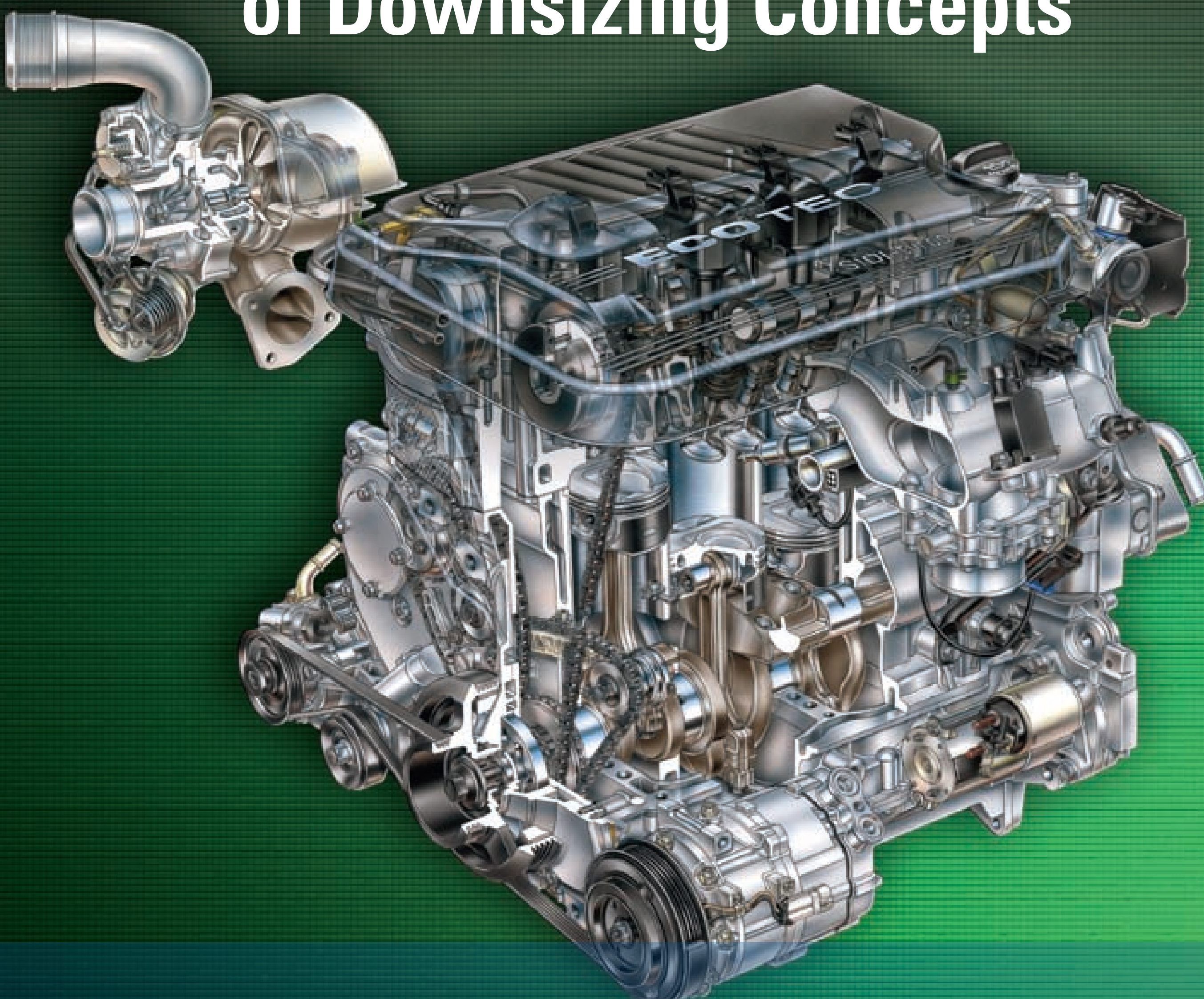
Differentiated Analysis of Downsizing Concepts



Applying downsizing, a given naturally aspirated engine is replaced by a boosted engine having a smaller displacement. In the past downsizing was mainly used for increasing maximum performance. Nowadays reducing fuel consumption by downsizing gains increasing importance for fuel economy. The detailed analysis by General Motors of fuel consumption maps showed the brake specific fuel consumption of a turbocharged engine is higher compared with a naturally aspirated engine on equal brake mean effective pressure basis. Only if a naturally aspirated engine and a downsized turbocharged engine are compared at the same torque level, the turbocharged engine can prove better fuel consumption in the low to mid torque range of the engine map.

1 Introduction

Traditionally downsizing is an engine concept with which small displacement engines provide the same performance as engines with bigger displacement. In order to provide the same maximum performance the engine with the smaller displacement is equipped with either a supercharger and/or a turbocharger. In the past this concept was mainly used when only limited package space was available, which prevents package of bigger and more powerful powertrains. This is especially true for a vehicle with front wheel drive and an inline-6 cylinder engine or V-engine with a large bank angle installed transversally to the drive direction. One of the most famous downsizing applications from GM Europe was the 2,0 l Family II-engine in the Opel Calibra, offering a maximum power of 150 kW and a maximum torque of 280 Nm. Performance data were equal or superior to those of the 3 l naturally aspirated inline-6-cylinder engine (150 kW/270 Nm) offered by GM at the same time. Main development objective for this turbocharged engine was to increase maximum torque and maximum power. An additional advantage of a downsized engine is its lower weight compared to the naturally aspirated engine, which contributes to better handling in FWD applications. Since then GM Europe has continuously increased the number of turbocharged engines, as it can be seen in **Figure 1**.

