# Improved Fuel and Energy Efficiency

## Through Optimized Bearing Design and Selection

**Mark Joki, The Timken Company**

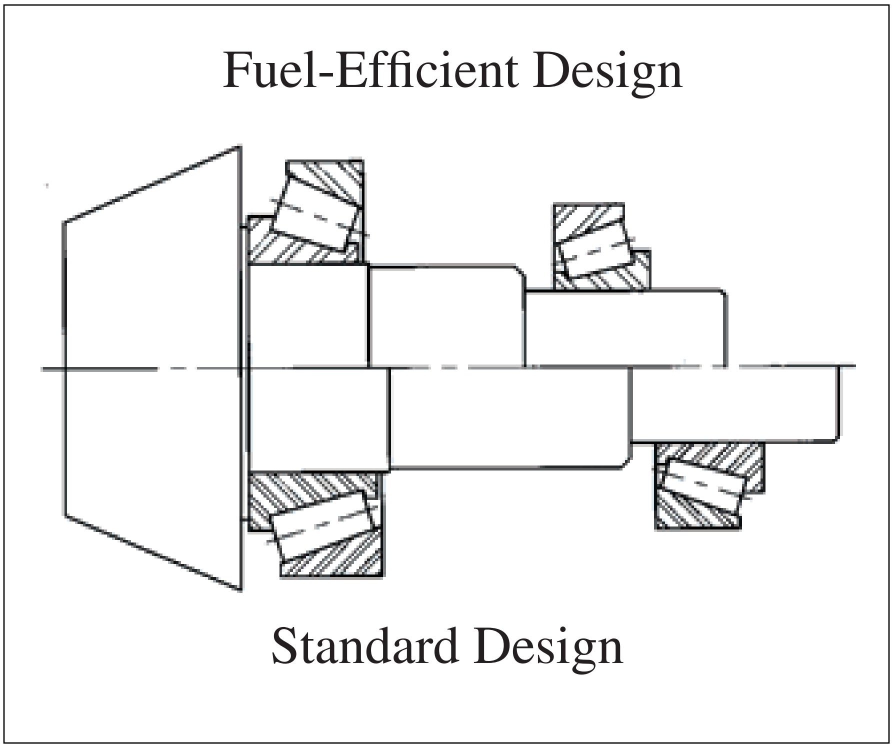

**Figure 1—The Fuel-Efficient Bearing Design Reduces the Axle Size and Weight.**

### Introduction

Today, better fuel economy is a main objective in the automotive development process. It remains top-of-mind with the auto industry and consumers because of costs and environmental impacts. Because the industry's average fuel-economy standard is required to increase by 40 percent by 2020, manufacturers and engineers are working to develop fuel-efficient, environmentally friendly and reliable designs for vehicles.

The benefits referenced in this article focus on the automotive industry, but obviously provide energy efficiency savings for industrial power transmission designs and applications, as well.

For driveline and transmission component suppliers, this translates into more challenging requirements for power capacity, weight, volume and power-loss characteristics of their products. More specifically, bearings on high-speed shafts in transmissions and on the pinions of differentials are a major contributor in the overall fuel-efficiency picture of the vehicle. An optimized design of the tapered roller bearings employed in these applications could significantly contribute to increased power availability—as well as mass and dimensions—translating into better fuel economy.

Driven to find a more efficient bearing solution, recent fuel-efficient tapered roller bearing (TRB) designs were compared to angular ball bearings solutions and standard TRB designs. The results proved that the fuel-efficient design reduced running torque, simultaneously meeting other technical requirements such as system life, stiffness, weight and package size.

More specifically, research and system analysis for alternative bearing arrangements was done on the pinion bearing arrangement in the rear axle (Fig. 1) and the transfer shaft bearings of a commercially available CVT (Fig. 2) because these two applications can have a high impact on fuel efficiency of the overall axle system.

## Proven Results

***Fuel Efficient Design for the Pinion Bearing Arrangement.*** To better understand the benefits of fuel-efficient TRB designs, The Timken Company defined a coherent bearing design strategy that significantly reduces the power loss and simultaneously maintains or improves some of the other system performance characteristics such as stiffness, operating temperature and debris resistance.

The basic concept was to convert the excessive bearing life margins into advanced design features, resulting in better efficiency. The other main principles promoted a reduction of the unnecessary bearing spread and the optimization of the raceway contact through adequate profiling.

