Secondary air injection with E-Boosting devices

S.Yadla[a], D.Terber[b], J.Keuler[a], P.Davies[c]
a Garrett Motion Germany GmbH
Max-Eyth-Strasse 35, 71088 – Holzgerlingen, Germany
b Garrett Motion Czech Republic s.r.o
V parku 2326/18, 148 00 - Prague, Czech Republic
c Garrett Motion
2 rue de l'Avenir, Zone Innova 3000, Thaon-les-Vosges, France, 88150

ABSTRACT

Future emission norms will focus on reduced idle and more aggressive driveaway strategies to further limit the cold start emissions of Gasoline engines in all geographies. Europe will likely be the first with EU7 RDE and will be followed by China VII and revisions to SULEV standards in the USA.

One promising solution is the use of Secondary Air Injection (SAI) for "cold start". The current industry standard is to use low power secondary air pumps, which are limited to catalyst heating strategies under engine idling conditions. However, for dynamic boundary conditions, the SAI source should be controllable precisely to regulate the exhaust lambda and at the same time be powerful enough to operate against high exhaust back pressure.

Electric boosting products, E-Compressors & E-Turbos, fulfil the SAI requirements of future emission regulations comfortably. Once the catalyst heating strategy is completed, they function as regular electric boosting devices, to improve engine efficiency and reduce emissions under normal operation.
In this paper, the various layouts of E-Compressors & E-Turbo enabling SAI and electric boosting are discussed.

1. INTRODUCTION

Hybridization of vehicle powertrains is accelerating due to the increasing pressure on the automotive industry to introduce greener vehicles, tightening emission limits and the challenging CO2 fleet average targets. EU7 is expected to be introduced between 2025 & 2027 and as per the current market forecasts and the majority will be hybridized in some way. Hybridization improves efficiency but also allows an additional degree of freedom to apply faster catalyst light-off strategies and to tackle cold start emissions. One way of reducing cold start emissions is by using the E-Machine for electric-assist, either by reducing the engine load depending upon the type of powertrain layout or also by completely driving the vehicle electrically with a decoupled engine performing its cold start strategy. This alone reduces the absolute level of cold start emissions significantly, provided that the battery SOC is intelligently managed to cover all possible driving & environmental scenarios.

Another benefit of hybridized powertrains is the availability of High-Voltage architecture for auxiliary devices. There is an increasing trend to decouple engine / powertrain auxiliaries and electrify them for better efficiency & flexibility of operation. (e.g., electrical AC compressor, active vehicle stability control, electric boosting, electrically heated catalysts, etc.)

2. CHALLENGES & REQUIREMENTS OF NEW EMISSION REGULATIONS

With the introduction of EU7, the proposal is to further tighten the emission limits and to extend the testing boundary conditions. The latest proposal for EU7 introduced by European Commission (1) focusses on fuel-neutral emission limits, robustness / durability of emission compliance, lower emission limits along with the introduction of new emission species amongst others. For the Real-Driving Emissions (RDE) regulation in Europe starting from 2017, emission tests are performed on-road with the help of Portable Emission Measurement Systems (PEMS). There is no fixed driving profile considered for the test, rather only a few guidelines to define the valid test boundary conditions. As a result, the vehicle driveaway could occur immediately after engine start and the engine idling phase could be considerably shorter. It is also a similar case in the USA with the ongoing discussions of ACCII regulation, where the idling time of the FPT75 cycle could be shortened from 20 sec to 8 sec. Additionally, CARB has proposed six special test cycles for High-Power Cold-Starts.

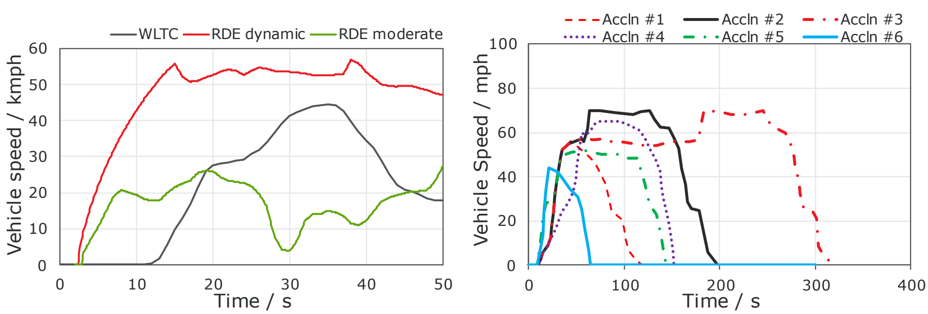

Figure 1: Cold start driving cycles / conditions (2)

