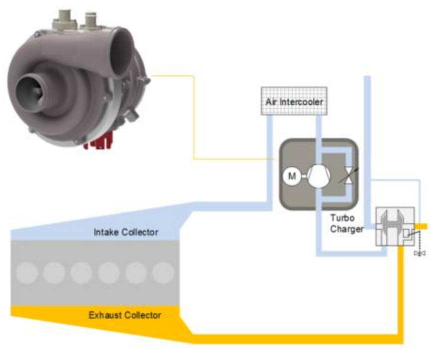
E-turbocharger

The e-turbocharger is an electric turbocharger; it is composed of a compressor, a turbine and an electric motor, which can be driven to support the compressor or to recover energy of the turbine. There are several variation possibilities depending on the positioning of the electric motor.



E- charger

The e-charger (also called as e-booster) is composed of a single compressor driven by an electric motor, which allows the electrical boost pressure regulation and control. This allows greater flexibility and dynamics on the one hand, but it brings an additional electrical consumer on the other hand. The e-charger can also be used to significantly increase the maximum engine torque.



Although the mechanical compressor is able improve the engine dynamic and to avoid the turbo lag, it offers less flexibility, needs additional mechanical connection to the engine drive and thus more installation space, so that this solution is not followed in this project.

The e-turbocharger could be a good long-term solution as it can improve the engine dynamic in the complete engine speed range, but it need to be well tuned for each engine type and power range. It cannot be used as an add-on solution for already existing machine in the field.

The e-charger is also able to improve the engine dynamic, the energy management compared to the mechanical charger is better, it is very flexible in terms of additional installation on the engine, the speed selection is completely independent and it allows a relatively simple comparison of e-chargers purchased from different suppliers.

Due to those advantages, LMB selects the e-charger solution for further analysis. The most promising e-charger will be integrated and tested on the Liebherr Diesel engine D9508 A7-05.

3.3 Engine schematic with integrated e-charger

The following figure 3 shows the schematic of the engine D9508 A7-05 with e-charger (B), integrated in-line to the standard turbocharger (D). As long as the e-charger is deactivated, the compressed air after the standard turbocharger bypasses the e-charger due to the parallel installed electric valve (A). The compresses air, weather only been compressed by the turbocharger or additionally by the e-charger, cools down to 40°C in the intercooler (C) before reaching the intake manifold and finally the combustion chambers. The electric motor of the e-charger need to be cooled by the engine coolant. In order to improve and to verify this concept, there will be performed several simulations and tests on the Liebherr diesel engines.

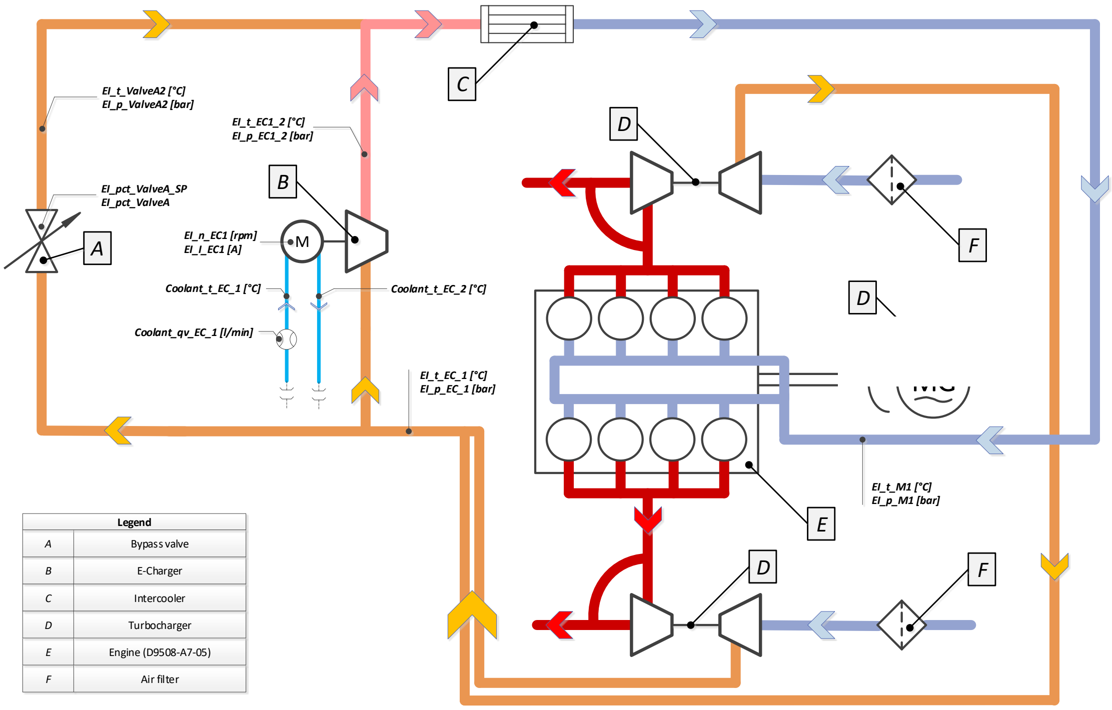


Figure 3: Engine schematic with integrated e-charger

4 Simulation

In order to investigate the benefits in terms of dynamics behavior, fuel consumption and emission reduction, several 1D simulations have been performed. Some engines candidates have been selected according to their application in the field.

The simulations have been performed using a Liebherr 6 cylinder diesel engine equipped with an e-charger, mainly two types of them have been tested. The models have been established by considering the following main components:

- turbocharger matching
- selected diesel engine
- LMB ECU control
- existing e-charger technology

4.1 Modelling of the electrical compressor

The electrical motor part has been considered in the simulation. The inertia of rotating parts and the available torque is mainly responsible for the dynamic behavior and time response of the electrical compressor.

Figure 4 shows an overview of the e-charger model established in AMESim:

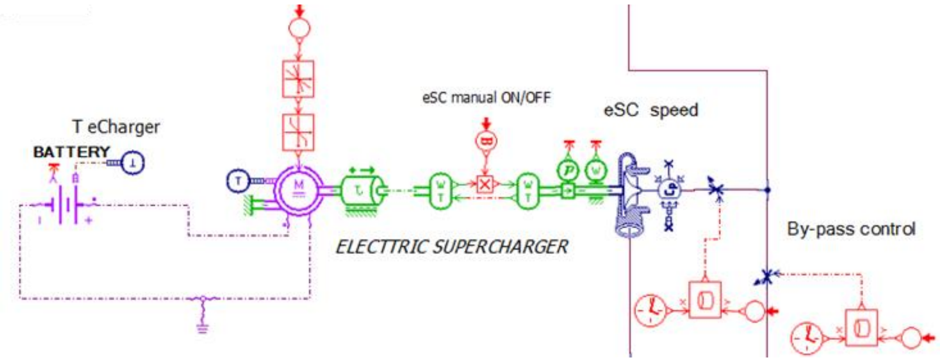


Figure 4: E-charger model (1D)

4.2 Engine models with different e-chargers and arrangements

Configuration 1:

In the first configuration, an e-charger has been tested that is usually designed for passenger car applications. In order to ensure a higher air mass flow rate, requested by heavy-duty diesel engines, two parallel arranged e-chargers have been used.

Those two electrical chargers together are arranged in series to the traditional turbocharger (figure 5).

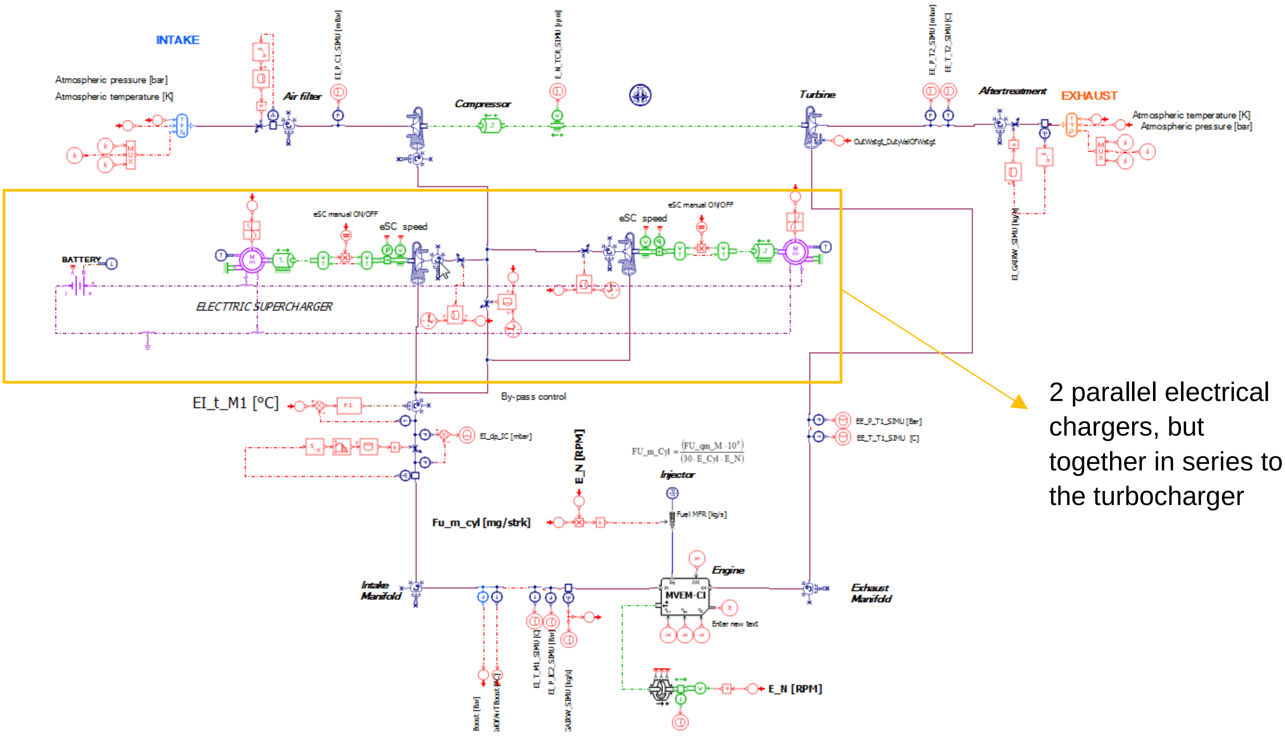


Figure 5: 1D-model of the configuration 1

Configuration 2:

In the second configuration, only one e-charger with a higher air mass flow range has been analysed. This e-charger is placed in series to the traditional turbocharger, as shown in the following figure 6:

