

Parametric Studies of the Impact of Turbocharging on Gasoline Engine Downsizing

S. M. Shahed and Karl-Heinz Bauer
Honeywell Turbo Technologies

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ABSTRACT

The internal combustion engine and associated powertrain are likely to remain the mainstay of mobility over the next twenty years and to remain a significant portion of the portfolio of technologies employed over a much longer period of time. Efficient combustion of all fuels (petroleum based or alternative) requires copious amounts of air particularly with downsized engines. Turbocharging technology thus becomes an even more critical part of reducing both global warming gas and urban pollutant emissions from IC engines.

Gasoline engine downsizing and turbocharging have been shown to improve fuel economy by ~20% in production vehicles. In addition to data over a wide range of engines/vehicles, the results of a simple analysis done on vehicles/engines/drive cycles are presented to show the benefits of turbocharging and downsizing in a parametric variation of downsizing in combination with other technologies. The analysis shows that 40% downsizing with turbocharging to restore the baseline torque curve gives about 21% reduction in fuel consumption. Fuel cut off during idling and coasting is estimated to give an additional 9% improvement, yielding a total of 30% reduction in fuel consumption. However, conventional turbocharging has been unable to supply enough air to maintain high torque at low speeds. Advances in turbo technology such as twin scroll turbine housing together with exhaust manifold design and direct injection have gone a long way towards meeting this need. In this paper, more advanced turbo technologies such as a parallel flow double sided compressor are presented that show

promise in addressing this issue as well as reducing turbo inertia and improving turbo efficiency at low speeds.

INTRODUCTION

The conventional gasoline engine is likely to remain the mainstay of mobility technology for the next several decades not only because of committed investment but also because it is not “conventional”. Continuous improvements such as variable valve timing, direct injection and several “degrees” of hybridization continue to keep the “conventional” gasoline engine viable and competitive. Turbocharging and downsizing of gasoline engines (1, 2) have been shown to reduce vehicle fuel consumption. Data from a wide range of production vehicles were compared to provide a “like to like” comparison to demonstrate fuel consumption reduction of 16-18%. In this comparison “best in class” vehicle data were selected to avoid the confusion introduced by “turbocharged sports cars” which were a part of the production vehicle mix (2). Such an analysis has the advantage of looking at a broad range of vehicles but lacks the rigor of “back to back” comparison. However, the earlier study (1) was a methodical and direct comparison in the same vehicle. It showed the same benefits of downsizing and confirmed the validity of benefits estimated from selected best in class production vehicles.

The analysis presented in (2) was taken further in (3), to show that downsizing can be combined with technologies such as fuel cut off during vehicle stops and decelerations together with “light/mild” hybrid (4, 5)

to give benefits equivalent to a full hybrid but without the added weight and cost penalties. In the present paper, this work is carried further using a *highly* simplified parametric analysis of turbocharged downsized engines-powertrains-vehicles to get further understanding of the impact of turbocharging and downsizing.

OVERALL APPROACH

The emphasis of this investigation is on the concept of engine downsizing and turbocharging and parametric studies associated with this technology. No attempt is made to study in detail the many other viable and effective engine, transmission and vehicle technologies or to use rigorous “predictive” models. Instead, simple curve fits to empirical data and extrapolations of data are used to approximate engine, transmission and vehicle performance as described below. The basic calculation procedure remains true to the physics of the effects of engine downsizing and turbocharging. So, while the model of the vehicle and powertrain may not be sophisticated and certainly will not be useful in studying the effects of design parameters associated with them, it is useful in studying the impact of engine downsizing and turbocharging.

VEHICLE – The vehicle is treated as a “constant” and calculations are done using simple aero drag, rolling resistance and inertia (acceleration) force equations as shown below. The US EPA driving cycle is used in a second by second calculation using vehicle speed (S_v) as input. Appropriate values for vehicle weight (M_v), frontal area (A_v), drag coefficient (C_d) and rolling resistance (C_r) are used and kept constant. Level ground is assumed in all calculations.

$$\text{Aero Resistance: } \frac{1}{2} C_{d_a} A_v S_v^2 \quad (1)$$

$$\text{Rolling Resistance: } C_r M_v g \quad (2)$$

$$\text{Inertia Resistance: } M_v a \quad (3)$$

In this simple formulation, rotational inertial resistance is neglected. Generally speaking, the rotational inertial component is a small fraction of the total (6). The power required to propel the vehicle is simply equal to the total resistance multiplied by the speed of the vehicle.

