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Design Optimization and Reliability Improvement of Tapered Roller Bearings: A Critical Review

Shreyas Thumar[1], Prof. Pranav Bhatt[2]

[1] PG Scholar, School of Engineering and Technology, Dr. Subhash University, Junagadh, Gujarat, India
[2]Assistant Professor, Mechanical Department, School of Engineering and Technology, Dr. Subhash University, Junagadh, Gujarat, India

[1] shreyasthumar@gmail.com
[2] pranav.bhatt003@gmail.com

Abstract - Tapered roller bearings are widely utilized in mechanical systems that require reliable transmission of both radial and axial loads. Their performance is influenced by internal geometry, load distribution, contact conditions, lubrication, operating environment, and manufacturing constraints. To enhance bearing reliability, it is essential to consider a range of interrelated design factors. Previous studies on tapered roller bearings have employed analytical methods, rating-life calculations, dynamic modeling, contact-stress analysis, finite element analysis, and optimization techniques. Optimization research demonstrates that modifying roller dimensions, pitch diameter, roller count, roller length, and contact angle can improve bearing performance. Additionally, numerical investigations highlight the importance of evaluating roller-raceway contact behavior and stress distribution under realistic loading conditions. This review critically examines research on the design and reliability improvement of tapered roller bearings, focusing on bearing geometry, load distribution, contact stress, rating life, analytical methods, numerical modeling, and design optimization. Studies are compared based on their objectives, design variables, analytical techniques, considered constraints, and performance criteria. Particular attention is given to the relationship between internal geometric parameters and bearing life, as well as the complementary roles of analytical and finite element methods. The review identifies major limitations in current methodologies, including the handling of realistic design constraints, treatment of manufacturing variability, consideration of combined loading, and integration of analytical and numerical approaches. Based on these findings, future research directions for reliability-oriented geometric optimization of tapered roller bearings are proposed.

Key Words: Tapered Roller Bearings, Design Optimization, Bearing Reliability, Fatigue Life, Contact Stress, Load Distribution

1. INTRODUCTION

1.1 Engineering Context

Rolling-element bearings are essential machine components used to support rotating shafts and transmit loads with low friction. Among different roller bearings, tapered roller bearings (TRBs) are widely used because they can accommodate combined radial and axial loads. Their applications include automotive systems, machine tools, locomotive axles, rolling mills, construction equipment, and power-transmission systems [2], [7].

The performance and reliability of TRBs are strongly influenced by their internal geometry and load distribution. Parameters such as roller diameter, roller length, pitch diameter, number of rollers, and contact angle can affect load-carrying capacity and fatigue life. Consequently, optimization of these parameters has received considerable attention in bearing design research [2], [3], [7]. Although standardized bearings are widely available, specific operating conditions may require careful selection or optimization of bearing geometry. Previous studies have investigated TRBs using analytical methods, rating-life models, numerical analysis, and optimization techniques to improve their load-carrying capability and reliability [1], [7]. Therefore, a critical review of existing research is required to understand the relationships among bearing geometry, load distribution, contact stress, fatigue life, and design optimization, while also identifying the limitations and research gaps that remain in the field.

1.2 Tapered Roller Bearings and Their Engineering Importance

Tapered roller bearings (TRBs) are rolling-element bearings designed with conical rollers and matching raceways. Their geometry enables them to support combined radial and axial loads, making them suitable for applications where both load components act simultaneously [2], [7]. TRBs are widely employed in automotive systems, locomotive wheel assemblies, machine tools, rolling mills, construction machinery, lifting equipment, and power-transmission systems [2], [7]. Their relatively high radial load-carrying capability and ability to accommodate thrust loading make them an important choice for heavily loaded rotating systems.

The performance of a TRB depends on the interaction between its internal geometry, applied loading, roller–raceway contacts, and operating conditions. Therefore, appropriate design and optimization of these parameters are important for achieving improved load-carrying capacity, fatigue life, and operational reliability [1]–[3], [7].

1.3 Factors Affecting Bearing Reliability

Bearing reliability is influenced by several interacting factors rather than by geometry alone. Applied loading and load distribution directly affect the contact forces developed

between the rollers and raceways, while contact stress is closely associated with fatigue damage and bearing life [1], [5]. Operating conditions also play an important role. Speed, lubrication, contamination, surface conditions, residual stresses, and material characteristics can influence the fatigue behaviour of rolling-element bearings [1]. In addition, internal clearance, angular misalignment, and variations in loading conditions can alter roller load distribution and consequently affect fatigue life [6].

For TRBs, internal geometric parameters such as roller dimensions, pitch diameter, number of rollers, and contact angle further influence load-carrying capability and rating life [2], [3]. Manufacturing tolerances can also introduce variations in these parameters, making robustness an important consideration during design optimization [2], [7]. Therefore, reliable TRB design requires consideration of the combined effects of geometry, loading, contact stress, lubrication, operating conditions, material behaviour, and manufacturing variations rather than optimizing a single parameter independently [1], [2], [7].

1.4 Need for Design Optimization

In conventional bearing design, standardized bearings are generally selected according to the required operating conditions and available catalogue dimensions. However, particular applications may impose specific combinations of loading, dimensional limitations, and performance requirements that cannot always be addressed efficiently through standard selection alone [3].