An important aspect for accurate results is correctly defining the operating conditions used for the design optimization exercise. This was done under the consideration of typical driving behaviors and of a fuel economy cycle (FEC) (Fig. 3).

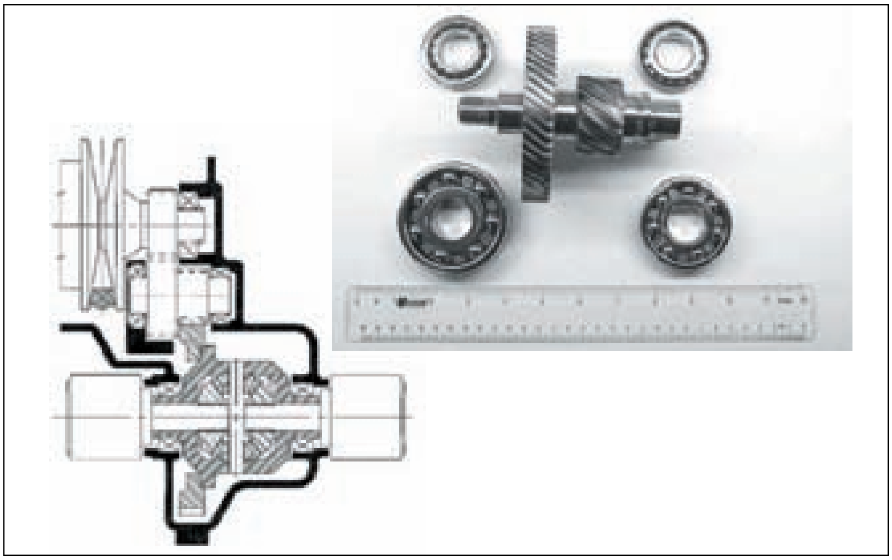

**Figure 2—CVT Transfer Shaft Bearing Positions.**

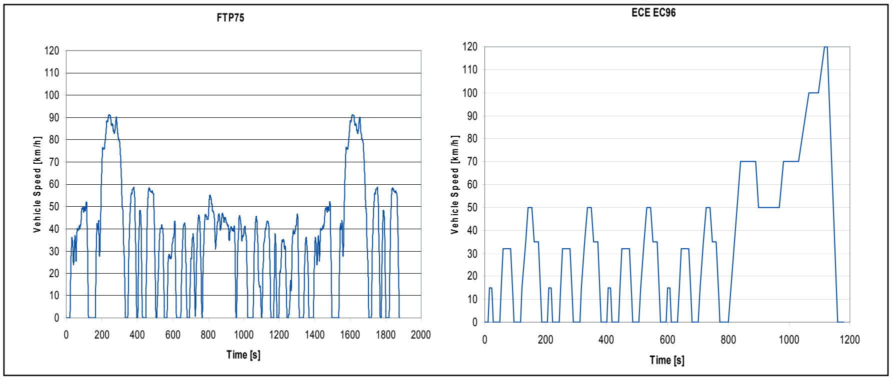

**Figure 3—FTP75 and ECE EC96 Fuel Economy Cycles.**

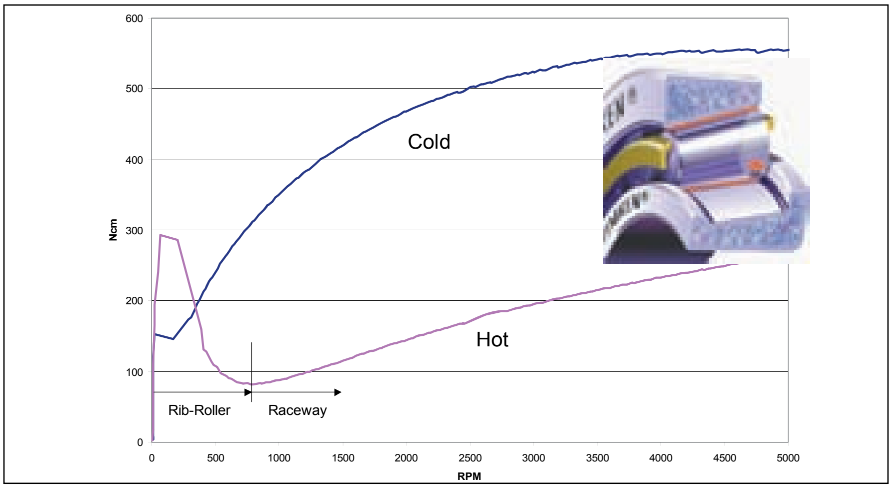

**Figure 4—Typical Tapered Roller Bearing Torque Behavior.**

For an axle application, the vehicle speed/time chart describing the FEC was converted into a diagram specifying the cycle percentage driven at a certain pinion gear speed range, and into a diagram depicting the relative energy lost by a unit of torque. The analysis showed that higher speeds bring the most significant contribution to the energy loss over the FEC. Accordingly, the design optimization will target the parameters directly involved with the high-speed torque reduction.