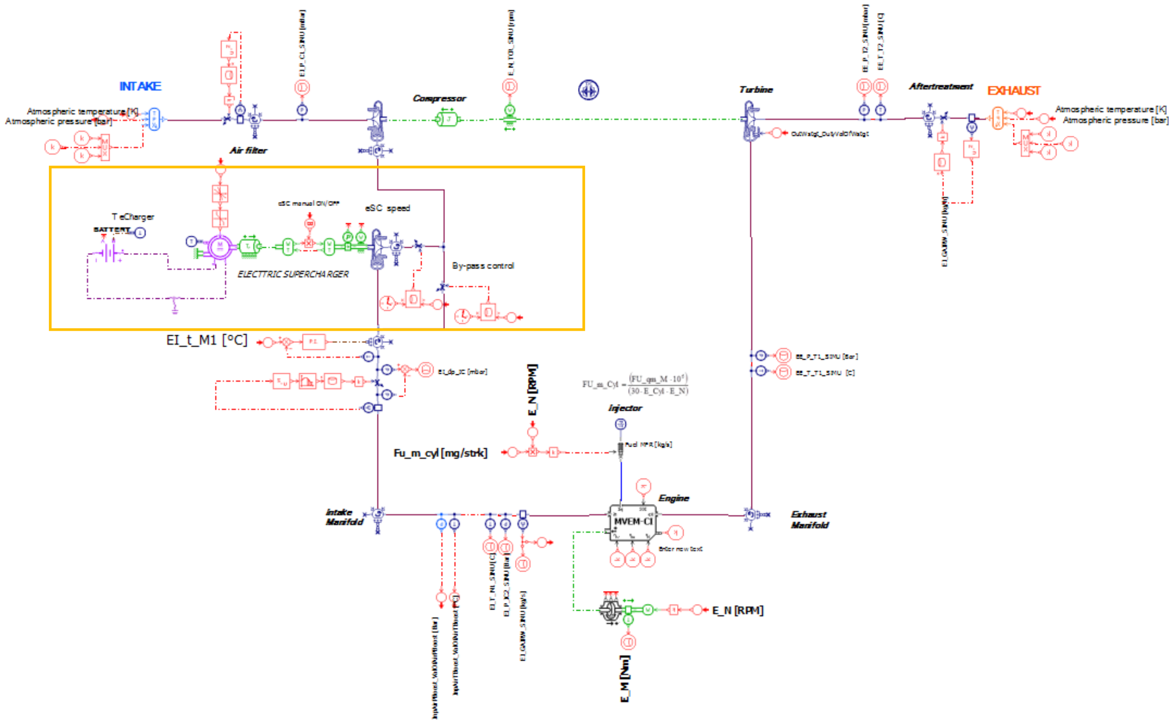


Figure 6: 1D-model of the configuration 2

4.3 Simulation results

Both simulations show the same trend improvements, so in this chapter only the results of the configuration 2 are presented, as this configuration is more interesting for series introduction due to one-part solution.

Figure 7 shows the main simulation results at constant engine speed.

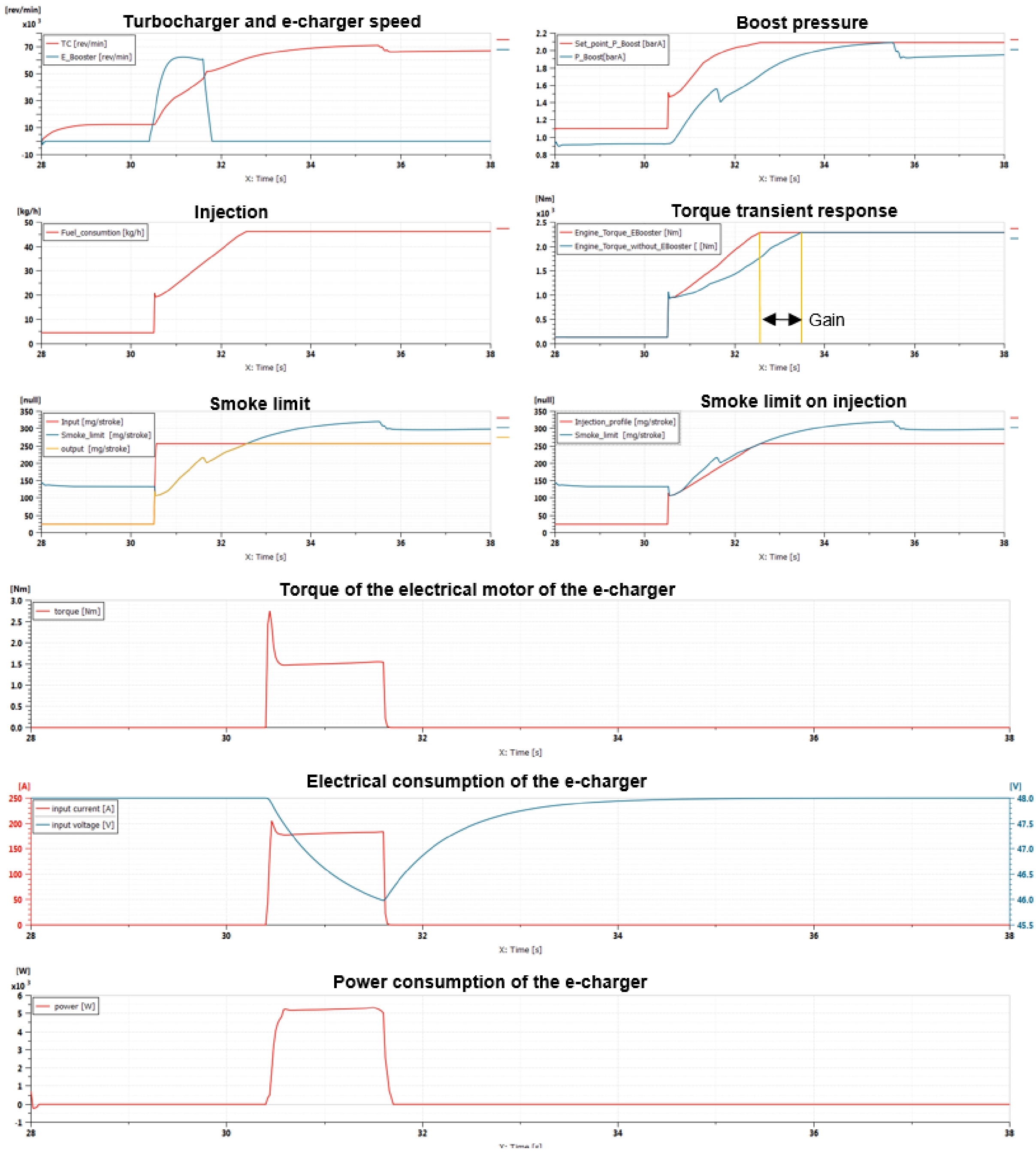


Figure 7: Results of the 1D-simulation

Figure 7 (Turbocharger and e-charger speed) shows the rotation speed curves of the turbocharger (red curve) and e-charger (blue). After the load step occurs, the e-charger speed increases rapidly with much higher gradient compared to the turbocharger and reaches its maximum speed in less than one second. This leads directly to a faster boost pressure build-up (Figure 7, boost pressure). In this diagram, the blue curve represents the e-charged boost pressure, while the red curve shows the set point curve of the boost pressure. During the load step event, the level of the set point curve is generally higher than the e-charged curve in order to prevent eventual boost pressure limitation, After a certain time, the e-charged boost pressure curve reaches the maximum level of the set point.

Figure 7 (Torque transient response) shows the torque response comparison between the standard (blue) and e-charged (red curve) engine. The dynamic behavior of the engine is improved, the addition of an e-charger allows a faster torque response from 10% of charge to 100%. The gain is about 30% for low speed range.

Figure 7 (Injection) shows the fuel consumption of the standard engine without the e-charger. Figure 7 (Smoke limit on injection) shows the same injection profile (red curve) and the smoke limit injection profile (blue curve) in comparison. The smoke limit profile represents the maximum allowed injection quantity in order ensure the requested torque. This diagram illustrates, that the engine without an e-charger is not able to reach the maximum smoke limit profile in the transient section due to lower boost pressure, which leads slower torque response.

The diagram (Smoke limit, figure 7) shows three different curves for the e-charged engine. The red curve (input) represents the injection request in order to reach the requested maximum engine torque. The yellow curve (output) represents the actual injected fuel quantity. The blue curve represents the smoke limit. While the injection request step occurs (red curve), the actual injected fuel quantity (yellow curve) is overlapping with the smoke limit curve (blue curve), which means that the engine is not limited by the boost pressure. After the actual injected quantity reaches the level of the requested one, the injection quantity does not need to increase anymore.

The three last diagrams in Figure 7 show the torque, electrical consumption and the power of the e-charger. During the period of activated e-charger, the mean torque of the electrical motor is about 1.5Nm. The corresponding current is about 180A, while the voltage drops from 48V to 46V. The mean power consumption is about 5.3kW.

The simulation results show the potential of the e-charger regarding torque transient response improvement. Diesel engine equipped with this charging technology is able to deliver a higher torque with a better dynamic behavior at lower engine speed.

The model of the diesel engine has been calibrated based on the test bench measurements. The ECU control has been established using the real configuration and parameter implemented on the real engine.

The waste gate control has been calibrated using a PI controller in order to reproduce the real behavior observed in test bench measurements.

The electrical and the torque consumption of the e-charger is correct according to the e-charger manufacturers and its dynamic behavior has been validated with measurements.

The operating points of the e-chargers are in a high efficiency zone of the map, which confirms the adequacy of the selected e-charger for this kind of application.

5 Measurements

5.1 Test definition

The definition of the load steps (figure 8) is generally based on the standard LMB load step definition with one exception. Contrary to the standard LMB definition, in the test cycle, the load is set up in Nm and not in percent in order to have always the same absolute base torque of the engine, as well for the reference as for all e-charger measurements. This is important in order to show the max potential of the e-charger.