For tapered roller bearings, several internal geometric parameters influence bearing performance. Studies have investigated the optimization of parameters such as roller diameter, pitch diameter, effective roller length, number of rollers, roller aspect ratio, and contact angle to improve rating life and load-carrying capability [2], [3], [7]. Design optimization is therefore important because improving one parameter may affect other performance characteristics and design constraints. For example, an optimized geometry must satisfy dimensional and strength requirements while maintaining suitable contact conditions and adequate fatigue life [2], [7].

Consequently, an effective TRB design approach should consider multiple design variables, operating loads, geometric constraints, contact behaviour, and reliability-related performance measures simultaneously. This provides the basis for applying analytical methods, numerical techniques, and optimization algorithms in the development of improved tapered roller bearing designs [2], [3], [7].

Research on tapered roller bearings has covered several aspects of bearing performance, including internal geometry, load distribution, contact stress, fatigue life, dynamic behaviour, and design optimization [1]–[7]. Different approaches have been used to study these issues, and the parameters considered in one study are not always the same as those used in another. For example, some studies mainly focus on bearing geometry and fatigue life, whereas others give greater attention to dynamic behaviour or contact stress [2]–[7]. This makes it necessary to examine the available research together rather than considering each approach separately.

2. REVIEW METHODOLOGY

2.1 Literature Search Strategy

The literature review focuses on the main research developments in the area of tapered roller bearings, with a special emphasis on bearing geometry, load distribution, contact behaviour, fatigue life, numerical analysis, and design optimization.

The studies cited cover a variety of aspects concerning the performance of tapered roller bearings (TRB). Some of the research is concerned with optimizing the internal dimensions of the bearing and the influence this has on its fatigue life or load-carrying capacity [2], [3], [7]. Another body of work looks at the dynamic behaviour, the distribution of load, and the conditions of contact between the rollers and the raceways [4]–[6]. More recent investigations use finite element methods to assess the stresses in the bearings and to create detailed bearing models [8]–[10].

The review did not merely involve optimization studies; it also took into account standards and technical literature since these provide the foundation for understanding bearing load ratings, static capacity, rating life, and practical bearing design [16]–[18]. They are especially useful when comparing research methodologies with established bearing-design practices.

The relevant literature was collected and the studies were then grouped on the basis of their primary technical focus. When making the comparison, account was taken of various factors such as the design parameters examined, the loading conditions, the analytical or numerical methods used, the optimization objectives, the constraints and the performance indicators. This method of organization aids in spotting the similarities and differences among the various approaches reported.

The papers were not merely summarized but were instead examined in a critical manner, with special focus being placed on the assumptions made by various researchers and on how well their methods take into account practical factors such as combined loading, contact stress, manufacturing variations, and operating conditions. The observations made as a result of this examination are then employed in the subsequent sections to talk about the present state of research and to point out the areas that need further investigation.

2.2 Search Keywords

The literature search was based on keywords related to the main technical areas of tapered roller bearing design and performance. The terms were selected to cover both the basic bearing behaviour and the approaches used for analysis and optimization.

The main keywords considered in the literature search included like, Tapered roller bearing, Taper roller bearing, TRB design, Bearing load distribution, Roller load distribution, Bearing contact stress, Bearing fatigue life, Tapered roller bearing optimization, Bearing geometry optimization, Bearing finite element analysis, Rolling bearing design optimization, Genetic algorithm bearing optimization, Robust bearing design

Different combinations of these terms were considered to locate studies addressing specific aspects of bearing behaviour. For example, terms related to load distribution and contact stress were useful for identifying analytical and numerical investigations, while combinations involving optimization, geometry, fatigue life, and reliability helped identify studies concerned with improving bearing design [2], [3], [7].

The keywords were not treated as separate topics. They were used in combination to identify literature covering the relationship between bearing geometry, loading, contact behaviour, life, and optimization. This helped maintain the focus of the review on the main research question rather than limiting the search to a single aspect of tapered roller bearing performance.

3. TAPERED ROLLER BEARING (TRB) FUNDAMENTALS, LOAD DISTRIBUTION AND CONTACT MECHANICS

3.1 Bearing Geometry and Operating Principles

The tapered roller bearing comprises an inner race, outer race, tapered roller, and a cage. The inner race and the raceway form the cone, and the outer race forms the cup. The rollers are located in between these two races and are kept rolling by the cage. The basic structure of the elements is illustrated in Fig. 1. Rollers and raceways have a tapered shape, which determines the special capacity of this type of bearing to withstand combined loads. As opposed to the case of a bearing whose main application is radial loading, in a TRB the geometry of the bearings makes it possible for the load to act on the roller-raceway contacts both radially and axially [2], [7].

