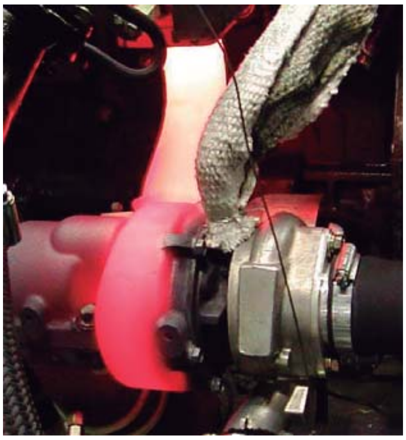

Development of the High-Performance and High-Reliability VG Turbocharger for Automotive Applications

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With the tightening of emissions regulations, the turbochargers used to supercharge air into engines are now essential products for automotive diesel engines. In Europe, where many of the passenger cars on the road are diesel-powered, a new generation of VG (Variable Geometry) turbochargers capable of controlling boost pressure with a variable nozzle vane on the turbine side is becoming the mainstream. The turbocharger performance has a direct impact on fuel consumption and the variable nozzle mechanism is used in high-temperature unlubricated environments. To respond, Mitsubishi Heavy Industries, Ltd. (MHI) has developed and commercialized a VG turbocharger which meets outstanding standards for performance and reliability.

1. Introduction

With the tightening of emissions regulations in Europe, Japan, and the United States, VG (Variable Geometry) turbochargers have been replacing the conventional turbochargers equipped with waste gate valves as the standard equipment for diesel engines. When operating at a high level of efficiency, the VG turbocharger improves the fuel consumption and drivability of an engine. VG turbochargers use a complicated mechanism to drive the nozzle vane in high-temperature unlubricated environments. As these components are inevitably used in a high pressure range and a wide-flow-rate range environment, operation at the turbine blade resonance point cannot be avoided. For this reason, there is a stronger demand from the industry for a higher level of reliability, such as enhancements in the wear resistance of the nozzle drive mechanism and the resonance resistance to the nozzle wake.

To respond to this demand, MHI has developed and commercialized a new lineup of high-performance and high-reliability VG turbochargers for passenger cars, trucks, and buses (**Table 1**).

2. Objective and structure of VG turbochargers

Turbochargers are designed to use exhaust gas from the engine in the turbine to supercharge high-pressure air to the engine by driving the compressor on the same shaft. VG turbochargers are a type of turbocharger equipped with a variable nozzle vane mechanism on the turbine side. VG turbochargers are capable of controlling supercharging pressure to optimum conditions by adjusting the nozzle opening according to the engine conditions. The chief benefit of this feature is an effective reduction of the engine's fuel consumption, as shown in **Fig. 1**.

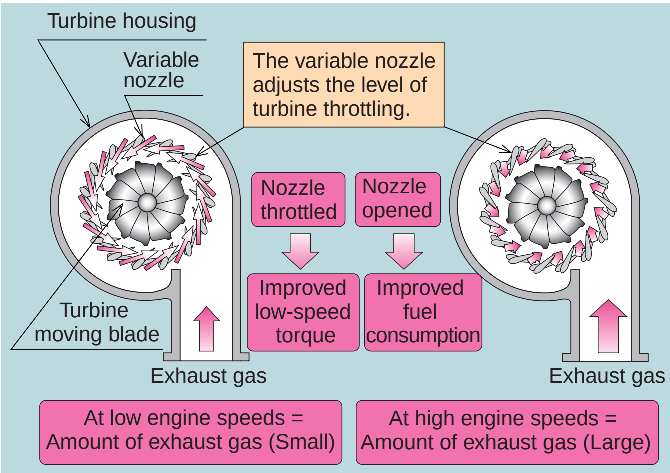

Fig. 1 Mechanism and effect of the VG turbocharger
The VG turbocharger controls boost pressure to an optimum value by throttling the nozzle vane during low engine speeds and opening it during high engine speeds.