The proposed emission limits can be achieved by breaking down the key requirements in the following categories:

- Cold start emission reduction
- **Faster Catalyst Light-Off**
- **Emission robustness under normal operation**
- Optimized control strategies – Engine & Powertrain
- Advanced After-Treatment Systems

In this paper, faster catalyst light-off measures & emission robustness under normal operation in combination with E-Boosting devices are addressed. Short urban trips will pose the biggest challenge for Gasoline powertrains, since most gaseous emissions occur within the first 30 seconds of operation after a cold start, until the catalyst has reached sufficient conversion efficiency. Under warm engine conditions or normal operation, it is essential for Gasoline powertrains in the future to maintain stoichiometric combustion throughout the engine operation area to ensure emission robustness. Electric Boosting devices such as E-Compressor and E-Turbo are key enablers of Lambda 1 operation, while maintaining or enhancing engine power density.

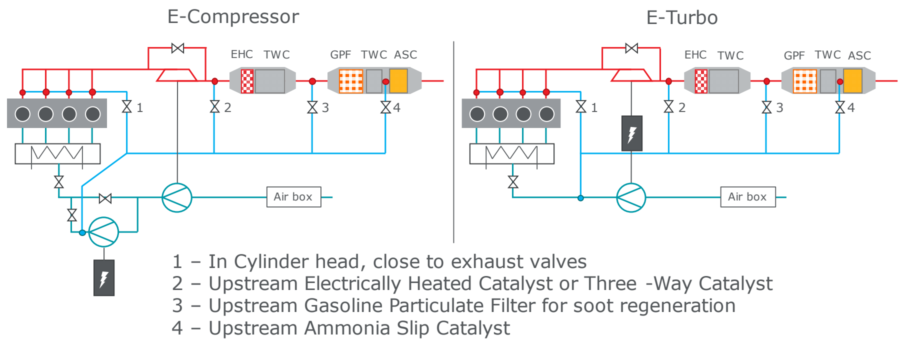

Figure 2: SAI layouts with e-boosting components

Figure 2 shows two alternative layouts of E-Compressor and E-Turbo systems combined with advanced EATS technologies considered for EU7 applications. In these configurations the E-Machines can provide both E-Boost and Secondary Air Injection functionality.

Another technology to improve cold start emissions is by using an electrically heated catalyst (EHC). With the help of an EHC, the catalyst can be brought to light-off temperature independent of engine operation. In HEV/PHEV architectures, the EHC can be deployed prior to engine start to heat up the catalyst and also to maintain the light-off temperature in the catalyst during overrun or long engine stop phases, by using intelligent operation strategies. The metallic substrate heats up rapidly achieving light-off after a few seconds. However, an engine start followed by cold exhaust gas flowing across the electrically heated catalysts would drop their temperature be-low the level needed for sufficient conversion efficiency. Therefore, an external air supply through the electrically heated catalysts is necessary prior to the engine start in order to achieve sufficient convective heat transfer to heat up the main catalyst as well. Since the main catalyst has a higher thermal inertia, it is more robust against the temperature drop resulting from the cold exhaust gas in the first seconds of engine operation. At the same time, the higher thermal inertia requires some time until the catalyst is heated up sufficiently (3). Therefore, a pre-heating strategy is mandatory before starting the engine. The duration & intensity of the pre-heating strategy is strongly dependent on the type of powertrain and OEM driveability strategy. However, for extreme conditions such as cold ambient conditions or low battery SOC scenarios combined with moderate power request from the driver, the driveability of the vehicle could be heavily restricted.

3. SECONDARY AIR INJECTION WITH E-COMPRESSOR

Garrett's new generation E-Compressor offers industry-leading motor power & efficiency, speed capability and aerodynamic performance. It is offered in 48 V and will be available in 400 V. Advanced power electronics design and thermal management allows the compressor to operate under a wide range of engine operation conditions. The system adopts a sealed ball bearing design capable of running at 90 kRPM and is very compact to ease system integration. The high efficiency electric motor and power electronics are paired with bespoke aerodynamics based on the type of application.