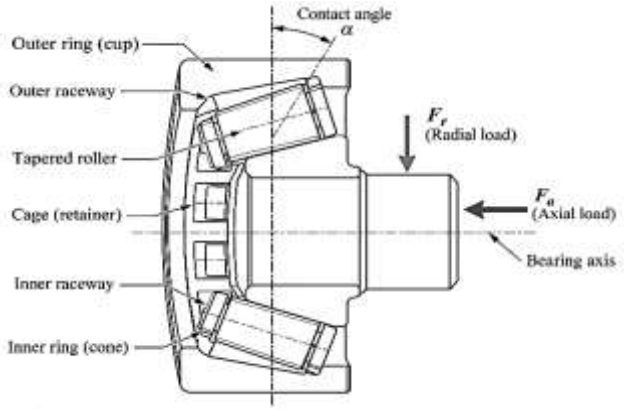


Fig – 1: Schematic representation of a tapered roller bearing showing its principal components, contact angle, and loading directions

There are many geometrical factors that play a key role in the analysis of the behavior of tapered roller bearings. From amongst them, some of the most common factors are the roller diameter, effective roller length, pitch diameter, number of rollers, and the contact angle [2], [3], [7]. These geometrical factors affect the surface area of contact, loading distribution, load capacity, and the expected life of the bearing.

The contact angle becomes especially important. The contact angle reflects the inclination of the effective roller–raceway contact relative to the bearing axis and affects the distribution of radial and axial loads in the bearing. For example, Dragoni [3] included the contact angle among the important parameters for optimization of tapered roller bearings in radial and axial loading conditions. Also, Tiwari et al. [2] used internal geometric parameters as design variables in their investigations.

In operation, the external load will be carried from one raceway to the other via the rollers. The loads in the rollers are not always evenly distributed. The distribution of the load in each roller depends on the geometry of the bearing and the conditions of operation. There have been extensive studies in both the analytical and dynamic aspects regarding the load distribution in the rollers [2], [4].

The operation process is made even more complex by the influence of such parameters as internal clearance, misalignment, varying load, and changing speed. These influences can affect the loading of each roller in the bearing and can influence the stresses that appear during the interaction of the rolling element with the raceway [4], [6]. It is necessary because these local stresses are directly connected with the life of the bearing. Thus, the geometry of a tapered roller bearing provides the starting point for understanding its load-carrying behaviour. The following subsection therefore considers how the applied radial and axial loads are distributed among the individual rollers.

3.2 Load Distribution in Tapered Roller Bearings

The load acting on a tapered roller bearing is not shared equally by all rollers. During radial and axial load, the rollers are subjected to different loads depending upon their angles of position, and some rollers bear relatively more load than the rest. This uneven load distribution is significant in assessing the behavior of a bearing [2], [4].

A simplified representation of the loading arrangement is shown in Fig. 1. The figure can be used to distinguish the externally applied radial load F_r from the axial or thrust load F_a, together with the corresponding direction of the roller–raceway contact force.

The actual load carried by the rollers depends upon a number of internal parameters like the number of rollers, pitch diameter, roller size, and contact angle [2], [3]. In order to calculate roller load distribution, Tiwari et al. [2] followed the approach of Stribeck and also took into account the loads during the optimization process of the bearing.

A rough sketch of roller loads is illustrated in Fig. 2. From the schematic, it can be seen that the roller loads change along the circumference of the bearing, and fewer rollers carry the larger load.

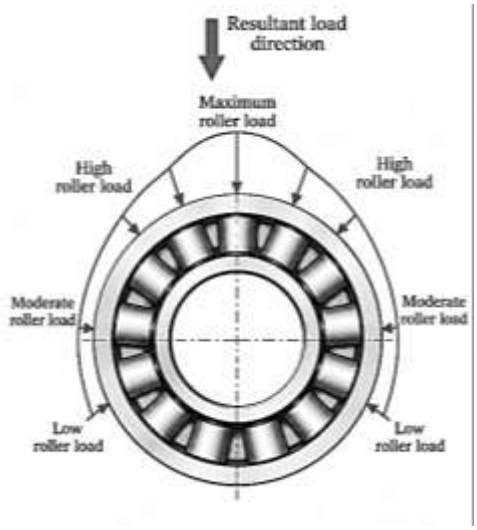


Fig – 2: Conceptual representation of non-uniform load distribution among rollers in a tapered roller bearing

Dynamic response could alter the loading pattern. The works of Deng et al. [4] take into account phenomena such as rolling, deformation, skewing, and friction; whereas Zheng et al. [6] have demonstrated that changes in external, loadings and conditions can affect the internal loading pattern and fatigue life predictions.

In addition to this, internal clearance and angular misalignment can affect the load sharing by the rollers [6]. Thus, computing the load for each roller constitutes an essential task before estimating the roller-raceway contact stress.

3.3 Roller–Raceway Contact and Contact Stress

The loads borne by each roller are transferred to the raceways through the roller-raceway contact. In the case of tapered roller bearings, this is usually regarded as line contact, resulting in localized contact pressure and stress [2], [4]. As the loads carried by the rollers are not equally shared, highly loaded rollers bear higher contact stress compared to those under lighter loads. Thus, the maximum contact stress is an important criterion for assessing the strength and fatigue resistance of the bearing [2], [5].

Factors that affect contact stress include roller loads, geometry of the bearing, materials used, and operating conditions. Variation in external loads, speed of rotation, internal clearance, and misalignment may further modify the contact conditions [4], [6]. Harris and Barnsby [1] noted the significance of contact stress and other factors affecting the fatigue behaviour of rolling bearings.

This makes contact stress an important connection between the load distribution and the bearing life. Changes in various parameters, such as roller diameter, effective roller length, pitch diameter, number of rollers, and contact angle will modify the contact conditions.