Table 1 Lineup of VG turbochargers from MHI

VG model	TD03	TF035H	TD04	TD04H	TD05	TD06	TD07	TF08
Engine displacement (L)	1.2-1.7	1.6-2.2	2.0-2.8	2.8-3.2	3.2-4.5	4.5-6.0	6.0-8.0	8.0-13.0
Engine output (kW)	40-60	70-100	90-130	130-150	150-180	180-200	200-240	240-350

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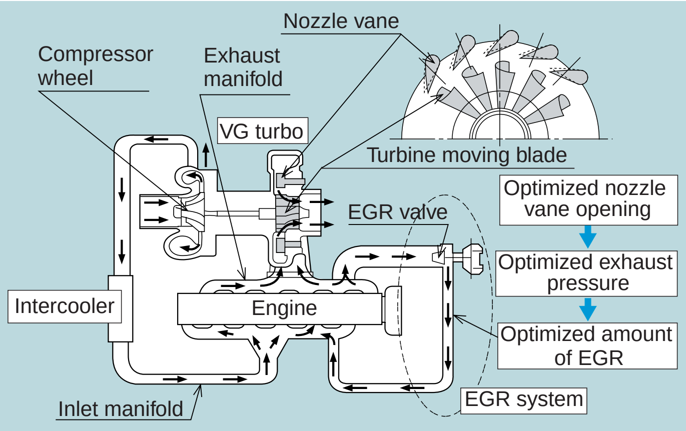

Fig. 2 VG turbocharger and EGR
Changes in the nozzle opening and engine exhaust pressure make it possible to control the amount of EGR.

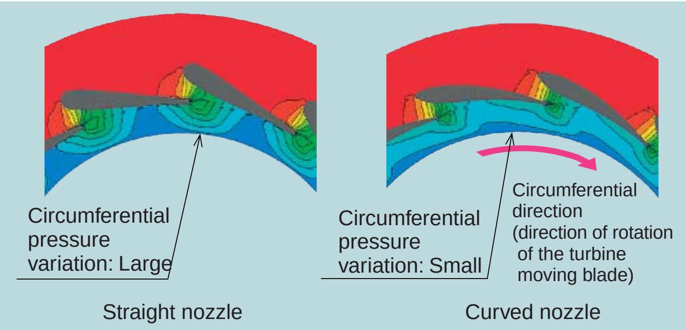

Fig. 4 CFD results for the new-type curved nozzle
MHI has developed a new-type curved nozzle with reduced circumferential static pressure distortion in the turbine moving blade inlet portion.

VG turbochargers have been applied over the last several years for the precise control of the EGR (Exhaust Gas Recirculation: Recirculation of exhaust gas to the intake) systems designed to reduce NOx (**Fig. 2**)(1). They are now widely adopted for this purpose. The variable nozzle vane mechanism of MHI's VG turbochargers is structured as a cartridge to eliminate the thermal effect of the turbine housing and thereby prevent sticking of the variable nozzle vane (**Fig. 3**)(2).

3. Performance enhancement

As mentioned previously, the industry now demands a more highly efficient VG turbocharger to optimize the benefits on fuel consumption. MHI has developed a high-performance turbine moving blade and also a high-performance VG nozzle vane. These are very important components.

3.1 High-performance VG nozzle

Figure 4 shows the curved nozzle developed and the CFD results. Our group changed the VG nozzle vane from a conventional straight vane to a curved vane, optimizing the shape to reduce the circumferential pressure variations at all of the nozzle openings. These modifications also helped to reduce the exciting force of the turbine moving blade during nozzle wake resonance, a phenomenon described later.

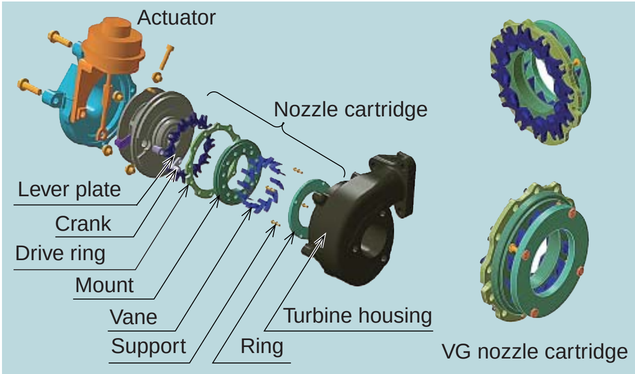

Fig. 3 Structure of MHI's VG turbocharger
The variable nozzle vane mechanism portion is designed as a cartridge to eliminate the thermal effect of the turbine housing.

