International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Review Article

A Review of Engine Downsizing and its Effects

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Accepted 12 March 2017, Available online 16 March 2017, **Special Issue-7 (March 2017)**

Abstract

The growing importance in research in automotive development is the replacement of bigger engines with compact yet powerful ones, and the reduction in greenhouse gases through exhaust. Different strategies are applied to comply with stringent emission regulations that are enforced on global automotive market. Internal Combustion(IC) Engine Downsizing is the method that serves both the purposes of providing the needed power and reducing fuel consumption. This report presents a brief information on various engine downsizing techniques used, the advantages of these techniques, their limitations and their effects on the performance of the engine. The report also provides us a few boosting methods used for a downsized engine to improve its performance as of a higher capacity engine, as downsizing an IC engine only may cause a dip in performance while improving other factors. The report draws attention towards the conclusions resulted from some experiments on the downsized engines. Also a brief information is provided on the effects of engine downsizing on an engine.

Keywords: *IC Engine, Downsizing, Exhaust Gas, Turbocharger, Supercharger, Valvetrain*

1. Introduction

1.1 Concept of Engine Downsizing

[1]Engine downsizing is defined as the use of a smaller engine in a vehicle that provides the power of a larger engine, through the use of recent technologies. The term generally relates to traditional internal combustion engines powered by petrol and diesel. Engine downsizing is a trending concept for vehicle engine manufacturers to provide efficient yet powerful engines.

1.2 Necessity of downsizing

The growing concern in automotive development is the formation of greenhouse gases through exhaust flow, primarily carbon dioxide. Legislations and increasing public awareness about global warming are leading vehicle manufacturers to reduce their carbon footprint. Original equipment manufacturers are making constant efforts to reduce greenhouse emissions and fuel consumption by developing through different areas though most of the emission and fuel consumption reduction is seen through increasing the efficiency of powertrain. Engine downsizing is considered the most effective strategy to improve the efficiency of powertrain(Oliver Lang, 2004)

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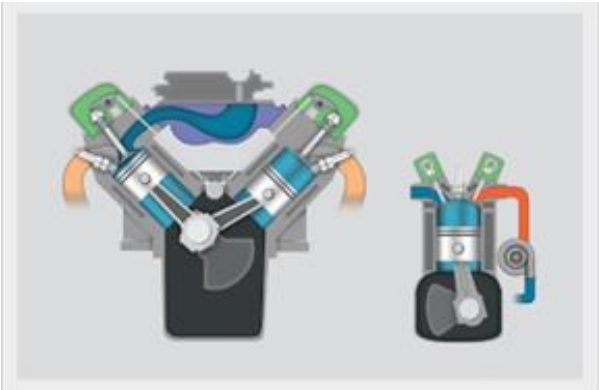

Fig. 1 Size difference between a non turbo engine on the left and turbocharged engine on the right, both producing same power.

2. The Rationale behind Engine Downsizing

A downsized engine offers different benefits to the well being. They are as follows:

1) Reduction in CO_2 and NO_2 emissions: Engine downsizing has proved a great dip in emission due to lesser fuel consumption and other important factors explained below.
2) Fuel consumption reduction: Optimization of the intake and exhaust valve timing at low engine speed with scavenging leads to a reduced residual gas content in the cylinder.

3) Decrease in the weight of engine block: Generally downsizing an engine is done by reducing the number of cylinders. This helps in the reduction of weight of the engine and thus the load on the engine decreases.
4) Lesser swept volume by piston: Due to decrease in the displacement of the piston, there is a decrease in friction between the piston and the engine bore. Hence the losses due to friction are reduced. This adds to the benefit of engine downsizing.

3. Types of Engine Downsizing techniques used:

The basis of most downsizing processes is increasing the performance by

1) Using turbochargers
2) Using superchargers
3) Using twin-charging

New methods that support downsized engines are use of the technologies below and/or with the those mentioned above

1) Direct fuel injection(DI).
2) Advanced exhaust gas recirculation (EGR).
3) Variable valve timing (VVT).