TRANSMISSION – The transmission is treated as a simple relationship between vehicle speed ($S_{\%}$) and engine speed ($N_{\%}$) with an assumed constant value of transmission efficiency. In this correlation vehicle speed of 200 kmph is treated as 100%, thus $S/S_{\max}$ is defined as normalized vehicle speed, $S_{\%}$. Normalized engine speed is defined as

$$N_{\%} = (N - N_{\text{idle}}) / (N_{\max} - N_{\text{idle}})$$

A purely empirical, simple linear relationship based on the average of many representative vehicles/transmissions is used and kept constant while other parametric changes such as engine downsizing are made.

$$\text{Engine Speed: } N_{\%} = A_1 S_{\%}$$

A transmission efficiency of 90% is arbitrarily assumed and kept constant at all speeds and loads. It is recognized that this is a highly simplified assumption, but it does not affect the essential conclusions about parametric variations in engine downsizing and turbocharging.

ENGINE – The engine performance parameters of concern in this study are speed, torque and efficiency (BSFC). Data from a large number of modern naturally aspirated and turbocharged gasoline engines were non-dimensionalized/normalized, averaged and cast into empirical curve fit equations. Rated speed, rated torque and best BSFC are used as the normalizing parameters. Thus

$$\text{Normalized BSFC} = \text{BSFC} / \text{Best BSFC} \times 100$$

$$\text{Normalized Torque} = \text{Torque} / \text{Rated Torque} \times 100$$

$$\text{Normalized Speed} = (N - N_{\text{idle}}) / (N_{\max} - N_{\text{idle}}) \times 100$$

It will be seen later that while this approach is “unconventional” it permits a direct comparison of engines of different displacements and rated speeds and a convenient as well as mathematically consistent tool for comparison.

The three graphs below are used to explain the basis and the limitations of this approach.

Figure 1 shows normalized BSFC of a representative naturally aspirated gasoline engine, plotted against normalized torque at a range of selected speeds. It shows the classic characteristic of a sharply rising BSFC at low loads, primarily due to throttling losses. The slight increase in BSFC at high torque due to increasing heat loss is also observed. By comparing the various speed lines the variation of BSFC as a function of speed can also be deduced.

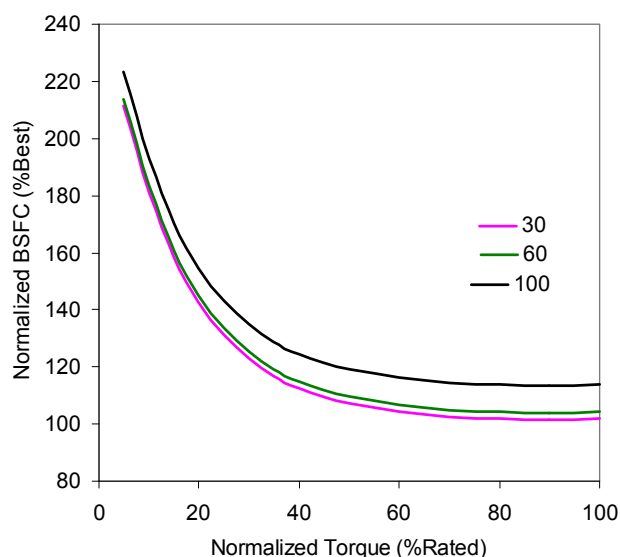


Figure 1: Normalized BSFC of a representative naturally aspirated engine plotted against normalized torque at selected normalized engine speeds of 30, 60 and 100 %.

This is made more explicit in Figure 2, showing normalized BSFC plotted against normalized speed at a range of selected constant torque values. Figure 2 reflects the changes in BSFC with speed due to changes in friction, volumetric efficiency and heat losses. Comparison of various constant torque lines reflects the variation of BSFC with torque (predominant throttling loss effect) already explicitly shown in Figure 1.