The typical torque behavior of a tapered roller bearing is shown in Fig. 4. At relatively low speeds, the rib-roller torque dominates, while at higher speeds, the roller raceway contact generates a higher torque contribution.

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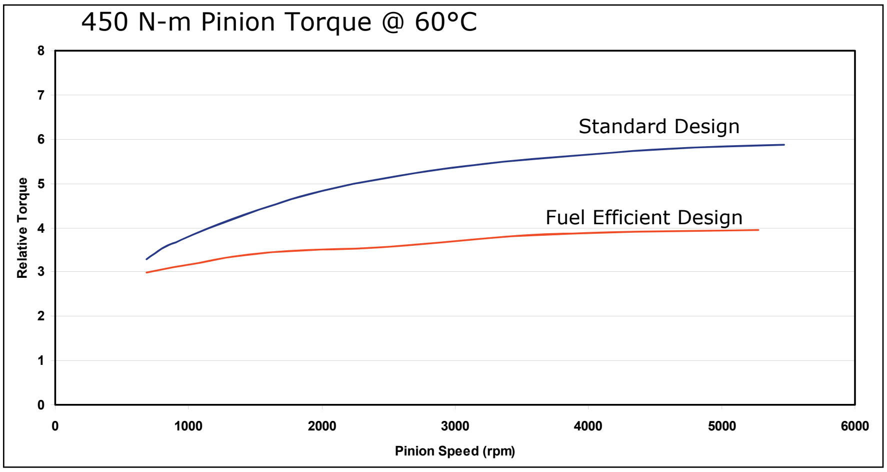

**Figure 5—Pinion Bearing Torque Test Standard Design vs. Fuel Efficient Design.**

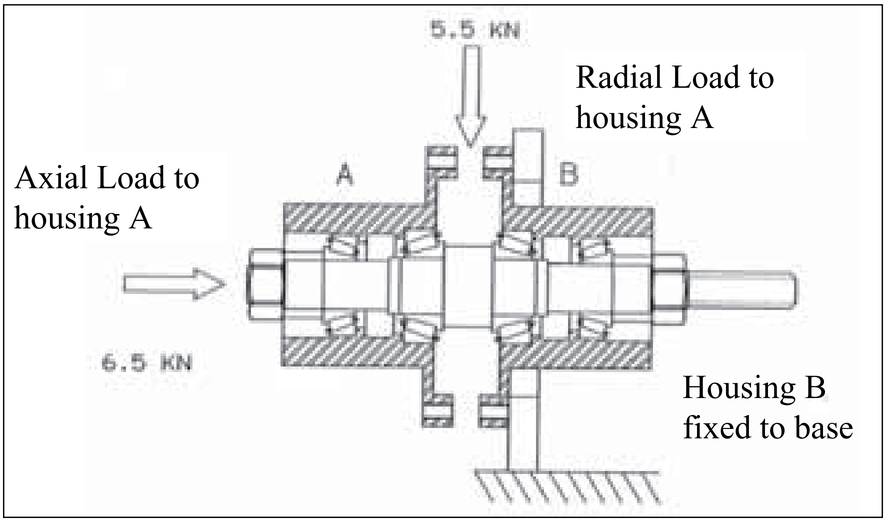

**Figure 6—Pinion Simulation Test Arrangement.**

**Figure 7—Bearing-in-a-Bearing Concept.**

In addition to torque behavior—based on the specific durability, stiffness and efficiency targets—the fuel-efficient bearing arrangement also offers the opportunity for axle housing weight and size reduction (Fig.1). This design was tested under various speeds, pinion torque and temperature conditions while compared to the standard design (Fig. 5). The test fixture is presented in Fig. 6.