Use of Turbocharger or Supercharger alone has now become obsolete. The reason is that the use of them without any supplementary device has comparatively lesser advantages. Newer technologies like Turbocharged Direct Fuel Injection and Variable Valve Timing are widely used in recent times for cars and light motor vehicles.

4. Downsizing using a Turbocharger

Despite of its lower displacement, the performance of a downsized engine can be maintained by injecting more air into the combustion chamber to burn additional fuel. Turbocharging provides the engine with the mass of air needed to ensure highly efficient and clean combustion.

In both petrol and diesel vehicles, the turbocharger comprises two assemblies: a centrifugal compressor and a turbine. Hot gases rotate the turbine which rotates the compressor as both are connected via a same shaft.

The compressor comprises an impeller and a diffuser, housed in the compressor casing. The impeller accelerates the air drawn from the atmosphere and forces towards the diffuser. The diffuser slows the fast-moving air which raises its pressure and temperature in the compressor housing. The compressed air is then directed to the engine. This way, more air is injected into the combustion chamber and burns the additional fuel needed to maintain engine power.

4.1 Problems in Turbocharging

One of the main problems with the use of only a turbocharger is that they do not provide an immediate power boost when you accelerate. It takes some time for a turbine to get up to the speed before boost is produced. this results in a feeling of lag when you accelerate, and then the car lunges ahead when the turbocharger starts operating.

One way to decrease this turbo lag is to reduce the inertia of rotating parts mainly by reducing their weight. This allows the turbine and compressor to accelerate quickly and provide the boost without any lag.

The flow of exhaust gases through the turbine and compressor is carefully controlled to prevent the turbocharger from overcharging at high engine speeds and also to maintain torque at lower engine speeds.

4.2 Using an Intercooler

An intercooler is a mechanical device used to cool a fluid, including liquids or gases, in multi-stage heating process, typically in a heat exchanger that removes waste heat in a gas compressor. They are widely known as air-to-air or air-to-liquid coolers. They improve the volumetric efficiency of internal combustion engines by forced induction with nearly isobaric cooling.

The efficiency of the induction system is increased by intercoolers by reducing induction air heat created by the supercharger or turbocharger. This removes the heat of compression of the inlet gas.

A decrease in intake air charge temperature helps in the induction of a more dense intake charge into the engine. The lowering of the intake air temperature also eliminates the danger of pre-detonation (knocking) of the fuel/air charge. This preserves the benefits of more fuel/air burn per engine cycle, increasing the output of the engine.(source:Honeywell)

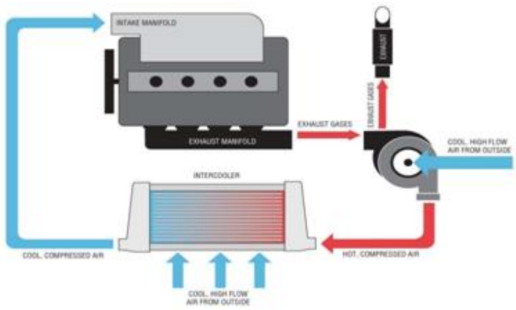

Fig. 2 Schematic of the position of Intercooler in a vehicle (source: www.turbosmart.com.au)

5 Developments in a Turbocharger

5.1 Two-Stage turbocharger

A conventional turbocharging systems present stalling issues at low speeds. In fact, the maximum compressor flow rate must be about the same of the full bore engine, in order to deliver the same airflow at maximum power. However, at low speed, boost pressure should be higher, for compensating the displacement reduction.

This problem is solved by a triple turbocharger. The triple turbocharger is conceptually similar to a 2-stage system (Rainer Golloch, *et al*, 2005), the only difference being that the high pressure stage is made up of two parallel machines, instead of one. The low pressure stage consists of a bigger turbocharger that delivers a flow rate about two times higher than that of the turbocharger in a conventional system. Conversely, the high pressure turbochargers are much smaller and are completely by-passed at higher engine speeds. In the triple layout, with a proper choice of each machine, the turbochargers of both stages may operate at high efficiency conditions, all over the engine speed range (Carlo Alberto Rinaldini, *et al*, 2015). The triple turbocharger is more complex than a twin-turbo, from two points of view: electronic control and packaging.