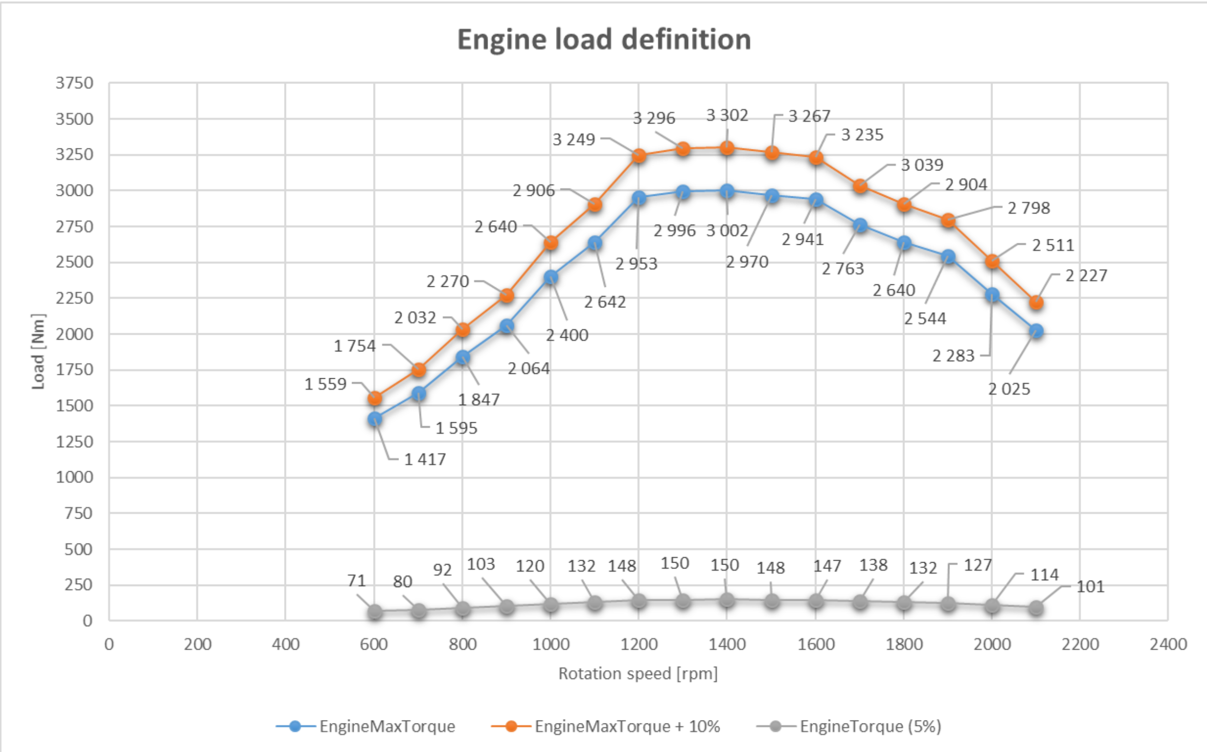


Figure 8: Engine load definition

5.2 Definition of the LMB load step cycle

The definition of one load step interval with short rest time shows table 1. All values in the table are fix and are identical with the standard LMB definition. The definition "*short rest time*" describes the time duration between two load step events (8 seconds).

Warm up duration	180 s
Up slope time	0.1 s
Step duration	20 s
Down slope time	2 s
RunOutTime	200 s
Time between steps	8 s

Table 1: Time definition of the load step cycle

The activation time and the running time interval of the e-charger are adjustable. Those two parameters can be set up before starting the load step cycle. Once they are defined, they remain fix during the load step measurement.

The following parameters were used:

- Activation time before load step: 0 sec. & 2 sec.
- Running time interval: 10 sec & 15 sec;

The figures 9, 10 and 11 show the overview of the load step cycle definition with short rest time:

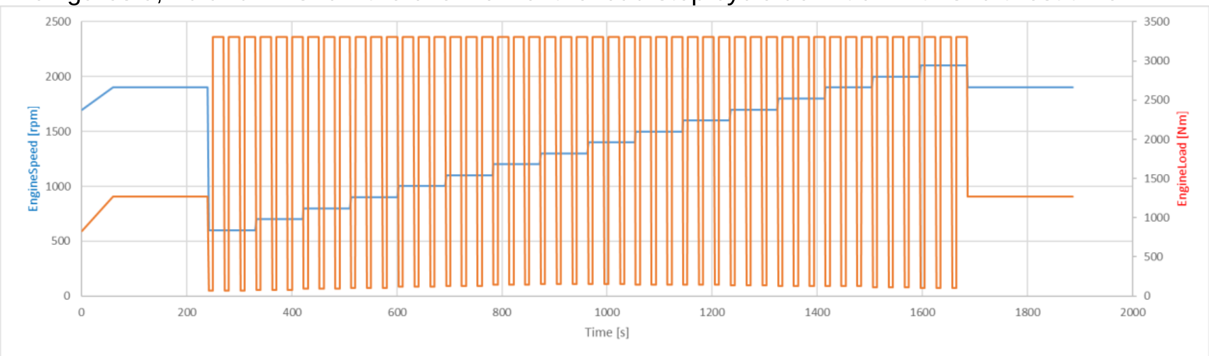


Figure 9: Complete load step cycle with short rest time

For each speed operating point, there are three load steps. The activation of the e-charger is done every third load step in order to respect the temperature limit of the coil in the e-charger.

The bypass valve is 100% open, when the e-charger is not running or when running in idle speed (5000rpm). The bypass valve is closed, when e-charger is activated.
Deactivation of the E-charger (idle speed) → Bypass-opens directly (100%).

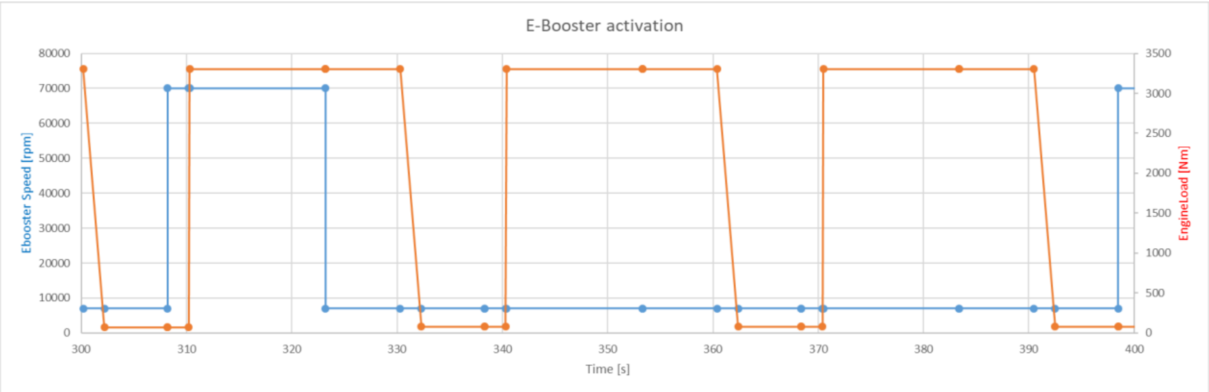


Figure 10: Activation strategy of the e-charger

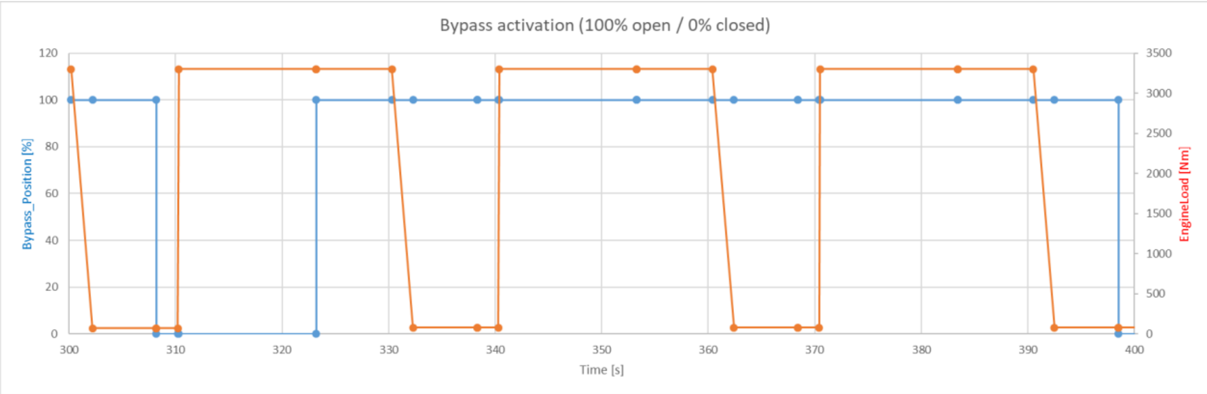


Figure 11: Activation strategy of the bypass valve

5.3 Criteria definition for the engine dynamic analysis

During the measurement campaign, several engine configurations were tested. In order to ensure the comparability of the measurement data regarding the engine dynamic, it is necessary to define criteria for the measurement analysis. The following criteria will be used:

- Response time 90% absolute torque from the reference measurement
- Time table (torque over time: t*, 0,5s, 1s, 2s, 3s)
- Torque gradient (Nm/s)

The definition of the response time analysis for reaching 90% of the engine torque is shown in figure 12. This criteria is very useful, as it visualize the dynamic behavior of the engine and shows directly the impact of the e-charger. Figures 12 and 13 show also the “boosted” engine torque (engine torque higher than the reference engine torque) in order to visualize the further potential of the e-charger, but for the final engine settings, the e-charger is only used to reach the maximum engine torque as fast as possible.

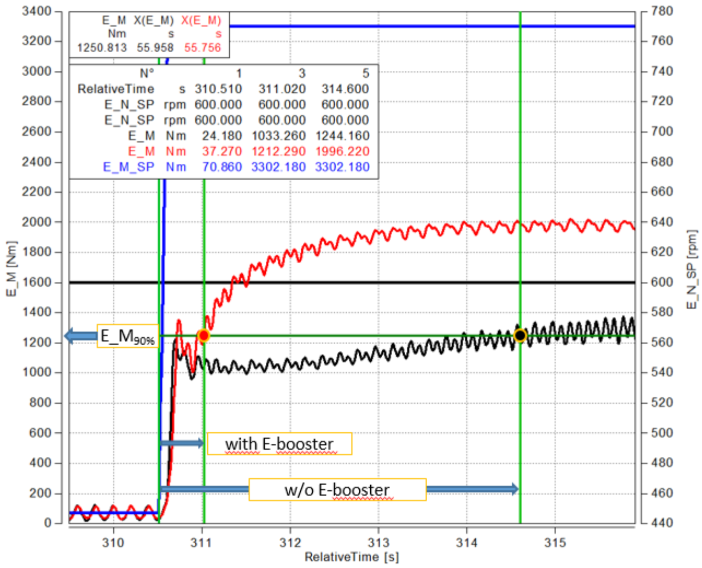


Figure 12: Definition of the response time analysis for reaching 90% of maximum engine torque

Figure 13 shows the second criterion, the so-called "time table definition". This criterion defines fixed time steps between the e-charger activation and the 90% of maximum engine torque and allows thus a more detailed analysis of the engine torque curve.

