

# Evaluation of System Configurations for Downsizing a Heavy-Duty Diesel Engine for Non-Road Applications

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## ABSTRACT

In recent years there has been a successful application of engine downsizing in the passenger car market, using boosting technologies to achieve higher specific power and improve fuel economy. Downsizing has also been applied in heavy-duty diesel engines for the on-highway market to improve fuel economy, motivated in part by CO<sub>2</sub> emission limits in place under Phase 1 greenhouse gas (GHG) legislation. In the non-road market, with Tier 4 emission standards already being met and no current plan for a GHG emission requirement, there has been less activity in engine downsizing and the drivers for this approach may be different from their on-highway counterparts. For instance, manufacturers may consider emission regulation break points as a motivation for engine displacement targets.

Many non-road applications demand a relatively high low-end torque and support the use of higher displacement engines. For these applications it can be more challenging to apply downsizing strategies while meeting the operation requirements of the machine, such as load factor. However, if successful, downsizing in these applications and reducing the engine size can provide improvements in fuel economy, reduce purchase price and provide packaging and machine layout improvement opportunities.

This work focuses on the application of downsizing in heavy-duty diesel engines applied to specific non-road applications where the opportunity exists to reduce the number of cylinders and thus the overall size of the engine. The main drivers here are packaging, production cost and fuel consumption. Various technologies, such as electrically assisted turbocharger, two-stage turbocharging, asymmetric twin scroll turbine and variable valve actuation, will be investigated to maintain performance requirements while reducing the number of cylinders.

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## INTRODUCTION

In recent years, research on diesel engines with the aim of increasing efficiency has been widely explored. Initially the push for increasing the efficiency of diesel engines was driven by the automotive market where stricter fuel economy standards required significant reduction in CO<sub>2</sub> emissions. It was demonstrated that smaller displacement diesel engines running at higher brake mean effective pressure (BMEP) levels with reduced friction resulted in higher engine efficiency. Various studies have explored the potential of downsizing diesel engines in the automotive market with the aim of increasing engine efficiency while meeting the performance and emission challenges [1, 2, 3].

Medium and heavy-duty engine and vehicle manufacturers must now also limit CO<sub>2</sub> emissions under GHG legislation jointly implemented by the EPA and the NHTSA in 2014. Challenges in this area will only continue to increase as the anticipated Phase II heavy-duty (HD) GHG standards are implemented. While passenger car diesel engines have already reached specific powers greater than 70 kW/L, on-highway HD diesel engines are yet to reach beyond 37 kW/L [4]. The difference partially lies in the fact that HD diesel engines need to

meet strict exhaust emission limits even at full load operation. In addition, a comparatively low nominal speed and high requirements in terms of durability further limit the ability to realize specific power increases in these applications [4].

Even with these limitations there has been effort to apply downsizing in the HD on-highway market, especially considering requirements under current and future GHG legislation. One such study conducted by the authors in reference [5], which downsized a diesel engine from 13L to 9L, showed that downsizing of the diesel engine was effective in reducing friction at all engine speeds. The authors concluded that reducing the displacement of the diesel engine improved heat balance and also achieved a reduction in fuel consumption. They also concluded that a two-stage turbocharging system was required to reduce pumping losses.

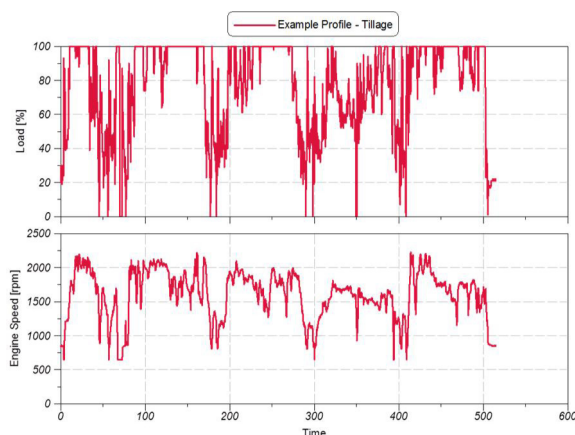
Looking into the non-road market, the application of downsizing is even less evident and there are currently no discussions regarding an introduction of GHG emission legislation. The main drivers for downsizing in the non-road market would likely be the production cost and packaging requirements along with efficiency improvements.