During the last years the development focus for boosted engines has changed and downsizing for the purpose of fuel consumption reduction has gained significant importance. Many recent publications have reported significant fuel consumption reductions, while at the same time offering superior performance. Reduced friction, lower pumping losses and further shifting the operation to more efficient load points are considered to be the main drivers for lowering fuel consumption. Does downsizing represent the silver bullet for fuel consumption reduction?

2 Physics of Downsizing

Downsizing means to replace an existing naturally aspirated engine by a boosted engine having a smaller displacement, but offering at least the same performance. For boosting the engine either a mechanical supercharger and/or a turbocharger can be used. If the main objective is to reduce fuel consumption, mainly a turbocharger is chosen because it causes lower parasitic losses than a supercharger. The combination of gasoline direct injection, cam phasing on intake and exhaust side and turbocharging represents the state of the art for modern boosted gasoline engines. In 2006 this

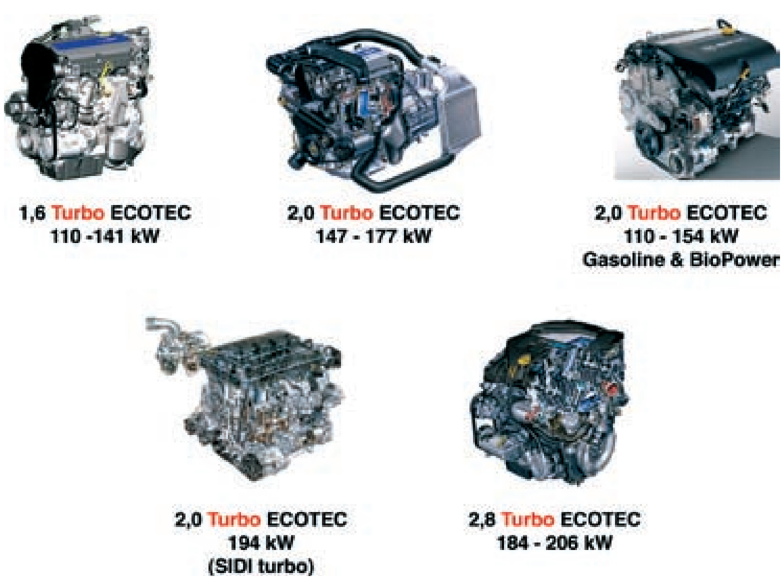
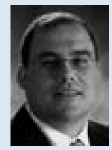


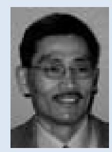
Figure 1: GM Europe turbo engines

The Authors

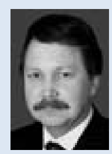
Achim Königstein
is Chief Engineer Gasoline Technology, GM Powertrain, Advanced Engineering in Rüsselsheim (Germany).



Prof. Dr.
Uwe Dieter Grebe
is Executive Director GM Powertrain, Global Advanced Engineering in Pontiac (USA).



Ko-Jen Wu
is Engineering Group Manager GM Powertrain, Advanced Engineering in Pontiac (USA).



Per-Inge Larsson
is Technology Leader Charging for Gasoline and Diesel engines, GM Powertrain, Advanced Engineering in Södertälje (Sweden).

combination was launched by General Motors [1]. For the study described in this paper this technology combination was transferred to a 1,4 l engine, a member of GM's small four cylinder engine family. The main development goals were:

- excellent Low-End-Torque (LET)
- low fuel enrichment demands for component protection
- low fuel consumption
- low smoke numbers.

The main engine data are shown in the **Table**. Based on simulation results cam profiles and turbocharger sizing were chosen in order to offer a maximum torque of 230 Nm (bmep. = 20,6 bar) already from an engine speed of 1,500 rpm onwards. Applying an extensive scavenging strategy [6] plays an important role in achieving the development goals regarding LET.

In order to avoid wetting of the cylinder liners by the injected fuel, multi-hole injectors were chosen and installed in the central position of the pent roof of the combustion chamber. This arrangement also leads to very low smoke numbers. This engine represents the basis for the analysis and assessment of downsizing concepts described in the following text.

Table: Main engine data

		1,4L SIDI turbo
Bore Diameter	mm	73,4
Stroke	mm	82,6
Displacement	ccm	1398
Compression Ratio	–	9,2 : 1
Fuel System		High Pressure Direct Injection Flow controlled HP fuel pump (200 bar) Multihole Injectors
Cam Timing		Dual- Cont. Variable Camphasers
Max. Torque @ engine speed	Nm 1/min	230 1.500 – 4.250
Max. Power @ engine speed	kW 1/min	103 4.300 – 6.000

3 Full Load Comparison between Turbocharged Engine and Naturally Aspirated Engine

In **Figure 2** full load torque curve of the 1.4 l engine with turbocharging, gasoline direct injection and cam phasing on intake and exhaust side is shown. It can replace naturally aspirated engines of up to 2.2 l displacement if only steady state torque is considered.