5.2 Hybrid turbocharging

A hybrid turbocharger is an electric turbocharger consisting of a high speed turbine-generator and a high speed electric air compressor. High electrical efficiency is obtained as there is no mechanical linkage between the turbine and the compressor. The hybrid turbocharger refers to a series hybrid setup, in which compressor speed and power are independent from turbine speed and power. This design flexibility leads to further improvements in turbine and compressor efficiency.

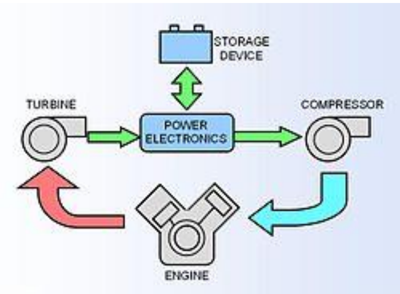

Fig. 3 Schematic of a Hybrid turbocharger system

5.2.1 Operating modes

A) Acceleration

When the driver presses the throttle, the hybrid turbocharger initially acts like an electric supercharger. The compressor motor is powered from the energy storage and allows it to accelerate to full operating speed in a short time interval. This rate of acceleration eliminates the turbo lag.

B) Charging

At high engine speeds excess energy is generated by the turbine than required by the compressor. This excess energy recharges the energy storage for the next acceleration phase or to power some of the auxiliary loads such as an electric air conditioning system.

C) Steady state

For the majority of the time the hybrid turbocharger is operating, the compressor and turbine power will be matched. Here the hybrid turbocharger efficiently transfers the electricity between the turbine and compressor.

6. Downsizing using a Supercharger

A supercharger is an air compressor that increases the pressure or density of air supplied to an internal combustion engine but with the help of mechanical power of the engine and not the exhaust gases like that of a turbocharger.

They are of two types of superchargers, mechanically driven and electrically driven. Mechanically driven superchargers may absorb as much as a third of the total crankshaft power of the engine and are less efficient than turbochargers. Electrically driven superchargers do not draw direct power from the engine, unlike conventional superchargers. At low engine speed, electric superchargers do not take much energy and are much effective.

6.1 Advantages of a Supercharger

The main advantage of supercharger is better throttle response, as well as the ability to reach full-boost pressure instantaneously. Engine-driven superchargers apply boost in direct proportion to the engine rpm.

6.2 Problems with using only a Supercharger

The thermal efficiency is less when compared with a similar turbocharger, because turbochargers use exhaust gas energy that would normally be wasted. The economy and the power of a turbocharged engine are usually better than the engines with only a supercharger.

7. Downsizing using Twin Charger

Twincharger is a combination of an exhaust-driven turbocharger and an engine-driven supercharger. A supercharger offers exceptional response and low-rpm performance as it has no lag like that of the turbocharger. Both the components work together to give maximum output mitigating the weaknesses of the other.

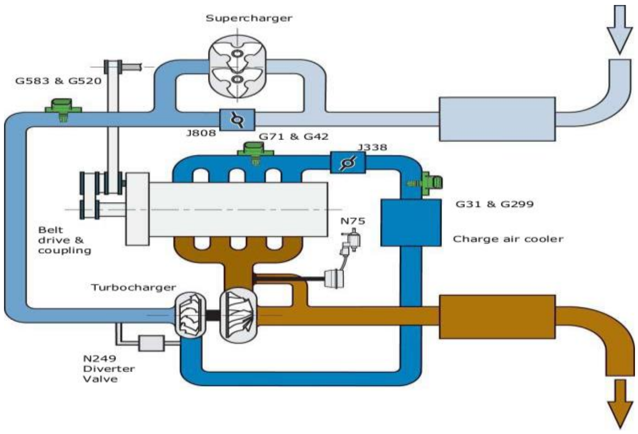

Fig. 4 Schematic showing the twin charging system (source: Volkswagen Club GTI)

7.1 Advantages of using a Twincharger

The proper combination of the two can offer a zero-lag with high torque at lower engine speeds and increased power at the higher speeds. Twincharging is therefore desirable for small-displacement, especially those with a large operating rpm, since they can take advantage of an artificially broad torque band over a large speed range. Hence twincharging is very useful in downsized engines.