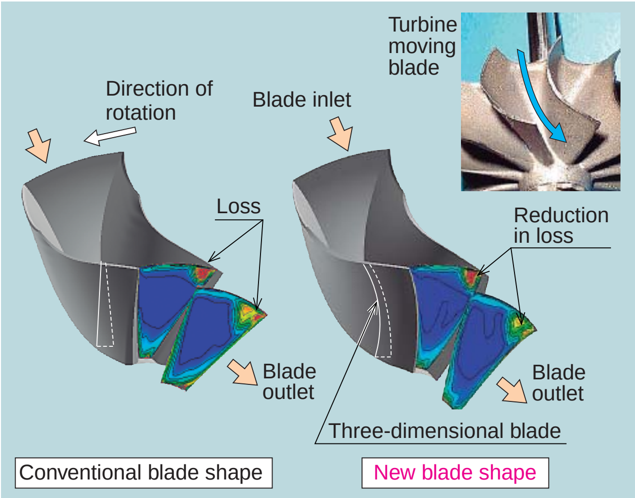

Fig. 5 CFD results for the new type turbine moving blade
MHI has developed a new three-dimensional turbine moving blade that reduces loss by preventing the accumulation of secondary flow at the moving blade outlet.

Further, the aerodynamic moment around the VG nozzle vane changes according to the nozzle opening. In the worst case, the opening-and-closing or closing-and-opening of the nozzle causes a hysteresis in the boost pressure which hinders the engine control. In addition, the moment and backlash generated as the nozzle link mechanism wears leads to an excessive rotation of the VG turbocharger which can result in an excessive boost pressure. These tendencies with the curved nozzle differ from those with straight nozzles. Thus, the pivot position of the curved nozzle was optimized to enhance both controllability and performance.

3.2 High-performance turbine moving blade

Losses in the turbine moving blade are concentrated in high locations in the suction surface at the blade outlet due to a secondary flow inside the blade, as shown in the CFD results in **Fig. 5**(3). In the new-type turbine moving blade shown in Fig. 5, we were able to reduce losses in the moving blade by making the blade three-dimensional to prevent a secondary flow. This new-type turbine moving blade conferred a large effect and improved efficiency by about 3% in the test of the turbine itself.

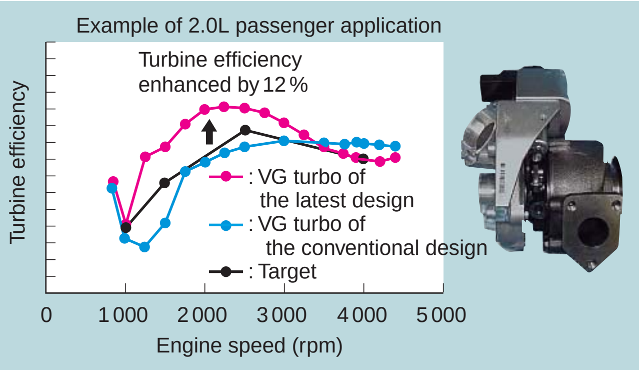

Fig. 6 Performance of the latest VG turbocharger (TF035H-VG)
The latest VG turbocharger shown on the right has enhanced turbine efficiency on the engine by 12 %.

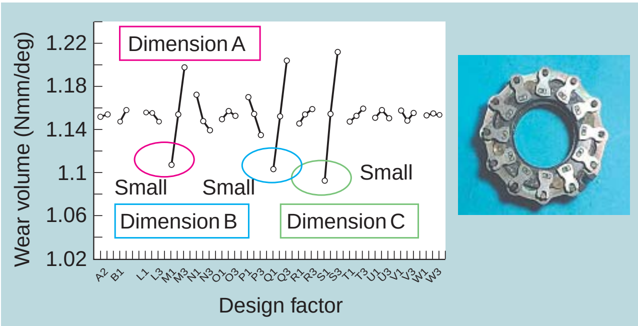

Fig. 8 Optimized shape and dimensions for the VG linkage
The Taguchi method was used to design parts with more robust dimensions and shapes against link wear.

3.3 Influence on engine performance

Figure 6 shows the TF035H-VG, the VG turbocharger model most recently developed by our group. The design combines the high-performance VG nozzle and high-performance turbine moving blade described above. This model is driven by an electrically operated actuator, and has been adopted for use in 2L-class passenger cars. Dramatic improvements in efficiency, especially at low engine speeds, lead to equally dramatic improvements in the fuel consumption and drivability in this model, as shown in Fig. 6. The TF035H-VG has been well received.

4. Enhanced reliability

As described above, VG turbochargers must operate in high-temperature unlubricated environments and remain fully workable in a high pressure range and a wide-flow-rate range environment. For these reasons, the turbine moving blade is susceptible to inevitable damage from nozzle linkage wear and nozzle wake resonance. Through the countermeasures shown below, MHI has improved the VG nozzle linkage by enhancing its wear resistance and resonance resistance to nozzle wakes.