But, steady state torque taken at engine test benches are normally not achieved in vehicles under transient conditions due to a delayed boost pressure buildup (turbo lag), especially not in low gears. Compared to conventional turbo engines (MPFI, fixed cam timing) this handicap can be significantly reduced by applying gasoline direct injection in combination with D-CVCP, twin scroll turbochargers, variable turbochargers and two stage turbocharging. Combining turbocharging with an electric motor connected to the crankshaft (hybridization) is rated even better when it comes to reducing turbo lag [2].

In the following the investigations are limited to conventional turbocharging, gasoline direct injection and dual continuously variable camphasing. Because of the expected negative dynamic effects of turbo lag and the longer overall gear ratio, the more conservative target of the 1.8 l engine instead of the 2.2 l engine was chosen for the following comparison.

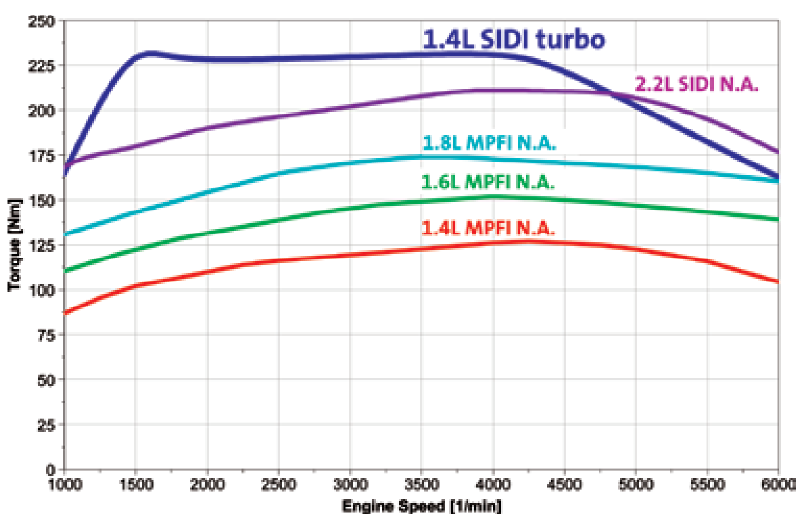


Figure 2: Full load comparison between naturally aspirated and turbocharged engines

4 Comparison of Part Load Fuel Consumption of Turbocharged and Naturally Aspirated Engines

The basic idea of downsizing is to reduce parasitic losses and to further make the engine operating at speed-load points with higher thermal efficiencies. This principle can clearly be derived from a fuel consumption map as shown **Figure 3**. Fuel consumption decreases with decreasing engine speed and increasing engine load (bmep – brake mean effective pressure).

Just as an example it is shown that when operating the engine at bmep = 2.86 bar instead of at bmep = 2,00 bar at the same speed of 2000 rpm, to reflect a displacement decrease from 1.8 l to 1.4 l, fuel consumption can be decreased by 14,7 %. But, this comparison does not allow assessing correctly the potential of

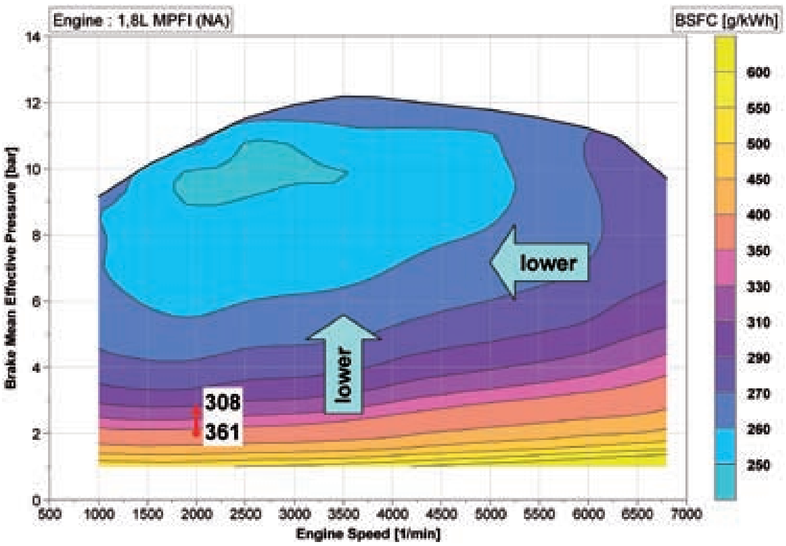


Figure 3: Shift of operating points during downsizing

downsizing because of the following simplifications:

- for both engines/displacements the same fuel consumption map is used
- unchanged gear ratio is assumed.

5 Fuel Consumption Maps of Turbocharged and Naturally Aspirated Engines

Figure 4 represents the comparison of the fuel consumption maps between the 1.8 l naturally aspirated and the 1.4 l turbocharged engine, respectively. Operating these two engines at the same specific load points, here shown for n = 2000 rpm / bmep = 2,0 bar, n = 3000 rpm / bmep = 3,0 bar and n = 4000 rpm / bmep = 5,0 bar, specific fuel consumption of the turbocharged is between 6 % and 11 % higher than that of the 1.8 l naturally aspirated engine. The root causes for this difference in fuel consumption are:

- lower compression ratio (ε = 9,2:1 vs. ε = 10,5:1) – about 4 to 5 %
- higher pumping losses – about 1 to 2 %
- higher parasitic losses (smaller displacement, higher oil flow demands (piston cooling, turbocharger, camphasers, etc.) – about 2 %.