Twincharging does not refer to a twin-turbo arrangement, but rather when two different kinds of compressors are used. They might be in a series or in a parallel combination

7.2 Problems in using a Twincharger

The main problem of twincharging is that the components and complex and expensive. Usually, to provide better response, smoothness and adequate power gain over a single-compressor system, expensive electronic and/or mechanical controls must be used.

8. Downsizing using Turbocharged Direct Injection (TDI)

8.1 Spark-ignition engine downsizing using TDI

Spark-ignition(SI) engine downsizing is now established as a 'megatrend' in the automotive industry, providing as it does an affordable solution to the twin issues of reducing tailpipe CO_2 emissions and improving fuel economy while providing improved drivability from gasoline engines.

The advantages of downsizing a 4-stroke spark-ignition (SI) engine stem chiefly from shifting the operating points used in the engine map for any given flywheel torque, so that the throttle is wider-open to the benefit of reduced pumping losses.

In TDI system a fuel injector sprays atomized fuel directly into the combustion chamber of each cylinder, rather than the pre-combustion chamber that was used in older engines. The engine uses turbocharger to increase the amount of air entering the engine cylinders. TDI system is also used with an intercooler. In combination, they improve engine efficiency, and therefore provide greater power outputs while also decreasing emissions and providing more torque than the non-turbo and non-direct injection petrol engine counterpart.

Because these engines have relatively low displacement and are quite compact, they have a low surface area. This reduces heat losses through the engine surface, and thereby increases engine efficiency, at the expense of slightly increased combustion noise.

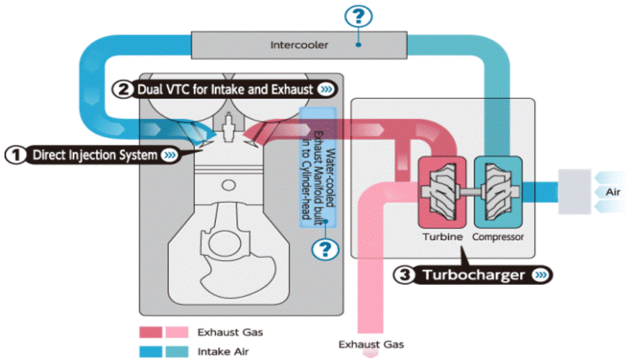

Fig. 5 Schematic of TDI technology (source: Honda worldwide)

8.2 Effects of TDI on engine performance

The BMEP of the engine can be increased significantly due to the effective increase in knock resistance afforded by the direct injection of the fuel into the cylinder due to its evaporative effect and also the introduction of fuel can be delayed until after the exhaust valves are shut.

At present, the spark retardation is necessary when operating such engines on petrol. This ensures that these very high levels of cylinder pressure cannot be achieved in practice, but with future engine technology and fuel development they may be approached even when operating on relatively low-octane regular petrol. (Turner, *et al*, 2010)

9. Use of Variable Valve Timing (VVT) in Downsized Engines

Variable valve timing (VVT) is used in spark ignition engines to improve fuel economy, reduce NO_x gas, and increase peak torque and power. The variable valve lift also makes an important role to the performance of the engine.

Without variable valve timing or variable valve lift, the valve timing is the same for all engine speeds and conditions, therefore compromises are necessary. An engine equipped with a variable valve timing actuation system is freed from this constraint, allowing performance to be improved over the engine operating range.