4.1 VG link material and shape optimization

As a mechanism used in high-temperature unlubricated environments and in high-vibration environments in engines, the VG linkage is highly susceptible

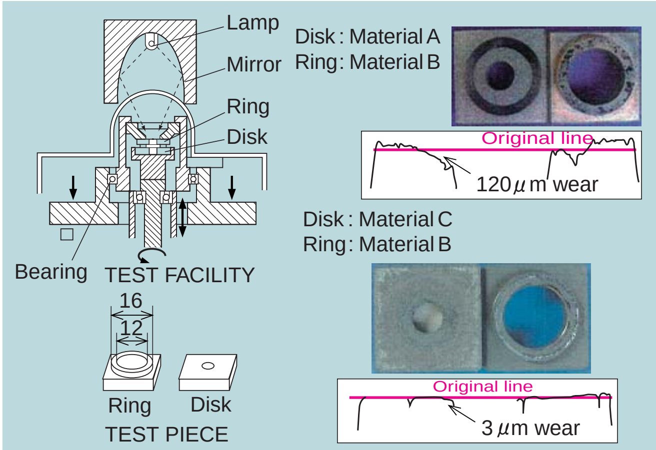

Fig. 7 High-temperature wearing test equipment and test results for optimum materials
Wear-resistant materials for the VG link were tested using the high-temperature wearing test equipment. An optimum material combination was adopted based on the test results.

to link wear. In trucks and buses, a valve is provided for the down stream of VG turbocharger exhaust, and is used as an exhaust brake. If the brake is used to close the valve, the VG turbocharger is placed in an environment even more susceptible to wear. As the wear of the link advances, the precision of the control of the boost pressure and EGR begins to deviate. This is why the ever stricter emissions regulations introduced over the last several years have created a strong demand for reductions in the wear of the nozzle link.

MHI has been improving the wear resistance through two approaches: adopting wear-resistant materials for the VG linkage and optimizing the shape and dimensions of the VG linkage.

Wear-resistant materials for the VG link were selected by a series of tests using the high-temperature wearing test equipment[4] shown in **Fig. 7**. Test conditions for the temperature, applied load, and friction speed were determined based on the conditions of use in the actual unit. More than a dozen combinations of various materials were tested. As shown in Fig. 7, we were able to find out a material combination that reduced the wear noticeably compared with the material combinations conventionally used. This material combination is now adopted for our latest VG turbocharger model.

The Taguchi method was used to optimize the shape and dimensions of the VG linkage by investigating which dimensions and shapes for parts were robust against link wear. **Fig. 8** shows the result of our optimization study. Out of the elements investigated, we found three shape factors that affected wear. Next, we built a prototype VG linkage based on this result and confirmed the wear-resistance effect in actual tests on the prototype (**Fig. 9**). The designs of the VG turbochargers for trucks and buses are based on the designs for passenger cars, but with further enhancements in the wear resistance of the shapes and structures adopted.

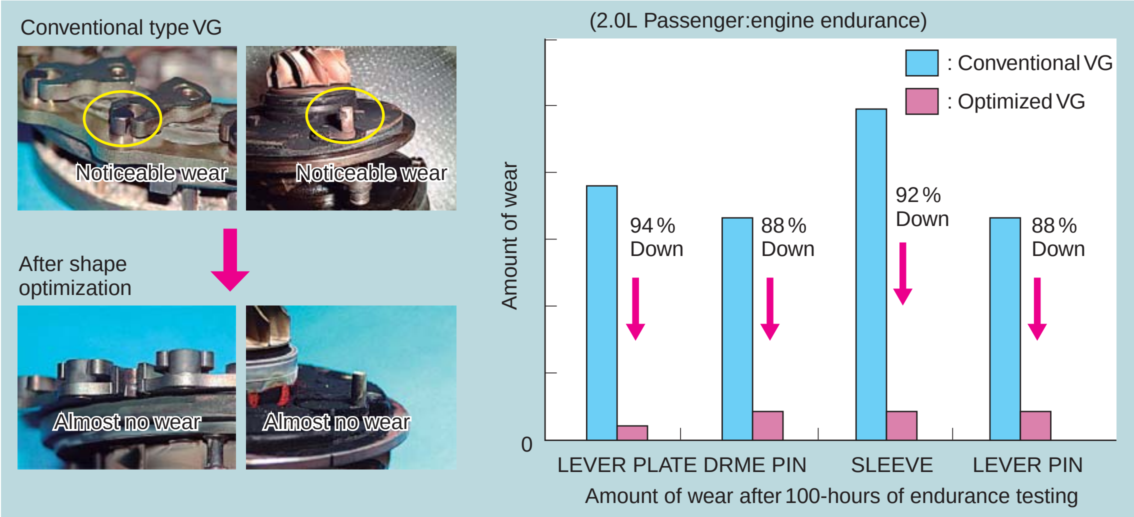

Fig. 9 Results of durability test on optimally shaped VG turbocharger
The optimal dimensions for a prototype VG linkage were determined based on the Taguchi method and a prototype was built. Substantial wear reduction was confirmed in the endurance test.

