Benefits of a Driven-Turbo for Hydrogen Internal Combustion Engines

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Abstract: Restrictive future CO_2 emission regulations are incentivizing evaluation of carbon-free fuels. This is particularly true in the difficult to electrify heavy commercial vehicle segment. The reemergence of hydrogen internal combustion (H_2 ICE) for large displacement engines can both expedite hydrogen adoption and reduce total cost of ownership. This paper will cover how the application of a SuperTurbo can address challenges unique to H_2 ICE. The research being presented is joint simulation conducted by AVL List GmbH and SuperTurbo Technologies on a 13L H_2 ICE. The GT Power model is calibrated from dyno testing at AVL of an operational engine and then modified with known and tested data from a mechanically variable SuperTurbo. The first H_2 ICE challenge that will be addressed is the requirement for the engine to maintain a lean-burn combustion strategy. Maintaining H_2 lean-burn is key to controlling NO_x formation and minimizing aftertreatment requirements. The high lambda requirement can create challenges for turbocharges when available turbine power is insufficient for the desired compressor power. The on-demand air functionality of the SuperTurbo negates this problem and can be used to optimize air-fuel ratio in steady-state and transient cycles. The simulation will show low NO_x formation through combustion optimization and time to torque transients equivalent to diesel. The second H_2 ICE challenge that will be addressed is how to maintain highest BMEP and BTE for hydrogen internal combustion engines with a SuperTurbo in order to close the gap to diesel and FCEV respectively. The availability of SuperTurbo enabled exhaust energy recovery through turbo-compounding, in combination with combustion optimization, will demonstrate an ability to improve H_2 ICE BMEP/BTE/BSFC

Key Words: SuperTurbo; H_2 ICE; Lean; Compound; Supercharging, Hydrogen; NOx, WHTC

1 Introduction

The SuperTurbo is a mechanically driven turbocharger that has been developed for commercial diesel engines to improve efficiency, emissions and performance. When presented with the unique challenges for hydrogen as an engine fuel, it became apparent that the SuperTurbo could specifically address several of the challenges seen on these engines. *Rapid response and precise delivery of airflow can allow a H_2 ICE to maintain a desired air fuel ratio (AFR) throughout dynamic operating conditions.*

This paper will primarily focus on a study of the 13L engine operating with port fuel injection (PFI) and zero exhaust gas recirculation (EGR). Understanding the performance and limitations with this architecture is a key starting point, as it represents the most expedient and cost-effective approach to early implementation of H_2 ICE. This paper will cover the WHTC cycle analysis and then more specific studies related to steady-state maps and load step transients. The effects of adding EGR will also be discussed. The baseline evaluated for the study is a VGT, however ongoing analysis of alternative boosting systems will also be discussed.

High excess Air Ratio (or Lambda) is critically necessary to prevent an exponential rise in engine NOx emissions for hydrogen engines[5]. Figure 1 below shows this relation as tested on the AVL engine. *Holding an optimal Lambda prevents NOx creation and also can prevent unwanted hydrogen slip conditions often seen with excessively high Lambda*. The SuperTurbo, by design, is an on-demand air system that is well suited to consistently control ideal Lamba conditions. This paper will show the challenges faced by traditional turbochargers when exhaust enthalpy is not adequate to maintain high compressor power, especially in transient cycles.

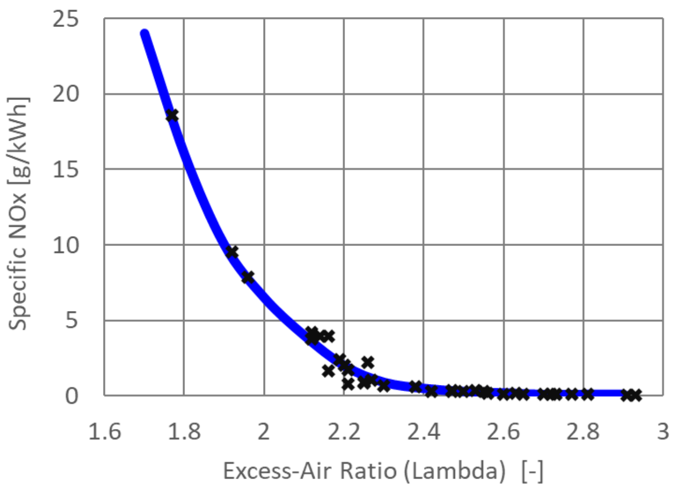

Figure 1: NOx vs Lambda from AVL 13L H2 ICE Testing

In addition to the problems created by the necessity to maintain lean-burn operation, there are several other areas that must be addressed for H_2 ICE. Reaching high BMEP levels is important for truck and equipment engines that require high relative power versus displacement. Maximizing BTE and BSFC to lower operating costs and extend vehicle range is also important.

2 Background

2.1 Engine and Model

AVL has successfully demonstrated the possibility to convert a 13L CNG heavy duty engine into a hydrogen engine.[4] The demonstrator has proved the feasibility to reach a BMEP of 21bar with BTE of 42% and single stage turbocharger. To achieve more flexibility on engine tests in view of boost pressure demands a turbocharger with variable turbine geometry was used.

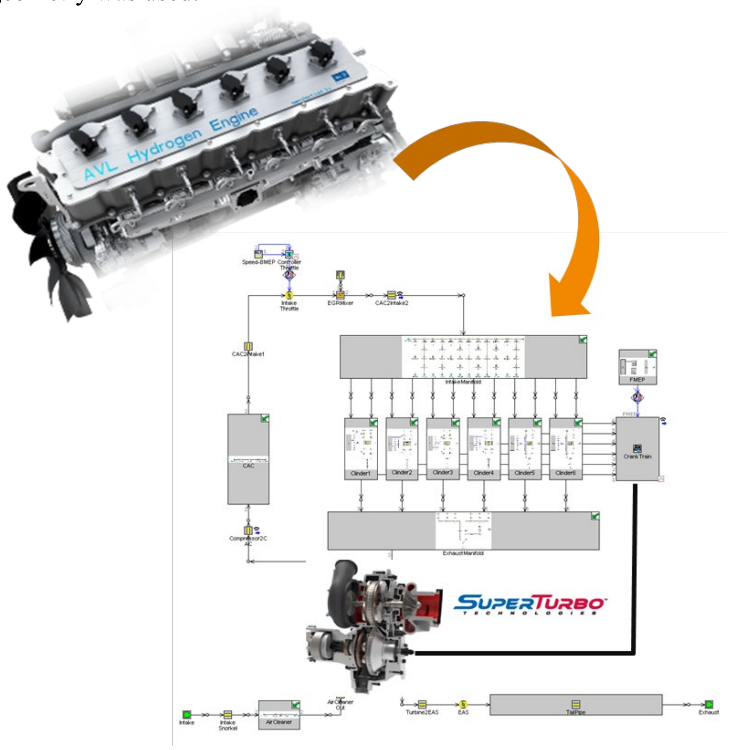

Figure 2: AVL 13L + SuperTurbo Engine Model

Table 1: 13L Baseline Engine Specification

Base Engine	HD IL6 CNG Application	
Properties	Unit	Value
Bore	mm	130,0
Stroke	mm	161,0
Volume/cylinder	ltr	2,14
Swept volume	ltr	12,82
Charging System	-	Single Stage TC / Intercooled
EGR System	-	Cooled high pressure

In order to show the benefits of the SuperTurbo technology on a hydrogen engine, investigations by means of 1D simulation were performed. A GT-Power (GTP) engine model with H2 combustion (MPI gas injection) was created and *calibrated to AVL's hydrogen engine test results*. This simulation model was the baseline for the investigations with the SuperTurbo charging technology. The model can calculate a complete engine map (from full load to low engine load of 4bar BMEP) for the investigation of different charging concepts. The hydrogen combustion is modelled based on test data and AVL experience. An engine data based NOx emission prediction is applied.