Many non-road applications demand a relatively high low-end torque compared to the on-highway applications. For these applications it can be more challenging to apply downsizing strategies while meeting the operation requirements of the specific machine.

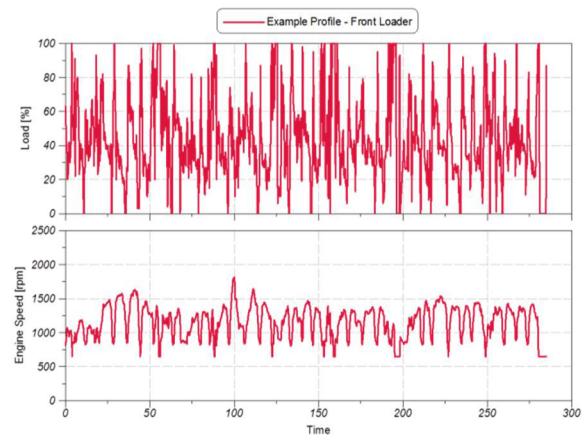
## TECHNICAL DISCUSSION

Although production cost and packaging optimization are the main drivers for downsizing in the non-road market, it is also critical to choose the applications that can most benefit from such an approach. Some off-road machines are produced with the requirement for a long service life before scheduled overhaul and thus the engines used in these applications are typically lower in power density (20 to 25 kW/L) to reduce stress levels.

However, there are certain applications in the off-road market that are well suited for engine downsizing. As an example, a mid-size tractor can be used in a variety of agricultural applications, such as field work or ancillary farm activities. For heavy field work applications, such as tillage, the mid-size tractor needs to be able to continuously operate at high loads and high speeds, whereas for ancillary agricultural applications, such as sand and manure loading, the low-end torque capability is a critical criteria along with good visibility and a small turning radius. Figure 1 presents two example operating profiles for a mid-sized tractor. In the tillage application we see that the engine mainly operates at medium to high engine speeds with a high load factor, whereas the front loader operation is highly transient and concentrated toward the low to medium engine speeds. Thus for the mid-size tractor, if a common engine architecture can be proposed that meets the requirements of both heavy agricultural field work and ancillary farm applications, it can be beneficial both to the end customer as well as to the manufacturer. This is just one example where downsizing can be an effective solution for the off-road market. Considering the size and diversity of applications found in the non-road market, there are likely many other applications that exhibit similar challenges and can benefit from a downsizing approach.



a. Example profile for tillage operation



b. Example profile for front loader operation

Figure 1. (cont.) Example operating profiles for tillage and front loader applications

To explore the potential of downsizing in a non-road application, the current study focuses on downsizing a six cylinder diesel engine typically used in a mid-size tractor for agricultural work to a four cylinder engine typically found in a mid-size tractor used for ancillary field work. The aim of the study is to explore technologies that can be applied to the smaller displacement four cylinder engine to meet similar low-end torque targets as achieved by the larger displacement six cylinder engine while also benefiting from the efficiency gains possible with a downsized engine due to higher BMEP levels and reduced friction losses.

To conduct this study, a GT-Power model of the base six cylinder diesel engine is first developed and calibrated against measured test data. A downsized four cylinder diesel engine model is then developed from the base engine model with similar torque targets and boundary conditions as defined for the six cylinder engine. Four main technology paths are explored to achieve the low-end torque requirements with the downsized four cylinder engine, specifically, electrically assisted compressor (E-boost), asymmetric turbocharging, two-stage turbocharging and variable valve actuation. In the end a comparison is made of the best performing architecture for each technology path explored along with a summary of their relative benefits and disadvantages.

## DEVELOPMENT OF BASELINE OFF-ROAD ENGINE DATA SET

The baseline test data used in this study was measured on a six cylinder 7.5 L diesel engine used in a medium-duty on-highway application. Key engine specifications are outlined in Table 1. A schematic of the engine layout is shown in Figure 2 while key performance parameters for the test engine are plotted in Figure 3. As shown in Figure 3, the engine produced a peak power of 228 kW at 2200 rpm while the peak torque of 1250 Nm was obtained from 1200 to 1600 rpm. The engine also applies approximately 27% cooled exhaust gas recirculation (EGR) at the peak power operating point.