A normal operation strategy for SAI requires low mass flow rates at high pressure ratios. Especially, under driveaway conditions, the SAI operation points are shifted towards even higher-pressure ratio compared to a typical 12 V SAI pump operation range. Advanced development tools are used within Garrett, to design dedicated aerodynamics for different SAI applications (5). The typical aerodynamics of the E-Compressor targeting wide engine operation window for E-Boosting & SAI is called the 'Performance' wheel and it is paired with the 7.5 kW_{DC} E-Motor. This wheel covers PR up to 1.8 and mass flow rates up to 0.17 Kg/s. For dedicated SAI application targeting high power density or large displacement engines, a special wheel has been developed which targets pressure ratios up to 2.1. This wheel can also enable E-Boosting up to medium engine speeds. By adapting the compressor wheel further, the surge margin can be optimized for EU7 boundary conditions by limiting the flow capacity of the wheel.

3.1. SAI LAYOUTS WITH E-COMPRESSOR

The more common SAI layouts use electric pumps in the "p1" position (figure 3, A) where inlet to the pump is located downstream the air filter and up-stream the compressor. The pump outlet is connected to the exhaust system, typically to the exhaust ports. In this layout, both a traditional side channel blower or an E-Compressor can be utilized. Typically, an on/off valve "a" is used to open or close the SAI channel. The SAI pump is used to precisely control the amount of SAI flow to the exhaust system to ensure stable stochiometric (or lean) operation upstream the catalyst. Alternatively, a fully controllable valve "a" can also be used. Additionally, a reed valve is used to prevent any potential backflow from the exhaust to the intake system. Valve "b" represents an engine throttle.

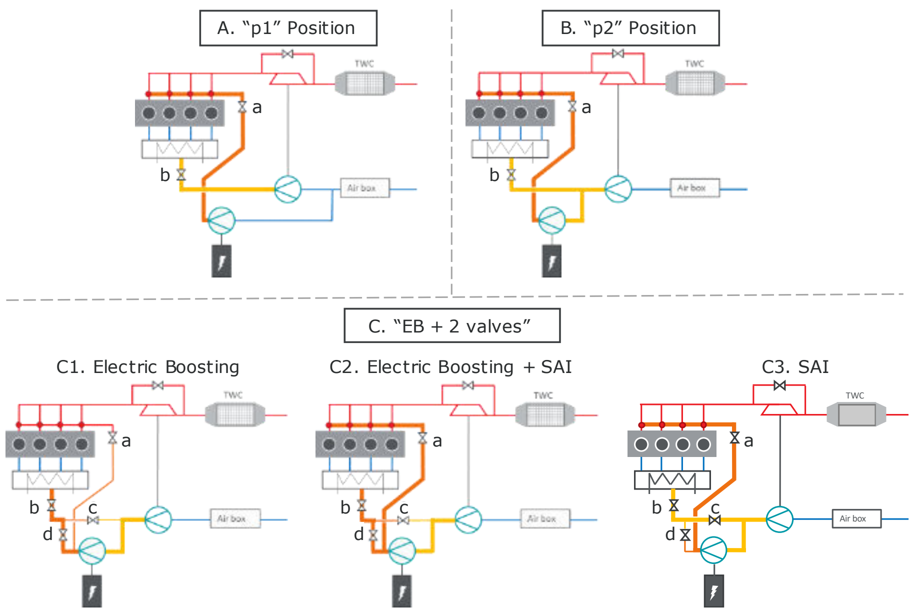

Figure 3: E-Compressor layouts

The pressure at SAI pump inlet is slightly lower than ambient pressure, due to the air filter losses. The pump needs to compress fresh air to a pressure level sufficient to compensate the pressure drop in the SAI channel & also the higher exhaust pressure. The "p1" position is therefore only suitable for low engine load applications with open wastegate. Higher loads and closed wastegate would lead to higher pressures upstream of the turbine and therefore higher demand on the pump's power and pressure ratio capability.