Values of speed, torque and BSFC used in the calculation of cycle fuel consumption are simply scaled using rated speed, rated torque and best BSFC values for the engine. This is a highly simplified approach which ignores the nuances and differences between engines and simply scales values as if all engines behave exactly the same. However, for the narrow purpose of this study i.e. parametric variation in engine downsizing and turbocharging such a comparison is reasonably valid. The numbers used in this study are representative empirical fits and reflect the variation of BSFC with speed and torque.

The numbers in Figures 1 and 2 represent the performance of a naturally aspirated gasoline engine. Similar empirical fits are developed for downsized turbocharged engines with various degrees of downsizing while maintaining the same rated power. This is described in further detail below.

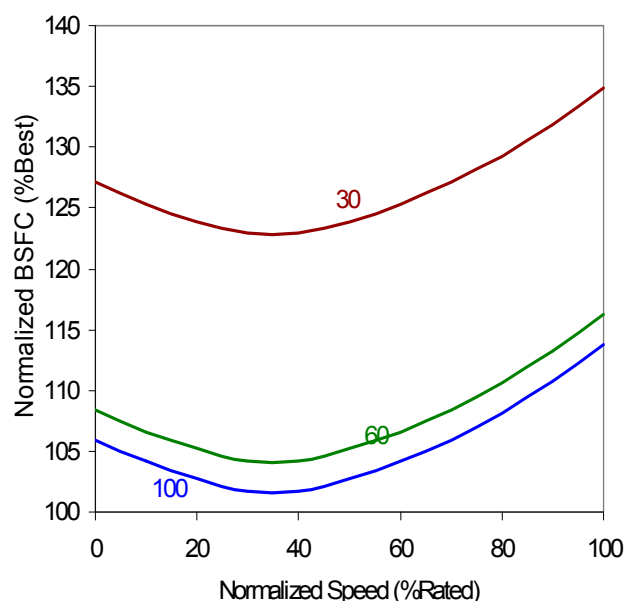


Figure 2: Normalized BSFC of the same representative naturally aspirated engine plotted against normalized speed at selected normalized torque values of 10, 30, 60 and 100% rated torque.

Figure 3 shows normalized BSFC of four engines plotted against normalized torque at optimum normalized speed. The four engines are the original, representative naturally aspirated engine (0% downsized) and three turbocharged downsized engines of the same rated power downsized by 20, 40 and 60% with appropriate turbocharging to restore torque to the same level as the original naturally aspirated engine against which they will be compared.

The best BSFC of the four engines is approximately the same with minor differences due to friction losses. In this set of calculations all engines are assumed to have the same best BSFC. The BSFC of downsized engines is better at part load conditions because the engine does not have to be throttled as much as the larger engine. For the severely downsized engine, the back pressure of the turbocharger begins to impose a slight penalty at high torque. Curve fits at a range of speeds were developed for all engines. The curves are not presented here for brevity and are similar to those in Figure 2.

It is possible that with a highly boosted engine compression ratio would have to be reduced slightly to avoid knock. The need for this and the effects are highly specific and are not considered in this analysis.

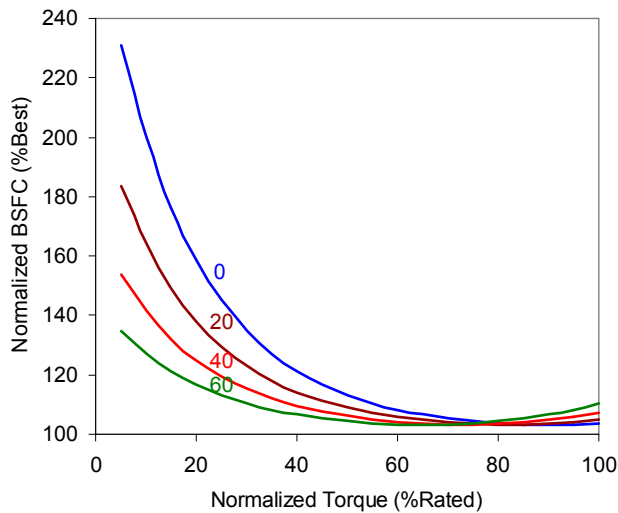


Figure 3: Normalized BSFC of naturally aspirated (0% downsized) and turbocharged 20, 40 and 60% downsized engines plotted against normalized torque at 50% normalized speed.