In general, the fuel-efficient bearings yielded 30 percent lower torque values over the entire speed range in a clean oil environment. At 2,500 rpm and 60 degrees Celsius, this represents a 0.33 kW power loss reduction.

Similar tests were conducted in a debris-laden environment, demonstrating additional benefits related to the wear characteristics and operating temperature of the fuel-efficient bearings. The amount of worn material and the temperature levels were significantly lower compared to the standard product.

The conclusive 36 percent parasitic torque reduction obtained with a fuel-efficient TRB represents the highest achievable efficiency level in the industry, even when compared with the tandem angular ball bearing solution, at a significantly lower cost.

### Power Density—
### Prerequisite for Fuel Efficiency

During decades of continuous innovation and improvements in bearing design, increased power density has continued to be a main design and development goal of The Timken Company. Power density can be defined as the ratio between the power transferred by a machine component and its size or weight, and the following features beneficially influence it:

- High load capacity per unit of radial section
- Clean material
- Optimized stress distribution over the bearing race profile
- Low roughness finishing

Applied consistently, these design principles lead to significant reduction in bearing envelope dimensions and to the concept of "bearing in a bearing"

(Fig. 7). The small bearing can carry the same amount of load as the large one, but can fit into its bore. Such design modifications allow smaller bearings to deliver an equal amount of power but with more efficiency.

In order to deliver superior results, it is critical that bearings are made from the highest grade materials to meet the increased demand for power density. To help explain this importance, the evolution of the Timken steel cleanliness compared to relative life estimates is shown in Fig. 8. By utilizing advanced manufacturing processes, the summed total length of inclusion stringers was reduced by several orders of magnitude.

Progress continues to be made in profiling the bearing races in order to improve the stress distribution (Fig. 9)—another important piece of the power density pie.

### Case Study of Possibilities

***TRB Selection and Design Optimization for a CVT Transfer Shaft Application.*** The commercially available CVT utilizes a fixed and a floating ball bearing to support the transfer shaft. Using fatigue life and rolling torque criteria as a guide, a TRB design was refined to result in an optimum TRB design for maximum efficiency. A comparison between the dimensional characteristics and the weight of the ball bearings and of the proposed tapered roller bearings is shown in Figure 10.

The most objective validation of the TRB selection can be obtained only through the comparison with the ball bearings' performance over a vehicle or transmission duty cycle. Using sophisticated simulation techniques, the influence of the environment and design characteristics on the bearing performance was accurately quantified.

An important aspect of this study is the reduction of the radial deflections at the gear mesh points, achieved by both TRB designs, with a beneficial impact on the noise and durability parameters of the gear train.

The *Syber* software package developed by The Timken Company allows the analysis of a complete system consisting of shafts, gears and bearings under a wide range of load, speed and temperature operating conditions. The output of the program contains fatigue life, contact stresses and running torque results for the bearings as well as deflection results for the shafts and gears, representing valuable information for the transmission designer.