Table -1: Major TRB Design Parameters and Their Influence

Design parameter	Influence on bearing performance
Roller diameter	Influences contact conditions, load-carrying capacity, and fatigue life.
Effective roller length	Affects the contact area and the load that can be supported by the bearing.
Pitch diameter	Influences bearing geometry, roller load distribution, and load-carrying capability.
Number of rollers	Affects how the applied load is shared among individual rollers.
Contact angle	Influences the distribution of radial and axial loads and the resulting contact conditions.
Internal clearance	Can alter the number of loaded rollers and the distribution of load among them.
Roller–raceway geometry	Directly affects contact pressure, stress distribution, and fatigue behaviour.
Operating load	Determines the magnitude and distribution of roller loads and associated contact stresses.

4. BEARING LIFE AND RELIABILITY

4.1 Bearing Rating Life

The bearing rated life is one of the key factors used to determine the fatigue life of a rolling element bearing. The rated life L_{10} of a rolling bearing is defined as the total number of revolutions completed by 90 percent of similar bearings before any signs of fatigue failure appear [1], [16]. The basic rating life is commonly expressed as:

$$L_{10} = \left(\frac{C}{P}\right)^{p}$$

Where, C is the basic dynamic load rating, P is the equivalent dynamic bearing load, and p is the life exponent. For roller bearings, the commonly used exponent is $p = \frac{10}{3}$ [16], [18].

In case of tapered roller bearings subjected to combined radial and axial loads, the equivalent dynamic load should include both loads. Thus, the inner geometry and contact angle become significant in defining the actual load situation [2], [3].

The notion of rating life allows having a common yardstick for bearing comparison. Nevertheless, it is a standardized fatigue-life parameter and not a description of all aspects connected with lubrication, contamination, misalignment, material behavior, or operational conditions [1], [18].

4.2 Fatigue Life of Tapered Roller Bearings

Fatigue life is strongly dependent on the stresses generated at the roller-raceway interfaces. Rolling contact

stresses can result in subsurface stresses that ultimately cause bearing fatigue and failure [1], [5].

In the case of TRBs, fatigue life calculation is influenced by internal load distribution and contact stresses. For instance, Tiwari et al. [2] connected bearing dimensions and roller load distribution to fatigue life, while Dragoni [3] accounted for fatigue life as a goal during optimization of bearings under combined loadings.

This implies that fatigue life of a TRB can be affected by variables including roller diameter, effective roller length, pitch diameter, number of rollers, and contact angle [2], [3], [7]. Higher loads on each roller will result in higher contact stress, thereby reducing fatigue life of the bearing.

The fatigue life of the tapered roller bearing can be influenced by dynamic conditions in which it operates. Deng et al. [4] studied the behavior of dynamic rollers, while Zheng et al. [6] looked into fatigue life in the presence of varying external loads and different rotating speed. These studies suggest that using the nominal load for life prediction might not account for all practical conditions.

Therefore, fatigue-life analysis serves as a crucial bridge between the design geometry of a bearing, load distribution of its rollers, contact stresses and reliability.

4.3 Factors Influencing Bearing Life

Fatigue life of a tapered roller bearing is influenced by many inter-related parameters. The applied load and roller load distribution play a major role in determining the magnitude of the contact force and stress generated between the rollers and raceways [1], [2].

Bearing geometry is also an important factor. Some of the geometrical parameters include roller diameter, effective length of the rollers, pitch diameter, number of rollers, and contact angle [2], [3], [7]. Higher stress at the point of contact may lead to higher chances of failure due to fatigue.

Conditions of operation also impact the bearing life. Operating speed, lubrication, contamination, clearance, and angular misalignment may vary the contact and load distribution [1], [4], [6]. The variation of loading and speed makes the life estimation process difficult as compared to calculations for a particular operating condition [6].

Other factors that may affect the bearing life are material properties, manufacturing errors, and dimensional tolerance. This has made robust optimization a necessity for bearing life studies [7].

These factors show that bearing life cannot be evaluated from load rating alone. A reliable design requires consideration of geometry, loading, contact stress, operating conditions, and manufacturing variation together.

Table -2: Factors Influencing the Fatigue Life and Reliability of Tapered Roller Bearings

Design parameter	Influence on bearing performance
Applied load	Determines roller loading and contact stress
Bearing geometry	Controls load distribution and contact conditions
Contact stress	Influences rolling-contact fatigue
Lubrication	Affects surface and subsurface fatigue behavior
Speed	Influences dynamic behavior and operating conditions
Internal clearance	Changes the number and distribution of loaded rollers
Misalignment	Can produce uneven roller loading
Manufacturing variation	Causes variation in geometry and predicted life

5. ANALYSIS AND MODELLING APPROACHES FOR TAPERED ROLLER BEARINGS

5.1 Analytical Methods

Analytical techniques offer a fairly simple way to assess the performance of tapered roller bearings through the use of known relationships between bearing loads and lives. These techniques are typically used for determining roller loads, equivalent bearing loads, rating life, and design limits [1], [2], [16], [18].

In case of TRBs, analytical techniques have the capability of taking into account both geometry and the effects of combined loading. This is the technique that was used by Tiwari et al. [2] through the use of analytical load distribution model based on Stribeck's approach as part of the bearing optimization process.

