Contents

Introduction
History
The choice: turbocharger or supercharger?
 Turbocharger sectors
- Medium- and Heavy-vehicle
- Light-vehicle
- Performance
- Small diesels

Market drivers
The European Union
The United States
- Key elements of the programme
  - GHG reductions;
  - Credit provisions;
  - Regulatory design;
  - Consistent improvements;
  - International context;
Japan
China
- 2.3 Phase IV
Other countries
Testing regimes
Criterion emissions
- Light-vehicle vehicles
- The United States
- Japan
- Europe
- China
- Other countries
- Medium- and heavy vehicles
Engine downsizing and down-speeding

Market dynamics and forecasts
Light-vehicle engines
- Europe
- North America
- Japan
- Greater China
Technologies
- Compressors

Technology
- Reciprocating compressors
- Screw compressors
- Centrifugal compressors
- Surge line
- Choke line
- Bearing systems
- Micro turbocharging
- Waste-gated turbochargers
- Turbo-compounding
- Electric turbo-compounding
- Twin-scroll turbochargers
- Variable geometry turbochargers
- Multi-stage turbocharging
- Parallel twin turbocharging
- Sequential twin turbocharging
- Regulated twin turbocharging
- Three-stage turbocharging
- Twin vortices supercharger
- Electric superchargers
- Charge air coolers (intercoolers)

The future of turbocharging
Titanium compressor impellers
Assisted turbocharging

Key technology from market participants
Continental/Siemens VDO
- New Czech facility
- New aluminium housing technology
Robert Bosch/Mahle Joint Venture
- First Chinese plant
BorgWarner
- Flex fuel turbo for South American market
- New China plant
- Supplying to Volkswagen in China
Cummins/Holset
- IHI Corporation
- Joint venture with Hyundai Wia
Mitsubishi Heavy Industries (MHI)
Eaton Corporation
Who-Supplies-Whom: Light-vehicle turbocharger suppliers by model

Turbocharger Supplier Profiles
BorgWarner
- Manufacturing plants
- R&D Addresses
- Map
Cummins
- Manufacturing plants
- R&D Addresses
- Map
Dong'an Engine
Federal-Mogul
- Manufacturing plants
- R&D Addresses
- Map

Georg Fischer
- Manufacturing plants
- R&D Addresses
- Map
IHI Corporation
- Manufacturing plants
- Map
Le Belier
Mitsubishi Heavy Industries
- Manufacturing plants
- R&D Addresses
- Map
NingboRico Auto
- Manufacturing plants
- Map
Weifang Fuyuan

Figures
Figure 1: Illustration of different types of turbocharged engine
Figure 2: China emissions standards
Figure 3: Engine downsizing trend forecast
Figure 4: Regional turbocharger penetration
Figure 5: Global light-vehicle engine production forecast by aspiration type, 2015
Figure 6: European supercharger/ turbocharger fitment by type, 2012–2017
Figure 7: Europe light-vehicle engine production forecast by aspiration type, 2015
Figure 8: North American forced induction and naturally aspirated penetration, 2012–2017
Figure 9: North American light-vehicle engine production forecast by aspiration type, 2015
Figure 10: Japan forced induction and naturally aspirated penetration, 2012–2017
Figure 11: Japan light-vehicle engine production forecast by aspiration type, 2015
Figure 12: Greater China forced induction and naturally aspirated penetration, 2012–2017
Figure 13: Japan light-vehicle engine production forecast by aspiration type, 2015
Figure 14: Global supercharger/ turbocharger engine production by type, 2012–2017
Figure 15: Fiat 500 Abarth’s 1.4-liter MultiAir® Turbo engine
Figure 16: BMW M3/M4 Turbo Charger
Figure 17: 2014 3.6L V-6 VVT DI Twin Turbo (LF3) for Cadillac CTS. Twin turbocharged with integral manifold mounted intercooler

Tables
Table 1: Timeline of implementation of global emission standards
Table 2: Global Emission Standards
Table 3: Types of turbocharged engine
CHAPTER ONE
Introduction
Over the past decade turbocharging in particular, but generally induction charging, has moved to become central to powertrain strategy globally. This has come about through a combination of market forces supported by a period of considerable product innovation.

In its race for more efficient powertrain and in order to reduce greenhouse gas emissions, forced induction, because of its inherent benefits, has become the prevalent technology. This is particularly true for the high performance diesel engines that take a large share in many markets and which need forced induction to overcome inherent problems with power and torque delivery. Furthermore, forced induction is essentially the enabling technology for downsizing and down-speeding, the key strategy being employed by OEMs in their quest for greater engine efficiency.