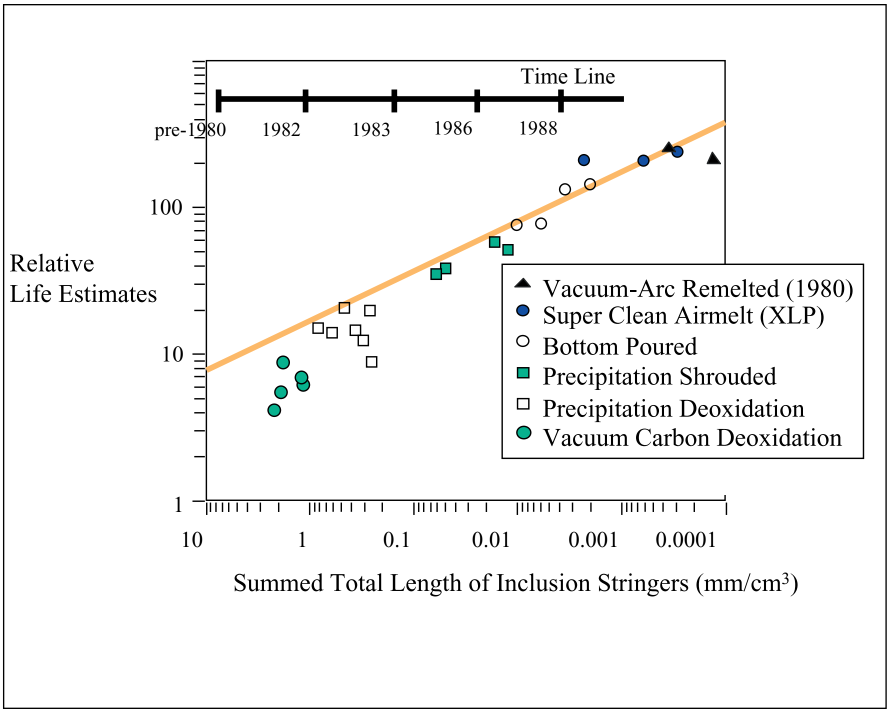

**Figure 8—Timken Steel Cleanliness Constant Improvement.**

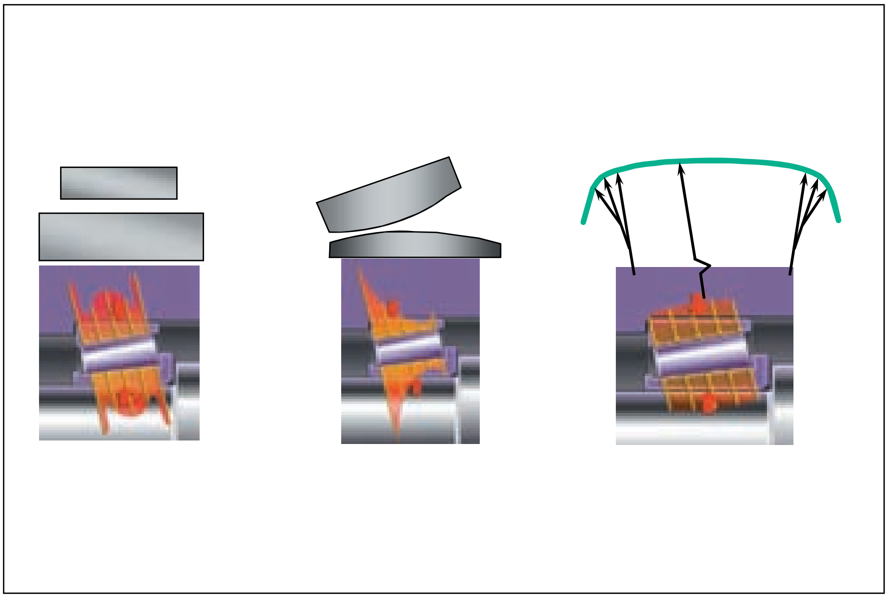

**Figure 9—Bearing Race Profile for Improved Stress Distribution.**

The target fatigue life (L10) on the duty cycle was 250 hours. Although several TRB design variations were considered in this study, only the comparison between the fixed and floating ball bearings used in the original transmission layout and two TRB designs are included here. The TRB designs included a commercially available standard design and a new design that featured a special race profile. The results of the simulation over the duty cycle demonstrated that both TRB designs meet the application requirements, validating their selection. Combined with the dimensional and

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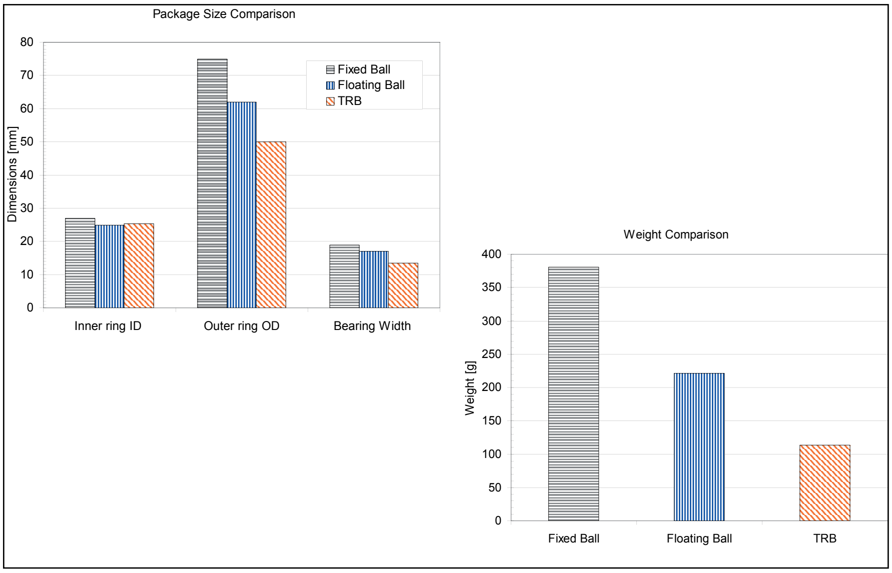