The 2010 EPA emission legislation for on-highway heavy-duty engines is more stringent when compared to the current emission legislation for non-road engines. This means that the base on-highway

engine required much higher EGR levels than typically applied for non-road engines, along with the application of a selective catalytic reduction (SCR) catalyst to meet the 2010 NO<sub>x</sub> emission targets. For the off-road market a variety of engine and aftertreatment configurations are applied to meet the Tier 4 final emission standards. Some of the common configurations used in the 6 to 8L engine displacement class are outlined in Table 2. The most common component used in all configurations is the SCR catalyst for NO<sub>x</sub> reduction. Most applications do not apply a diesel particulate filter (DPF) and mainly rely on low particulate matter (PM) combustion systems to meet the Tier 4 final PM emission levels. There is also one configuration that does not use EGR, producing high levels of engine-out NO<sub>x</sub> emissions and addressing them through application of a high efficiency SCR.

Table 1. Base engine specification

|                             |                                                  |
|-----------------------------|--------------------------------------------------|
| <b>Displaced volume</b>     | 7.5 L                                            |
| <b>Compression ratio</b>    | 17.6:1                                           |
| <b>Power density</b>        | 30 kW/L                                          |
| <b>Peak firing pressure</b> | 220 bar                                          |
| <b>Aspiration</b>           | Single-stage turbocharged with charge air cooler |
| <b>EGR</b>                  | External cooled high pressure EGR                |

Table 2. Common engine and aftertreatment configuration used to meet Tier 4 final emission standards

| # | #Cyl. / Displ.(L) | Power density (kW/L) | T/C Config.  | EGR | DOC | DPF | SCR |
|---|-------------------|----------------------|--------------|-----|-----|-----|-----|
| 1 | 6 / 6.7L          | 33                   | Single Stage | yes | yes | no  | yes |
| 2 | 6 / 6.7L          | 30                   | Single Stage | no  | yes | no  | yes |
| 3 | 6 / 7.7L          | 34                   | Two Stage    | yes | yes | no  | yes |
| 4 | 6 / 7.8L          | 37                   | Two Stage    | yes | yes | yes | yes |

