

Experimental Evaluation of Advanced Turbocharger Performance on a Light Duty Diesel Engine

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ABSTRACT

For diesel engines to meet current and future emissions levels, the amount of EGR required to reach these levels has increased dramatically. This increased EGR has posed big challenges for conventional turbocharger technology to meet the higher emissions requirements while maintaining or improving other vehicle attributes, to the extent that some OEMs resort to multiple turbocharger configurations. These configurations can include parallel, series sequential, or parallel-series turbocharger systems, which would inevitably run into other issues, such as cost, packaging, and thermal loss, etc.

This study, as part of a U.S. Department of Energy (USDoE) sponsored research program, is focused on the experimental evaluation of the emission and performance of a modern diesel engine with an advanced single stage turbocharger.

A production IHI (Ishikawajima Harima Heavy Industries) turbocharger was selected as the base architecture for the turbocharger design with optimizations focused on compressor impeller and turbine wheel designs.

An advanced impeller design was used on the compressor side to improve the efficiency and surge margin at low mass flow areas of the compressor map, allowing greater EGR flow while extending the flow capacity by using an active casing treatment on the compressor cover.

Mixed flow turbine technology was used on the turbine side, due to its performance characteristics; particularly high efficiency at low speed ratios relative to the base conventional radial flow turbine. This characteristic is relevant to increased EGR operation required for future diesel applications.

Both steady state and transient engine dynamometer testing of FTP transient cycles at Tier II Bin 5 emission levels show that the advanced turbocharger technology enables around 3% fuel economy improvement on the engine while meeting the same emissions level.

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INTRODUCTION

Engine manufacturers are continually faced with the challenges of meeting more stringent emission regulations while maintaining the customer requirements for fuel economy improvement. This challenge has required future turbochargers to have good efficiency at low flow area and sufficient surge margin, while customer demand and market competition drive for high power or high power density characteristics. This combination of competing requirements translates into turbocharger designs that have high efficiency

over wide operation range on both the turbine and compressor. Instead of having two or three turbochargers arranged in series, or parallel and operated sequentially, as some auto manufacturers have successfully demonstrated in production vehicles [1, 2], this project focused on a single-stage turbocharger solution for high-efficiency operation over wide operation range. A single-stage solution provides benefits from constraints on packaging, cost, durability, and potential heat dissipation concerns in the boost system.

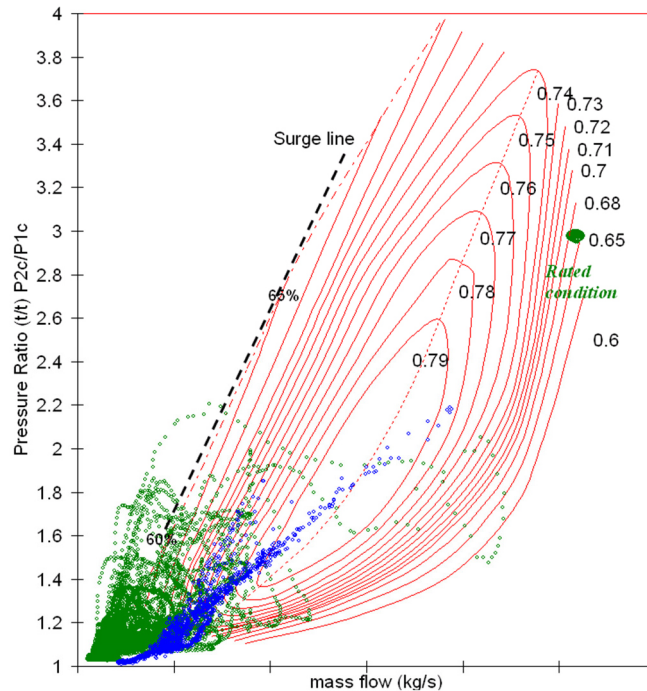


Fig. 1. Customer driving cycles and rated power conditions represented different and competing requirements on the compressor

Figure 1 highlights the design space or limitations for a centrifugal compressor that is bound on the high-flow side by compressor choke lines and the low-flow side by compressor surge line. Customer driving cycles are typically dominated by operation in low mass flow areas, while rated power is located near choke lines. These limitations define the biggest challenge to a single-stage compressor design when it is designed for superior efficiency at low mass flow area to achieve low fuel consumption, while gaining extra flow capacity near choke point for high horsepower.

Turbine side design has been mostly radial flow so far for automotive applications, even though for the last 15 years EGR usage has been increased due to the requirement of reduction in feed gas NOx emissions. High EGR demands translate into high turbine expansion ratios at low flow areas, causing small nozzle vane open positions (for variable geometry turbine), low turbine speed, and low mass flow through the turbine. Also, high back pressure due to aftertreatment system also increases the turbine inlet temperature. These requirements have driven operation points towards the low speed ratio (U/C) area, as shown in Fig. 2. The U/C is defined as follows:

$$\frac{U}{C} = \frac{U}{\sqrt{2C_p T_{in} \left[1 - (\pi_T)^{\frac{1-\gamma}{\gamma}} \right]}}$$

Where:

U is turbine tip speed;

T_{in} turbine inlet temperature;

π_T turbine expansion ratio;

C_p is specific heat capacity at constant pressure

γ is the ratio of specific heat of exhaust gas

Therefore, the challenge for future generation turbine designs is to improve the turbine efficiency in the area where U/C is between 0.3-0.5, which is relevant for flowing higher EGR for low NOx emission and fuel consumption. Conventional radial flow turbine designs, widely used in the automotive industry, are not efficient in the low U/C area of the turbine map.