This configuration might not be capable of fulfilling ‘extended’ RDE boundary conditions (1). Dynamic driveaway events or PHEV engine starts at high loads could be particularly challenging and SAI could help shorten the time to catalyst light-off, as well as reduce raw NOx emissions through in-cylinder enrichment. To address such high engine load scenarios, two-stage compression can be used by including the turbo-compressor in the SAI path. This is especially convenient when placing the pump inlet at the turbo-compressor outlet which is named as the “p2” position. Although this layout imposes new challenges in terms of packaging and bearing sealing, the performance gain in terms of SAI operation range is significantly increased by running at higher pressure in the SAI channel. The “p2” layout (figure 3, B.) does not require additional valves in comparison to “p1” position. Furthermore, “p2” position can enable electric boosting by adding valve “c” (EB with one valve). To further optimize both electric boosting and SAI operations, one more valve “d” (EB with two valves) can be introduced. With this layout, three control strategies are possible: Electric boosting only (figure 3, C1.), SAI only (figure 3, C3.), and electric boosting with SAI combined (figure 3, C2.).

For electric boosting, control valve “c” needs to be placed downstream of the branch point leading to the pump. Valve “c” is an on/off valve that can be either electrically controlled or more conveniently, it can be a passive valve opened by a positive pressure difference upstream and downstream the valve. A passive valve is lower cost and is often more compact since it does not require an actuator. By closing the valve “c”, all the air compressed in main turbo compressor is forced to the SAI pump for second stage compression.

Electric boosting can also be used together with SAI, if valve “a” and valve “d” are opened while valve “c” is closed. In this case, the throttle controlling the engine power ensures that the compressors can deliver sufficient secondary air flow by limiting the engine transient response. This may result in increased calibration and control efforts but on the other hand, valve “d” is not mandatory for electric boosting nor SAI. The benefit of having valve “d” is to separate SAI channel from the engine intake manifold. It allows the same operation as “p2” when valve “d” is closed, and valve “c” is opened. This improves power requirements as well as controllability of the pump. It also prevents the throttle, charge cooler and intake piping from operating at relatively high pressure which is needed to drive enough SAI during high engine load operation.

Table 1: Comparison of SAI layouts

No.	Parameter	“p1”	“p2”		
		No EB	No EB	EB with one valve	EB with two valves
1	Packaging	++	+	0	-
2	Additional Valves	+	+	0	-
3	Power Requirement	-	++	+	++
4	SAI Operation Range	-	++	+	++
5	EB Capable	NA	NA	++	++
6	Controllability	+	+	-	+
7	Sealing	++	-	-	-
8	System cost*	+	+	0	-

**Assumption: SAI pump specification remains unchanged for all layouts*

4. SECONDARY AIR INJECTION WITH E-TURBO

Garrett's 48V 5kW$_{DC}$ E-Turbo is a series production proven solution that enables full engine map lambda 1 at high power density and offers transient performance improvement. It's also suitable and beneficial to be used as SAI pump to utilize the full advantage of the electric machine. Hence, this device was selected for more detailed SAI capability investigation through 1D simulations in chapter 5. As made reference to in chapter 2, E-Boosting devices such as the E-Turbo can help heating electrically heated catalysts heat up quicker. This operation is being investigated by Garrett in the course of ongoing test campaign within the EU project "PHOENICE" (4).

4.1. SAI LAYOUT WITH E-TURBO

As shown in figure 4, SAI can be realized with the E-Turbo by adding introducing a valve 'a' between the compressor outlet and the SAI path. Upgrading an existing ICE with an E-Turbo requires to increase turbine size to reduce p3. LET is then maintained by using the electric machine. This leads to reduced residuals, PMEP and improved SAI flow. Furthermore, compressor can be updated for high PR which further improves SAI flow, especially in high engine loads. The figure 4 shows possible SAI layout with an E-Turbo as well as comparison of envelopes of the baseline compressor with the E-Turbo compressor optimized for high load SAI operation.

