The Design, Development and Application of a New Range of Turbochargers for Light Commercial Vehicle Markets.

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Abstract: In response to customer demand for durable, reliable wastegate and variable geometry turbochargers for the light-/medium-duty diesel engine market, Cummins Turbo Technologies embarked upon the design of a new range of turbochargers.

Leveraging nearly 60 years of experience in the design of market-leading turbochargers for medium- and heavy-duty diesel engines, Cummins Turbo Technologies has partnered with global customers to deliver a design ‘fit for market’, which embraces ‘design for manufacture’ to ensure cost, quality and durability targets are achieved.

The paper describes how Six Sigma tools have been used to select, develop and successfully launch the new range of turbochargers.

Key words: Market analysis and requirements; Concept selection; Durability; Reliability; Design for manufacture; Engine braking; Thermal regeneration.
1 Introduction

Owing to the ever-increasing need for fuel economy, increased engine performance and reduced emissions, there is a growing strategic requirement for cost-effective turbocharging solutions throughout the automotive sector in general. More specifically, market research and analysis carried out by Cummins Turbo Technologies suggests that there is a particular requirement and opportunity to supply turbochargers with higher performance and improved durability to the Light Commercial Vehicle (LCV) market.

There is no globally accepted definition of a ‘Light Commercial Vehicle’ but in broad terms it includes vehicles with diesel engines having swept volumes of between 2.3L and 5.0L. Engines in this sector typically have more arduous duty-cycles than passenger cars and they need a greater focus on reliability and durability. However, more sophisticated turbocharging solutions are required to enable engines to comply with increasingly stringent emissions limits. The introduction of carbon dioxide (CO₂) reduction targets for LCV within the European Union, which begin to take effect in 2014, increases the need for sophisticated turbocharging techniques such as Variable Geometry and Two-Stage systems that also enhance fuel economy.

Market research conducted by two independent global market research organisations indicated that current passenger car/LCV turbochargers with Variable Geometry (VG) fall short of the full durability and reliability expectations of LCV manufacturers. This prompted Cummins Turbo Technologies’ decision to leverage its expertise and experience of supplying turbochargers that satisfy the tougher duty-cycles of heavy-duty diesel engines and apply similar technology into the LCV sector, a market previously not served by our company. This would not only deliver lower total cost of ownership but also provide manufacturers of vehicles and engines in the LCV market with a new alternative to their existing turbocharger supplier.

2 The LCV Turbocharger Market

Research of the LCV turbocharger market in 2007 concluded that it is worth US$1.5 billion a year. It is the second largest sector within the global turbocharger market: although considerably smaller than the passenger car sector, the market for LCV turbochargers is bigger than that for on-highway truck and bus. With large LCV markets in China expected to grow at 16-20 percent a year, worldwide growth is forecast at 12 percent per annum to 2015. In the past Cummins Turbo Technologies had limited experience of this sector, but that is changing, not least because of the introduction in 2008 of the Cummins ISF 2.8L and 3.8L engines, designed specifically for light commercial applications. Demand for VG turbochargers for LCV is poised to grow as manufacturers turn to VG technology in both single- and two-stage configurations to help them meet the emissions limits and corporate CO₂ targets already mentioned.

All VG turbochargers currently used in the LCV market employ swing-vane technology as a means of adjusting their swallowing capacity in order to extend their flow range. Cummins Turbo Technologies’ sliding wall VG technique, proven in the more arduous duty cycles of heavy-duty diesel engines, would provide superior
reliability and durability. It would also facilitate thermal management of exhaust after-treatment systems and can be used for engine exhaust braking.

Our own benchmark testing indicates that the application of VG turbochargers derived from current passenger car designs is unlikely to fulfil LCV durability demands. During a 1000 hour durability test conducted by Cummins Turbo Technologies a competitor’s VG turbocharger failed after approximately 300 hours. Failure was attributed to wear on the swing vanes used in the VG turbine. The wear occurred on the vane pivot axles, introducing play that led to the vanes jamming. Our market research confirmed that vehicle and engine manufacturers had also encountered durability shortcomings with swing-vane turbochargers during endurance testing. This supported our belief that there was a requirement and an opportunity for a new robust VG turbocharger for LCV. However, in taking Cummins Turbo Technologies beyond its familiar medium- and heavy-duty diesel engine market it was imperative that we thoroughly evaluated both business opportunities and risks. In order to ensure that we had a completely balanced and objective view of the market, we used a Voice of the Customer (VoC) process. This established the true market requirements and allowed us to rank and weight the various individual needs.

