

Vehicle Level Parameter Sensitivity Studies for a 1.5L Diesel Engine Powered Passenger Car with Various Boosting Systems

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ABSTRACT

Several diesel passenger car boosting systems were studied to assess their impact on vehicle performance and fuel economy. A baseline 1.5L diesel engine model with a single VGT turbocharger was obtained through Gamma Technologies' fast running model library. This model was modified to explore multiple two stage boosting systems to represent the anticipated architecture of future engines. A series sequential turbocharged configuration and a series turbocharger-supercharger configuration were evaluated. The torque curves were increased from that of the original engine model to take advantage of the increased performance offered by two stage boosting. The peak cylinder pressure for all models was limited to 180 bar.

Drive cycle analysis over the WLTP was performed using these engine architectures, while assessing the sensitivity to various system parameters. These parameters include: vehicle weight and aerodynamic drag, EGR target maps, level of downspeeding, and turbocharger inertia. Vehicle performance and fuel economy was evaluated for the different boosting configurations to determine which vehicle design characteristics are complimented by the individual boosting configurations, and which are hindered. The simulation results demonstrate that the turbocharger-supercharger configuration provides benefits in both fuel economy and performance for all of the vehicle parameter variations studied. Specific trends between these benefits and each of the varied vehicle system parameters are presented as well.

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INTRODUCTION

Engine downsizing has been an industry trend for many years as a method for improving fuel economy by increasing average engine load, thus decreasing specific fuel consumption. The negative aspect of engine downsizing is reduced performance. This reduced performance can be remedied by boosting the engine with either a mechanical supercharger or an exhaust driven turbocharger. Many of the current production light duty petrol engines in Europe are boosted, while nearly all of the light duty diesel engines in Europe are boosted. These production diesel engines are currently all boosted with exhaust driven turbocharger technology; whereas, there are current production petrol engines boosted with either an exhaust driven turbocharger or a mechanical supercharger.

Current production boosted light duty diesel engines are almost exclusively boosted with a single stage. There are high performance applications utilizing two stage boosting, but the majority of current production engines can meet customer performance expectations with a single boosting device at current industry accepted levels of downsizing. However, further engine downsizing is expected to occur in order to further decrease vehicle fuel consumption to meet both regulatory targets and customer demand. Two stage boosting is an option to allow further reduction in engine displacement while maintaining performance. The BMW 2.0L N47D20 engine rated at

150 kW is an example of a current production diesel utilizing a two stage exhaust driven turbocharger system to meet high specific power targets. Another method for reaching, or exceeding, this specific power level on a diesel engine is to use a mechanical supercharger in conjunction with an exhaust driven turbocharger. The VW 1.4L TSI [1] is a petrol engine utilizing this type of boosting system to enable a very downsized engine, while achieving acceptable drivability in the midsized vehicles in which it powers.

Another method for decreasing vehicle fuel consumption is engine downspeeding. This strategy involves running the engine at lower average engine speeds, thus moving engine operating points to higher efficiency regions on the engine map. A vehicle maneuver, such as a 0-100 km/hr acceleration or a regulated drive cycle like the worldwide harmonized light vehicles test procedure (WLTP), requires a certain amount of integrated power to execute. Downspeeding an engine decreases the average operating speed over this maneuver while increasing the average load to maintain the required integrated power. Engines boosted solely with exhaust driven turbochargers can exhibit large levels of "turbo lag" at these low engine speeds/high engine load conditions, especially when accelerating from an idle condition. Downspeeding turbocharged engines degrades vehicle transient performance and drivability, thus limiting the level of downspeeding achievable. An engine can be equipped with a

mechanical supercharger to greatly increase its transient response, thus allowing further downspeeding. Even so, there is a limit to the amount of downspeeding that can be used to decrease fuel consumption, as this paper demonstrates.