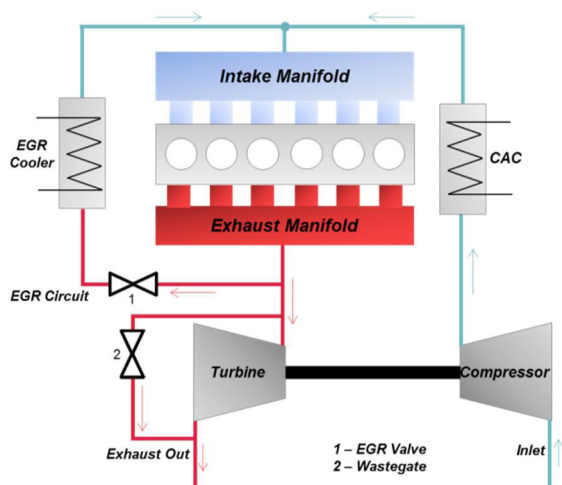


Figure 2. Base engine layout

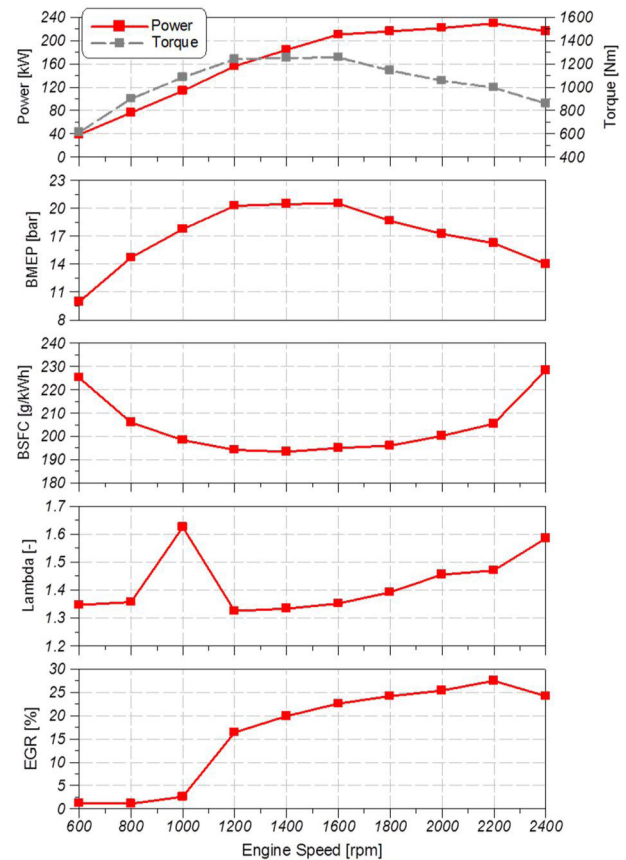


Figure 3. Full load performance data measured on the base on-highway engine

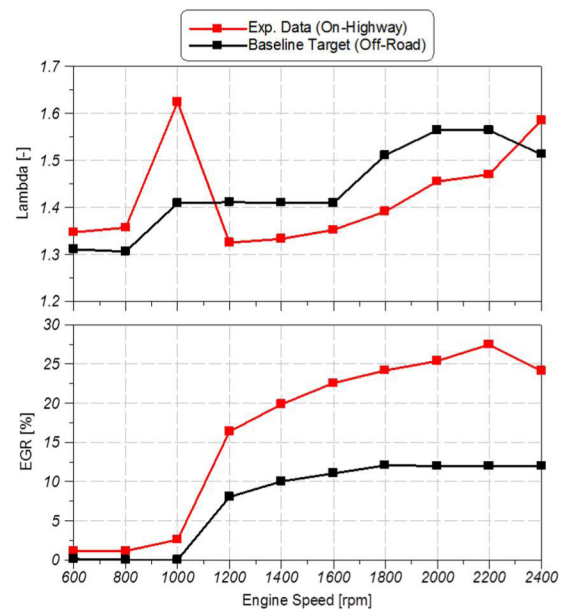


Figure 4. Comparison of EGR and lambda targets for the on-highway and off-road engines

To develop a base data set for the off-road engine in this study we assume the final configuration would consist of a single-stage turbocharger with external cooled high pressure EGR using a DOC/SCR system for exhaust aftertreatment. For the off-road simulation, higher lambda targets were set compared to those applied on the on-highway engine as shown in Figure 4. The higher lambda targets

were implemented to target an application without DPF. The EGR requirements for the off-road engine were also reduced by about 50% which would result in a higher engine-out NO<sub>x</sub> emissions target at the rated power point as highlighted in Figure 4. The EGR percentages applied at the full load curve are comparable to similar displacement non-road engines in production using SCR-only aftertreatment.

## SIMULATION SETUP

The simulation setup effort consisted of developing a baseline GTPower model for the on-highway version of the engine followed by creating a modified baseline GT-Power model for the off-road version of the same engine targeting lower EGR levels and higher lambda across the complete full load curve while maintaining similar power targets as the baseline on-highway engine. Figure 5 compares the performance of the baseline on-road and off-road GT-Power simulations results against the measured experimental data.

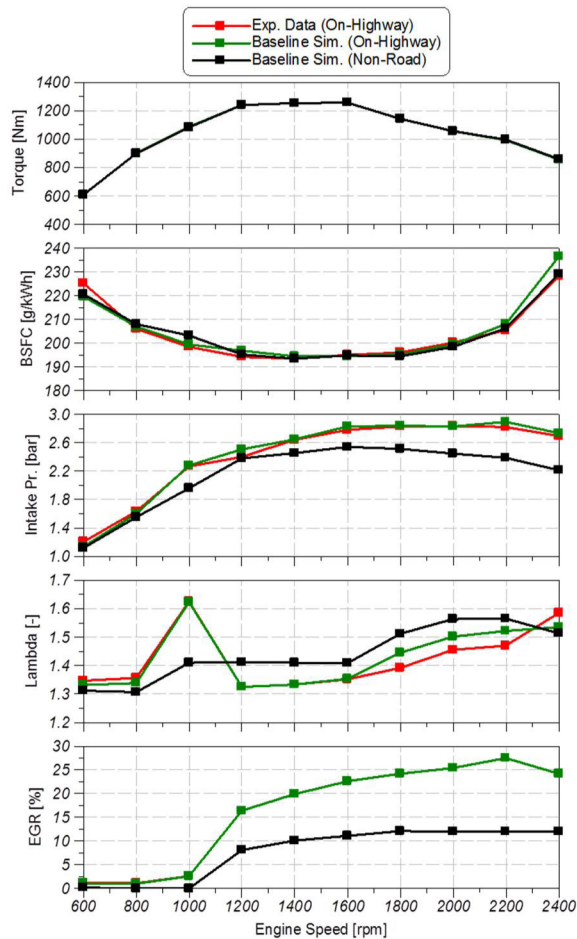


Figure 5. Comparison of experimental vs. GT-Power simulation results across the complete full load curve