The main strength of the analytical approach is its lower computation need, which makes it a good choice for preliminary design and optimization work. Another benefit of using analytical equations is that the effects of each individual parameter can be studied independently. The main limitation of the analytical approach is that these approaches make certain assumptions about load distribution, contact conditions, material properties, and operating conditions. This means that the complexity of the contact problem cannot always be captured by analytical equations [2], [4]. In practice, the analytical approach is often employed as the first step in designing and optimizing bearings.

5.2 Finite Element Analysis

FEA is commonly applied to analyze stress, deformation, and contact behavior of tapered roller bearings. In contrast to simplified analytical approaches, FE can give a more detailed

picture of the roller-raceway contact and stress distribution [5], [8], [9].

Contact stress analysis of a double row tapered roller bearing was carried out by Yang et al. [5] using SolidWorks and ANSYS software. A modeling method of tapered roller bearing using FEA was introduced by Gao et al. [8], whereas Wu & Peng [9] utilized FEM for static analysis of tapered roller bearings. FEA is especially helpful when there is a complicated design of the bearing or when local stress and deformation should be analysed.

However, FEA results depend strongly on geometry, material properties, contact definitions, boundary conditions, and loading assumptions. Consequently, appropriate modelling assumptions and validation of the numerical model are important for obtaining reliable results [5], [8], [9]. Overall, FEA provides a useful numerical tool for evaluating the structural and contact behaviour of TRBs and can support geometry optimization when analytical methods alone are insufficient.

5.3 Modelling and Dynamic Simulation

Dynamic models can be used for analysing the dynamics of tapered roller bearings under variable operating conditions. In contrast to static analysis, dynamic models can account for such factors as roller motion, friction, skew and tilt, varying external load [4], [6].

For instance, Deng et al. [4] analysed the dynamics of TRBs accounting for roller motion, contact deformation, friction, skew and tilt. Zheng et al. [6] studied the effect of oscillating external load and rotation on the fatigue-life behavior of TRBs and demonstrated that varying operating conditions could influence the load distribution within the bearing. Dynamic models, therefore, offer a better insight into the dynamics of the bearing compared to traditional static analyses. They are especially useful for such applications when the operating conditions are variable or complex roller motion exists [4], [6].

Dynamic models may also be utilized to understand the impact of operating conditions on the contact between rollers and raceways and on fatigue life prediction. Dynamic models, however, usually involve much more complex equations and need much higher computation compared to basic analytical models. The application of dynamic models is only necessary when a detailed analysis of bearing behaviour is needed. In summary, dynamic modeling is a useful tool that can provide additional information about the time-varying nature and load distribution in tapered roller bearings.

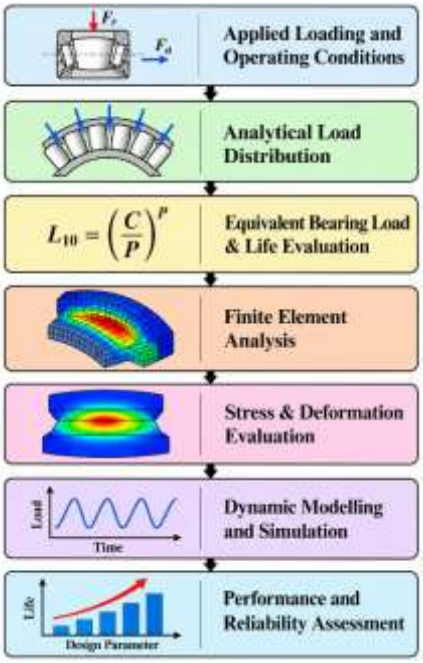


Fig – 3: General Analytical and Numerical Analysis Framework for Tapered Roller Bearings

6. DESIGN OPTIMIZATION OF TAPERED ROLLER BEARINGS

Design optimization has become an important approach for improving the performance of tapered roller bearings because several internal geometric parameters influence load distribution, fatigue life, and load-carrying capability simultaneously. Previous studies have applied mathematical optimization and evolutionary algorithms to identify suitable combinations of bearing dimensions while satisfying geometric and strength constraints [2], [3], [7].

6.1 Design Variables and Optimization Objectives

The performance of a tapered roller bearing depends significantly on its geometrical structure. Some of the design parameters studied are pitch diameter, roller diameter, effective roller length, number of rollers, aspect ratio of the rollers, and the contact angle [2], [3], [7].

According to Tiwari et al. [2], some of the design variables for optimizing tapered roller bearings are pitch diameter, roller diameter, effective roller length, and number of rollers. In Dragoni [3], design parameters studied include pitch diameter, roller geometry, roller fill, aspect ratio, and contact angle. These references clearly show that the optimization of the geometry of the bearing cannot be done by studying one parameter at a time.

The optimization criteria usually depend on fatigue life improvement, dynamic load carrying capacity, or overall bearing performance. Tiwari et al. [2] proposed the formulation of the optimization problem based on bearing rating life, whereas Dragoni [3] took into account the maximum rating life for combined radial and axial loads. Verma and Tiwari [7] attempted to maximize the fatigue life along with design variable changes.

Therefore, the choice of design variables and optimization criteria should take into account both the bearing performance and geometrical constraints of the bearing itself.