The same kind of comparison was done for different turbocharged and naturally aspirated engines offering similar performance and basically the same results were achieved. Still this does not represent the correct comparison to assess the fuel consumption potential of downsizing because it does not take into account the shift in load points. If in-vehicle fuel consumption is concerned a comparison has to be performed at same crankshaft torque or better yet at same wheel torque if different gear ratios are allowed. Such comparisons will be performed in the next two steps.

6 Comparison of Fuel Consumption at Same Crankshaft Torque

If the fuel consumption comparison is performed on equal torque basis, the difference in displacement is reflected in a shift of the operation points, i. e. the engine with the smaller displacement is operated at higher brake mean effective pressures. The result is shown in **Figure 5**. Starting from a 6 to 11 % higher fuel consumption as shown in Figure 4, comparing the two engines at the same torque leads to fuel consumption decrease of as much as 4.2 % for the lightest load point for the turbo case. The fuel consumption benefit decreases with increasing engine speed and torque. In order to gain a better understanding of these dependencies the fuel consumption value of the naturally aspirated engine is divided by that of the turbo engine at each speed and torque point throughout the entire map of the naturally aspirated engine, **Figure 6**. Areas where the fuel consumption ratio is bigger than 1.0 indicate lower fuel consumption for the turbo engine. Areas where the fuel consumption ratio is

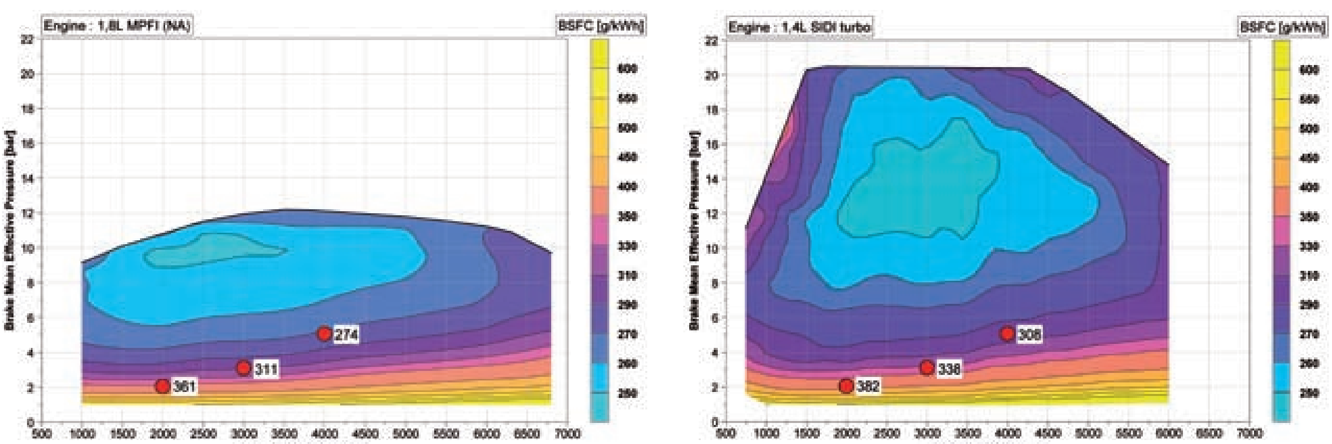


Figure 4: BSFC-map comparison between 1.8 l NA engine and 1.4 l turbo engine

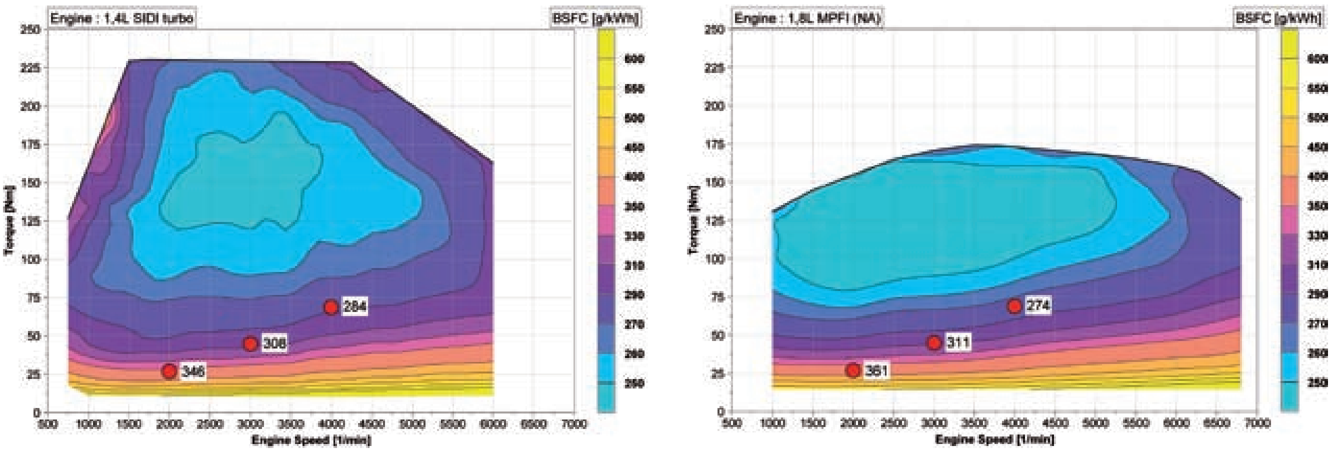


Figure 5: BSFC map comparison between a 1.8 l NA engine and a 1.4 l turbo engine (basis: engine torque)