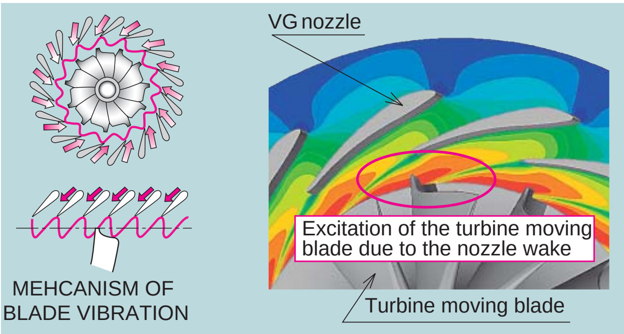

Fig. 10 Mechanism of nozzle wake resonance
Pressure variation due to the nozzle wake excites vibrations in the turbine moving blade. Resonance occurs when the moving blade passes the wake in a cycle that coincides with its natural frequency.

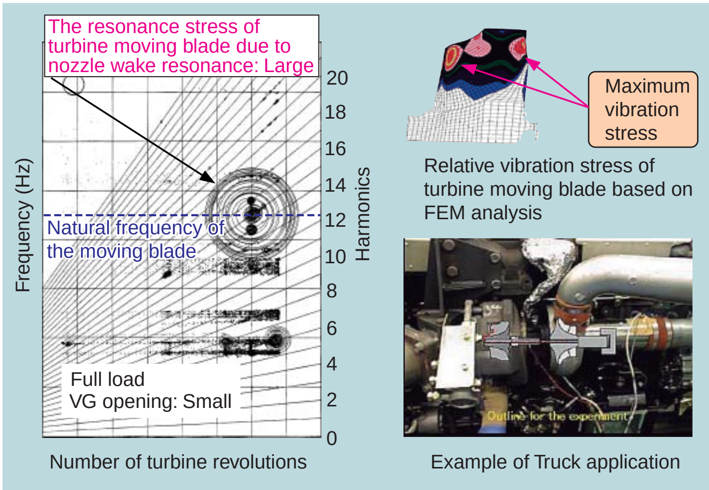

Fig. 11 Comparison between measurements of turbine blade resonance stress and the results of FEM analysis
The turbine blade stress during VG nozzle wake resonance was measured and compared with the FEM result to enhance the accuracy of our analyses.

4.2 Countermeasures for nozzle wake resonance

VG turbochargers must be capable of operating at any point within a high pressure range and a wide-flow-rate range environment. Inevitably they must operate at turbine moving blade resonance points within the operation zone. Nozzle wake resonance is the result of vibrations in the turbine moving blade excited by the pressure distortion conferred by the wake in the nozzle wake flow (**Fig. 10**). The resonance occurs when the moving blade passes the wake in a cycle which coincides with its own natural frequency.

MHI measures blade resonance stress in actual engines under various operating conditions using VG turbochargers for trucks and buses. We can enhance the accuracy of our resonance stress analyses by comparing these measurement results with FEM results (**Fig. 11**). This analytical system helps us to estimate blade stress during nozzle wake resonance and to use our estimations to reduce the exciting force, tune the resonance point, and enhance the strength of the moving blade. Through these improvements, we can protect the turbine moving blade against damages due to nozzle wake resonance. To cope with the resonance points inevitably encountered within the operation zone, we confirm the vibration resistance strength by operating VG turbochargers under actual engine conditions until the high-cycle fatigue limit is reached (**Fig. 12**).

4.3 Reliability track records in the market

Figure 13 shows the results of a Weibull analysis carried out to confirm the reliability of the TD03L-VG, the MHI VG turbocharger for passenger cars released commercially in 2003. The B10 life (life based on a failure probability of 10%) of the TD03L-VG is a travel distance of 5 million km. If the life of passenger cars is assumed to be 100 000 km, the failure probability in the market is 0.025% (250 ppm). This VG turbocharger incorporates an optimum material combination as a design provision to handle wear in the VG linkage. The lifetime of MHI's newer VG turbocharger now being sold commercially is expected to be even longer.