2.2 SuperTurbo

The SuperTurbo designed for commercial vehicles covers an engine displacement range from 7L to 15L. It combines and improves upon the capabilities of a supercharger, turbocharger and turbo-compounder. The internal components are common across this range while the turbine and compressor designs are changed based upon the individual engine requirements. With 90% part commonality, the device is designed to economically scale and cover most of the heavy commercial industry. *In order to maximize benefits, this large SuperTurbo is specified with a continuous power limit of 30 kW (primarily for compounding) and an instantaneous power limit of 50kW (primarily for supercharging).* The SuperTurbo is designed to mechanically integrate with the engine through connections at either the PTO or FEAD. The mechanical connection includes a controlled clutch and torsional damper. The core components or subassemblies are designed as cartridge-like units that are contained in a common housing. The two core components are the speed reducing fixed ratio planetary which controls the turbo shaft and the CVT which allows for overall ratio adjustment[8]. The primary control centers around delivering precise boost pressure and MAF. While following air commands the SuperTurbo will be supercharging when turbine power is less than compressor power (example: transient) and likewise compounding when turbine power exceeds compressor power (example: highway cruise or higher engine power).

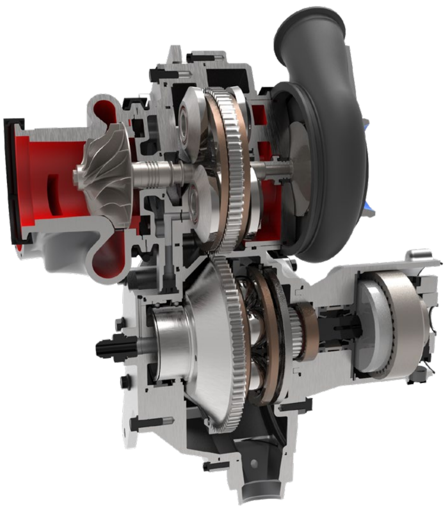

Figure 3: SuperTurbo cross section

3 WHTC Simulation Results

With future regulations focused on cycle-based compliance, the most important simulation result from this study is the comparative World Harmonized Transient Cycle (WHTC). Figure 4 shows a comparison of the VGT (from both engine test and calibrated simulation) with two different SuperTurbo control strategies. Future NOx regulations (Euro7, China7, CARB, EPA) [1,3] are focused on ultra-low NOx emissions and hydrogen engines will need to meet or exceed the most stringent standards.

The peaks of instantaneous NOx output during WHTC transient sections with the VGT highlight a fundamental challenge. Holding high Lambda during transient sections is difficult given available turbine power in comparison to desired compressor power. This results in large peaks of NOx creation as shown in Figure 4. The accumulated NOx is also shown in total grams through the cycle.

The SuperTurbo was simulated with two different control strategies. The 'recovery' cycle as shown in blue emphasizes turbo-compounding and has less aggressive Lambda targets and supercharging response. The 'boosting' control strategy emphasizes aggressive supercharging response and higher Lambda targets to eliminate cycle NOx peaks. These strategies were controlled by adjusting minimum Lambda constraints as well as targets with the SuperTurbo controller.

Also shown in Figure 4 is the total WHTC cycle work performed by the VGT and the two different SuperTurbo control strategies. This metric will translate to vehicle driveability. As could be expected, access to supercharging power will increase cycle work for a given Lambda. For an H_2 ICE equipped with a SuperTurbo this increase in cycle work does not come with a correlating NOx penalty, as high Lambda values are maintained through the cycle. If the VGT was pushed to increase cycle work, it would require a drop in Lambda and correlating rise in NOx.

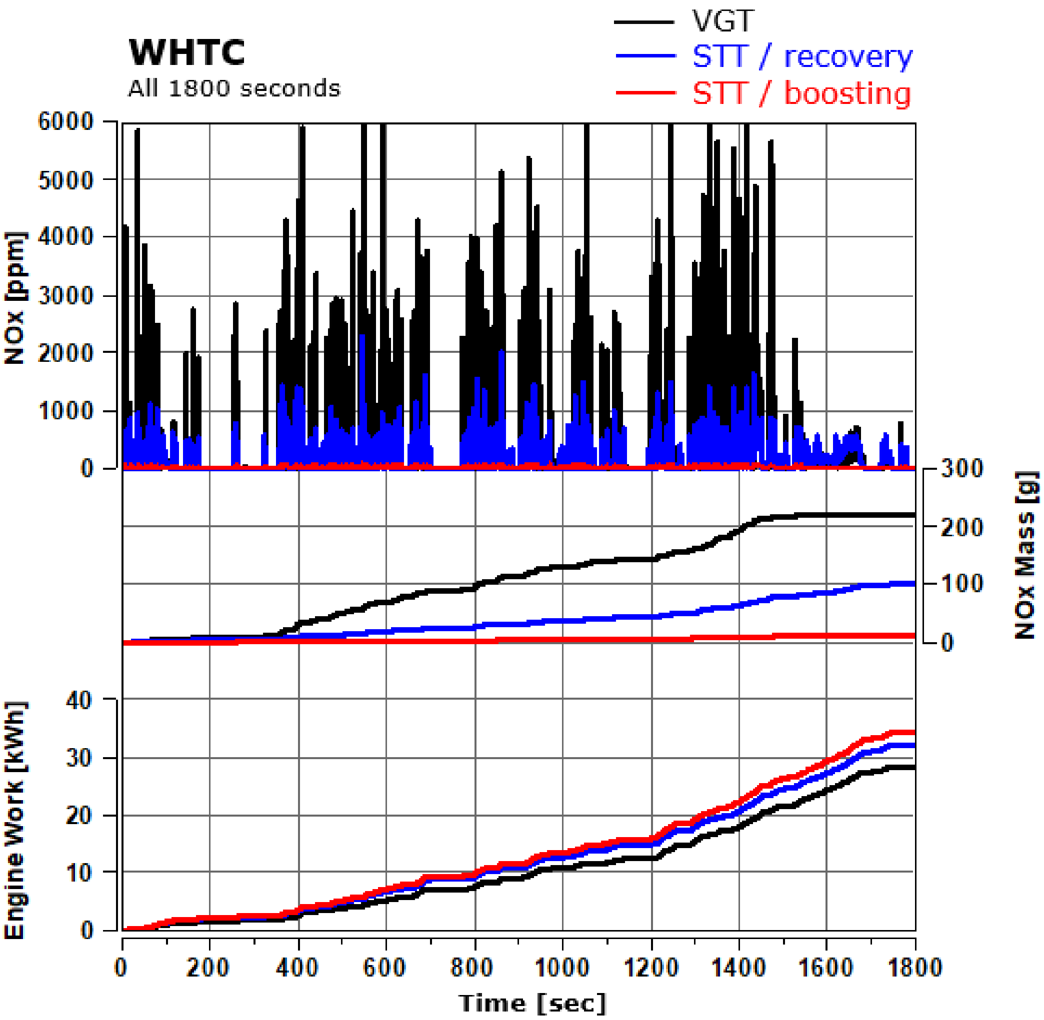

Figure 4: Comparative WHTC NOx and Engine Work

Access to supercharging power has demonstrated the ability to lower NOx and increase transient response + engine work. It could be assumed that pulling supercharging power from the engine would have a negative net effect on engine efficiency. However, this simulation, and subsequent OEM analysis has shown that efficiency actually improves when utilizing the SuperTurbo in the more aggressive 'boosting' mode. When supercharging the SuperTurbo is only taking power from the engine to overcome inertia and compensate for inadequate turbine power. The turbine is still actively feeding the transient rise and thus the SuperTurbo is combining exhaust power and crankshaft power to 'efficiently' supercharge.