The authors have been involved in numerous simulation studies and hardware demonstrations using supercharged boosting systems on diesel engines to assess vehicle performance and vehicle drive cycle fuel economy [2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. Some of this work compared single stage boosting systems [2, 3, and 4], while the majority of this work compared two stage boosting systems [5, 6, 7, 8, 9, 10, 11]. The two stage boosting work would normally compare a turbocharger-turbocharger (TT) (two turbochargers in series) against a supercharger-turbocharger (ST) system (supercharger upstream of the turbocharger) and a turbocharger-supercharger (TS) system (supercharger downstream of the turbocharger). The work typically involved downspeeding the transmission shift schedule of the supercharged variants to match that of the series sequential turbocharged variants over a vehicle performance metric (0-100 km/hr acceleration time, ¼ mile acceleration time, etc.). Downspeeding the transmission shift schedule allowed for trading the increased performance of the supercharged variants for improved drive cycle fuel economy while not sacrificing any performance compared to the turbocharged variants. This method of comparison has its merits, but consumers expect increases in both fuel economy and performance with future vehicle releases.

The authors decided to take a broader look at comparing different two stage systems by introducing variation to several engine or vehicle parameters. These parameters included varying vehicle weight, level of downspeeding (transmission shift schedule), exhaust gas recirculation (EGR) target maps, and turbocharger inertia. These parameters can be very influential for both vehicle performance and vehicle fuel economy and thus were studied to identify areas of competitive advantage for different boosting systems. These parameter variations are also important for looking out into the future where vehicle weight reduction for improved fuel economy, increased levels of EGR for emissions control, and reduced turbocharger inertia for improved performance can be implemented. Much of the previous work showed TS boosting systems to deliver superior fuel economy and similar performance over ST systems; therefore, the only boosting systems presented in this study are a TS system and a TT system.

Previous work had also focused on matching torque curves between different boosting systems regardless of engine design constraints. This is a good method for comparing the transient response of different engine system while maintaining the same steady state performance targets. For this study, the authors decided to take an engine designers approach by selecting a peak cylinder pressure limit and maximizing engine torque curves individually for each boosting system based on this limit and target air/fuel ratios. The simulations for this study are intended for boosting system evaluation and do not optimize driveline NVH.

BACKGROUND

The baseline engine for this simulation study is a 1.5L 4 cylinder turbocharged diesel engine. This engine has two boosting configurations: a TT and a TS boosting system. Table 1 shows the static engine parameters. Figure 1 shows the air fuel ratio (AFR) limits used for all configurations studied. Vehicle specifications are based on a European market passenger car equipped with a six speed manual transmission. The parameter variations in this study are vehicle weight, level of downspeeding, EGR level, and turbo inertia.

Table 1. 1.5L Engine Specifications

Displacement	1499 cc
Bore	76.9 mm
Stroke	80.7 mm
Engine Configuration	Inline 4 Cylinder
Compression Ratio	16:1
Peak Cylinder Pressure Limit	180 bar
Fuel Type	Diesel

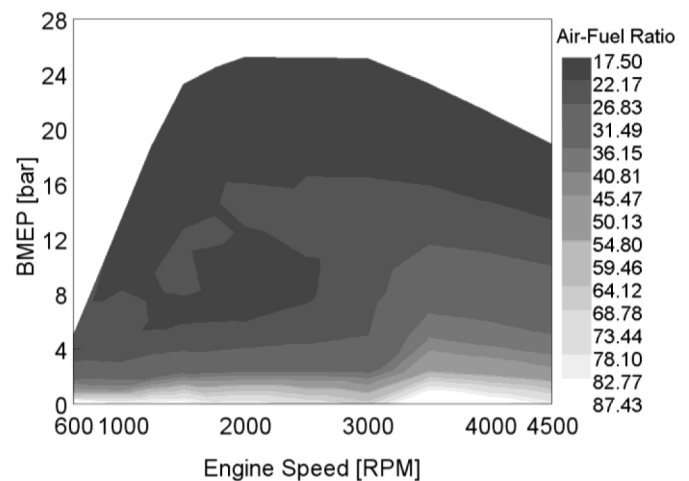


Figure 1. AFR Map

The three vehicle weights studied are shown in Table 2 along with the other parameter variations that are studied. The motivation for studying a range of vehicle weights with the same displacement engine is in line with the trend of vehicle manufacturers using common engines across platforms.