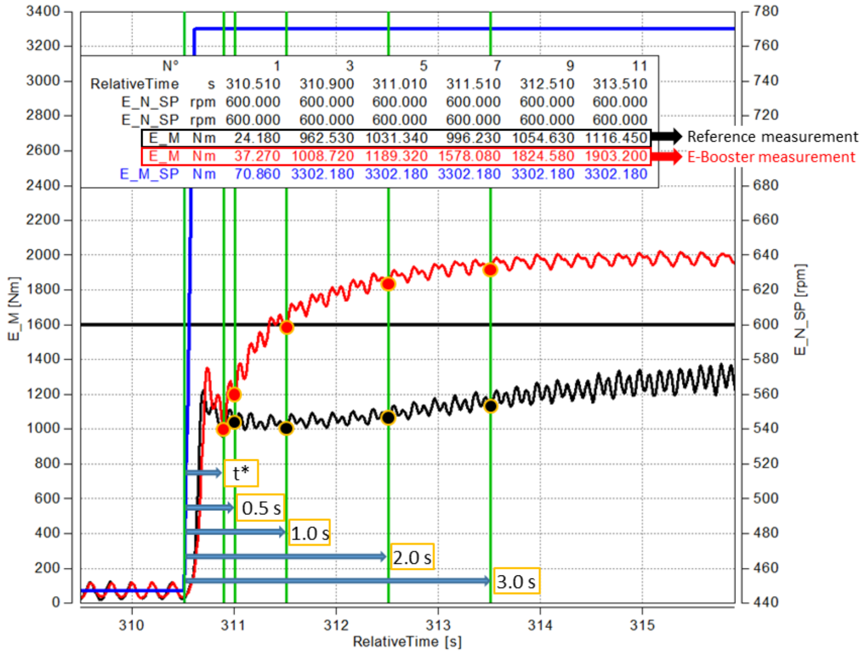


Figure 13: Definition of the time based torque analysis after the e-charger activation

This result example of the time table comparison is shown in table 2.

	Time [s]				
	t*=0.4	**0.5**	**1.0**	**2.0**	**3.0**
Reference measurement [Nm]	963	1031	996	1055	1116
E-Charger measurement [Nm]	1009	1189	1578	1825	1903

Table 2: Time table of the torque curve comparison

5.4 Engine dynamic results

During the measurement campaign, engine configurations have been tested and analysed. The first configuration (blue bar) is the standard engine without an e-charger and represents the reference. The second configuration (orange bar) shows the time response of the engine using e-charger, which is only integrated on the test bench and connected to the engine with test bench piping. This configuration is not optimized regarding the optimal air path length, but it allows to test and to relatively compare different e-charger brands in order to select the best one for the engine integration. The third configuration (grey bar) represents the engine with integrated e-charger (FM_EC).

Figure 14 shows the time response for reaching 90% of engine maximum torque for three different engine configurations.

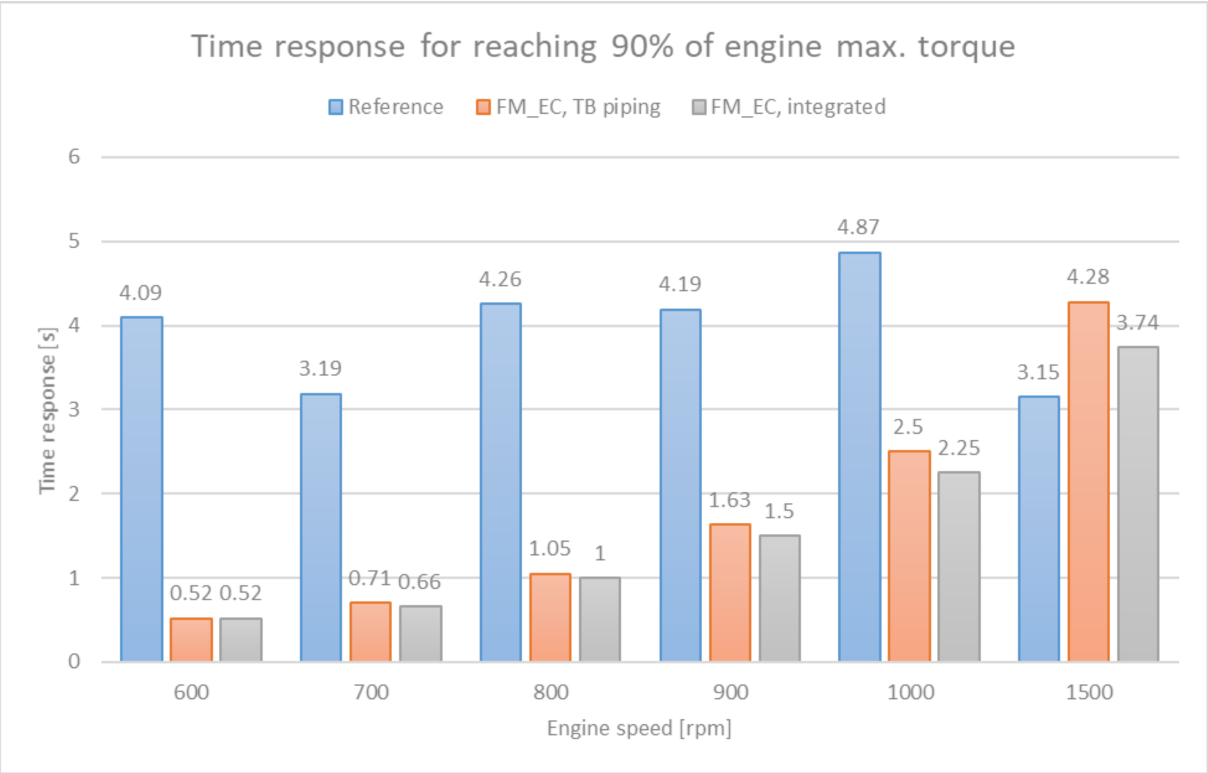


Figure 14: Time response overview

In the speed range between 600 and 1000 rpm, the diagram shows that the time response is significantly reduced using the e-charger. At 600 rpm, the time response with e-charger is almost 8 times faster and at 1000 rpm almost 2 times.

The diagram shows also the limits of the e-charger at speed ranges over 1000 rpm, as the current e-chargers are not designed for higher capacities. Nevertheless, the important engine operation range at lower speeds is well covered by the tested e-charger FM_EC.

The best results delvers the configuration 3, but the difference between configuration 2 and 3 is almost negligible. The difference in piping length and thus the air volume, which need to be compressed by the e-charger, seems to have no significant negative impact in this measurement campaign.

Figure 15 shows the complete overview of the engine torque comparison of the three different configurations at five pre-defined time intervals after e-charger activation. Each diagram represents one engine speed range.

Taking a look at the engine speed range for instance at 700 rpm, 0.5 seconds after the e-charger activation, there is a toque difference of 17% compared to the reference engine. After 1 second, the difference increases to already 38%. At 600 rpm, the difference is even higher and reached its maximum of 74% after 2 seconds.

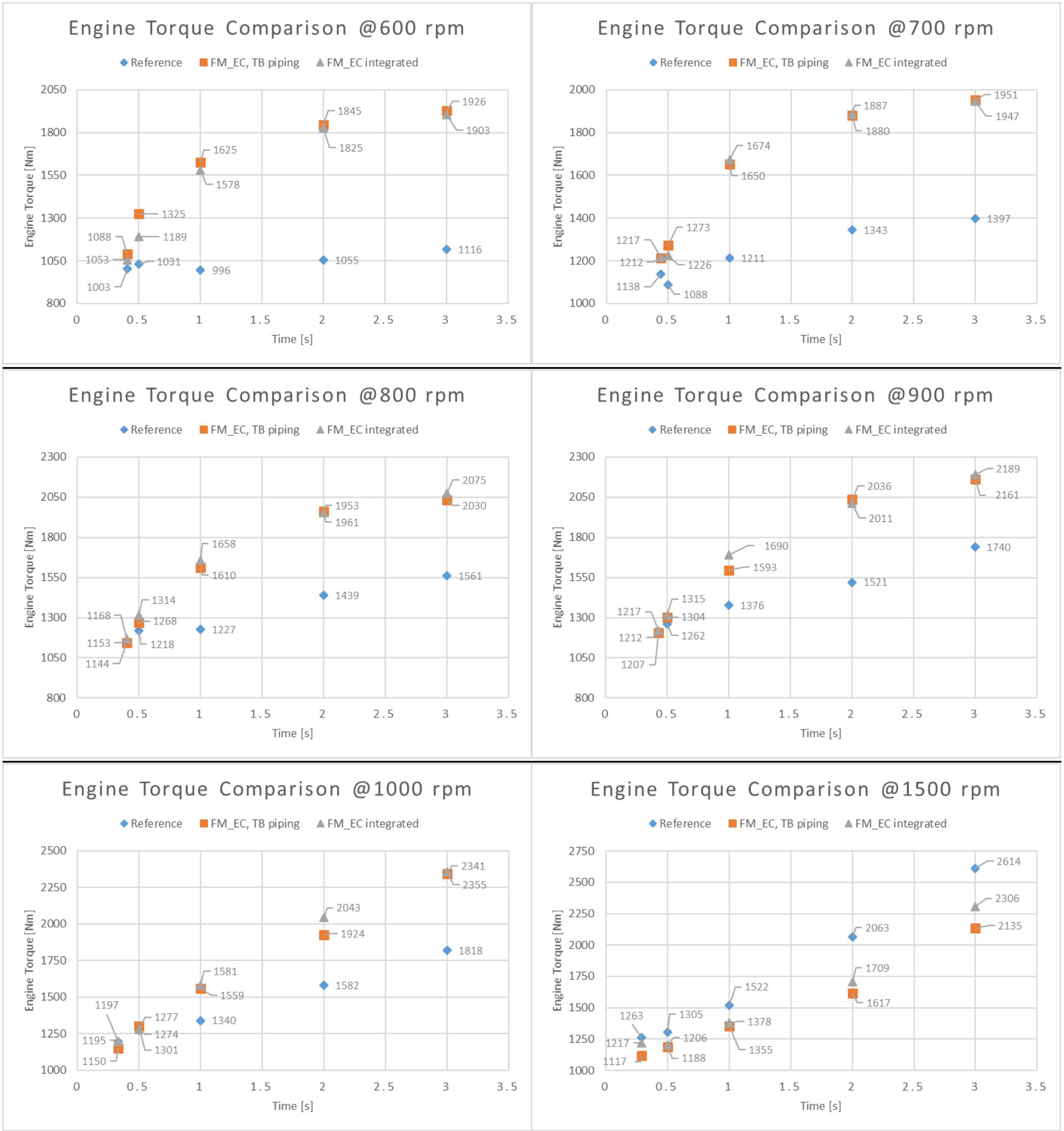


Figure 15: Engine torque comparison for different engine speed ranges

5.5 Engine dynamic improvement

The engine test bench measurements have shown that in the engine speed range between 600 and 1000 rpm a strong dynamic improvement can be achieved and that the e-charger is an appropriate solution for the drawbacks of doing an engine downspeeding.
For example for a load step the 90% time response can be reached in 40% and up to 80% less time depending of the engine speed and the e-charger activation anticipation. Above 1000rpm there is not benefit to use the e-charger.