6.2 Optimization Methods and Constraints

Various optimization approaches have been used in bearing design. While analytical optimization may help in finding the influence of each individual geometric parameter, evolutionary approaches are helpful where multiple design variables and nonlinear constraints exist [2], [3], [7].

The study conducted by Tiwari et al. [2] employed an evolutionary optimization approach involving geometric, bearing-standard, and strength constraints. The approach included analytical load distribution and fatigue life evaluation to find out feasible solutions. The study of Dragoni [3] involved constrained optimization to improve rating life of tapered roller bearings subjected to simultaneous loading.

The application of evolutionary optimization technique has also been made in relation to manufacturing variation. Verma and Tiwari [7] devised a robust optimization approach in which manufacturing variations in design variables were taken into consideration to maximize fatigue life. It is due to the reason that optimized geometry of theoretical nature does not necessarily give satisfactory results when manufacturing tolerance is considered. Hence, optimization of TRBs practically involves constraints of geometry, strength, size of the bearing, contact and manufacturability, apart from fatigue life optimization [2], [7].

6.3 Reliability-Oriented and Robust Optimization

Conventional optimization techniques involve the search for the optimal solution providing the highest value of the selected performance index, under predetermined operational conditions. On the other hand, the actual bearing is subjected to the uncertainties in manufacturing process, operating conditions and geometric parameters. Consequently, the actual performance of the system may deviate from the optimized one.

The question was handled by Verma and Tiwari [7] who proposed the robust optimization approach accounting for design parameters variations when maximizing fatigue life. The study shows that the goal of optimization should not only include achieving high theoretical life but also be sensitive to the variability in parameters.

Other optimization efforts showed that variation in geometry may greatly affect the load distribution and rating life of the bearing [2], [3]. It means that the reliability-oriented optimization approach should take into account the effects of geometric parameters, loads, contact interaction, fatigue life and manufacturing variability.

Thus, all discussed efforts show the evolution from the conventional geometric optimization towards more complex and robust solutions. In the future optimization approaches would benefit from the combination of analytical bearing models and numerical contact and stress analyses of the optimized system.

7. COMPARATIVE AND CRITICAL ANALYSIS OF PREVIOUS STUDIES

The reviewed literature shows that tapered roller bearing research has developed from conventional analytical life calculations toward numerical modelling, dynamic simulation, and optimization-based design. However, the studies differ considerably in their objectives, design variables, loading conditions, and analysis methods. A comparison of these approaches helps identify the strengths and limitations of current TRB research.

7.1 Comparison of Existing Approaches

The previous research works can be generally classified according to the major topic that each one is dealing with. Tiwari et al. [2] and Dragoni [3] were mostly interested in the study of bearing geometry and rating life under simultaneous loads. The methods presented here show how variations in the inner dimensions can affect the bearing life, taking into account the geometry and strength limitations.

As for the dynamic behavior of a bearing, this problem was analyzed by Deng et al. [4] through the roller displacement, friction, skew, and tilt. Also, Zheng et al. [6] have developed the approach toward the fatigue life calculation under alternating loads and rotational speed.

The use of numerical methods has also gained more popularity in recent years. Yang et al. [5] conducted research on contact stress through the use of SolidWorks and ANSYS software, whereas Gao et al. [8] and Wu & Peng [9] have looked at finite element modeling and static analysis of tapered roller bearings. These types of methodologies are especially helpful when it comes to analyzing the stress and deformation of a system where analytical expressions may fail to provide an adequate solution.

The optimization process has become more robust. Verma & Tiwari [7] took into account manufacturing tolerances while trying to maximize fatigue life.

7.2 Critical Evaluation of Existing Research

From the studies presented above, it is clear that there is no one method of analysis alone that can deal with all the features of the TRB behavior. The analytical methods are computationally efficient and effective for preliminary designs and optimization processes; however, they are based on certain assumptions of the load distribution and contact behavior [2], [3]. The finite element analysis gives more insights into the stress and deformation; however, it requires accurate geometry, contacts, material characteristics, and boundaries [5], [8], [9].

Dynamic analysis gives further information about roller dynamics and changing conditions; however, it requires more precise data inputs and computational work [4], [6]. Optimization process identifies optimal bearing geometry but

depends heavily on certain factors such as design variables, objective functions, constraints, and assumptions of the model [2], [3], [7].

A further limitation is that several studies focus primarily on one performance aspect, such as fatigue life, contact stress, dynamic behaviour, or geometric optimization. The interaction between these factors is less consistently addressed. Manufacturing variation and realistic operating conditions are also not treated uniformly across the literature [6], [7].

Overall, the literature indicates a clear need for a more integrated approach in which analytical calculations, numerical stress analysis, operating conditions, and optimization are considered together. Such integration can provide a stronger basis for developing TRB designs with improved performance and reliability.