Table 2 below shows a summary of NOx emissions and fuel consumption through the WHTC for the different boosting systems and strategies. It is not surprising that more boosting equates to higher Lambda and thus lower NOx. *Interestingly, more boosting from the SuperTurbo also equates to the lowest fuel consumption.* This higher efficiency comes from several sources. The SuperTurbo does turbo-compound through much of the cycle, which mostly negates the cumulative supercharging power draw. The maintenance of lean-burn conditions keeps temperatures lower and reduces heat transfer. Most importantly the control over AFR facilitates improved combustion and closed cycle efficiency. In cylinder efficiency should be the primary objective for air handling and is fundamental to on-demand air systems like the SuperTurbo.

Table 2: WHTC BSNOx and BSFC

	BSNOx [g/kWh]	BSFC [g/kWh]
VGT	7.8	85.4
STT / more recovery	3.1	83.1
STT / more boosting	**0.28**	**79.7**

Table 2 shows that conceptually the 'boosting' strategy applied to the SuperTurbo can result in Euro6 complaint NOx on the WHTC without aftertreatment. It is still advisable to consider an SCR for different cycles and real-world driving. Euro7 and similar standards will require NOx aftertreatment, although they could be significantly simplified with these low levels of engine out NOx.

To further understand what the SuperTurbo is doing through the cycle, Figure 5 outlines both the power and accumulated work of the device. The 'recovery' cycle with a less aggressive Lambda target has smaller supercharging power peaks and higher levels of turbo compounding. The net effect is >1 kWh recovered back to the engine over the cycle. The 'boosting' cycle with a higher Lambda target has large supercharging peaks into the ~35kW range and less compounding. Again, the SuperTurbo mechanical specification is 50kW of instantaneous supercharging power and 30kW of continuous compounding. The 'boosting' control strategy results in a more balanced, yet slightly negative total SuperTurbo cycle work. Given the overall results as shown in Figure 4 and Table 5, this appears to be the optimal strategy despite not having net positive compounding work, as the benefits to in-cylinder efficiency outweigh the drop in compounding work.

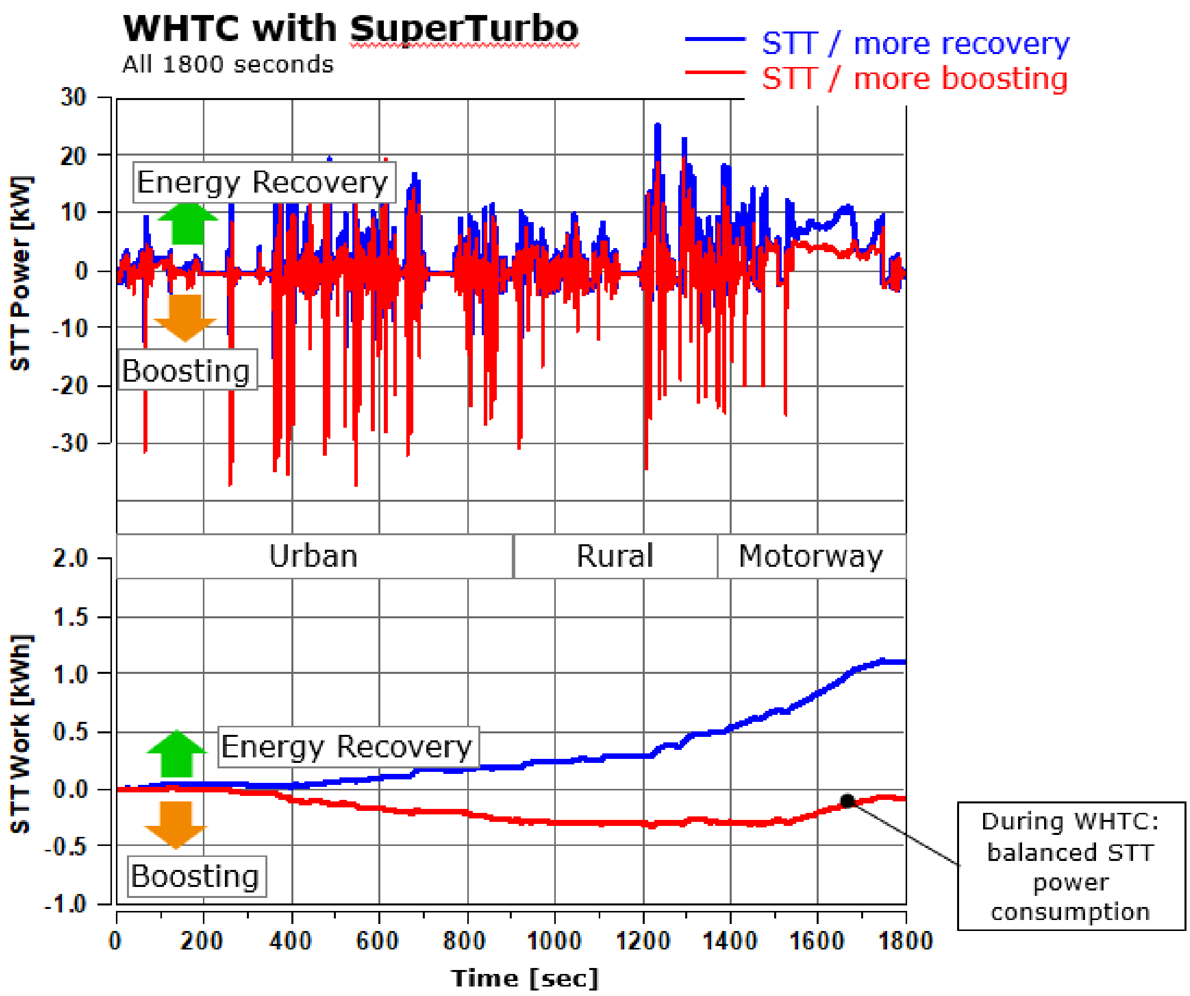

Figure 5: WHTC SuperTurbo Power and Work

To better understand the full cycle results, it's also necessary to analyse specific sections of the cycle in more detail. Figure 6 highlights the 460-488 second section of the WHTC. This section of the WHTC was chosen to highlight intensive gradient load increases. The result compares how the VGT and SuperTurbo respond with different Lambda limiters applied.

The VGT (as shown in black) has a Lambda lower limit applied at 1.8. Referencing back to Figure 1, this limit is justified as a minimal value for this engine, given the excessive NOx production at lower Lambdas. With that limit in place, the VGT struggles to follow the WHTC demand curve for BMEP. There are also large NOx peaks created when Lambda drops to that limitation. This result highlights the challenges when there is no access to external power, other than exhaust power, to increase boost pressure. Thus, the fundamental trade-off between engine response and NOx creation is more clearly shown for exhaust driven turbochargers.

The SuperTurbo (as shown in red) is able to apply a Lambda lower limit at 2.4. This higher Lambda limit results in near elimination of the NOx peaks in this transient section. Additionally, the SuperTurbo is able to better follow the BMEP demand trace of the cycle. This section of the WHTC as shown in Figure 6 is demonstrative of the full cycle results that were previously shown in Figure 4.