lower than 1.0 show lower fuel consumption for the naturally aspirated engine. In the area between 0.98 and 1.02 the fuel consumption is considered to be similar between the two engines. The diagram indicates that the advantage in fuel consumption mainly depends on torque and less on engine speed. The second message is that only up to a certain torque, here about 50 Nm, the turbo specific disadvantages in bsfc can be compensated by load point shifting.

7 Impact of Downsizing Factors on Fuel Consumption Benefits

In the previous chapter the strong dependency of the fuel consumption savings on engine torque was shown. This dependency raises the question what the right downsizing factor for minimum fuel consumption would be. The downsizing factor is defined as the quotient of the displacement of the naturally aspirated engine divided by the displacement of the turbocharged engine. In the following the 1,4 liter turbocharged SIDI engine is compared with the following naturally aspirated engines:

- 1.4 l MPFI (small 4-cylinder gasoline engine family)
- 1.6 l MPFI (medium 4-cylinder gasoline engine family)
- 1.8 l MPFI (medium 4-cylinder gasoline engine family)
- 2.2 l SIDI (large 4-cylinder gasoline engine family).

The results are shown in **Figure 7**. It can be easily seen that with a turbocharged engine having the same displacement as the naturally aspirated engine no fuel consumption benefit can be demonstrated. On the contrary, fuel consumption is on average about 8 to 10 % higher. Such a variant must be considered as a pure performance variant. With increasing downsizing factor an operating area grows in which bsfc of the turbocharged engine is lower than that of the naturally aspirated engine. Additional bsfc benefits can be gained if the naturally aspirated engine is a member of the next bigger engine family. The explanation for this is that moving from one engine family to the next bigger engine family the parasitic losses also grow for the reason that (mostly) each engine family is laid out for its most powerful version. Beginning with a downsizing factor (DSF) of about 1,3 a significantly big area where bsfc of the turbocharged engine is lower can be achieved.

Figure 8 indicates the areas on the fuel consumption map in which the 1,4 l turbo engine (installed in a compact car) is operated when running on the new European driving cycle (NEDC). It is also displayed what amount of fuel is used in each area relative to the overall consumed fuel mass. The lines of constant power indicate engine power required to run the test. The following conclusions can be drawn:

- about 1/3 of the consumed fuel is used up in areas where the fuel consumption of the turbocharged engine is

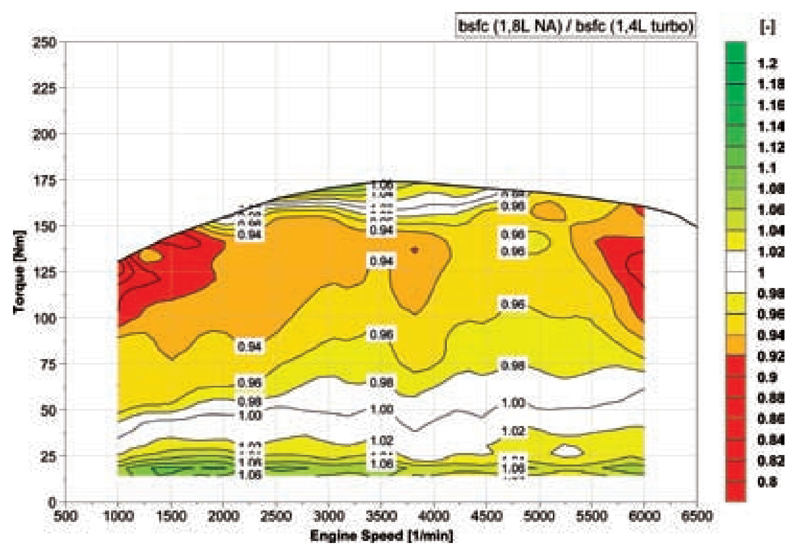


Figure 6: BSFC map of 1.8 l NA engine relative to 1.4 l turbo engine

lower than that of the naturally aspirated engine
- about 1/3 of the fuel is consumed in the area in which fuel consumption of the turbocharged engine is similar to that of the naturally aspirated one
- about 1/3 of the consumed fuel is used where the turbocharged engine has higher fuel consumption
- 2/3 of the fuel is consumed in load points requiring less than 15 kW

Based on these findings it must be concluded that in order to achieve a real significant fuel consumption reduction additional fuel consumption reduction must be found. Typically this is achieved by using longer transmission gear ratios and/or a longer final drives. Longer gear ratios/final drives can be justified by the following facts:

Rated speed of a turbo engine is typically between n = 5000 rpm and 5500 rpm – rated speed of a naturally aspirated engine is typically between 5600 rpm and 6500 rpm. Assuming the same rated power it means that overall transmission ratio of a turbocharged engine has to be longer in order to achieve the same top speed.