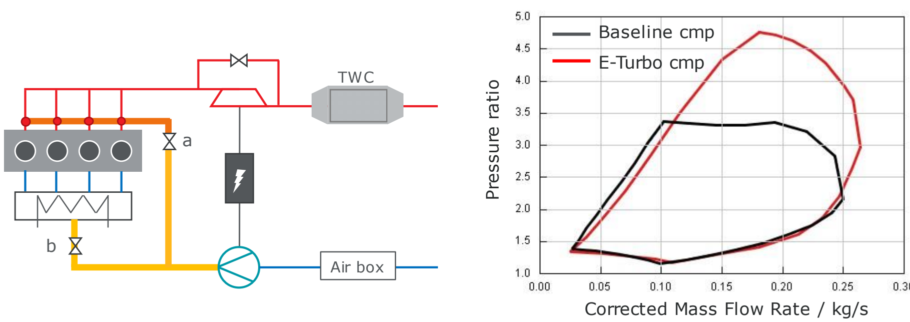

Figure 4: E-Turbo with SAI

4.2. SAI OPERATION WITH E-TURBO

E-Turbo SAI layout from the figure 4 requires 4 controllable parts to control the SAI flow and engine air flow: Wastegate; Throttle; SAI valve & E-motor

Control strategy of all these parts need to be adapted during the SAI operation to prioritize sufficient and stable SAI flow. From previous investigation on SAI with E-compressor (5), it was discovered that it is beneficial for SAI flow to operate with closed wastegate. The downside of increased p3 is outweighed by elevated p2. This was also confirmed in the case of E-Turbo via simulations.

The throttle strategy is to control the engine performance, although the priority during transient operation needs to be the SAI flow. Therefore, acceleration during engine cold start which is enhanced by the EB machine must be limited. The full throttle opening leads to reduced secondary air pressure while p3 increases. This leads to reduced SAI flow even if SAI valve and E-motor is saturated at their maximum limit. This is also the case for E-compressor in "EB plus one valve" layout. The "p1" and "p2" layouts don't offer EB functionality and therefore the acceleration is not as fast. But since their SAI channels are separated from the engine intake system, this allows higher secondary air pressure than throttle inlet pressure.

The SAI flow itself can be controlled in two ways. If an on/off SAI valve is used, then E-motor controls the SAI flow through regulating the SAI pressure. If fully variable SAI valve is used, then the E-motor can be controlled to its maximum power. SAI valve then regulates the SAI flow.

5. SAI OPERATION – E-COMPRESSOR VS. E-TURBO

The following sections are dedicated to the comparison of SAI performance with E-Compressor and E-Turbo through 1D simulation results. Chapter 5.1. describes the simulation model configuration and its boundary conditions. Steady state results in chapter 5.2. show comparison of expected engine map coverage of SAI with E-Compressor and E-Turbo, as well as maximum achievable engine power with SAI for different SAI layouts. Transient SAI performance comparison is simulated on RDE acceleration to full-load power in section 5.3.

5.1 BOUNDARY CONDITIONS – E-COMPRESSOR VS. E-TURBO

A 1D gas-exchange simulation model was setup in GT-POWER for comparing Garrett's 48 V 7.5 kW_{DC} E-Compressor in "EB plus 1 valve" layout with Garrett's series production 48 V 5 kW_{DC} E-Turbo. The scenario is an upgrade of an existing engine to become EB capable and high load SAI capable with minimum hardware changes. Therefore, the baseline TC was carried over for simulations with E-Compressor, while updated wheels were used for the E-Turbo. The E-Compressor is capable of 90 krpm and uses high flow "performance" wheel.

The baseline model for the simulations is a 4 cylinder, 2.0L TGDI engine adapted for SAI application. The secondary air channels in the cylinder head are connected to the exhaust ports and the diameter of the secondary air passages is limited, so that the structural integrity of the cylinder head is not compromised. This leads to a high pressure drop of 650 mbar at 100 kg/h of steady state flow. Standard ambient conditions and steady-state temperature solver (instead of transient) were used in the simulations, which results in higher temperature in both, intake and exhaust geometry, leading to higher volumetric flows and therefore higher pressure drops. This can be considered as a conservative approach for the SAI performance. The 50% burn point is retarded to 30°ATDC for oxidation stability in the exhaust system (6) as well as to increase enthalpy to improve catalyst light-off time. However, combustion optimization on the testbed is required to get a full MFB50% map for SAI operation. Retarded combustion leads to a higher air mass flow requirement for the same load and therefore higher demand on SAI pump for the same in-cylinder enrichment. The target for enrichment is lambda = 0.8, which corresponds to secondary air mass flow of 25% compared to the main engine flow.

All the boundary conditions for the simulations are listed in Table.