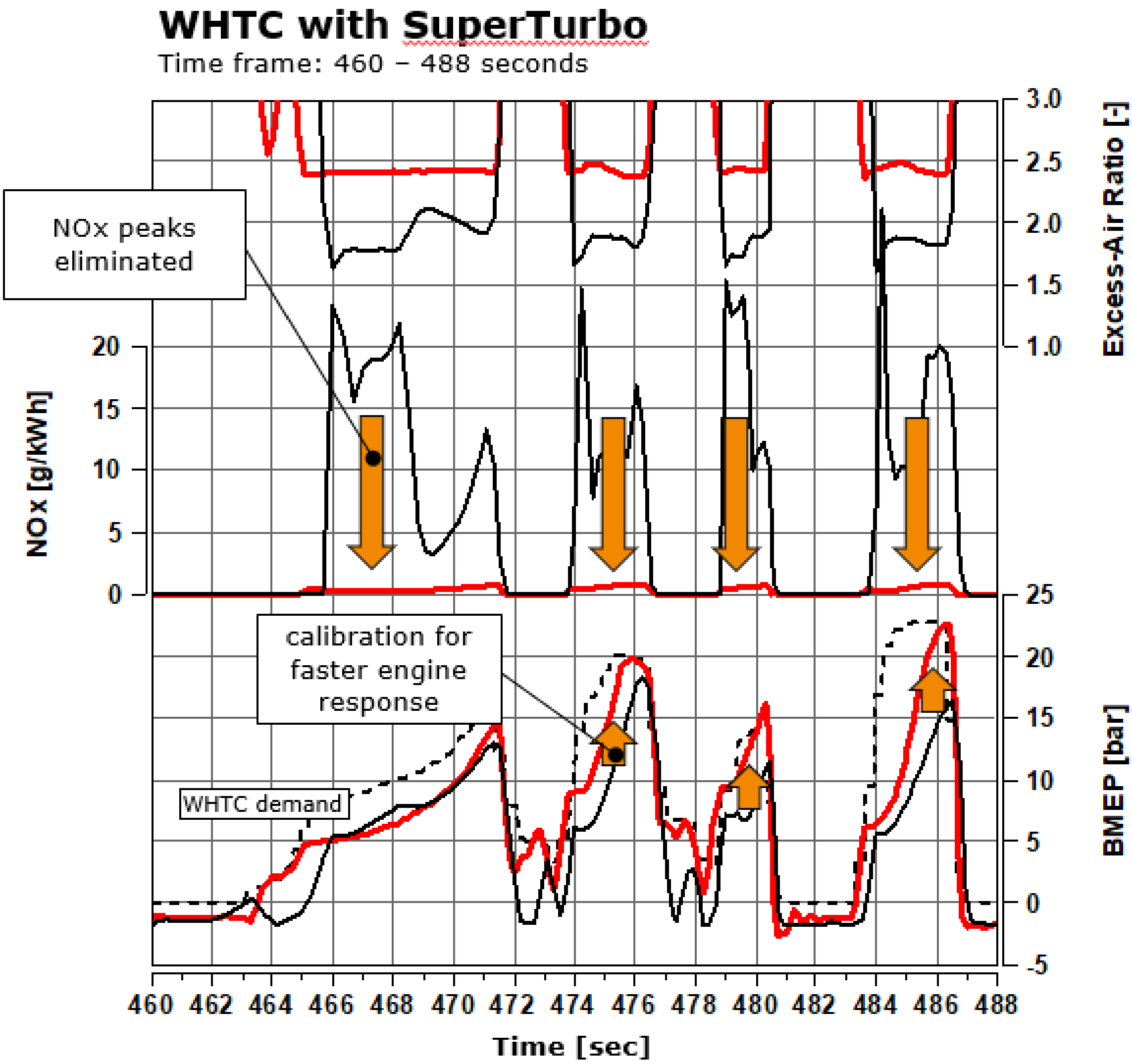

Figure 6: WHTC Transient Section

The conclusions drawn from the full WHTC H_2 ICE simulation are that having a driven-turbo like the SuperTurbo can:

- *Achieve ultra-low cycle NOx*
- *Improve total engine work and driveability*
- *Improve fuel efficiency*

4 Transient Simulation Analysis

The AVL and SuperTurbo project also included a variety of specific transient response evaluations, some of which will be shared in this paper. Looking at individual transients in more detail can be helpful to understand the full cycle results. The primary constraints and variables to balance against each other in transient scenarios are: Lambda limits, NOx creation, and torque/power response. Figure 7 below shows the VGT sensitivity to Lambda limits from 1.8 to 2.2 and compares them against the SuperTurbo at the highest 2.2 Lambda target.

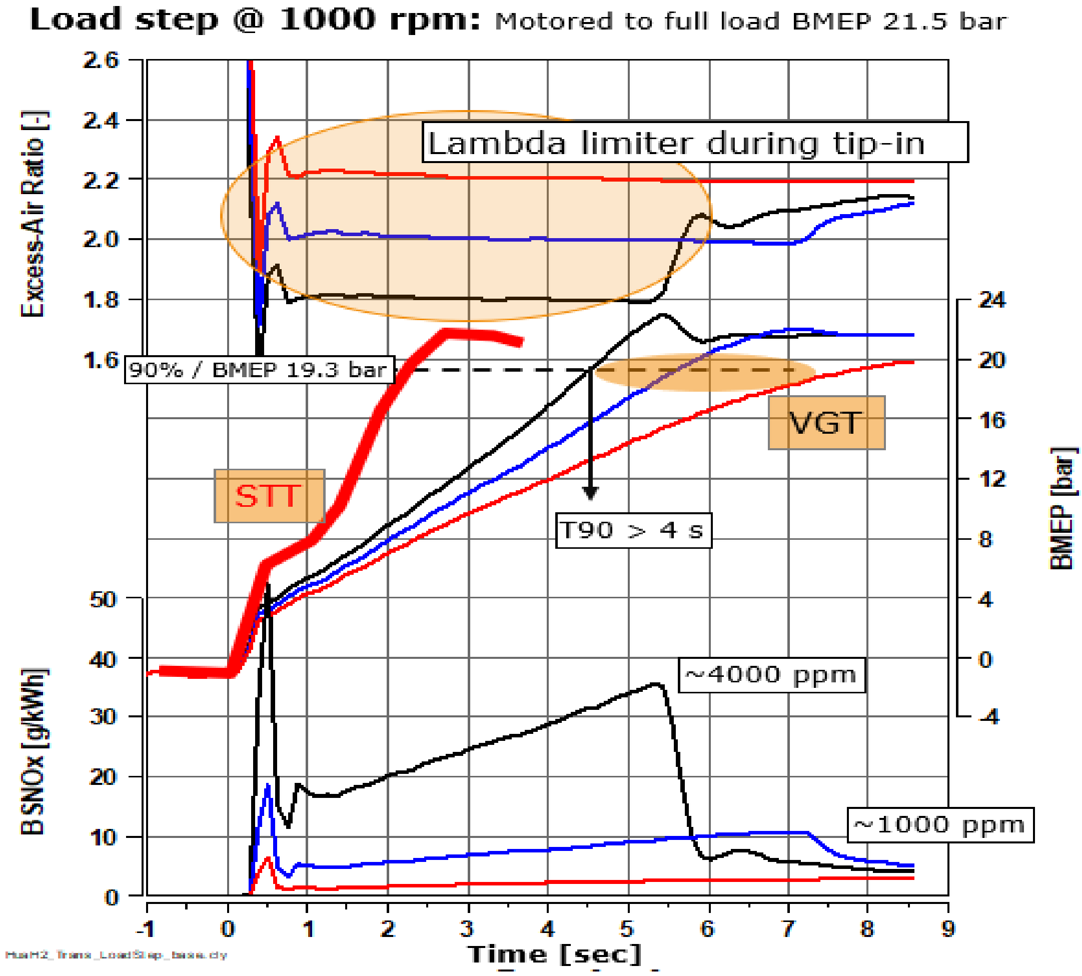

Figure 7: Variable Lambda transients VGT vs SuperTurbo

In these scenarios the SuperTurbo is able to hold a Lambda target of 2.2 and achieve time to 90% BMEP in 2.2 seconds. The VGT, with a similar Lambda target is stretched to an 8 second transient. Decreasing the transient response time of the VGT requires relaxation of the Lambda limiter which results in the expected rise in NOx creation. Further reduction of transient response to achieve SuperTurbo like response would result in unacceptable NOx levels.