Assuming the same rated power, a turbocharged engine typically offers significantly higher peak torque and also its torque plateau is significantly wider. If the same elasticity requested a longer final drive becomes feasible.

As a downside of applying a longer final drive the wheel torque is reduced proportionally and take-off may become an issue, especially if the delayed torque buildup is considered as well – a phenomenon which is also known from turbocharged Diesel engines.

If the overall transmission gear ratio is decreased, the engine operating points are moved along the lines of constant power to lower engine speeds and higher engine torques. The change in fuel consumption caused by the longer final drive is shown in **Figure 9** for the test cycle relevant power levels. With reduced engine speeds the fuel consumption decreases as well. The gradient of these curves become flatter the higher the power level is. The first derivation of the fuel consumption with respect to engine speed describes the fuel consumption reduction in % per percentage engine speed reduction, assuming that power is kept the same. This dependency is shown in **Figure 10**.

For example, if there is a power demand of 15 kW and the engine speed is 2000 rpm fuel consumption can be reduced by about 2 % if a 10 % longer final drive is applied; but, with the same final drive about 8 to 10 % fuel consumption reduction can be gained if just 4 kW is required. In order to fully understand the impact of downsizing on in-

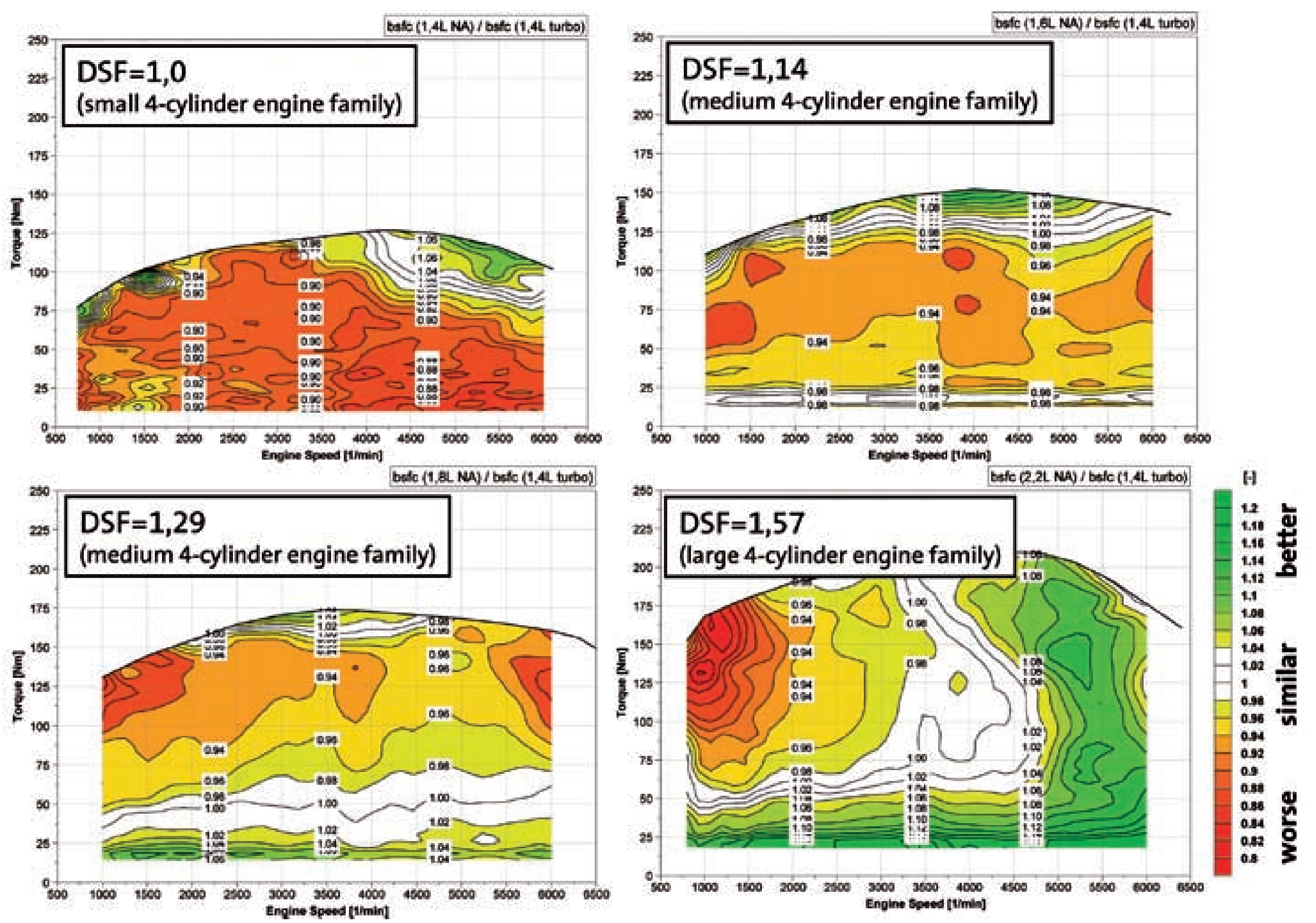


Figure 7: Impact of downsizing factor on fuel consumption reduction

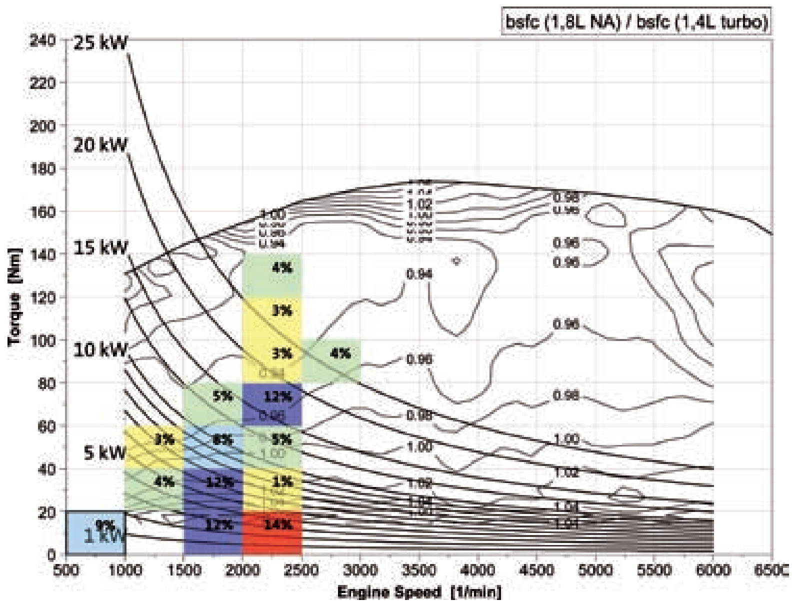


Figure 8: Fuel consumption as a function of torque and engine speed in MVEG-B test cycle