Table 2: Simulation boundary conditions

No.	Parameter	Description
1	Engine	2.0TGDI, 4 cylinders, 20 bar BMEP, 135 kW
2	Temperature solver	Steady-state wall temperature solver
3	EATS	Secondary oxidation model, TWC model
4	Ambient conditions	1 bar, 25°C
5	SAI channel Δp	650 mbar at 100 kg/h steady flow (flow bench)
6	SAI Layout	"EB plus 1 valve" and E-Turbo
7	SAI Valve	On/Off
8	SAI Pump	E-Compressor and E-Turbo
9	SAI Control	Compressor speed, SAI valve fully opened
10	Electrical efficiency	85%
11	Combustion strategy	MFB50% = 30°ATDC (retarded)
12	Valve phasing	Advanced exhaust valve opening
13	Wastegate strategy	Closed
14	Turbocharger(TC)	Twin scroll baseline / E-Turbo (optimized wheels)

5.2 STEADY STATE SIMULATIONS – E-COMPRESSOR VS. E-TURBO

The following study is a steady-state comparison of maximum engine load which can be achieved with 25% of SAI with using E-Compressor and E-Turbo. The figure 5 shows maximum achievable BMEP with SAI up to engine speed of 4000 rpm. The E-Turbo is capable to support the engine with SAI to full load operation up to ~3000 rpm. At 4000 rpm, 25% of SAI can be achieved up to 14.4 bar BMEP. The E-Compressor covers slightly smaller area by ~2 bar BMEP at 3000 rpm and ~1 bar BMEP at 4000rpm compared to the E-Turbo, even with the power advantage of 2.5 kW. This is caused by the difference between baseline TC wheels and E-Turbo wheels. While the baseline TC needs to start opening the wastegate from 3000rpm to stay within its compressor speed limit, the E-Turbo keeps the wastegate closed and the p3 is still significantly lower due to the high permeable turbine.

The figure 5 also shows all the described SAI layouts in terms of maximum achievable power with 25% SAI. While the E-Compressors are using 7.5 kW_{DC} peak e-motor and baseline TC, the E-Turbo uses 5 kW_{DC} peak machine and optimized wheels.

- The layouts "p1" and "p2" use the dedicated SAI wheel as these layouts are not EB capable.
- The "EB plus 2 valves" also uses the dedicated wheel and therefore offers transient support only in low engine speeds.
- The results show that "p1" is not a suitable layout if high load SAI operation is required.
- "p2" benefits from pre-compressed air from the main compressor and achieves the best SAI performance.
- "EB plus two valves" brings the full benefit of "p2" layout and offers EB capability.
- The E-Turbo and E-Compressor in "EB plus 1 valve" layout offers the best EB capability but with slightly lower SAI performance, especially at high engine speeds and loads.

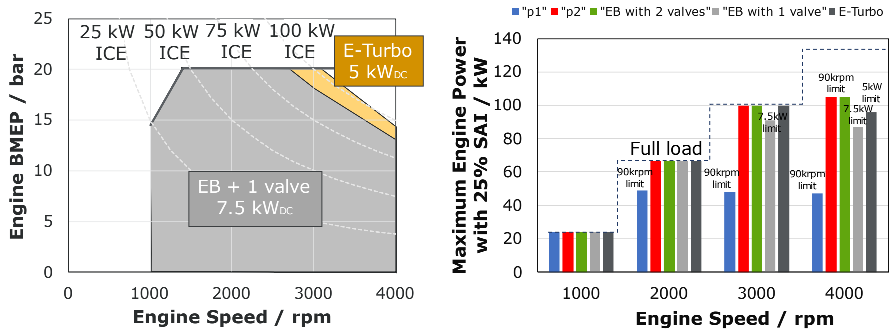

Figure 5: Maximum ICE steady-state achievable performance with 25% of SAI

5.3 TRANSIENT SIMULATIONS – E-COMPRESSOR VS. E-TURBO

As discussed in chapter 2, SAI operation under RDE conditions is essential. Hence another part of the comparison of E-Compressor and E-Turbo is a transient driveaway scenario with SAI operation. The boundary conditions are as in table 2 with a few exceptions. The E-Motors are requested to run at peak transient power and the secondary air mass flow is controlled by an SAI valve. MFB50% is targeted for optimal combustion and drivability. A transient wall temperature solver to predict the warm-up behavior was used, with an initial temperature of 25 °C. An in-cylinder lambda of 0.8 is targeted and is switched to stochiometric combustion if lambda upstream catalyst drops below 1. This condition also triggers SAI operation shut-off. The in-cylinder lambda behavior in figure 6 is an indicator of how long E-Compressor and E-Turbo sustain requested SAI mass flow. The driveaway scenario with SAI can be supported by E-Compressor for around 3.2 s, reaching engine power of around 106 kW. This is more than the steady-state results show and it's caused by the transient temperature solver and optimised combustion used for this study.