The main purpose of this report are the measurements of the dynamic improvement with several tests and cycles, but other side effects were also measured like the effect to the emissions and the consumption.
Engine optimisation potential were analysed for one engine working point, and some electrical measurements have been realised. From the electrical point of view, the e-charger version selected for the measurements is easier to be integrated in comparison with the 48V solution because it is working with a 24V voltage, and then no dual electrical board with a higher voltage is necessary. Even so, due to the strong current necessary to speed up the e-charger the compatibility to the existing system especially regarding the vehicle other current consumer and the effect to the battery must be analysed.

5.6 Emission reduction

5.6.1 Soot emissions

Figure 16 shows the impact of the e-charger on the exhaust gas smoke. The engine configuration with the e-charger significantly leads to lower exhaust gas smoke amount:

- Maximum smoke level without e-charger: 14.5%
- Maximum smoke level with e-charger: 3%

The measurement has been done without changing the ECU calibration.

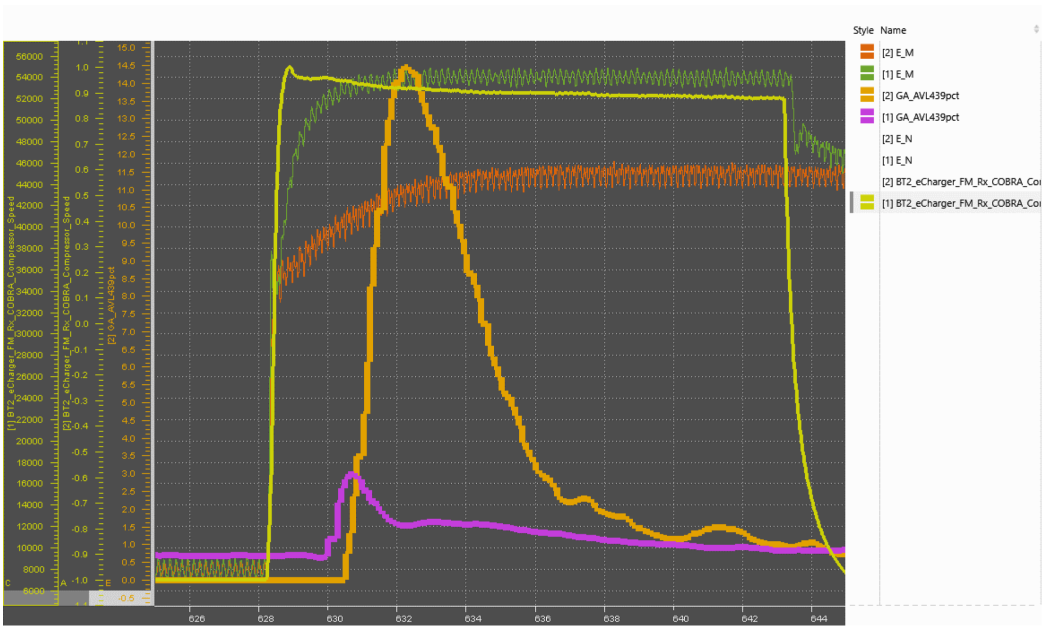


Figure 16: Impact of the e-charger on the exhaust gas smoke: reference (brown); e-charger (pink)

5.6.2 NOx emissions

Generally, the e-charger improves the engine consumption in low speed and high torque regions, it decreases soot production, but without post calibration of the rail pressure or the start of injection, it increases the NOx emissions. The impact of the e-charger on the NOx emissions without post calibration is shown in figure 17.
The engine is operating at 600 rpm and 1300 Nm. At 38000 rpm (e-charger speed), the NOx emission is about 100% higher compared to the reference engine.

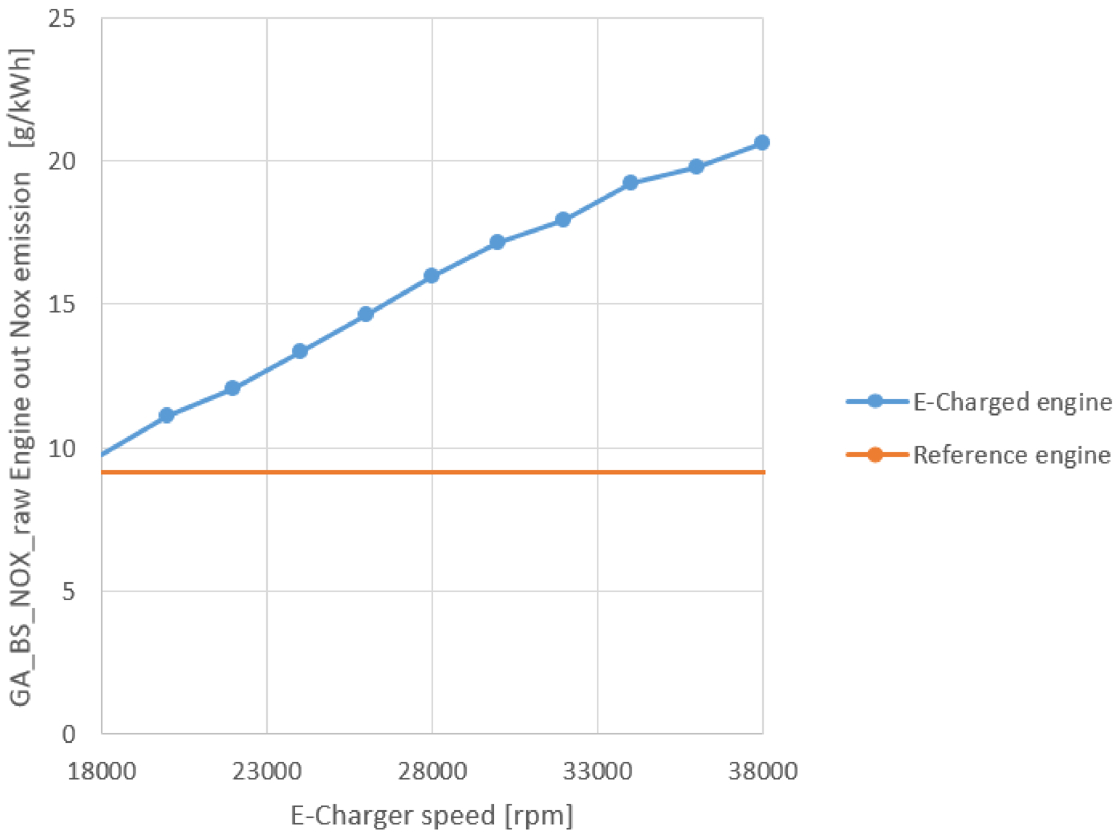


Figure 17: Impact of the e-charger on NOx emissions without post calibrations

In the following optimization phases, the e-charger speed is kept at 38000 rpm (maximum e-charger speed).

Start of injection (SOI) variation

The electrical power consumed by the e-charger was supplied by the engine generator. Injection pressure was not modified. The e-charger speed setpoint was 38'000rpm and the coolant temperature was about 85°C.