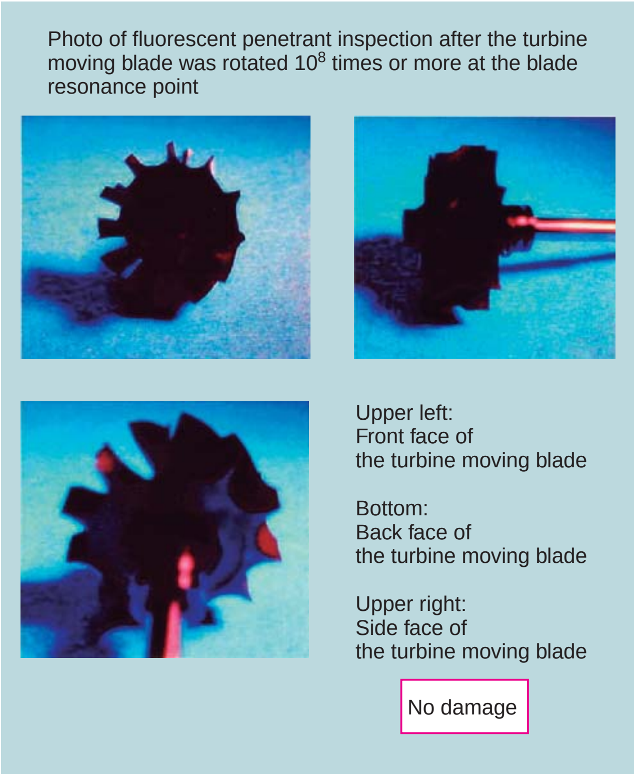

Fig. 12 Turbine moving blade after nozzle wake resonance endurance test
We induced vibrations of the turbine blade under resonance conditions in the engine until the material reached its fatigue limit. Next, we confirmed an abnormality-free condition by an inspection with fluorescent penetrant.

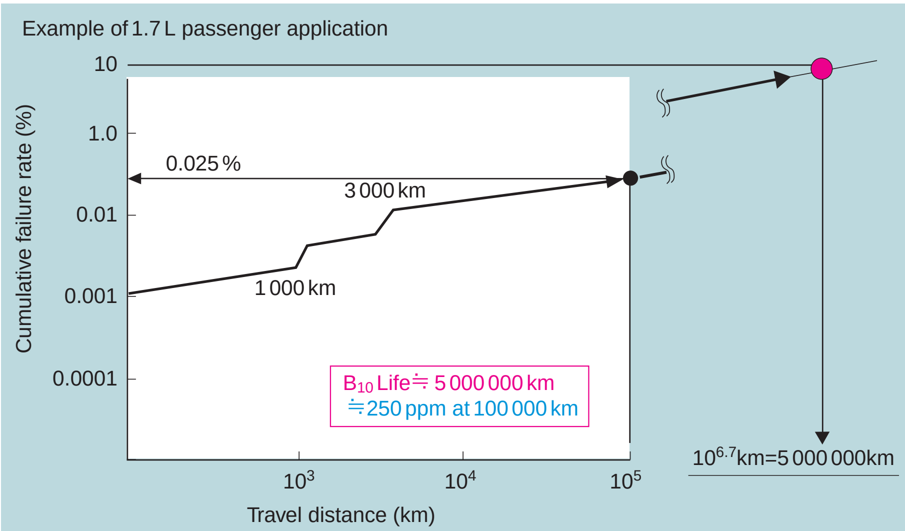

Fig. 13 In-service (market) reliability of MHI's VG turbocharger for passenger cars
By a Weibull analysis of VG turbochargers now being sold commercially, we confirmed a long life and low failure rate of our VG turbocharger.

5. Conclusion

With the tightening of global emissions standards, the conventional turbocharger with the waste gate valve is rapidly being superseded by a new generation of VG turbochargers with improved fuel efficiency, drivability improvement, and even EGR control for NOx reduction. VG turbochargers rely on a complicated mechanism to drive the nozzle vane and have to perform with higher efficiency and reliability in a wide operation range under conditions of severe use. To respond to these needs, MHI has developed and commercialized a lineup of VG turbochargers which perform outstandingly and reliably not only for passenger cars, but trucks and buses as well.

We hope to improve the performance and reliability of our VG turbochargers further in the future and contribute to society through the development of earth-conscious, low-emission vehicles.

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