Another transient sensitivity test was run just on the SuperTurbo and can be seen in Figure 8. In this scenario the time to torque/BMEP for the transient was held constant at ~2.8 seconds. For the SuperTurbo to meet this response time at Lambda 2.2 it requires ~13kW or supercharging draw. To push NOx down to significantly lower levels, the SuperTurbo can target a Lambda of 2.6, which would require ~32kw of supercharging draw. As the minimum Lambda limit is increased, the engine transient response does not suffer, as the SuperTurbo can simply compensate through increased supercharging power.

Analysis like these (and others) were completed to show both the flexibility and limits of a controllable driven-turbo. These results show how one can target a transient response time and adjust a NOx output within a given power limit (and correlating boost response) from an on-demand air system.

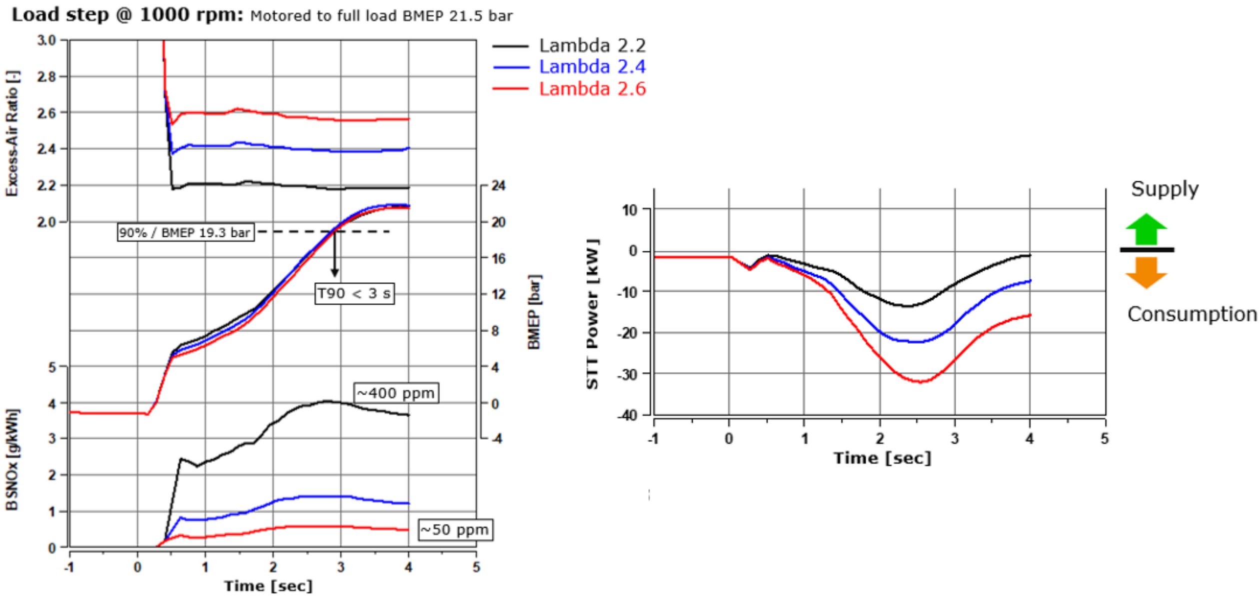

Figure 8: Utilization of SuperTurbo Power to Lower NOx

5 Steady State Analysis

Simulation of steady state conditions is fundamental to building the full drivecycle analysis and establishing those models. Properly matching turbine and compressor maps all begin in the steady state environment. The AVL + SuperTurbo simulation project included several iterations of different turbine and compressor options. The turbine design balances compounding power, pumping losses, turbine efficiency and pressure ratio (and ability to drive EGR if desired). The turbine can be designed to target compounding and efficiency at different engine operating points which then have correlating sacrifices at other points. Example: a more restrictive turbine will increase compounding power at lower engine power and speeds, but will have higher pumping losses at rated power. A more free flowing turbine will perform well at rated power, but not maximize exhaust power collection for on-highway cruise conditions. Since the SuperTurbo has reduced concerns over turbine weight and inertia and no concern for overspeed, it allows a different approach to efficient turbine design[7]. Compressor maps for H_2 ICE and their need for high Lambda operation are uniquely stressed. Single stage compressors need to maximize pressure ratio and mass flow to facilitate lean-burn along the lug curve, especially for high BMEP applications.

The tuning of the turbine and compressor maps for the AVL 13L engine were focused on the mid rpm ranges with power in the 75-100% range. Figure 9 below shows a comparison of BTE for the SuperTurbo vs. baseline VGT. Peak BTE gain aligns with maximum turbo compounding power, however turbine design was specifically modified to add benefits to areas central to on-highway vehicle operation. BTE benefits are the result of both compounded exhaust energy recovery and the ability to tune optimal air flow for combustion efficiency.