It is also worth commenting that this strategy also brings far greater demands on transmissions, as the inherent powertrain flexibility of the pre-turbocharging era is no longer available and both flexibility and additional efficiency gains are being sought here as well.

Since the 1990s, five key influences have combined to change the nature of turbocharger and supercharger technology:

- Materials improvements;
- Refinement enabled by improved computer modelling;
- The widespread introduction of direct injection in both gasoline and diesel engines;
- Improved sensor technology; and
- more efficient systems design.

The basic concept behind induction charging, whether through conventional supercharging or turbocharging is to increase the amount of air being forced into the vehicle's engine, along with an increase in fuel. This has the effect of increasing engine power output without increasing the swept volume. To achieve this, intake air is compressed by a compressor that is driven by the pressure of the exhaust gas (turbocharger), directly from the engine crankshaft (mechanical supercharger) or by an electric motor (electric supercharger).

Clearly therefore forced induction of some kind is critical in attaining optimum efficiency from engines, either for increased vehicle performance or in order to attain a given vehicle performance with a smaller, more fuel efficient engine.

The amount of air forced into the engine can be further increased by cooling it during the intake stage between the compressor and the engine through a charged air cooler or ‘intercooler’, via an air-to-air or water-to-air heat exchanger, although, at least in part, intercoolers are used to remove the heat generated during compression.

Increasing the amount of air-fuel charge in the engine can also cause other heat problems including knocking, which is the result of the combustion of the fuel-air mixture occurring more rapidly than is ideal, and pre-ignition, which is when the mixture in a spark ignition engine ignites under pressure before the spark plug fires. Fitting a turbocharger to an engine that has not been enhanced accordingly can also result in a lean fuel-air mixture, which can also cause overheating. Consequently, turbocharged and supercharged engines need to be designed accordingly with, for example, piston rings further from the combustion zone than in a normally aspirated engine, a suitable fuel injection control system, a lower compression ratio and a higher octane fuel specification.

Changes are also required in the vehicle transmission, as power and torque delivery characteristics can change significantly from normally aspirated engines. This means that in order to achieve acceptable vehicle performance, transmissions have an increasingly important role to play and transmission control electronics is a critical aspect of vehicle design.

Further technology to control turbocharger ‘boost’ pressure includes ‘blow-off’ valves and ‘waste-gates’. A ‘blow-off’ valve is situated on the air intake side of the turbocharger and is designed to release excess intake air pressure as the engine decelerates during gear changes, or if the driver releases the accelerator when boost pressure is high. A waste-gate is situated on the exhaust turbine side of a turbocharger in order to re-route some of the exhaust gas flow away from the turbine once a set intake pressure is reached. However, these issues do not arise where supercharges are concerned because of the instantaneous turbine response, and further enhancements can potentially be achieved through the intelligent control of electrically driven superchargers.

In terms of turbochargers the exhaust system driving the turbine takes time to reach the required pressure and, in combination with the rotational inertia of the turbine as it accelerates, results in ‘transient delay’ or ‘lag’ so that there is a pause between the driver depressing the accelerator and the increase in engine power output. There are a number of strategies designed to combat lag, and in some cases eliminate it altogether. These are examined later in this report.
The obvious and most pressing beneficial need for turbocharging is related to the challenge to improve fuel economy and reduce CO₂ and other emissions. Adding a turbocharger does not automatically save fuel in itself but it does mean that a smaller turbocharged engine can achieve the same power output as a much larger engine, without compromising fuel economy under lower power demand conditions (engine downsizing).

Where once turbocharging was considered a technology for high performance and sophisticated engine design, today it is becoming ubiquitous. The predominant strategies of downsizing and down-speeding to improve efficiency cannot be implemented without forced induction, and its various methods and technologies are now centre stage in internal combustion engine (ICE) design.

On the other hand, OEMs around the world are grappling with a considerable compromise: every design that reduces engine size or component size must be countered by a boost to available power from that engine through supercharging and turbocharging. Turbochargers add weight to the vehicle but are more valuable in terms of power delivery for each vehicle. The solution is to create new designs in structure and function, so that the downsized engine is as powerful in torque and low-end as the customer demands.

Engine downsizing has long been acknowledged as an important route to the improvement of fuel economy. In general terms, a smaller engine has less internal friction so that less energy is wasted merely in moving its components. It also has less thermal inertia, which means that it warms up more quickly and is thus more thermally efficient in a typical mixed-duty, real-world operation.