For the on-highway simulations burn traces from the test data were directly applied in the simulation model. However, for the off-road simulations that used lower EGR levels, the burn traces were modified appropriately to speed up the combustion relevant to a reduction in EGR percentage. The factors with which the burn traces were modified were determined from test data acquired on a single

cylinder engine with similar power density and EGR percentage differences. In addition, for the off-road simulations the turbocharger was re-matched to meet the updated EGR and lambda targets.

Comparing the baseline on-highway experimental and simulation data plotted in Figure 5, it can be shown that the target torque values, along with boost pressure, lambda and EGR targets, are well matched. The torque targets for the off-road simulation are also matched well with the on-highway data, along with comparable brake specific fuel consumption (BSFC) values as shown in Figure 5. Also visible are the higher lambda and lower EGR targets applied for the off-road simulations resulting in lower intake pressure requirements.

In the subsequent sections, the off-road simulation results plotted in Figure 5 will be used as baseline for comparing the performance of the downsized four cylinder engine with four main technology paths applied as outlined in the technical discussion section.

## SIMULATION RESULTS

### Downsized Four Cylinder Engine with Single-Stage Turbocharging

The GT-Power model for the downsized four cylinder engine was developed from the baseline six cylinder model by removing two cylinders while maintaining the same geometric parameters and air handling system layout as the baseline six cylinder engine as shown in Figures 2 and 6. Key differences in the six cylinder and four cylinder engine models are outlined in Table 3. The torque, lambda and EGR targets for the downsized four cylinder engine were kept similar to those used for the six cylinder off-road engine model as outlined in Figure 5. Also, since the power density of the engine was increased by 50%, an increased peak firing pressure limit of 260 bar was established for the downsized engine.

In the effort to downsize the off-road engine, multiple challenges were encountered. The power density requirement for the downsized off-road engine is quite aggressive (45 kW/L) when compared to state-of-the-art HD diesel engines in the same displacement range, as shown in Table 2. The low-end torque requirements are also more demanding when compared to an automotive or on-highway application. The proposed aftertreatment layout does not include a DPF, which requires use of higher air/fuel ratios to meet the PM emissions targets. In keeping with the downsizing objective, moderate levels of EGR were also applied to the downsized engine to keep the size of the SCR aftertreatment system at a minimum. The challenging goals put forth in this study should help in understanding the downsizing potential for an off-road engine with the proposed emission compliance strategy.

The initial performance evaluation for the downsized four cylinder engine has been optimized in two steps. In the first step the turbocharger layout is optimized for peak power and torque operating points (case #1), while in the second step the turbocharger layout is optimized for the complete full load curve (case #2). The

performance comparison for the two downsized cases against the baseline six cylinder is plotted in Figure 7, while Table 4 provides an overview of the percentage improvement in BSFC for the two cases.

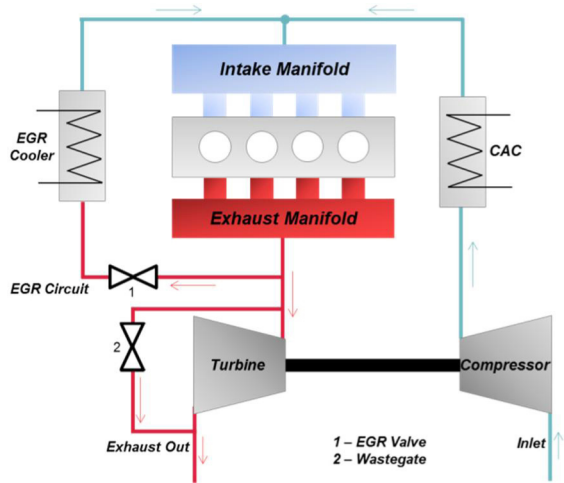


Figure 6. Downsized four cylinder engine schematics with single-stage turbocharging