**Figure 10—Package Size and Weight Comparison between the Fixed and Floating Ball Bearings and the TRBs.**

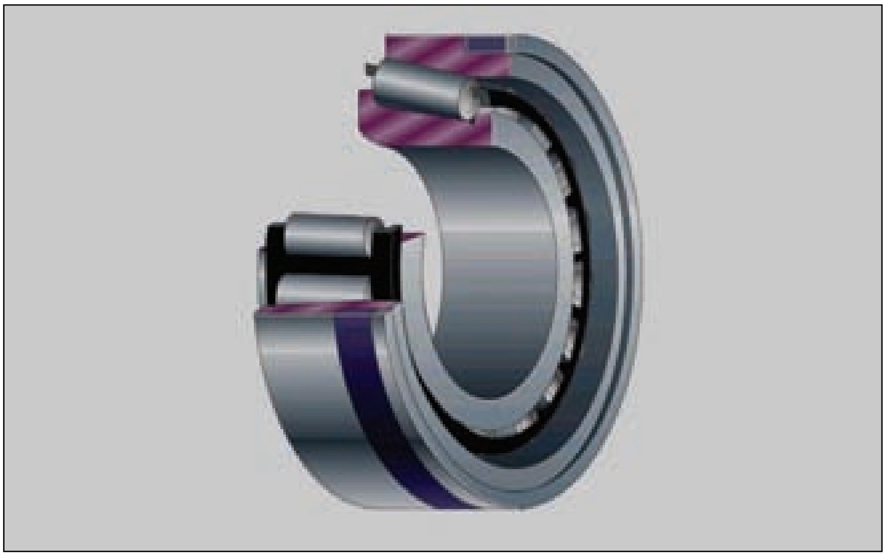

**Figure 11—Thermal Compensating Tapered Roller Bearings.**

weight advantages shown in Figure 10, this translates into remarkably high power density for the TRB.

The special profile TRB design, optimized for the present application, reduced the stress level along the cone race, especially the edge stress at the roller-cone contact (Fig. 9), significantly increasing the fatigue life compared to the standard design.

The differential thermal expansion between the transmission housing (aluminum) and the transfer shaft (steel) is minor in this case, due to the compactness of the design. It also did not affect the bearing setting and, implicitly, the life performance. Over the assumed operating temperature range of –40 degrees to 120 degrees Celsius, the differential thermal expansion resulted in a maximum setting variation of 0.18 mm.

The preload force corresponding to the extremes of the dimensional setting did not exceed 800 N per bearing. At nominal dimensional settings, the preload force per bearing reached 300 N, relatively small compared to the gear loads. For the duty cycle, the resultant gear axial load varied from 12,500 N to 2,500 N (helix angle 33 degrees and 38 degrees for the large and small gear, respectively). However, for compensating the thermal effects in aluminum or magnesium transmissions with larger bearing spacing, adequate tapered roller bearing design solutions were commercially available (Fig. 11).

Important to note, the reduction of the radial deflections at the gear mesh points, achieved by both TRB designs, offered a beneficial impact on the noise and durability parameters of the gear train.

***Evaluating Efficiency for the CVT.*** The emphasis of the CVT case study is not only on the superiority of the tapered roller bearings in regard to power density, but also their better efficiency characteristics. The overall vehicle efficiency is reflected in the test results over a fuel-economy cycle.

The currently used fuel economy cycles are FTP75 in the United States and ECE EC96 in the European Community (Fig. 3). A detailed analysis of these cycles shows the percentage of total cycle time for each transfer shaft speed operating condition. Taking into account the dependency of the bearing running torque on the operating speed, this analysis is essential for the bearing efficiency evaluation.

In order to isolate the bearing power loss from other transfer shaft system losses caused by the gears, drag, etc., the bearing running torque measurements were conducted on a test rig configuration similar to the one represented in Figure 6. The external loads applied on the rig were intended to simulate the loading conditions to which the bearings are subjected on a transfer shaft transmitting two reference torque values of 100 Nm and 200 Nm, respectively. The test bearings were located in the central positions, theoretically carrying the entire applied load. Two ball bearings similar to the floating position on the transfer shaft were used as slave bearings.