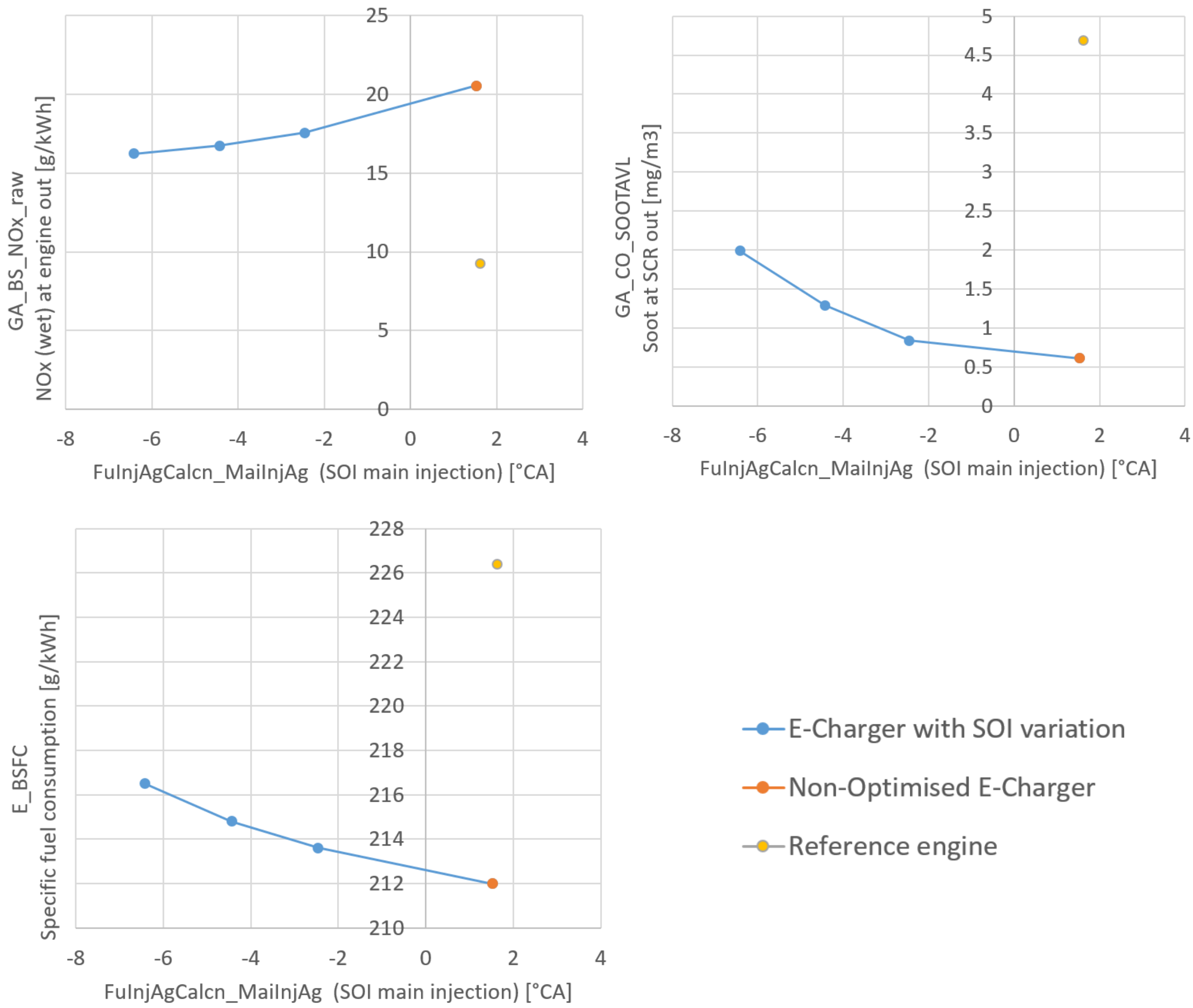


Figure 18: Impact of start of injection on NOx emissions

Figure 18 shows, that decreasing of SOI impacts positively the NOx production, but the specific consumption and the soot production increase at the same time. However, with -6.4° of SOI, NOx value remains high (16.2g/kWh) regarding the target (9-10g/kWh).

Injection pressure variation

The electrical power consumed by the e-charger was supplied by engine generator. Start of injection was not modified. The e-charger speed setpoint was 38'000rpm and the coolant temperature was about 85°C. The injection pressure was progressively decreased. The impact of the injection pressure variation in shown in figure 19.

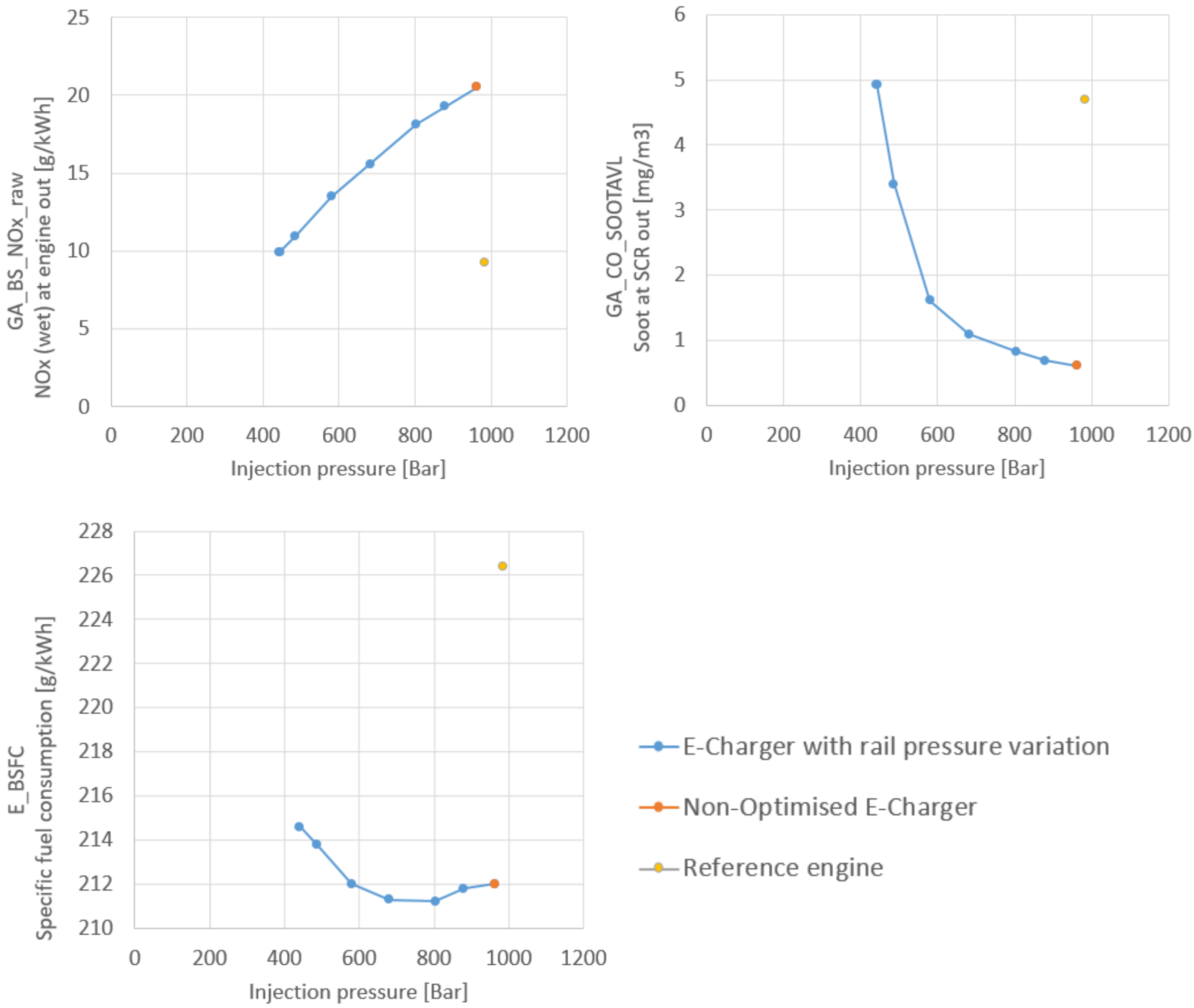


Figure 19: Impact of the injection pressure on NOx emissions

Reduced injection pressure level leads to lower NOx production. At 445 bar, the NOx emissions is in the region of 9.9 g/kWh, which is within the NOx target of 9-10g/kWh. The gain in consumption is still good (-5.2%) and the soot production remains at almost the same value (increase from 4.7 to 4.9 mg/m3).

5.7 Engine efficiency improvement

The efficiency of the engine has been improved in the low speed and full load range, one of the driver of the fuel efficiency is the combustion improvement in low speed range. Figures 20 and 21 show the maps of fuel efficiency improvement in percentage depending on the engine speed and engine load:

Goal of measurement:
The goal of these measurements is to evaluate the impact of the e-charger on engine static consumption for different e-charger speed ranges.

Test definition:
For each measurement point, the engine is set with a constant speed and torque. A stabilisation of minimum 5min is applied before a measurement has been averaged on one minute. The engine calibration has not been modified. The e-charger is supplied by the engine generator and the coolant temperature is set at 40-60°C.

A reference map is performed with the e-charger at idle speed. The idle consumption of the e-charger is considered as negligible.
A map has been performed with an e-charger setpoint at 38’000rpm (figure 20). This speed corresponds approximatively to the maximal electrical power consumed by the e-charger, which can be delivered by the standard engine generator at 600rpm.
That means, the e-charger speed can be restricted by the e-charger coil temperature but not by the maximum generator current in order to perform energy balance.

Secondly, a map has been performed with an e-charger setpoint at 30’000rpm (figure 21). The goal was to analyse the evolution of the consumption with reduced speed.

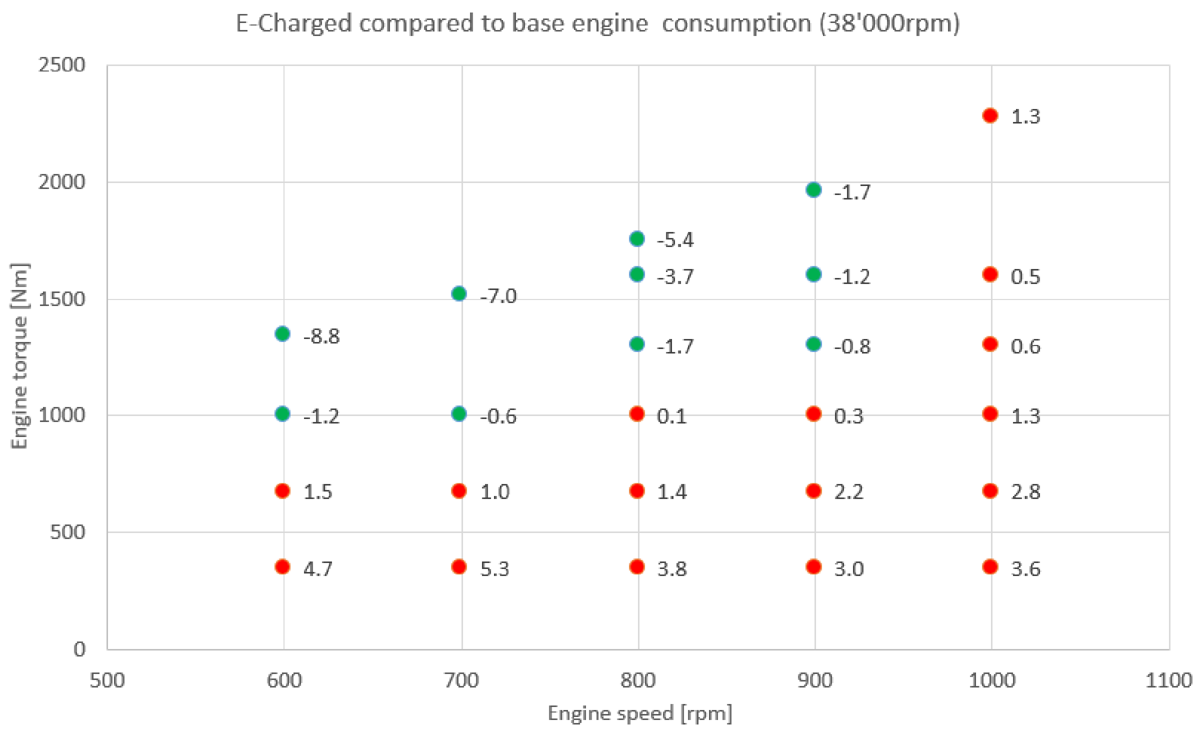


Figure 20: Map of fuel efficiency improvement (%), e-charger operating at 38000 rpm

Analysis

The z-axis on the previous graphic (figure 20) represents the consumption difference without and with the e-charger operating at 38000 rpm.
The calculation is based on the injected fuel quantity FU_m_CYL [mg/str] at an iso brake torque and speed.
In the region of red points (with positive number), the e-charged engine consumed more than the reference engine.