The key themes to emerge from our LCV VoC process were:

- High performance
- Improved engine emissions
- Reduced CO₂
- Low noise
- Reliable and durable
- Low cost, high value

Potential customers were identified as Cummins and OEM (original equipment manufacturers) serving the LCV market in China, India and Europe.

The same range of small turbochargers could also be applied to other light-duty diesel engine on-highway applications, the industrial and construction market and to marine and power generation applications. The turbocharger could serve as the smaller (high-pressure) stage of a two-stage system on engines with swept volumes of between 6L and 8L. Attempting to cover a broad range of applications like this would mean designing a flexible base product suitable for a B10 life of 800 000 km at the upper end of the spectrum, with cost-out options for a B10 of 400 000 km for lighter applications.
3 Outline Costings

Market research provided information on price levels of current LCV turbochargers and on customers’ price expectations. We then assessed our own engineering development costs and drew up a forecasted costed bill of materials. At this stage, the material costs were estimated because the detailed design had not been finalised. The worst-case scenario was used. This process involved making certain assumptions concerning manufacturing strategy, source of components and Cummins Turbo Technologies’ production location.

A capital analysis included the cost of building four new turbocharger test cells, tooling and manufacturing plant. These preliminary costings indicated that the new range of turbochargers could be manufactured at an acceptable cost, enabling us to meet market price expectations.
4 Design Concepts

Initial development work focused on two design concepts. Both employ the sliding wall VG technique. Functional prototypes of both were built for testing.

4.1 Option 1

Option 1 is based on a scaled-down version of the third generation of Cummins Turbo Technologies’ Holset heavy-duty diesel engine VG turbocharger. Anticipating that the fundamental characteristics of the larger Holset turbochargers could be carried over to a scaled-down version, Option 1 was therefore perceived as a low-risk option in terms of its performance. The prototype successfully completed a 500 hour endurance test. Its key features include:

- VG mechanism mounted within the bearing housing
- New generation of electronic actuator and mechanism
- No static load on actuator
- High resolution (>500 steps)
- Absolute position sensing
- Oil-lubricated VG mechanism

Option 1’s design also included some less desirable aspects:

- Bespoke bearing housing for each application
- Large turbine and compressor flanges
- Long rotor shaft
- Rolling element bearings may claim additional space
- Bearing housing requires water cooling

Figure 1: Option 1, as used for early prototype testing.
4.2 Option 2

Option 2 is a completely new concept. Its key features and advantages include:

- VG mechanism mounted in the turbine housing, not the bearing housing
- Standard core for both VG and wastegate versions, providing flexibility and cost savings
- Eliminates need for water cooling of the bearing housing
- Actuator type and location can be varied to suit application - flexible packaging

Two concerns with Option 2 were:

- Concept unproven by Cummins Turbo Technologies, so potentially higher risk
- High temperature VG mechanism without lubrication

Several design variants of Option 2 were considered. Having selected the best of these, 15 different configurations were investigated for performance, actuation load, braking and thermal management. The configurations included an assessment of various shroud shapes and diameters. Different seal sizes were also evaluated. There were 48 separate tests in all, leading to the optimum Option 2 configuration.

Figure 2: Option 2 during early prototype testing.
5 Concept Selection

Prototype testing led us to conclude that both options had comparable efficiency. Their Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) performance was also similar. Both exhibited less distress than a swing vane turbo during a 500 hour mixed-mode engine test. At this point we revisited the VoC exercise and market research in order to ensure that pure technical merits did not obscure the overall business objectives. The VoC work was invaluable in the creation of a highly structured decision-making process that pulled together all the many strands of the project and underpinned this critical stage. It guaranteed that all customer requirements were appropriately considered and weighted in selecting which of the two concepts to take forward.

5.1 Selection Criteria

Our selection was based upon 16 key criteria, grouped under four categories:

- Product
- Business Case
- Capability
- Modularity

Each of the 16 criteria was weighted 4, 3, 2, or 1. Scores of 1, 3 or 9 were awarded to Options 1 and 2 for every criterion. The scoring of each criterion was the responsibility of the member of the team best placed to make that judgement. The scoring exercise was a large undertaking. For example, Pugh matrices were used to review and compare the performance and durability of each individual component and system for both concepts. A global manufacturing functional excellence group studied the quality aspect of the two concepts, also identifying potential logistical and manufacturing issues. Good design for manufacture was vital. Scalability was scored after assessing the ease of scaling each unique component.