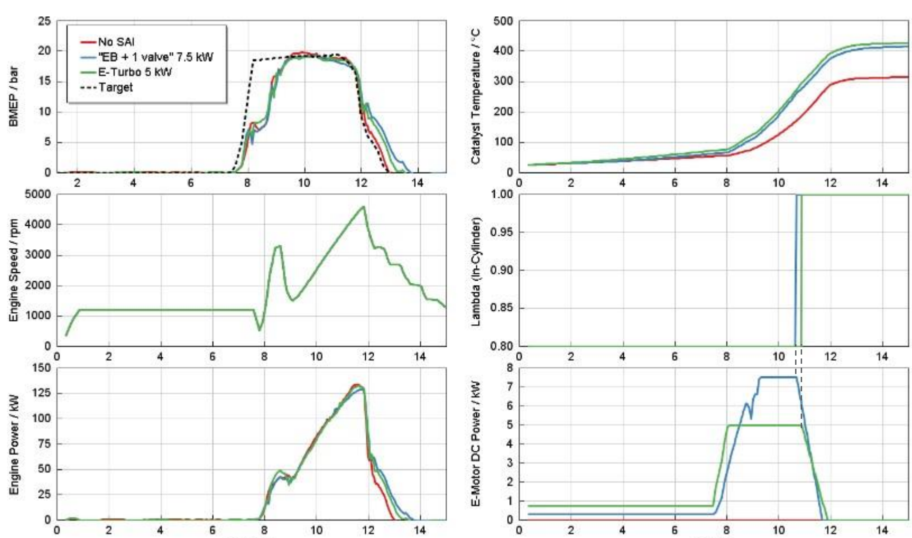

Figure 6: RDE acceleration to full load with SAI

The E-Compressor can increase the temperature by 100° C by the end of the maneuver in comparison with acceleration without SAI. The E-Turbo can support SAI operation 0.2 s longer, achieving engine power of around 114 kW and increasing the catalyst temperature by another 12° C by the end of the maneuver in comparison with the E-Compressor. During this driveaway event, NOx emissions are reduced by 6 times due to SAI. Even higher engine powers with SAI are possible by optimizing the pressure drops in the system, such as in the SAI channel and SAI valves.

6. CONCLUSION

Future emission norms will focus on reduced engine idling times and more aggressive driveaway scenarios to further limit the cold start emissions of gasoline engines in all geographies. Europe will likely lead the way with EU7 and RDE (over extended boundary conditions) and will be followed by China VII and revisions to SULEV standards in the USA.

Garrett's simulations suggest that while the current SAI pumps in the power range of $800W_{DC}$ to $1kW_{DC}$ do a good job for applications homologated to the current SULEV norm, where a 20s idle warm up is allowed, this will not be satisfactory in the future.

Both 7.5 kW_{DC} E-Compressor in "EB plus 1 valve" layout with the baseline TC and 5 kW_{DC} E-Turbo with optimized wheels are capable of similarly significant reduction of catalyst light-off duration by maintaining SAI even at high engine load and speed operation. The E-Compressor performs very well even with the baseline TC with low PR compressor and relatively low permeable turbine. We can expect even better SAI performance with optimized baseline TC. The E-Turbo on the other hand takes full benefit of optimized wheels and delivers similar SAI performance as the E-Compressor with lower maximum power needed.

NB: This paper is based on simulation studies and the findings are being tested in a vehicle environment at the time of writing this paper. The authors look forward to presenting actual test results at a future date. All simulations presented here were also performed at sea-level ambient conditions. This study will be extended to high altitude conditions in the very near future, but logic and initial investigations suggest that the SAI compressors would have to operate at even higher powers and duty cycles under such aggravated conditions.

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