A consumption improvement due to the e-charger appears at low speed and high torque. That means, it is more interesting to let the e-charger permanently engaged in those regions. Furthermore, the response time of the engine will be better.

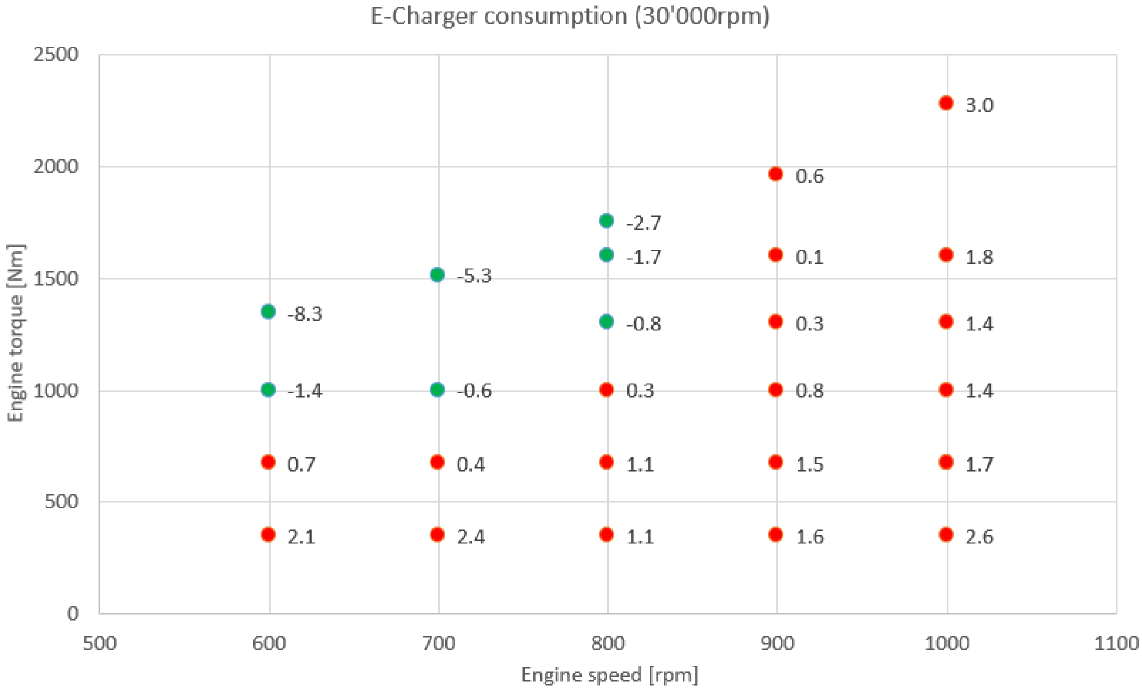


Figure 21: Map of fuel efficiency improvement (%), e-charger operating at 30000 rpm

With the decrease of the e-charger speed, the region of consumption improvement is smaller (figure 21). At 900 rpm, it is not anymore interesting to engage permanently the e-charger. In partial load the region is not increased. As a conclusion, it is not interesting to reduce the e-charger speed in order to improve the consumption.

6 Conclusions and outlook

LMB load step

In the engine speed range of 600 to 1200 rpm, LMB load step measurements show for all tested configurations a significant improvement of the engine dynamic by using an e-charger. Due to the lower volume in the air path, the engine dynamic is indeed better with the integrated e-charger compared to the chassis piping configuration, but the effect was not very significant.
At 600 rpm and synchronous e-charger activation, it takes only 500 ms to reach the 90 % of the maximum engine torque whereas the standard configuration with 4 seconds is about 8 times slower. At 700 rpm, the e-charger configuration needs 660 ms, whereas the standard configuration with 3.2 seconds is about 5 times slower. At 1000 rpm, the e-charger configuration still has more than 2 times better engine dynamic. For engine speed ranges over 1200 rpm, the e-charger activation has a negative impact on the engine dynamic and thus should not be activated (chapter 5.4).

Static consumption and emission

In low speed and high torque region, the e-charger improves the engine consumption.
The use of the e-charger without post calibrations (rail pressure or start of injection) increases the NOx and decrease soot production. One working point was optimized to reach the same emission level (soot and NOx) compare to the base engine. The consumption reduction pass from 8% (not optimized emission) to 5%.

Electrical aspect

From the electrical point of view, the measurements show that it is possible to use and drive the e-charger with an 180A alternator and batteries with the restriction of the voltage drop down to 24VDC. The impact of the voltage drop to the dynamic of the e-charger and then to the Diesel engine torque is negligible.
The following aspect were not considered in the measurements:
- The vehicle current consumer
- The voltage drop effect to the consumer and the error detection
- The effect to the battery aging
- The battery charge and discharge cycle during a working cycle

The maximum electrical power at which the E-charger can work for a long time is dependant of two factors. The maximal deliverable generator current and the e-charger coolant temperature. If the E-charger is cooled by engine coolant (~85°C) the power is limited to 2.2-2.3kW.

Next steps after end of project

As the e-charger project has been sucessful, there is currently a planning concerning the distribution of tasks between the pre-development and serial development. The next steps is to perform a vehicle test and analyse the cost for eventual serie introduction.