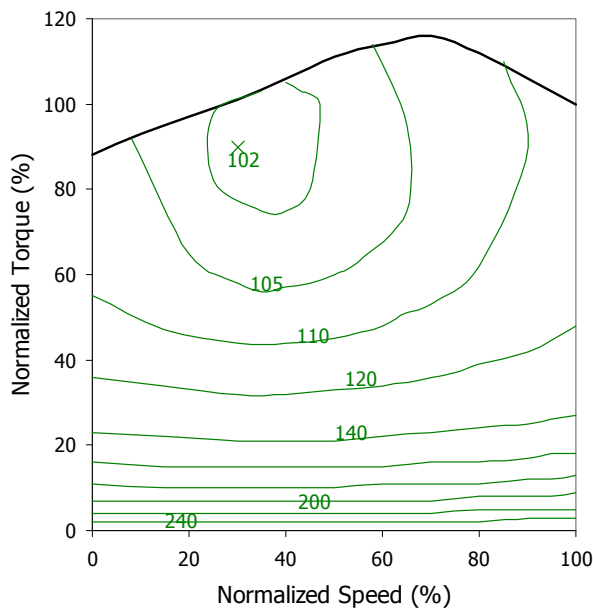


Figure 4: Normalized BSFC contours of naturally aspirated engines developed using curve fit equations described in Figures 1 and 2.

Using these curve fit equations BSFC contours were developed to illustrate the variation of BSFC with speed and torque. Such contours (green and labeled as normalized BSFC - % best BSFC) are shown in Figure 4 for the naturally aspirated engine. At the top of the contours the rated torque curve is also shown (black). It is seen that the best BSFC island lies around 85-90% torque and 50-60% speed and the BSFC rises sharply as torque is reduced. It also rises (although more

gradually) as speed is changed away from 50% in either direction. Of course, the same trends can be deduced from Figures 1 and 2 but illustrated with greater impact in Figure 4.

In much the same way, Figure 5 shows BSFC contours of a turbocharged 40% downsized engine. Curve fit equations as described in Figure 3 for 50% rated speed together with similar equations at other speeds were used to generate contours shown in Figure 5. It is seen that the best BSFC island is centered at a lower torque because of less throttling. It is also wider in range and the BSFC does not rise as sharply at lower torque as in Figure 4, once again due to less throttling. Similar contours were developed for 20 and 60% downsized engines but are not shown here for brevity. Examination of these figures shows a progressive lowering (low torque) of the centre (marked by an "X") of the optimum BSFC area (sweet spot).

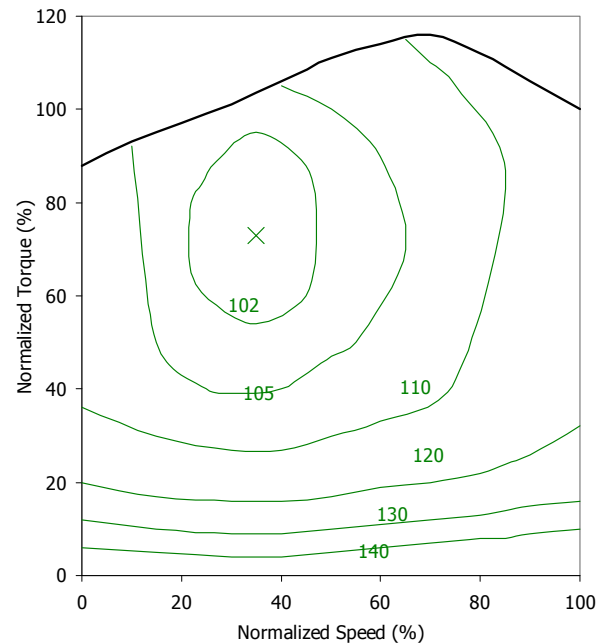


Figure 5: Normalized BSFC contours of turbocharged 40% downsized engine engines developed using curve fit equations as described in the text.

Reference is made to Figure 2 of the paper by Peter Walzer (7) in which similar BSFC contours of naturally aspirated and 50% downsized turbocharged engines are presented.

The curve fit equations of BSFC as a function of speed and torque are used in parametric studies of engine downsizing and its impact on vehicle fuel economy over the US EPA test cycle.