Table -3: Comparative Summary of Reviewed Research Studies

Author (s)	Year	Research Focus & Method	Key Parameters / Objective	Key Findings
Harris and Barnsby [1]	2001	Bearing life; analytical life-rating approach	Contact stress, load, lubrication, fatigue	Established the importance of stress, lubrication, material and operating factors in rolling-bearing fatigue-life prediction.
Tiwari et al. [2]	2012	TRB design optimization; genetic algorithm	Pitch diameter, roller diameter, effective roller length, number of rollers; maximize fatigue life	Demonstrated that TRB internal geometry can be optimized using a constrained genetic-algorithm approach to improve fatigue-life performance.
Dragoni [3]	2017	TRB optimization under combined loading; analytical optimization	Contact angle, roller geometry, radial/axial load ratio; maximize rating life	Showed that an optimum contact angle exists for a given load ratio and can improve bearing rating life.
Deng et al. [4]	2017	Dynamic TRB analysis; dynamic modelling	Roller motion, friction, skew, tilt, load distribution	Demonstrated the influence of dynamic roller behaviour and contact conditions on internal bearing response.
Yang et al. [5]	2019	Contact-stress analysis; SolidWorks and ANSYS	Combined loading, roller–raceway contact, stress distribution	Demonstrated the usefulness of numerical analysis for evaluating contact stress and load distribution in TRBs.
Zheng et al. [6]	2020	Fatigue-life analysis under variable conditions	Oscillating load, speed, misalignment, internal clearance	Showed that variable loading and speed can influence internal load distribution and fatigue-life prediction.
Verma and Tiwari [7]	2020	Robust TRB optimization; evolutionary algorithm	Geometric variables, manufacturing variations; maximize fatigue life	Demonstrated the importance of considering design-variable variations and robustness during fatigue-life optimization.
Gao et al. [8]	2025	TRB finite-element modelling	Bearing geometry, contact and structural behaviour	Proposed an FE modelling approach for detailed numerical investigation of tapered roller bearings.
Wu and Peng	2025	Static TRB analysis;	Static loading, stress and	Demonstrated the application of

[9]		FEM	deformation	FEM for evaluating static structural behaviour of tapered roller bearings.
Devarajan et al. [10]	2025	Contact-fatigue analysis	Roller–raceway contact and fatigue behaviour	Investigated the relationship between contact conditions and fatigue behaviour in tapered roller bearings.
Dandagwhal and Kalyankar [11]	2019	Rolling-bearing design optimization	Bearing design variables; advanced optimization technique	Demonstrated the application of advanced optimization techniques to improve rolling-bearing design.
Kim et al. [12]	2016	Angular-contact bearing optimization	Bearing geometry and operating parameters	Showed that optimization of internal bearing parameters can improve bearing performance under specified design constraints.
Knežev et al. [13]	2017	Internal geometry optimization	Internal bearing geometry	Demonstrated the effect of internal geometric parameters on bearing performance and the potential for geometry optimization.
Gismeros Moreno et al. [14]	2024	Contact modelling of rolling bearings	Contact geometry and smooth-contact formulation	Demonstrated improved representation of contact behaviour through a smooth-contact modelling approach.
Mendi et al. [15]	2010	Gear–bearing system optimization; genetic algorithm	Gear module, shaft diameter, rolling bearing	Demonstrated that simultaneous optimization of gear and bearing-related parameters can improve overall system design.

8. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

There has been considerable development in the analysis and optimization of tapered roller bearings in the literature reviewed; however, there are certain areas that require further attention. Most of the work done on bearing life, contact stress, dynamic behavior, or geometric optimization does not incorporate the effects of all these factors at the same time [2] – [7]. It becomes difficult to determine the reliability of the bearing with regards to realistic operating conditions using the above approach. One area where analytical and numerical models have not yet been integrated effectively in most of the studies is one of such areas.

Another area that requires improvement in some optimization studies is the analysis of roller load distribution. Since the roller loading plays a part in fatigue life and contact stresses, future studies should focus on this aspect as well [2], [4].

Consideration is also needed for the effects of manufacturing variability and dimensional tolerances. Robust optimization has indicated that variability of design parameters may impact fatigue-life performance [7]. Realistic tolerances and sensitivity analysis should be included in future investigations to guarantee reliable post-manufactured optimized designs.

Variable operating conditions represent another issue to be considered. Variations in load, speed, clearance, and misalignment may affect internal load distribution and fatigue-life estimation [4], [6]. Optimized geometries of TRBs should be examined for variable operating conditions in addition to nominal loads.

In the end, future work should consider practical design constraints in addition to analytical calculations and stress

analysis including geometry, strength, dimensional and manufacturability restrictions [2], [3], [7]. In view of these deficiencies, future research should look at reliability-based optimization taking into account realistic operating conditions, manufacturing variations and geometric constraints.

Table -4: Research Gaps and Future Research Directions

Research gap	Future research direction
Limited integration of analytical, numerical, and fatigue-life approaches	Develop an integrated framework combining analytical calculations, FEA, contact stress, and fatigue-life evaluation
Simplified roller load distribution and contact behaviour	Consider detailed roller-level load sharing and contact behaviour under combined loading
Limited consideration of manufacturing variation	Incorporate dimensional tolerances, sensitivity analysis, and robust optimization
Simplified operating conditions	Evaluate optimized designs under variable load, speed, clearance, and misalignment
Limited practical constraints and validation	Include geometric, strength, dimensional, and manufacturability constraints and validate optimized designs numerically or experimentally

9. CONCLUSION

Tapered roller bearings are essential machine parts in cases where there is a combination of radial and axial loads, and their performance depends on internal geometry, load distribution, contact stress, operating conditions, and fatigue properties. From the reviewed literature, it is clear that such parameters as roller diameter, effective length of the roller, pitch diameter, number of rollers, and contact angle may greatly affect bearing life and fatigue properties [2], [3], [7].