The outcome of this comprehensive selection procedure was the decision, made in early 2009, to develop Option 2 and to archive Option 1. The areas in which Option 2 scored significantly higher than Option 1 were overall performance; installation and flexibility; cost; scalability; manufacturability and logistics.
Table 2: Design concept selection criteria and results

<table>
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<tr>
<th>Category</th>
<th>Criteria</th>
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6 Product Development

While determined to bring the benefits of technology proven in harsher, heavy-duty diesel applications, it was equally important to challenge design rules and limits at every opportunity. While developing Option 2 to become what is now the Holset HE200 series, we had to examine and test the relevance of heavy-duty rules for LCV applications. Although selected as the better concept, Option 2 was not without its own design challenges. For example, one objective was for each turbocharger size in the range to have family features, such as a similar style, parts count and assembly method. This would allow each to be assembled on the same line until sales volumes are sufficient for separate assembly lines. This meant forward thinking to take account of future possible bearing systems and wheel sizes.

While Cummins Turbo Technologies’ sliding-wall VG principle is well established in service over 14 years, its application to the new small Holset HE200 series broke new ground. This was recognised early in the project when the Option 2 design concept was considered unproven and to carry more risk than Option 1. Moving the VG mechanism from the bearing housing to the turbine housing is the main design novelty, but the VG mechanism itself is also different in one key respect.
Whereas our heavy-duty VG turbochargers have a sliding nozzle-ring and a fixed shroud, that configuration is reversed in the HE200: the shroud moves and the nozzle ring and vanes are fixed.

In order to fully explore the implications of this we established a Six Sigma project to gain a deeper understanding of the forces from the exhaust gas pulses acting on the nozzle and shroud. The work involved in-depth analysis of the factors affecting loads within the shroud and led to a methodology for predicting nozzle loads. This prediction method cuts development time and cost by reducing the number of iterations of different nozzle vane configurations and seal sizes/positions when seeking the optimum solution. The VG configuration adopted for the HE200 series reduces the potential for wear by reacting the nozzle torque directly into the turbine housing. This not only relieves the VG mechanism from having to react to this load but also makes it less sensitive to pressure pulsations. Minimising the pulsating aerodynamic loads acting on the shroud produces benefits in terms of the VG mechanism’s durability, linkage design and the sourcing of cost-effective actuators with the appropriate torque capability.

Figure 3: Modular approach produces different versions from common core.

The use of a modular approach for the HE200 series, using a common core for both VG and wastegate versions, would help to control parts proliferation but the risks and compromises of using common parts had to be thoroughly understood. It was essential that modularity generated volume-related cost savings rather than giving rise to expensive over-specification that served no purpose and risked alienating the customer.
The new turbocharger range is designed to accommodate VG, wastegate and fixed geometry requirements. VG versions use water-cooled ‘smart’ electric actuation. Wastegate versions use an air-operated actuator and their design makes it possible to mount the actuator in one of several locations.

![Figure 4: Alternative mounting points for the wastegate actuator](image)

### 6.1 Performance

Cummins Turbo Technologies underlined its commitment to the small turbocharger market by investing US$5m in four new state-of-the-art test cells for the project, designed to ensure that every aspect of performance is evaluated as thoroughly as possible. Having selected the better of the two options, a concept verification unit was built in spring 2009, to be used for performance testing.

Applying our inverse design techniques [1] and knowledge of compressor and turbine design for demanding heavy-duty applications, the performance of the new range of turbos is noticeably different from current LCV turbo designs. Competitor benchmarking shows that the new Holset HE200 series has more compressor map width than others, evidence that Cummins Turbo Technologies is delivering improved product performance in this market segment.

Compressor maps are generated on gas stands. Extrapolation down to very low pressure-ratios is carried out using our similarity method before processing the data into other formats such as SAE and CMP for use in engine simulation programs such as GT-Power. This avoids intermediate manipulations and the risk of subsequent errors by the software end-user.
Figure 5: Compressor map width comparison.