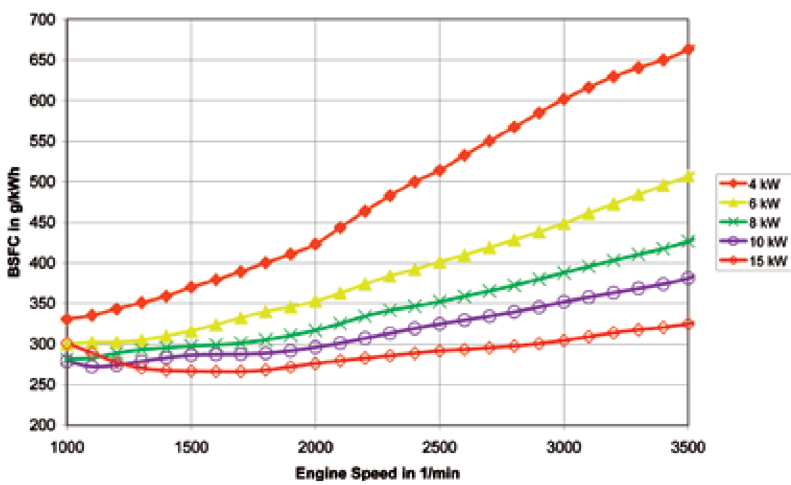


Figure 9: Specific fuel consumption as a function of engine speed (change) at constant power

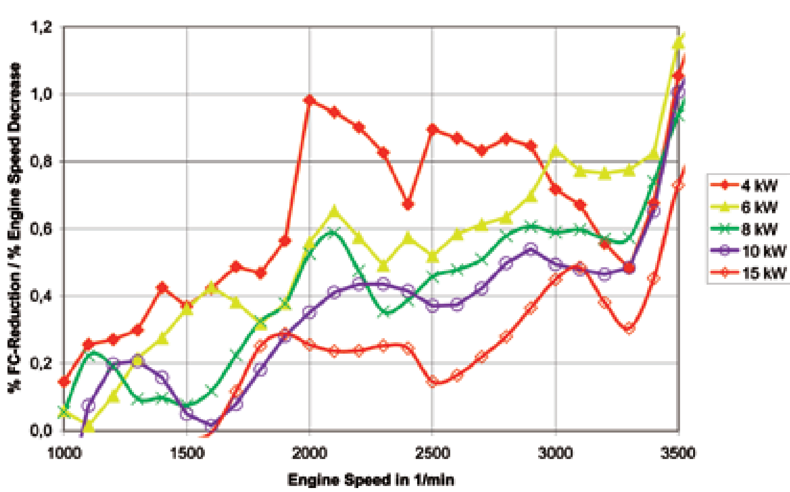


Figure 10: Fuel consumption reduction per engine speed change as a function engine speed and power

vehicle fuel consumption complete test cycle simulations were performed.

8 Test Cycle Simulation – Fuel Consumption in the New European Driving Cycle (NEDC)

In **Figure 11** the results of final drive variation for the 1.4 l turbocharged engine as well as for the 1.8 l naturally aspirated engine in a compact car are shown. Fuel consumption in NEDC is shown as a function of a performance index, which represents a characteristic for acceleration, elasticity and top speed. Each dot in each curve represents one final drive. Each dotted line connects points for the same final drive for each engine. Target area is in the lower left corner, representing minimum fuel consumption and highest drive performance (short acceleration times). The following conclusions can be drawn:

- The longer the final drive the more the fuel consumption decreases; as the performance index deteriorates.
- Making the final drive longer is limited by requirements regarding take-off and drive quality.
- Having the same final drive performance of the turbo engine is better than of the naturally aspirated engine. Its fuel consumption benefit is about 7 %.
- At a similar performance index (and longer final drive) fuel consumption of the turbo engine is about 10 % lower compared with the NA engine.
- Choosing a Diesel type transmission-ratio spread (wide) fuel consumption can even be reduced by 11 % and offering the same performance as the NA engine.