When using TRBs under nominal setting (300 N per bearing), the 100 Nm and 200 Nm applied torque on the transfer shaft translates to four loading conditions. These conditions, plus the non-radially loaded pure spin condition, were used for a "one-to-one" comparison between the tapered roller bearings and the ball bearings, as well as the basis for the summation of the total measured torque of the bearing sets supporting the transfer shaft.

The measurements were conducted at three temperature levels: 30, 50 and 80 degrees Celsius, representing the different phases of the fuel economy cycles. The torque increase for the highest preload of the TRB was within 5 percent of the total running torque due to external loads. The measurement results proved the superior efficiency of the standard TRB design compared to the floating ball bearing, which, in turn, is more efficient than the fixed ball bearing. The TRB efficiency can be enhanced further through the special new design, which contains some elements derived from the fuel-efficient design strategy. The measurement results also showed a very good overlap with the torque values calculated using the *Syber* package.

The impact of these torque characteristics on the total power loss over the two representative fuel economy cycles is shown in Figure 12.

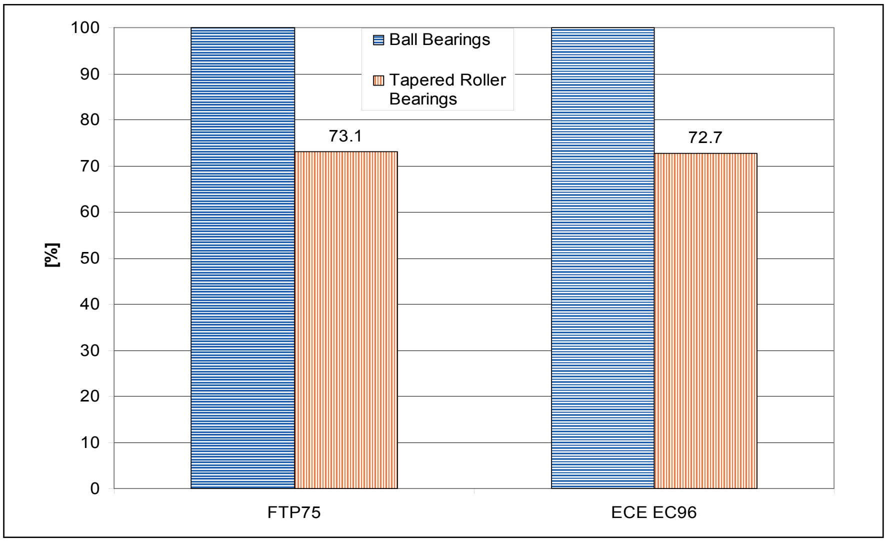

**Figure 12—Relative Power Loss Performance over a FE Cycle (approx. 27% power-loss reduction by using the Efficent New Design TRBs).**

Additionally, the TRB resists debris by its continuous, self-cleaning, lubricant-pumping action. A ball bearing, with its deep groove race, traps and retains debris. Clean-sealed ball bearings are better protected from contaminants, but the running torque increases significantly due to the seals.

The running torque of the TRB, under the same operating conditions, is considerably lower than the torque of the equivalent ball bearings supporting the CVT transfer shaft. Furthermore, in compact-designed automotive transmissions and axles, minimal variations due to thermal effects maintain the system life and the efficiency performance of the TRB at a superior level compared to the equivalent ball bearings.

The debris resistance of the TRBs contributes to a better running torque performance by eliminating the need for the clean-sealed technology, which involves the additional seal torque. Under the typical operating conditions of the most popular fuel economy cycles (FTP75 and ECE EC96), the TRBs provide major improvements—approximately 25 percent power loss reduction on the CVT transfer shaft analyzed in this study.

## Conclusion

With the challenges that lie ahead for more fuel and energy-efficient designs, continued efforts to develop, test and implement better designs and alternatives will continue.

Fuel-efficient bearing design solutions that meet the needs for power capacity, weight, volume and power-loss characteristics will stay top of mind for component suppliers.

For more information on fuel-efficient designs, electronic analysis tools and engineering solutions, visit *www.timken.com*.

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