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8 Appendices

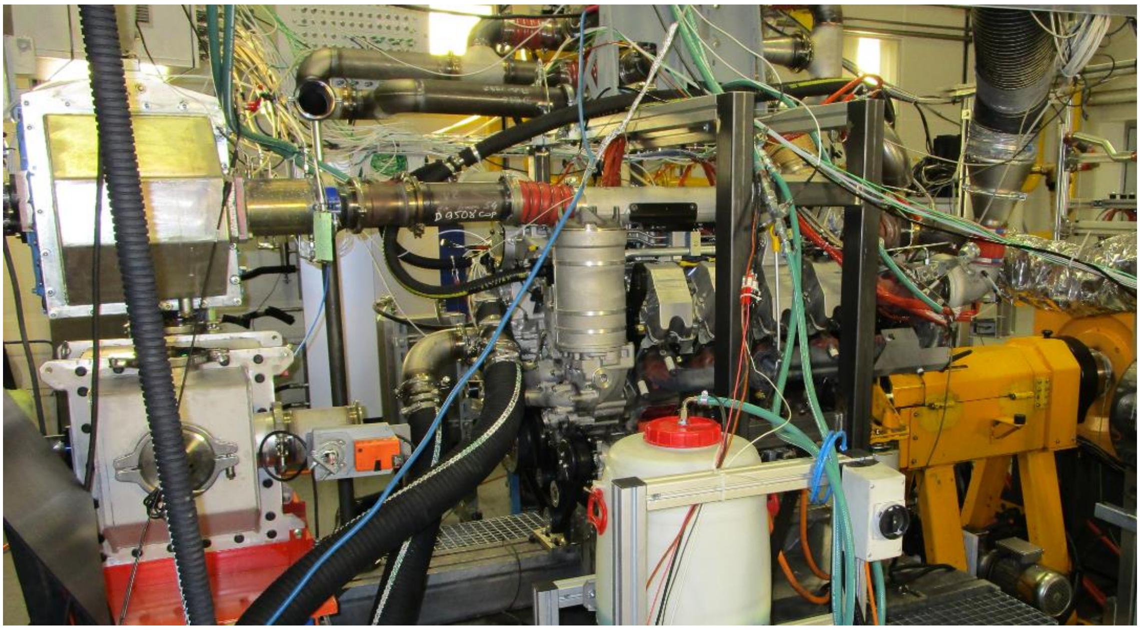

Figure 22: Standard engine configuration, reference measurement

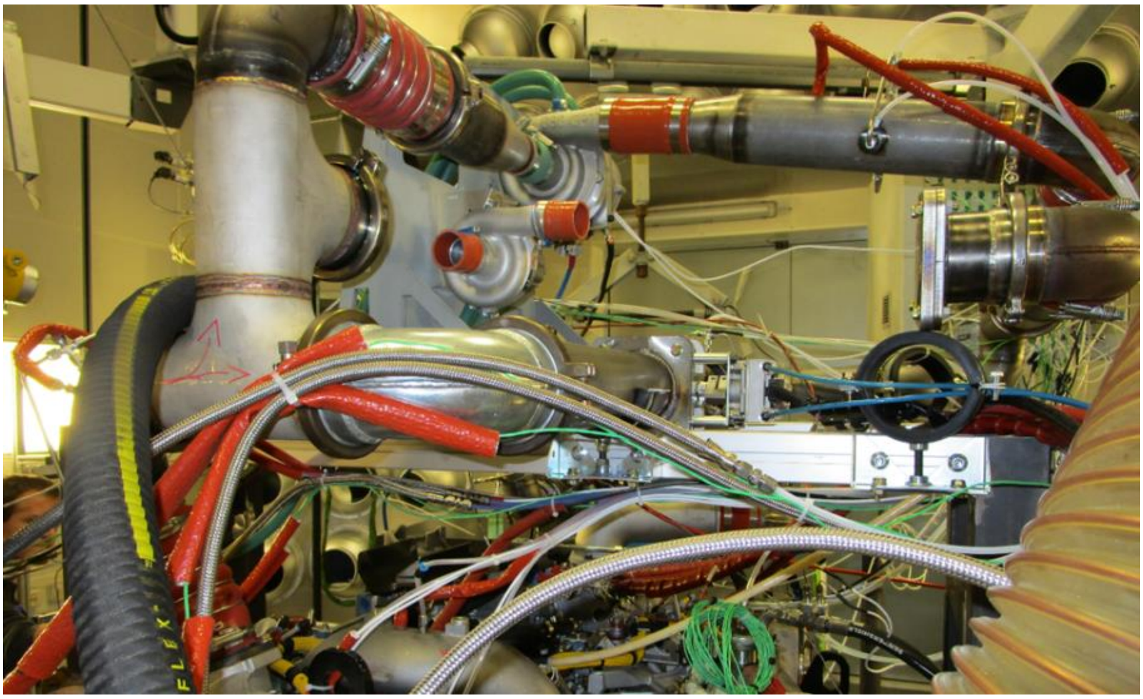

Figure 23: E-chargers testing, assembled on the chassis for easy comparison

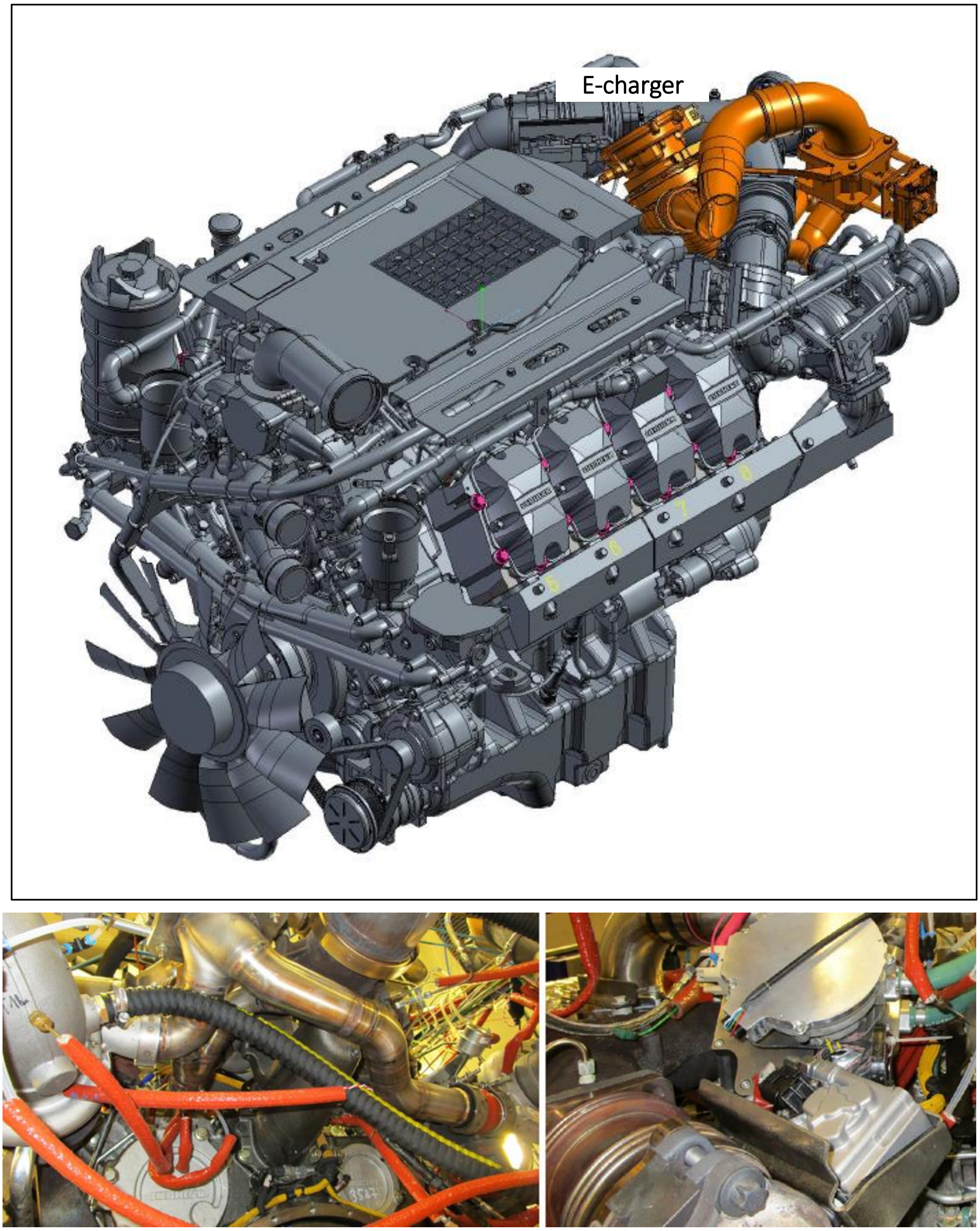

Figure 24: E-charger integrated on the engine with compact piping

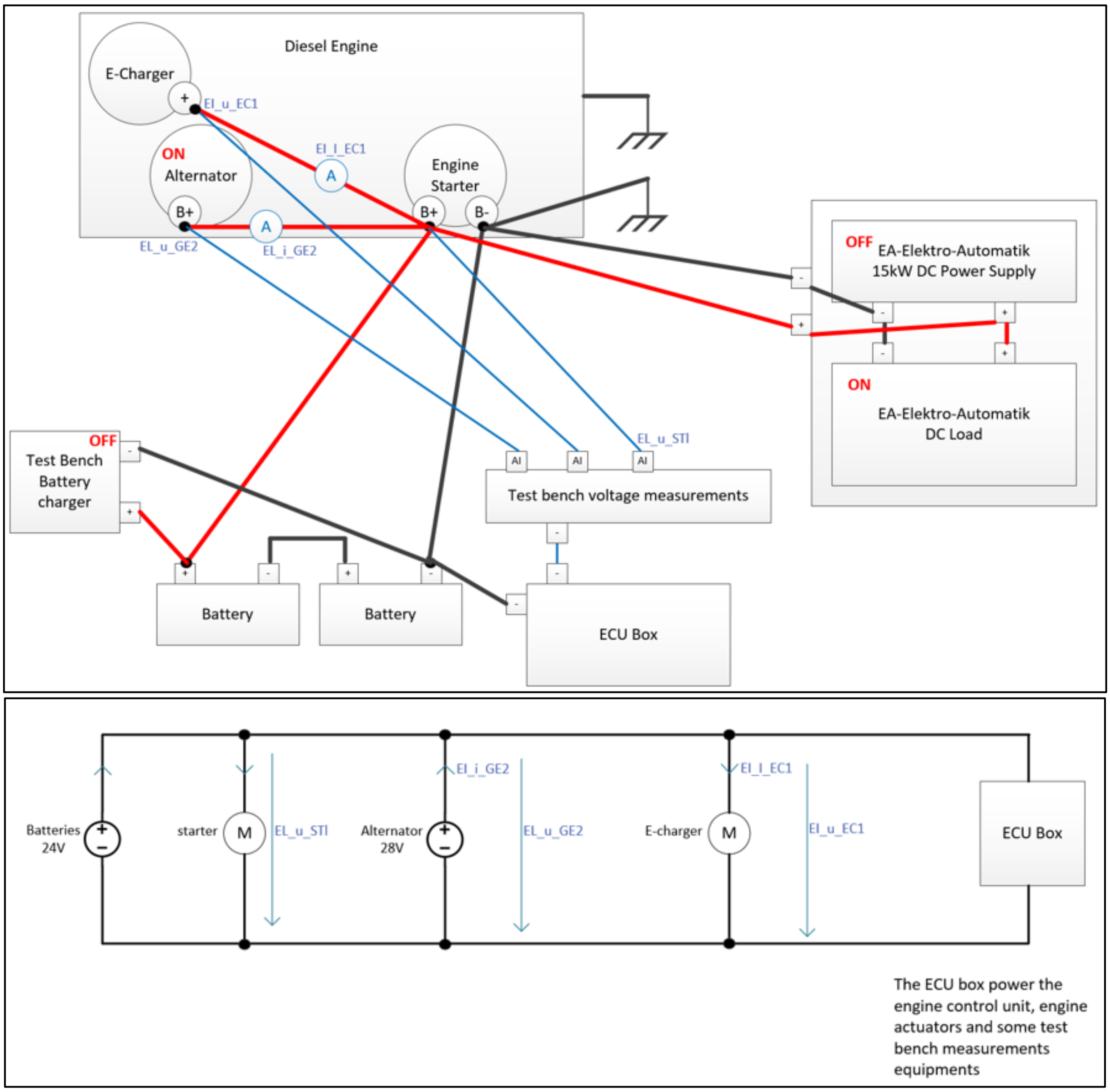

Figure 25: Simplified electrical wiring schematic

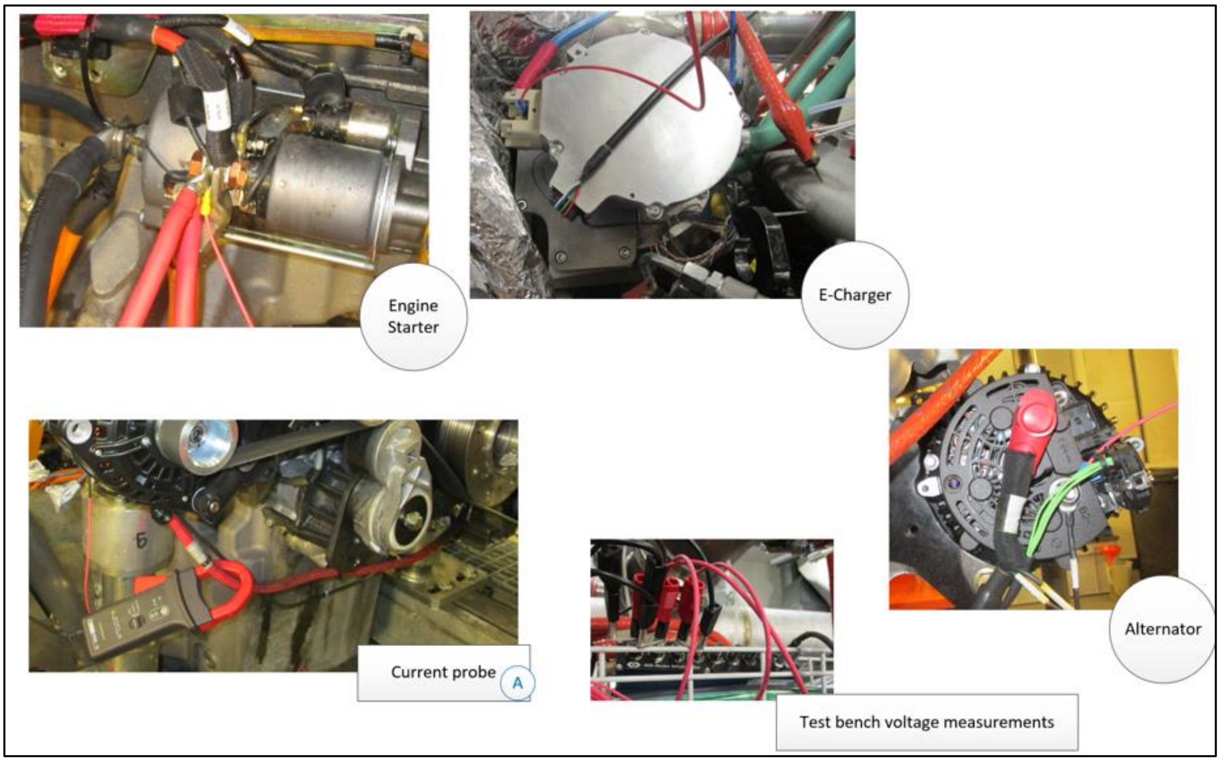

Figure 26: Electric wiring pictures