It is evident from the review that analytical approach remains effective for load distribution and rating-life evaluation as well as initial optimization, whereas finite-element analysis and dynamics give additional information on contact stress, deformation, roller behavior, and operating conditions [4]–[9]. In addition, optimization procedures have proven their effectiveness in improving bearing life under geometric and strength restrictions [2], [3], [7].

Nonetheless, the literature review also reveals the fact that the methods mentioned are used in isolation. The critical issues such as manufacturing tolerances, roller load distribution, operating conditions, contact behavior, and design limitations are not taken into account all at once. This means that the future work needs to be devoted to the integration of analytical and numerical analysis with the optimization process.

Thus, it can be stated that the existing research forms a good basis for the design optimization and reliability improvement of TRBs. An integrated approach, which takes into account bearing geometry, loadings, contact stresses, fatigue life, manufacturing tolerances, and limitations will help design better TRBs.

REFERENCES

1. T. A. Harris and R. M. Barnsby, "Life Ratings for Ball and Roller Bearings," Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, vol. 215, no. 6, pp. 577–595, 2001.
2. R. Tiwari, K. K. Sunil, and R. S. Reddy, "An Optimal Design Methodology of Tapered Roller Bearings Using Genetic Algorithms," International Journal for Computational Methods in Engineering Science and Mechanics, vol. 13, no. 2, pp. 108–127, 2012.
3. E. Dragoni, "Optimal Design of Tapered Roller Bearings for Maximum Rating Life under Combined Loads," Mechanics & Industry, vol. 18, Art. no. 112, 2017.
4. S. Deng, J. Gu, Y. Cui, and W. Zhang, "Dynamic Analysis of a Tapered Roller Bearing," Industrial Lubrication and Tribology, 2017.
5. K Yang, G Zhang, Y W Wang and S Cai, "Contact Stress Analysis of High-Speed Railway Double Row Tapered Roller Bearing Based on SolidWorks and ANSYS," IOP Conference Series: Materials Science and Engineering, vol. 504, Art. no. 012073, 2019.
6. J. Zheng, J. Ji, S. Yin, and V.-C. Tong, "Fatigue Life Analysis of Double-Row Tapered Roller Bearing in a Modern Wind Turbine under Oscillating External Load and Speed," Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2020.
7. Shashikant Kumar Verma, Rajiv Tiwar, "Robust Optimum Design of Tapered Roller Bearings Based on Maximization of Fatigue Life Using Evolutionary Algorithm," Mechanism and Machine Theory, 2020.
8. X. Gao, S. Ren, and Z. Zhang, "A Tapered Roller Bearing Finite Element Modeling Method and Its Application," SSRN Electronic Journal, 2025.
9. Jiahua Wu, Yu Peng, "Static Analysis of Taper Roller Bearings Based on Finite Element Method," Journal of Physics: Conference Series, vol. 3009, Art. no. 012071, 2025.
10. C. Devarajan, P. Saran, and R. Balaji, "Design and Analysis of Contact Fatigue in Tapered Roller Bearings," Proceedings of the International Conference on Knowledge, AI and Mechanical Engineering (ICNKAI-2025), 2025.
11. R. D. Dandagwhal and V. D. Kalyankar, "Design Optimization of Rolling Element Bearings Using Advanced Optimization Technique," Arabian Journal for Science and Engineering, 2019. DOI: 10.1007/s13369-019-03767-0. 11_dandagwhal2019
12. S.-W. Kim, K. Kang, K. Yoon, and D.-H. Choi, "Design Optimization of an Angular Contact Ball Bearing for the Main Shaft of a Grinder," Mechanism and Machine Theory, vol. 104, pp. 287–302, 2016. 12_kim2016
13. M. Knežev, A. Živković, M. Zeljković, D. Lukić, and C. Mlađenović, "Internal Geometry Optimization of Angular Contact Ball Bearings," Machine Design, vol. 9, no. 4, pp. 139–144, 2017. 13_KneevMachineDesign
14. R. Gismeros Moreno, F. Marques, E. Corral Abad, J. Meneses Alonso, P. Flores, and C. Castejon, "Enhanced Modelling of Planar Radial-Loaded Deep Groove Ball Bearings with Smooth-

Contact Formulation," Multibody System Dynamics, vol. 60, pp. 121–159, 2024. DOI: 10.1007/s11044-023-09952-2. DOI

15. F. Mendi, T. Başkal, K. Boran, and F. E. Boran, "Optimization of Module, Shaft Diameter and Rolling Bearing for Spur Gear Through Genetic Algorithm," Expert Systems with Applications, vol. 37, no. 12, pp. 8058–8064, 2010. DOI: 10.1016/j.eswa.2010.05.082.
16. Bureau of Indian Standards (BIS), IS 3824:2002 – Rolling Bearings – Dynamic Load Ratings and Rating Life, New Delhi, India: BIS, 2002.
17. Bureau of Indian Standards (BIS), IS 3823:2002 – Rolling Bearings – Static Load Ratings, New Delhi, India: BIS, 2002.
18. SKF Group, SKF Rolling Bearings Catalogue (Catalogue 17000 EN), Gothenburg, Sweden: SKF Group, 2018.