ADVANCED TURBOCHARGER DESIGN AND DEVELOPMENT

Advanced Compressor Design Concept

Over the past few decades, there has been continuous effort to extend the compressor operation range without compromising efficiency on a single stage compressor. Uchida [3], Fraser [4], Mohtar [5] and Nikpour [6] studied variable geometry inlet guide vanes (VIGV) on compressor performance. While all these different VIGV designs, either center mounted or circumferentially mounted, can effectively extend the compressor operation range, the efficiencies at low

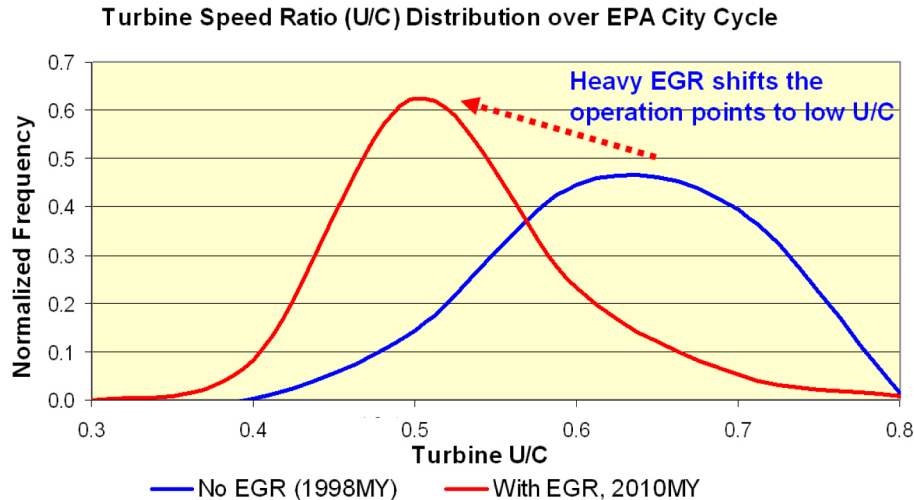


Fig. 2. Increased amounts of EGR drive the turbine to operate more time at low U/C area where a typical radial flow turbine is not very efficient

and high mass flow areas are more or less compromised by this action.

Fisher [7] recommended using casing treatment (also called ported shroud) to extend turbocharger compressor operation range, which has proven to be an effective, economically viable, and widely-used solution for compressor operation range extension. Yamaguchi from IHI [8] has investigated the impact of guide vanes inside casing treatment on the extension of surge margin; Sakaguchi [9] further did a comparison of full and half height guide vanes inside casing treatment for surge margin improvement. According to Sakaguchi, guide vanes inside casing treatment can adjust the flow incidence to suppress the circumferential component of the velocity. Barton from Honeywell [10] published research results using vanes in the shroud instead of vanes inside ported shroud to extend the compressor operation range. Sivagnanasundaram [11] recently reported a very comprehensive numerical optimization of injection slot geometry of a casing treatment for best efficiency and performance trade-off.

In the past 4 years, funded by the U.S. Department of Energy, Ford Powertrain Research has been working with Concepts NREC, Turbo Solutions, and a few turbocharger suppliers on advanced turbocharger technologies that promote higher efficiencies over wider flow ranges than conventional turbocharger designs. Extensive numerical analyses have greatly assisted the optimization process, leading to advanced compressor and mixed-flow turbine that has superior efficiency over wide operation range [12].

The numerical study revealed that [12] the introduction of split blades may introduce shock wave induced blockages at near choke conditions and unlike the other viscous related aerodynamic blockages, these shock wave induced blockages near the leading edge of splitters may be utilized to extend the choke flow capacity.

Figure 3 illustrates the CFD predicted flow field of a transonic compressor impeller near choke condition. At 85% of span-wise along the meridional patch, increase of relative Mach (Fig.3b) number is accompanied by a decrease in static pressure (Fig.3a). Based on this CFD generated visualization, a new compressor design concept is introduced that is substantially different from conventional practices, for transonic impeller designs that have been used for a few decades. The concept utilizes the pressure depression right after the shock wave, to inject additional flow, bypassing the blade passage throat, thus extending the compressor operation range without compromising efficiency. Compared with a conventional injection slot for casing treatment, the post-shock wave injection can pull in more air, effectively extending the choke capacity of the compressor.

Conventional casing treatments normally have a single slot that serves both as a bleed slot (out of mainstream into shroud) during surge and an injection slot (into mainstream from shroud) during choke. This forces current design practices to focus on the trade-off between low-end surge and efficiency improvement and maximum flow capacity. The advanced compressor concept allows the design to be focused on low-end efficiency improvement with reduced tradeoff for low-end surge. A conventional impeller is represented by the relatively small blade angle (relative to rotational axis) at the impeller inlet (Fig. 4). As illustrated by Fig. 4, at low-flow conditions, flow separation (Fig. 4b) will occur at the leading edge of impeller when the mass flow rate is low, potentially leading to efficiency loss and the onset of stall or surge. The advanced impeller uses a large blade angle at the impeller leading edge (for both full and splitter blades) that better matches relative velocity of the air when the mass flow is low (Fig. 4a). This will lead to better low-end efficiency and better surge margin, although it will lead to choke capacity penalties.