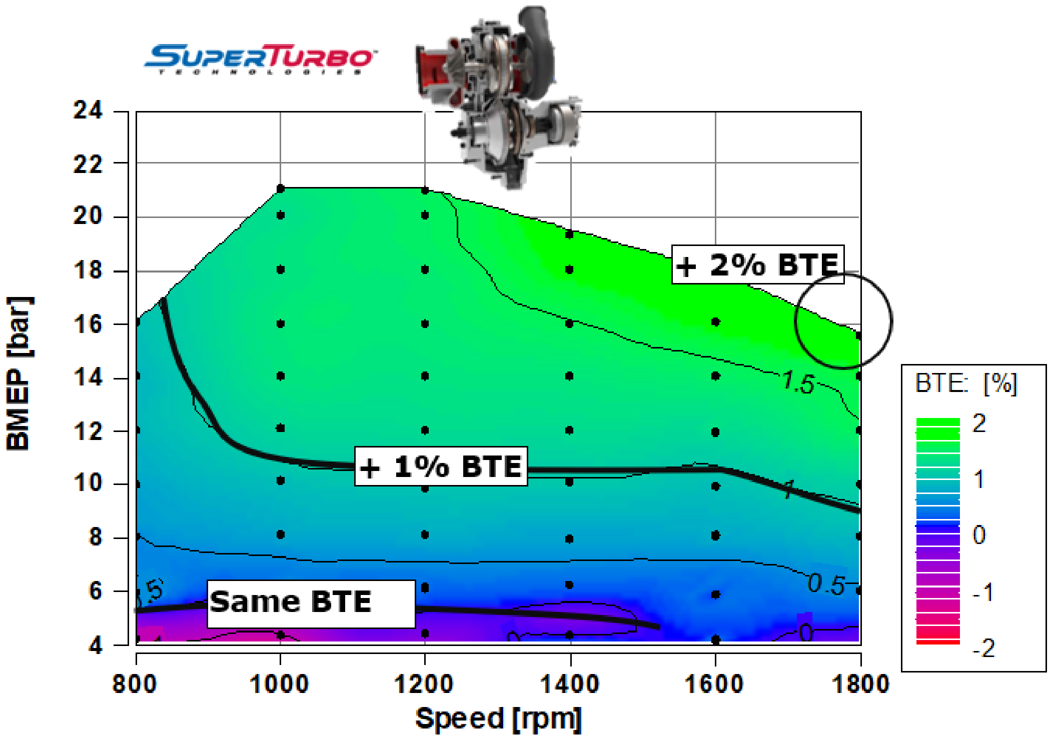

Figure 9: BTE Comparison of VGT vs SuperTurbo

Understanding the source of steady state efficiency gains also requires clarity on one of the unique functions of the SuperTurbo. The compounding of exhaust power back to the engine is predictable in the steady state environment, and obviously more dynamic in a transient cycle. The simulation study has shown that there is available exhaust enthalpy to create compounding conditions on the 13L hydrogen engine.

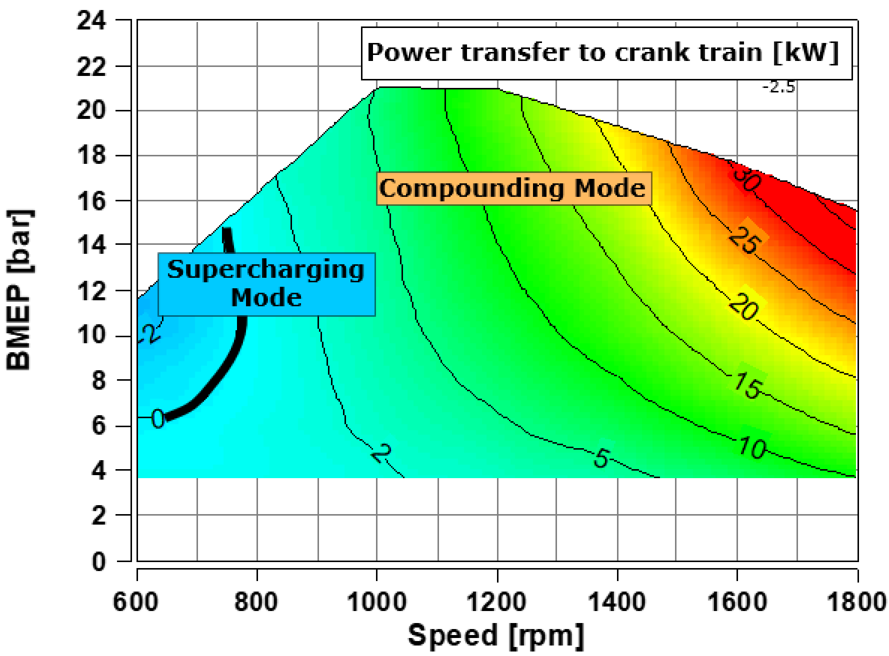

Figure 10: SuperTurbo Steady State Power

Compounding power will adjust according to several factors, among them: turbine efficiency, turbine pressure ratio and inlet temperature, required compressor power, SuperTurbo speed command, and several others. Figure 10 shows a steady state analysis of how the SuperTurbo is operating. High levels of compounding, as expected, occur in regions where there is significant exhaust energy. While in-cylinder combustion efficiency is always prioritized, the compounding effect can contribute significantly to overall engine efficiency. There are regions where upwards AFR adjustment can and should be made by accessing supercharging power. In the case of H_2 ICE, supercharging should be applied in steady state conditions requiring higher Lambda values not otherwise achievable with standard turbochargers. Low RPM and high load conditions can benefit from efficient supercharging (small adds to turbo power) to reach a more optimal AFR for both combustion and NOx creation.

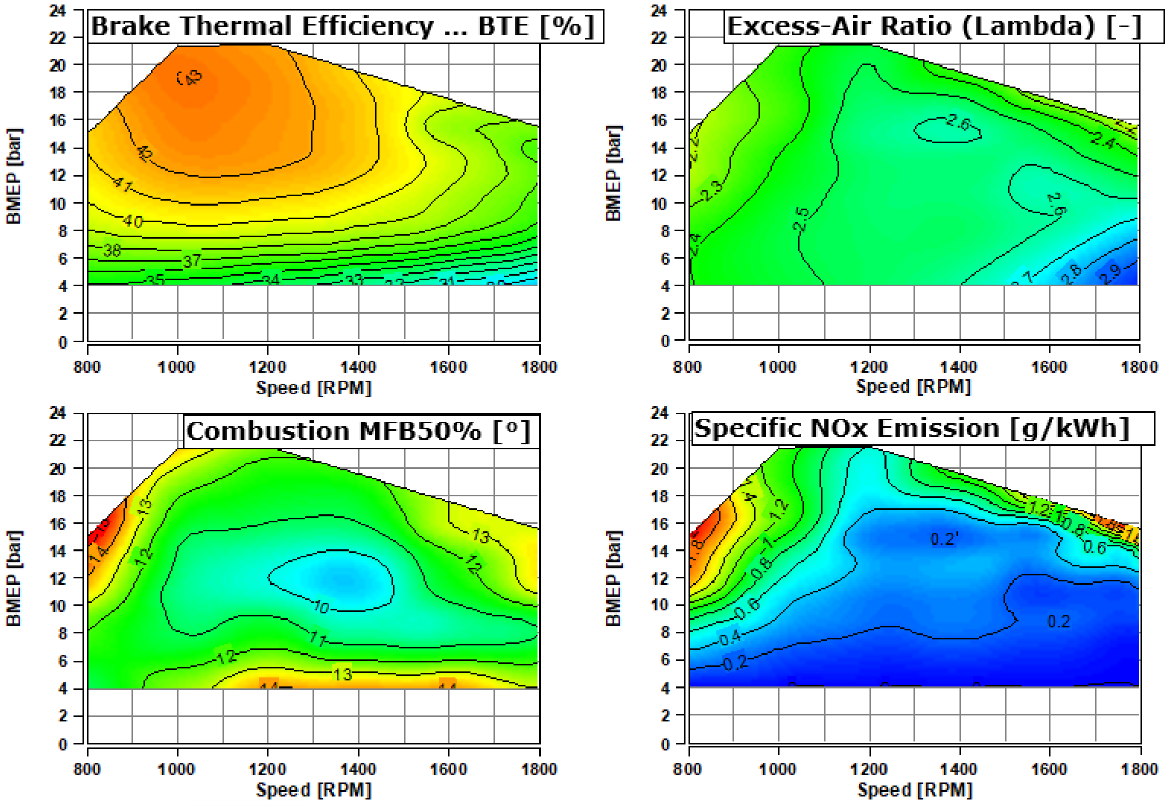

Figure 11: SuperTurbo Stead State Maps

As noted in section 2.1, the baseline VGT equipped engine had a peak BTE of 42%. The SuperTurbo steady state analysis broadened the efficiency region and improved it to 43% while also increasing the full load BTE as seen in Figure 9. Of course, these steady state results can be adjusted based on a variety of aero changes and specific strategies. Figure 11 contains steady state maps showing BTE, Lambda, MFB50, and NOx. Steady state Lambda is well controlled and lug curve NOx is low. However, it is always of note that steady state NOx is not the fundamental challenge for H_2 ICE. Transient cycle NOx is the paramount problem to be addressed.