Cummins Turbo Technologies is the only turbocharger manufacturer serving the LCV market mapping turbines at a wide range of speeds and loads on a dynamometer. We recognise that simulation of turbocharger performance is becoming increasingly important for ‘virtual’ engine design. Our approach to mapping means we can provide test-cell data to populate almost the entire data range required for engine simulation work with minimal extrapolation. This allows us to develop tools that automatically generate .TRB files for GT-Power. Prediction of part-load performance is of particular relevance as transient cycle emissions tests become more challenging, emphasising the need for good emissions performance at low loads and during transient response. Working as a development partner with engine manufacturers Cummins Turbo Technologies can provide this valuable extra turbine map data to give our customers a competitive edge in their emissions predictions.
Figure 6: Turbine map data generated on the dynamometer

Conventional SAE format turbine data:

Cummins Turbo Technologies dynamometer turbine data:

Figure 7: Turbine data spread for conversion to GT-Power TRB format.
6.2 Reliability and Durability

This was at the very heart of the HE200 project, demonstrating that the fundamental durability and reliability advantages of Cummins Turbo Technologies’ sliding wall VG technology had been successfully translated from heavy-duty product, where B10 life is at least one million kilometres, to the new small turbochargers for LCV.

The key benefit of using a sliding wall instead of swing vanes to adjust swallowing capacity is the reduction in moving parts. There are approximately 85 per cent fewer wear sites, delivering obvious benefits. Our earlier market research and benchmark testing of rival products had indicated that swing vane VG designs were unlikely to satisfy LCV market durability demands.

Endurance testing started in July 2009, carried out on a Cummins four-cylinder, 3.8L ISF diesel engine. The 1000 hour endurance test used a general purpose, medium-duty cycle test modified to include the operation of the VG turbocharger. The duration of one test cycle is 900 seconds (15 minutes) and is repeated until the turbocharger has completed 1000 hours. The VG unit was cycled between 80 and 55 per cent closed (two seconds at each) during the torque peak mode. This cycling accounted for 25 percent of the test cycle time. The VG was operated at a range of fixed positions during the remaining 75 percent of the cycle. One of the modifications made to the test cycle was to include an extra ‘High Actuator Load’ mode. This entailed running the VG in the 90 per cent closed position for 60 seconds of each cycle.

On completion of the 1000 hour test:
- There were no component failures
- The turbocharger is still in working condition at test completion
- General condition is good
- There are no soot traces anywhere outside the turbocharger
- A drift in turbocharger performance was identified during the test

The drift in performance was evaluated in detail. Turbine inlet pressure decreased gradually as the test progressed, causing a consequential gradual reduction in the compressor’s boost pressure. This fell by 0.14bar between the start and the end of the 1000 hour test. This is an unacceptable loss of performance. Subsequent analysis attributed it to wear in the VG mechanism. Although the actuator was moving to its commanded position the wear meant that there was a loss of motion, so the VG was not closing quite as much as intended. This was confirmed by a reduction in turbocharger speed of approximately 8000rpm during the course of the 1000 hour test. Most of the motion lost was attributed to wear of the cross-shaft carrying the yoke that acts on the moving shroud. Wear of the cross-shaft in its bushes led to a gradual increase in lash of the long lever in the VG mechanism. These are new components and the endurance test results underline why we were correct to flag up the unproven nature of this design concept and the new VG mechanism as potential risks for Option 2 (section 4.2). Attention to the specification of the cross-shaft/bushes resolved this issue.

Over 15000 hours of Design Verification Plan (DVP) testing was completed, including actuator and mechanism endurance tests, fatigue testing and thermal-cycle tests. The bearing system has been subjected to a range of specific tests including those that evaluate the effects of hot shut-down, cold start/oil delay and
contaminated oil. The complete turbocharger has been subjected to salt- and sand-spray tests and containment (burst) testing. This test programme directly addresses the two perceived risks mentioned above and we are confident that our new small turbochargers deliver class-leading reliability and durability for the LCV market.

6.3 Engine Braking

Engine braking is a long-established practice in large commercial vehicles. Traditionally it has been accomplished either by closing a simple butterfly valve or gate valve in the exhaust system, or by means of a compression release device in the engine. The exhaust-mounted valve generates exhaust back pressure, in turn pressurising the pistons on their exhaust stroke and so generating a braking torque. The compression release brake works by opening the engine’s exhaust valves near the top of the compression stroke, releasing the pressurised gases into the exhaust system. This means the pistons’ compression work is not recovered in the expansion stroke, temporarily turning the engine into an air-compressor. This compression work generates the braking torque.