Table 3. Engine specification comparison - Base six cylinder vs. Downsized four cylinder

|                      |                                  |                                  |
|----------------------|----------------------------------|----------------------------------|
| Displaced Volume     | 7.5 L                            | 5.0 L                            |
| # of Cylinders       | 6                                | 4                                |
| Compression Ratio    | 17.6:1                           | 17.6:1                           |
| Power Density        | 30 kW/L                          | 45 kW/L                          |
| Peak Firing Pressure | 220 bar                          | 260 bar                          |
| Aspiration           | Single-stage turbocharged w/ CAC | Single-stage turbocharged w/ CAC |
| Firing Order         | 1-5-3-6-2-4                      | 1-3-4-2                          |

As shown in Table 4, when compared against the baseline engine and case #2, better BSFC is observed for case #1 at both peak power and peak torque points. The high power density of the engine helps in improving engine efficiency in both cases. However, the larger improvement in BSFC in case #1 is mainly driven by the optimum sizing of the turbine at the peak power operating point.

The disadvantage of sizing the turbine optimally at peak power point in case #1 is clearly apparent in the low-end torque performance where 35% lower torque is achieved at 1000 rpm compared to the base engine. For case #1 the lambda targets are also not met from 600 rpm to 1400 rpm. However, for case #2, where the turbine sizing was optimized to improve the low-end torque performance, the torque requirements could be met at 1000

rpm while the baseline lambda targets were also achieved for engine speeds above 800 rpm. Even with optimization focused on low speeds, the torque curve of case #2 is lower by 35% at 800 rpm. Another disadvantage with this approach is that the improvements in specific fuel consumption at the peak power point reduced from 6.7% to 3.0% for case #1 and case #2, respectively.

Especially at the higher speeds, the pumping mean effective pressure (PMEP) losses for case #2 are higher, as the turbine was sized to improve the low-end torque, which results in worse BSFC values for case #2 when compared to case #1. The intake manifold pressures are higher for the downsized engine cases as higher boost levels are required to achieve the lambda targets. The highest intake pressure observed was approximately 3.6 bar.

When approaching the engine downsizing with a single-stage turbocharger and conventional hardware, gains in specific fuel consumption can be realized at higher engine speeds. However, torque targets of the baseline engine cannot be achieved at lower engine speeds. In the subsequent sections, the possibility of improving the air handling capability of the downsized engine will be explored in an effort to maintain the low-end torque performance.

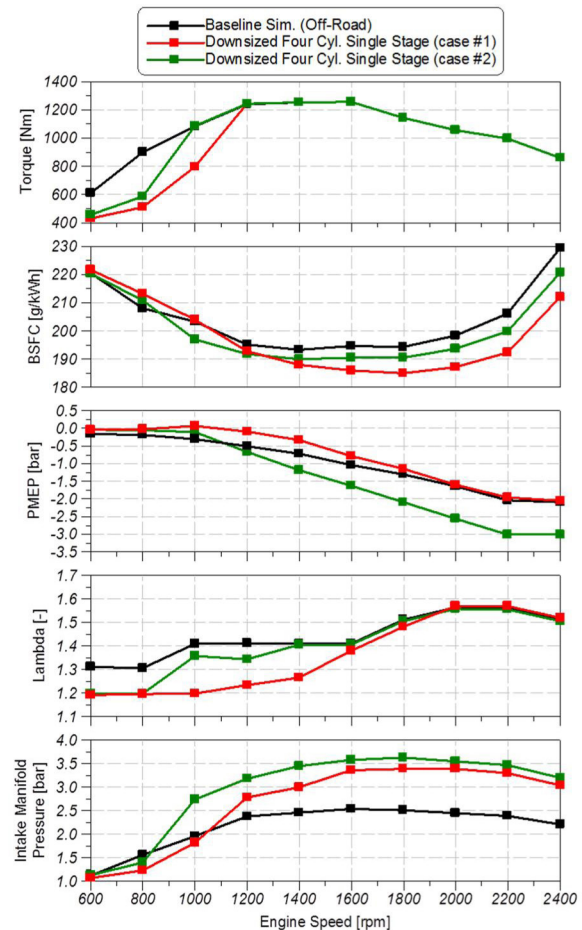


Figure 7. Comparison of GT-Power simulation for downsized four cylinder engine vs. baseline six cylinder engine with single-stage turbocharging