All of the simulation results shown up to this point have been based on PFI with no EGR. By design this simulation project was focused on proven and tested architectures for H_2 ICE which could also translate to expedient implementation and low total system cost.

6 Additional Analysis

6.1 Two Stage Turbo

Two stage turbo (2ST) systems have advantages on H_2 ICE applications. They can create more total boost pressure and mass flow. This can aleviate concerns for Lambda control on steady state maps for high BMEP lug curves. Two stage turbos can also have small high pressure stages designed for rapid boost rise during transient response.

Two stage turbo systems will also have compromises when applied. High pressure stages will need waste gate and bypass control. Interstage cooling is required to maximize benefits, which is space consuming, complicated and expensive. Perhaps most important is the issue of aftertreatment temperature control. Two turbines with two heat sinks and two pressure drops will adversly affect aftertreatment inlet tempertures, especially during cold start operation.

Again, for H_2 ICE the focus should remain on transient and cycle performance. Figure 12 adds the two stage turbo into load step transient analysis with the VGT and SuperTurbo. In this analysis the Lambda limit is locked at 2.2 for all boosting systems. The two stage turbo outperforms the VGT in the simulation and shows better ability to capture available exhaust energy and provide a faster rise in airflow. BMEP rise for the 2ST is half that of the VGT and yet 2 times that of the SuperTurbo. The two stage system is not capable of reaching the diesel response region at this Lambda limit. The 2ST struggles significantly with a transient 2.4 Lambda limit that is not an issue for the SuperTurbo.

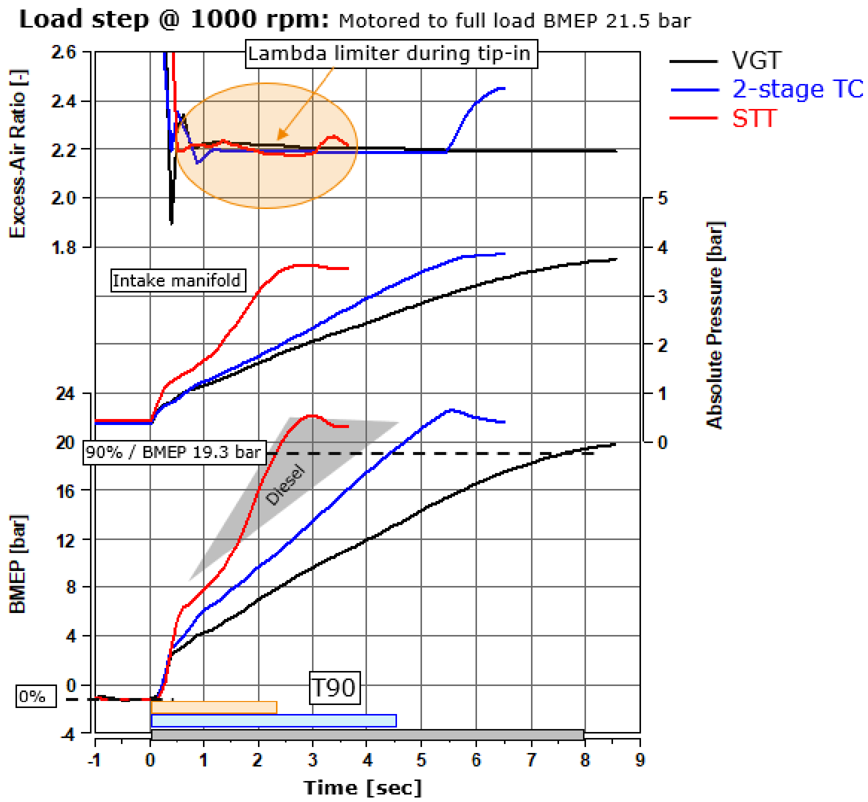

Figure 12: SuperTurbo vs VGT vs 2ST Transients

While the SuperTurbo was able to run the full WHTC with a Lambda target of 2.4, the two-stage turbo again shows compromises similar to the VGT. This echoes a fundamental lack of energy in the exhaust to power the boosting needs of H_2 ICE lean burn.

Figure 13 shows the effect and sensitivity of the 2ST when asked to move into torque response ranges equivalent with today's diesel engines. An attempt to decrease transient response to ~3 seconds results in a large spike in NOx creation. Conversely any attempt to have the 2ST match the SuperTurbo transient Lambda of 2.4 would equate to an elongated BMEP response.

The general conclusion from the studies to date is that H_2 ICE boosting systems would be most effective with access to additional supercharging power for air compression.

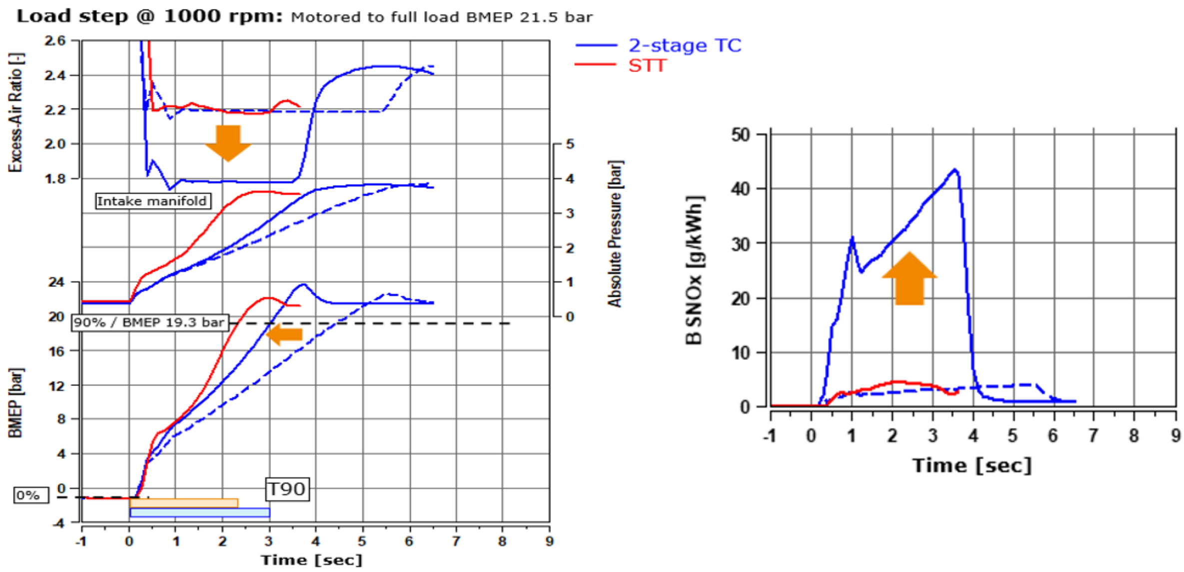

Figure 13: Two Stage Turbo Compromise

Additional boosting solutions are being developed and evaluated. Electrified turbochargers can fundamentally perform the same function as the mechanically driven SuperTurbo. Refer to Figure 5 for simulated power requirements to estimate the specifications (power/voltage/current) that would be required to duplicate the results. Electrified superchargers in combination with a secondary turbocharger could potentially challenge these results and are under evaluation. The electric compressor power/voltage and the system state of charge will be of prime concern.

6.2 System Costs

Total H_2 ICE system costs can be lower with a driven turbo like the SuperTurbo. The SuperTurbo is more expensive than a VGT alternative, but a fully compliant engine and Exhaust Aftertreatment System (EAS) can be a lower total cost. Figure 14 below shows the AVL estimate of EAS component reduction for future European emission compliance.