In addition, as light vehicle car engines operate at well below their point of peak efficiency in day-to-day use, by substituting a smaller capacity unit operating at higher specific load, combustion and gas exchange process can be more efficient.

There are, however, also some practical limits to downsizing a conventional four-stroke engine. The main obstacle to downsizing is the achievement of good low-speed torque and launch feel.

A boost system applied to a downsized engine will produce more torque, but this is limited by the onset of less than optimal combustion as higher pressures and temperatures are reached; this is a problem particularly pronounced at lower engine speeds.

In addition, higher cylinder pressures require larger connecting rod and crank bearings to accommodate the increase in load. This in turn can increase friction, limiting the benefits of downsizing.

To operate successfully, highly boosted four-stroke engines must therefore use a lower static compression ratio, which then reduces efficiency and negates the benefits of any further downsizing. Launch feel can also be a challenge for turbocharged engines due to the time required to accelerate the turbocharger from idle to generate boost pressures. Mechanically driven superchargers can help to resolve this issue, but these devices also increase losses and reduce efficiency.

Hybridisation, or using electric power to augment low-end torque, is a well-proven route to enabling further levels of downsizing. However, while this approach works successfully in many products, it brings significant additional cost and complexity in the shape of the hybrid powertrain, power electronics and energy management systems.

Thus, despite the very significant advantages today of using turbochargers and superchargers in combination with alternative powertrain strategies, there are significant limitations emerging at the edges of the performance envelope in this respect, and it is these limitations that engineering development is looking to challenge.

An interesting trend has emerged in the passenger vehicle market such that while diesel engines have led the downsizing revolution in Europe, gasoline engines are catching up. Diesels have led the passenger market by a slim margin in recent years, with over 50% of passenger vehicles sold in Europe having these engines, and diesels have proven to be more easily downsized and turbocharged. It is argued that ICEs remain the predominant powertrain for the next decade, although they will be adjuncts to electrical powertrains in the future and not the sole propulsion system. In the meantime attention must be paid to making ICEs downsized (and right sized).

Development of turbocharging the next generation of very small gasoline engines is in full swing, with three objectives in mind: minimising the weight and displacement added to the powertrain, making power potential equal to or better than larger engines, and meeting all Euro 5 and soon Euro 6 NOx emission limits.

According to estimates by Honeywell, the number of passenger vehicles with turbocharged engines is expected to increase globally by 80% by 2017 over 2012. This change is driven by the need to deliver improved fuel-efficiency,
performance and reduced greenhouse gas emissions.

Turbocharged engines are projected to be on 36 million passenger automobiles sold globally in 2017, representing almost 40% of all new light vehicle sales in that year. In 2011, turbochargers were fitted to 20 million new vehicles sold globally, or about 25% of all vehicles.

The United States, India and China are expected to lead the global growth as consumers and automakers in these markets search for ways to get improved fuel economy, whether through gasoline or diesel engines. In Europe, where turbochargers are already on two-thirds of passenger vehicles, the technology is expected to gain even more ground as OEMs meet more stringent CO₂ emissions requirements.

“One of the earliest automotive turbocharged engines recorded was manufactured by Major Frank Halford in the UK in 1923 and the first turbo-diesel heavy-duty truck went into production in 1938 by another Swiss engine manufacturer known as Schweizer Mashinenfabrik Saurer (Swiss Machine Works Saurer).

During the 1940s, turbocharger design improved significantly along with the development of heat resistant materials and complex intercooler options. In the 1950s more and more engine manufacturers such as Cummins, Volvo and Scania experimented with the use of turbochargers, perhaps due in part to Fred Agabashian, who qualified for pole position in the Indianapolis 500 in 1952 with a Cummins diesel-engined racing car. From this point forward, turbochargers revolutionised the automotive industry, and GM is generally credited with the first production turbocharged automotive engine in the shape of the A-body Oldsmobile Cutlass released in 1962. The first production turbo-diesel passenger car, the Peugeot 604, was introduced in 1978.

From 1977 through to 1989, Formula One racing entered what is known as the ‘Turbo Era’ with Renault being the first OEM to apply turbocharging to its Formula One projects. It was not long before Honda, BMW, Ferrari and many others followed suit. In the 1970s and 1980s, OEMs sought turbocharging technology as a means to develop more power from their engines without forfeiting fuel consumption, and while turbochargers are now widespread on almost all automotive diesel engines, the technology has become a vital ingredient in the quest to lower emissions. To this end, new technological developments such as two-stage or compound turbochargers, variable geometry turbochargers, the combination of a turbocharger and a supercharger, and the use of an electrically-driven supercharger with or without a