An engine requires large amounts of air when operating at high speeds. However, the intake valves may close before enough air has entered each combustion chamber, reducing performance. On the other hand, if the camshaft keeps the valves open for longer periods of time, as with a racing cam, problems start to occur at the lower engine speeds. This will cause unburnt fuel to exit the engine since the valves are still open. This leads to lower engine performance and increased emissions. (Atul Gupta, et al, 2013)

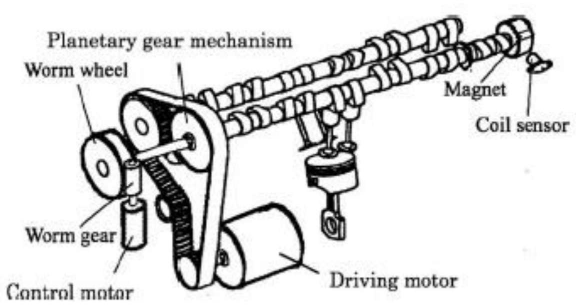

Fig. 6 Schematic of VVT using control motor

9.1 Effects of VVT on Engine Performance

During most of its average life, a road engine is run under low load and low speed conditions. It is known that load reduction in spark-ignition engines is traditionally realized by introducing additional losses during the intake stroke by means of a throttle valve. In these operating points, the engine efficiency decreases from the peak to values dramatically lower. The optimization of intake and exhaust valve timing can provide significant reductions in pumping losses at part load operation.

9.2 Challenges in VVT technology

VVT needs two or three extra gears and a belt drive which increases the size of the drivetrain. Due to engagement of actuators with cams, there are chances of increased friction on the cam surface that may cause degradation of the cam.

The main factor preventing this technology from wide use in production automobiles is the ability to produce a cost effective means of controlling the valve timing under the conditions internal to an engine. The valve timing events have to occur at precise times to offer performance benefits. Electromagnetic and pneumatic camless valve actuators offer the greatest control of precise valve timing, but, in 2015, are not cost effective for production vehicles. (Atul Gupta, *et al,* 2013)

10. Advanced exhaust gas recirculation for Downsized Engines

In IC engines, exhaust gas recirculation (EGR) is a nitrogen oxide (NO_x) emissions reduction technique used in petrol/gasoline and diesel engines.

10.1 Working of EGR

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. Providing only EGR actually drops the performance of engine by 10-13%, but with recent technologies optimizing the control variables like boost pressure, A/F ratio and spark advance, same performance is achieved as that of an engine without EGR system. (E. Galloni, *et al* , 2013)

10.2 Effects of EGR in Downsized Engines

EGR operation allows higher boost pressure values and leaner A/F mixtures at a given knock intensity level. In particular, when EGR is utilized, a proper optimization of the main engine control variables (i.e. boost pressure, air to fuel ratio and spark advance) allows achieving the same performance level of the engine running with pure A/F charge, meanwhile the exhaust temperature and knock intensity remain the same and the specific fuel consumption significantly decreases. (E. Galloni, *et al* , 2013)

11. Effects of Engine Downsizing on Losses

A downsized engine tends to produce lesser loss in terms of friction due to reduced surface area. Engine downsizing reduces mechanical losses, but at a lower rate than is proportional to displacement. Pumping losses are dependent on the operating conditions and must be calculated for each driving mode. But they are still reduced due to downsizing. (Ryujiro Nozawa, *et al*, 1994)

Conclusions

Engine downsizing is a continuous developing process and many new methods of achieving better power and fuel efficiency at low engine capacity are being developed. For an IC engine, possible benefits in fuel consumption are between 10 and 30 % depending on the degree of downsizing and the combustion process. Though the maximum speed of a vehicle is reduced by downsizing, there are many experiments which suggest the existence of optimal engine displacement. It is expected that the combination of turbocharging, direct injection and variable valve timing will become the standard in the future. High performance engine variants can be realized without major drawbacks in their usable speed range. It is also observed that friction losses for unit displacement increase in smaller engines, and the use of favorable regions on the fuel-consumption map may improve the fuel economy.

Thanks to downsizing, the petrol and diesel engines of the future could have just two cylinders and a displacement of lower than a liter, and provide required torque and power without producing high amount of pollutants.

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