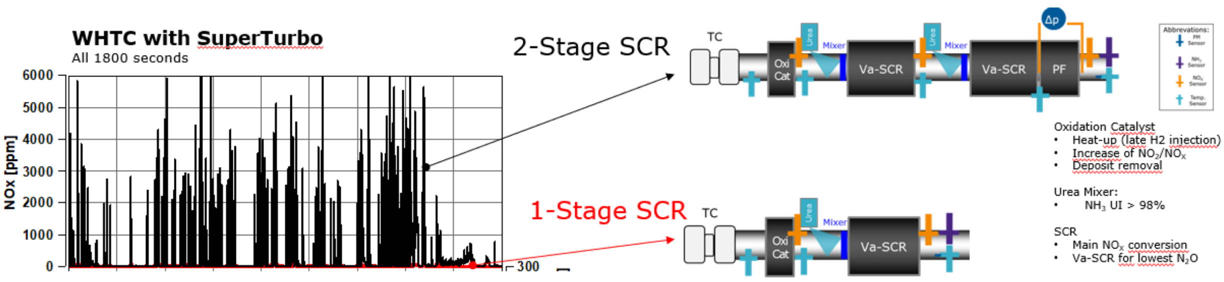

Figure 14: AVL Estimate of EAS requirement

This study proposes that H_2 ICE system architectures can be produced in the near future at a low net cost and technology risk. This includes PFI, No EGR, and a downsized SCR based EAS. There is also no requirement to the change the electrical architecture for mild or high voltage electrification or hybridization of the vehicle.

An acquisition cost study has been completed that consolidates and evaluates all options to produce an H_2 ICE system that includes options for fuel injection, air handling, EGR and electrified components. Fort H2 ICE there are opportunities to lower the total system cost by investing in air management as a key

6.3 Boosting Option Comparisons

Following the detailed comparison of the mechanically driven turbo to the baseline VGT, the simulation analysis is progressing to include a variety of boosting options for H2 ICE. Figure 15 shows a current example of comparing boosting choices with key considerations for H2 ICE. The background assumptions and resultant simulation data plus costing data used in these comparisons will be topics for upcoming papers and presentations.

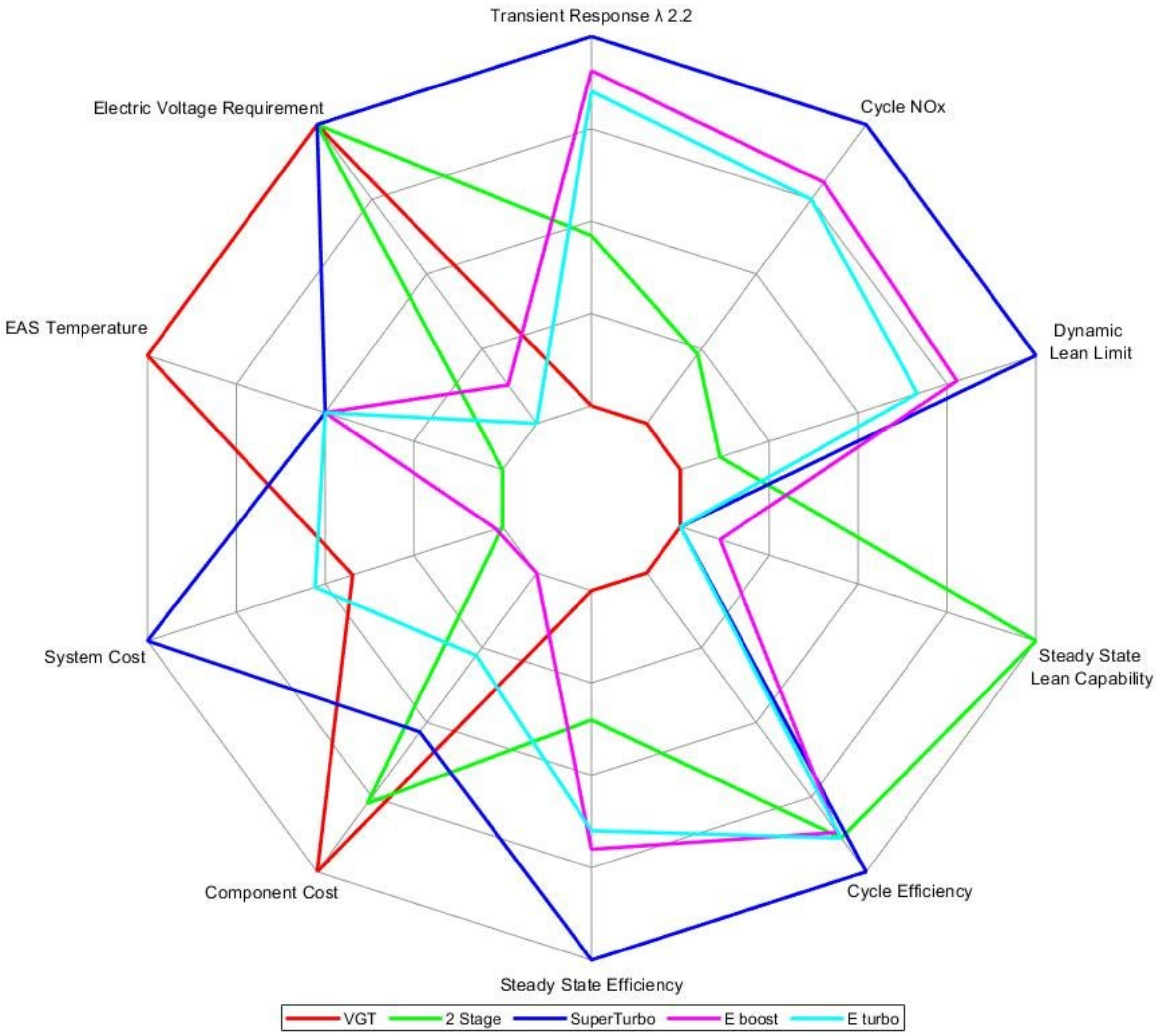

Figure 15: Boosting Options Spider Chart

7 Summary and Outlook

The results presented here are select portions of current knowledge developed over a year of joint simulation efforts by SuperTurbo and AVL on hydrogen combustion. The conclusions of the work is that a mechanically driven turbo with SuperTurbo specifications shows:

- *Faster, Diesel-like torque build up can be achieved, even at high Lambda*
- *NOx peaks during acceleration can be fully eliminated*
- *Significant raw NOx reduction towards EURO VI emission requirements can be demonstrated*
- *Simplifications in the EAS system are feasible (single stage SCR, less Urea consumption)*
- *Lowest fuel consumption in the WHTC is achieved*

Several H2 ICE hardware testing projects are planned or underway for 2023. Beyond OEM test programs, the SuperTurbo and AVL teams will also be validating the simulation data presented in this paper with a dyno test in Graz. Additionally, the SuperTurbo is a key component of the Class 8 H2 ICE vehicle demonstration program underway with an industry consortium as Southwest Research Institute (SwRI).

The SuperTurbo diesel product is currently undergoing accelerated DVP testing at SuperTurbo test cells as well as Detroit (Livonia) test sites with Linamar/McLaren. Linamar is the contracted production partner for the SuperTurbo and commercially available product will be in 2024/25.

Linamar/McLaren-Livonia SuperTurbo-Colorado

Figure 16: SuperTurbo DVP Test Execution

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