The simulation results indicate the importance of a long final drive/transmission gear ratio on high fuel economy. In order to implement those transmissions ratios successfully the engine must offer high torque already at lowest engine speeds. Measures how to achieve excellent LET characteristic are described at the beginning of this paper. The 1.4 l SIDI turbo w/ D-CVCP offers a torque of 230 Nm already at 1500 rpm and seems to be well suited.

The demonstrated fuel economy benefits are valid for the selected engine-vehicle combination. They strongly de-

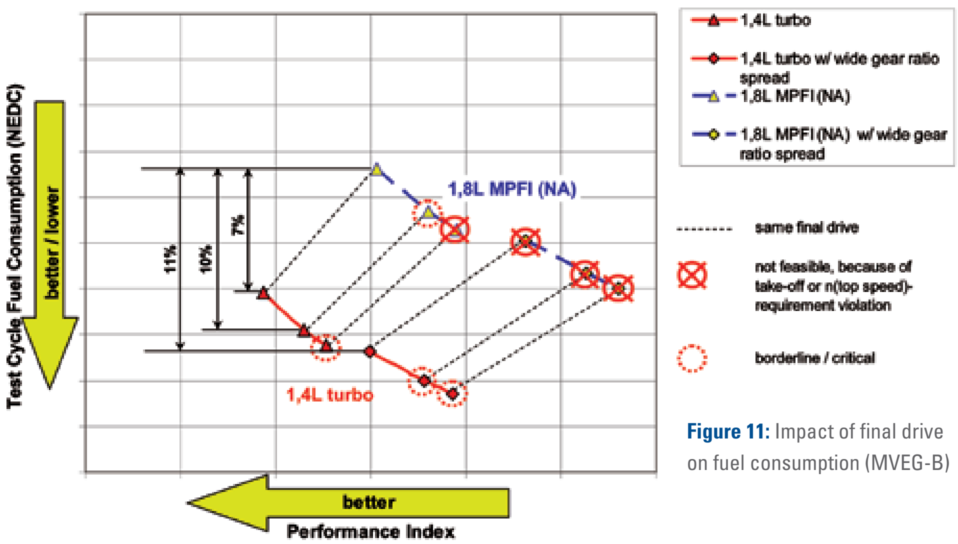


Figure 11: Impact of final drive on fuel consumption (MVEG-B)

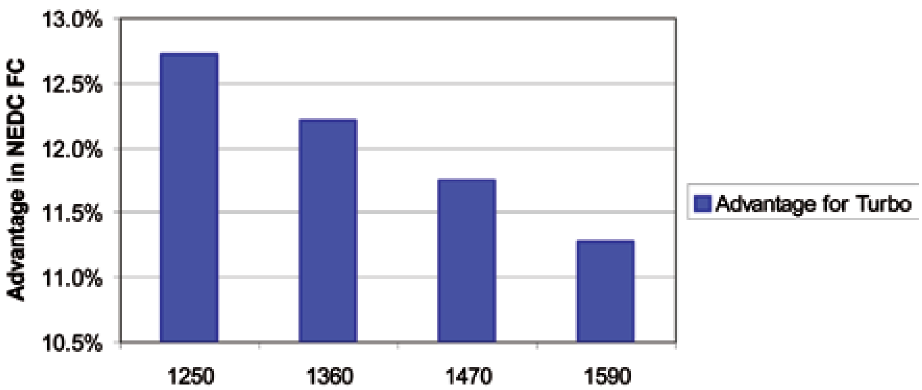


Figure 12: Impact of vehicle weight on FC-reduction potential

pend on the vehicle mass. The impact of the vehicle mass on the fuel consumption reduction potential is shown in **Figure 12**. With increasing vehicle weight the fuel consumption reduction potential decreases.

9 Summary and Conclusions

Detailed analyses have shown that in-vehicle fuel consumption can be reduced significantly by downsizing. In order to achieve this it is important that the displacement of the turbo engine is significant lower than that of the naturally aspirated engine. A downsizing factor of at least 1,3 seems to be required in order to get a significant area in the fuel consumption map where fuel consumption of the turbo engine is lower than that of the NA engine. Further improvements have to be accomplished by shifting operating points to higher loads by applying longer overall gear ratios. In order to overcome potential take-off issues it is mandatory that the engine offers an excellent LET-characteristic. Gasoline direct injection in combination w/ D-CVCP and turbocharging represents an appropriate technology to meet this requirement. For the comparison described in this paper the 1.4 l turbo engine can prove an 11 % fuel consumption reduction over the 1.8 liter naturally aspirated engine. The potential becomes smaller as the vehicle weight increases.

References

[1] Groff, E.; KönigsteinN, A.; Drangel, H.: Der neue 2,0L Hochleistungs-Turbomotor mit Benzindirekteinspritzung von GM Powertrain. 27. Internationales Wiener Motorensymposium 2006

[2] Grebe, U.D., Larsson, P.-I., Wu, K.-J.: Vergleich von Aufladesystemen für Ottomotoren. 28. Internationales Wiener Motorensymposium 2007