Table 2. Sensitivity Study Parameters

Parameter	Levels Investigated
Vehicle Weight	1250 kg, 1500 kg, 1750 kg
Downspeeding	Maximum Downsped, Intermediate Downsped
EGR	Base, Moderate Increase, Large Increase
Turbo Inertia	Base, 50% Reduction, 83% Reduction

Downspeeding in this study is accomplished by lowering the shift points for the TS configuration. The gear ratios and final drive ratio are held constant. The maximum level of downspeeding is determined by matching the TS performance to the TT for a 0-100 km/hr acceleration. A less aggressive, intermediate level of downspeeding is also evaluated.

Varying emissions control strategies used by vehicle manufacturers require differing levels of EGR. In order to study the robustness of the boosting systems, a range of EGR levels is explored. The base EGR map is representative of the levels used in a 2010 production engine. The EGR rates are increased by a moderate and large amount, as shown in Figures 2, 3, and 4.

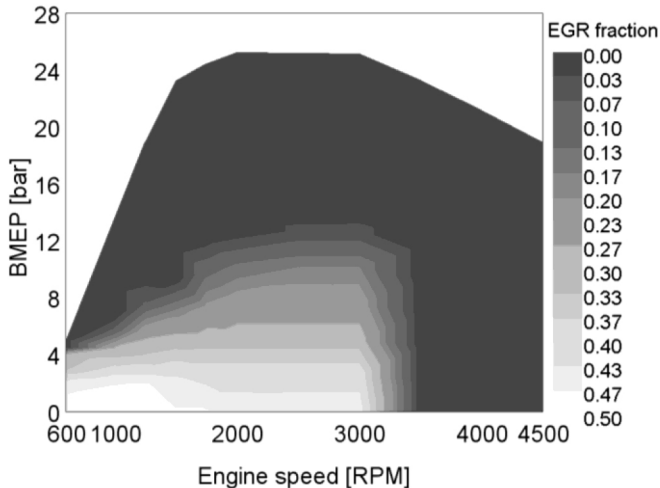


Figure 2. Base EGR Map

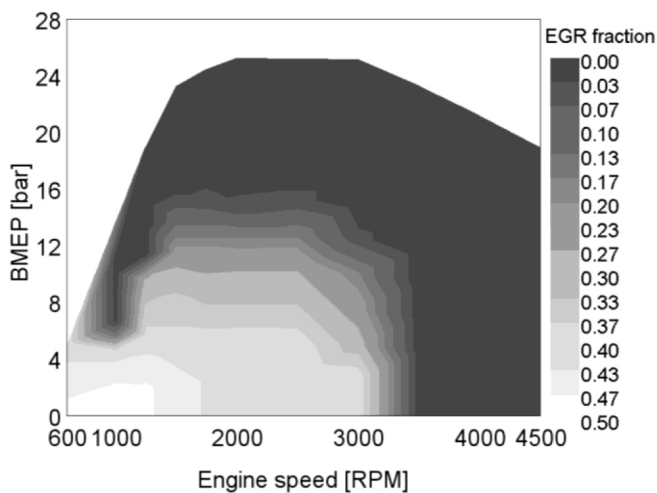


Figure 3. Moderate Increase EGR Map

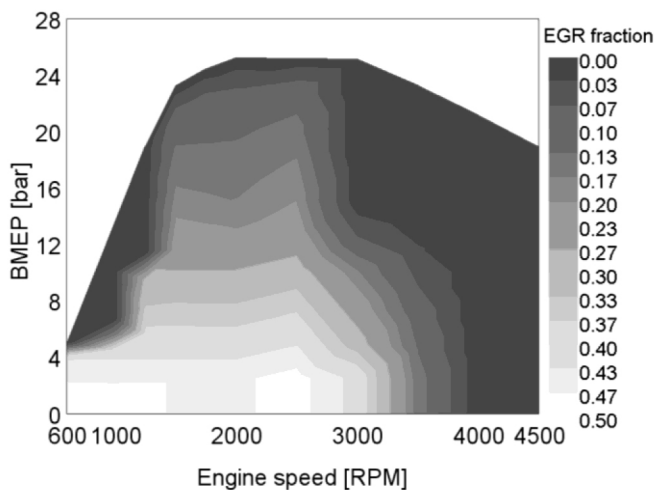


Figure 4. Large Increase EGR Map

One method to reduce turbocharger response time is utilizing low inertia wheels. Two reduced levels are studied, as shown in Table 2. The reduction levels are aggressive and not necessarily feasible, but provide a conservative comparison against future improved turbochargers.