The VG turbocharger can be controlled so that it replicates the braking function of the butterfly or gate valve in the exhaust. Closing down the VG turbine generates backpressure in the exhaust manifold. A VG turbocharger can also enhance the action of an engine compression release brake by generating a boost pressure in the inlet manifold that increases the amount of compression work, thus braking the vehicle more effectively. Closing down the VG turbine like this produces a huge increase in the loads on its mechanism. Cummins Turbo Technologies sliding wall VG is durable under these loads.

Although engine braking is currently not often used on smaller LCV, Cummins Turbo Technologies’ market research identified that some customers would like to provide this form of auxiliary braking because it extends the brake system service life, pushing out vehicle service intervals and cutting maintenance costs. Using the VG turbocharger to generate exhaust backpressure provides this additional braking function without the cost of adding a butterfly valve in the exhaust.
6.4 Thermal Regeneration of Exhaust After-treatment

Common solutions to the low emissions challenge have seen an increasing number of LCV that utilise Diesel Particulate Filters (DPF) in their exhaust systems. This number will grow as emission limits are tightened all around the world. Finding the most effective way of regenerating the DPF is therefore a major issue for many LCV manufacturers. This is particularly so in the case of LCV with duty cycles that involve low average speeds and/or light engine loads. Their exhaust temperatures may fail to reach the level required to burn the soot particulates trapped in the DPF. In order to prevent the DPF becoming blocked it is necessary to use an active regeneration system such as a downstream fuel-doser in the exhaust system. This injects a dose of fuel that burns in the Diesel Oxidation Catalyst (DOC), producing a temperature spike in the DPF that triggers combustion of the trapped particulates. Alternatively, an air-intake throttle valve may be partially closed to temporarily increase the fuel-air ratio, raising the temperature of the exhaust gas.

The use of a VG turbocharger makes it possible to eliminate both these DPF regeneration systems, avoiding their additional costs. The VG turbocharger can be managed to deliberately generate very low turbine efficiency, making the engine work harder and therefore elevating exhaust temperature. To achieve this entails running high expansion ratios across the turbine, which imposes high loads on the VG mechanism. The durability of the sliding-wall VG technology makes it uniquely able to withstand these loads.
Figure 9: Effect of using VG turbocharger to raise exhaust temperature on heavy-duty diesel engine.

7 Product Range

After three years, the project team reached a significant milestone this year with the start of production of the new small turbocharger range in the Cummins Turbo Technologies plant in Wuxi, China. Production of the wastegated HE200WG began on schedule in June, with the first examples going to Cummins for use on the ISF engine. The VG version, the HE200VG, is due to enter production in the middle of 2012.

Impellers are available as either cast or MFS (machined from solid) aluminium in 54mm or 58mm diameters. The first turbine wheel available, 49mm in diameter, is made from the nickel-based alloy Inconel.

The HE200 series will be followed by the slightly larger HE250 series, leveraging the scalability benefits of the modular design. This has a flow range of 28-60 kg/s√(K)/MPa compared with the HE200’s 15-42 kg/s√(K)/MPa and will also be available in fixed-geometry, wastegated and VG versions. The smaller HE150 series is scheduled to go into production next, starting with wastegated and fixed-geometry versions in December 2013, followed by the VG variant in December 2014.
Table 3: Product Range Summary

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<th>HE200</th>
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8 Summary

This small turbocharger project marks a turning point in the life of Cummins Turbo Technologies, taking the company into a completely new sector of the global turbocharger business and one that is both large and growing quickly. The new turbochargers will suit a plethora of LCV and other light-duty applications meeting Euro-3 to Euro-6, US EPA 2010 and 2013 and Tier 4 exhaust emissions limits. They provide engine manufacturers with a new cost-effective alternative that delivers outstanding levels of reliability and durability. This is coupled with the extra functionality that will become increasingly highly valued for LCV applications in future. The thorough design and development process outlined in this paper allowed us to break new ground with the confidence that our reputation for durable and reliable turbochargers proven in the heavy-duty diesel engine market is carried with us.

References