The performance for all of the different engine and vehicle configurations will be evaluated over a 0-100 km/hr acceleration time. Fuel economy will be presented as fuel consumption over the WLTP cycle that is planned to be the successor to the current NEDC for both fuel economy and criteria pollutant emissions [12].

SIMULATION METHOD

The fast running model (FRM) engine database, purchased from Gamma Technologies, is a collection of 1-dimensional engine models created by Gamma Technologies and correlated to its own collected test data. The benefit of a FRM over a detailed engine model is that simulation time is greatly reduced, yet a high level of fidelity is maintained. This is primarily achieved by lumping pipe objects together on the intake and exhaust side of the detailed engine model. The model still captures the low frequency and primary engine order dynamics, while sacrificing only the higher frequency wave dynamic content that is generally not of interest for longer duration transient simulations. The models are still fully capable of crank angle resolved transient simulation, while decreasing run time by a factor of 10 or more [13]. The FRM library enables researchers, without production engine models of their own, to investigate the system level effects of different technologies.

The focus of this study is the diesel powered passenger car segment; therefore, the 1.5L I4 diesel VGT engine model is selected from the FRM library as a starting point for all of the simulation work. The baseline engine model has a single variable geometry turbocharger (VGT) and high pressure loop exhaust gas recirculation (HP EGR), as shown in Figure 5.

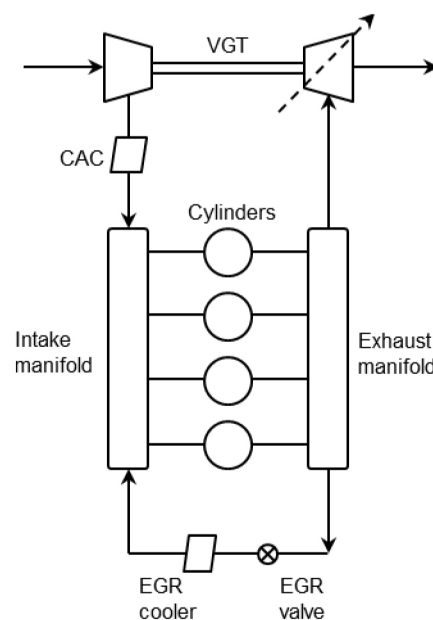


Figure 5. Schematic of the baseline engine



The baseline engine model is converted from single stage to two stage boosting in the following configurations:

- Two Turbochargers in series (TT)
- Turbocharger and Supercharger in series (TS)

For both configurations, the in-cylinder AFR's from the baseline single VGT engine are maintained. The HP EGR loop is also retained, while using the same EGR rates as the baseline. The base engine utilizes GT-Suite template model based controllers for actuating the EGR valve and controlling the injectors, and these model based controls are maintained in the modified models as well. For the EGR sensitivity study, it was necessary to convert the engine models to a low pressure loop configuration in order to achieve the elevated EGR percentages. The same boosting device sizes are maintained for both EGR configurations, after ensuring that they are still capable of meeting all targets.

Turbocharger-Turbocharger Model Development

The low pressure stage in the TT engine model is a fixed geometry turbocharger (FGT), and the high pressure stage is a variable geometry turbocharger (VGT). As shown in Figure 6, the FGT features a wastegate, while the VGT has a controllable bypass loop. This system is based on a current production two stage boosting system [14]. The two turbochargers are derivatives of actual turbochargers used in a previous study [8]. Both of the units are sized to efficiently provide the required boost, as well as meet the target EGR levels. The two stage system creates higher levels of boost across the entire engine operating range. This enables increased low speed engine torque without sacrificing engine peak power.

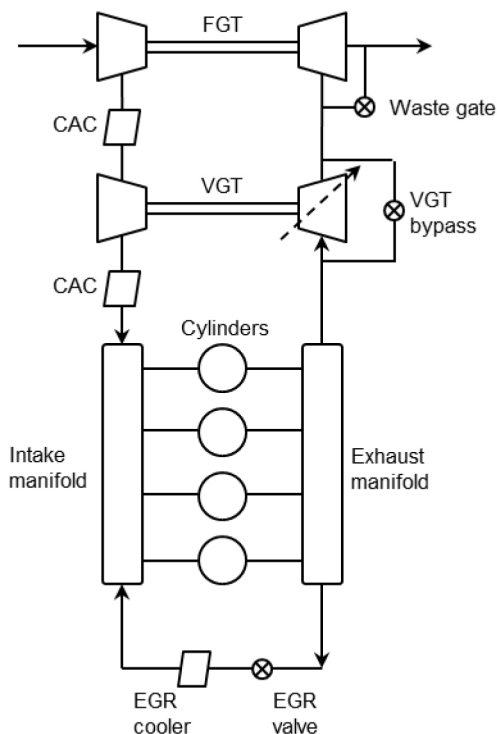


Figure 6. Schematic of Turbo-Turbo Engine

Utilizing the higher boost capability, the rated engine torque and power are increased from the baseline model by raising the allowable peak cylinder pressure from 165 bar to 180 bar. The 165 bar peak cylinder pressure limit found in the baseline engine model is typical for single stage boosted diesel engines of this size and power output. The increase to 180 bar allows for an adequate increase in performance enabled by the two stage boosting systems, differentiating its performance from the single stage boosting version while still maintaining AFR and EGR rates.

Higher boost pressures at low engine speeds are achieved by controlling the rack position of the VGT. As shown in Figure 7, the VGT rack is used to control boost up to the 2500 to 3000 rpm engine speed range (mode 1). At higher engine speeds, the VGT turbine is bypassed to avoid low efficiency operation, and the larger FGT regulates the required boost through wastegate control (mode 3). There is also an intermediate range between rack control and wastegate control, where controlling boost with the VGT bypass is more efficient (mode 2). The control modes are overlaid on the BSFC contour for the TT engine. The steady state control mode regions shown are found by operating the engine across its range of speeds and loads with each potential control mode, and then selecting the one that is most efficient while also meeting the required boost and EGR targets and staying to the right of the surge line. This control strategy is similar to that of some current production series turbocharger engines, which may also incorporate a high pressure compressor bypass that can be opened near peak power operation [14]. However, very little restriction across the compressor is seen in the model at such operating points, so such a bypass is not included in favor of reduced controls complexity.

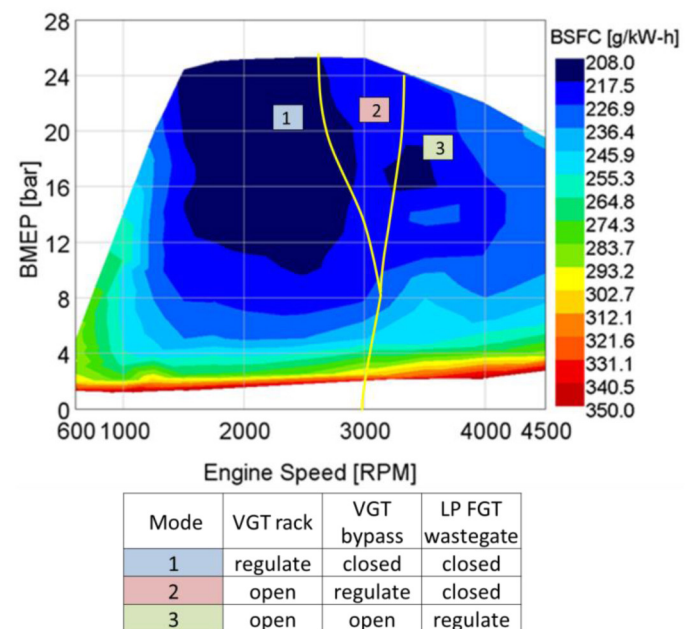


Figure 7. Turbo-Turbo Control Mode Map

The high pressure stage is smaller and utilizes a VGT, enabling it to react more quickly to transients than the low pressure stage FGT. This results in faster boost response. Therefore, when there is a sudden