MOTION DESIGN GUIDE
PLAIN LINEAR BEARINGS IN CONTEXT

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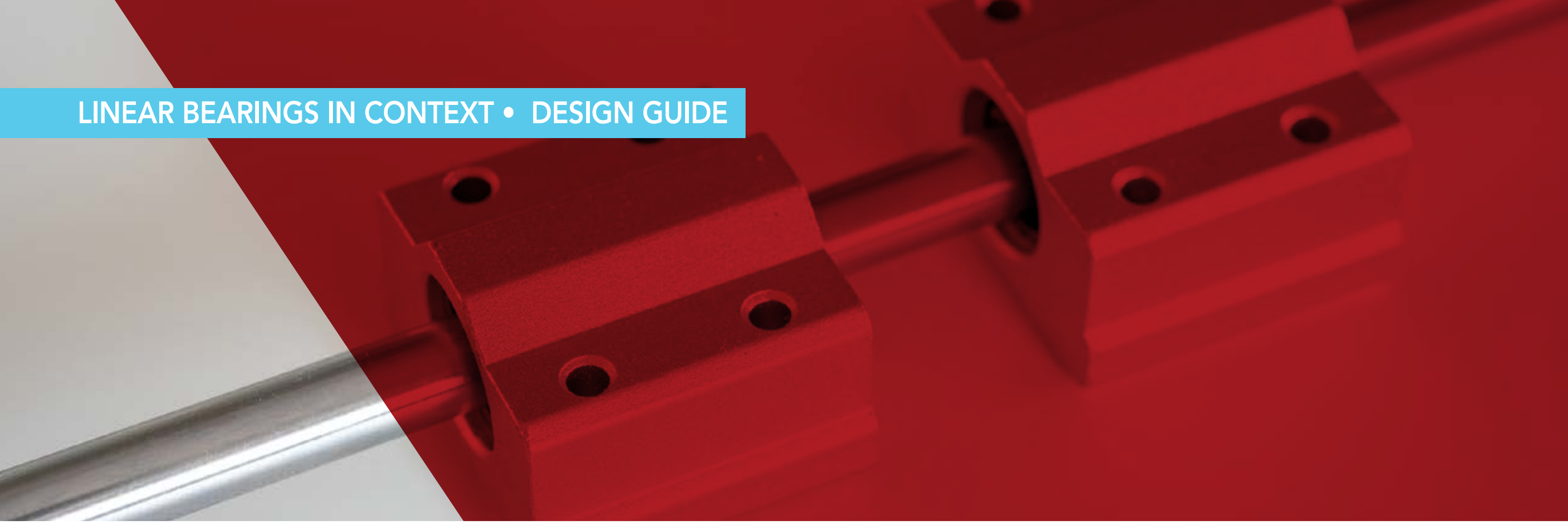
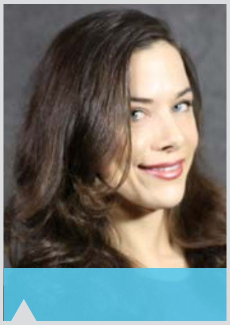


LINEAR BEARINGS IN CONTEXT • DESIGN GUIDE

Linear bearings include mechanical components that allows relative motion between two surfaces — with one surface supporting the other and minimum friction between the two. The two basic types of linear guides include plain (sliding motion) and rolling element … with the same general function but vastly different design and performance characteristics.

In this Design Guide, the editors of Design World explain basic linear-bearing terminology and detail the most common linear-bearing types …. as well general ways to quantify the performance and capabilities of linear bearings for sizing, selection, and installation. Special emphasis is placed on plain linear bearings. Deep dives on crossed-roller slides, accuracy and preload, rolling-element linear bushings, and ball splines are included in other Design Guide installments.

DANIELLE COLLINS
Senior editor



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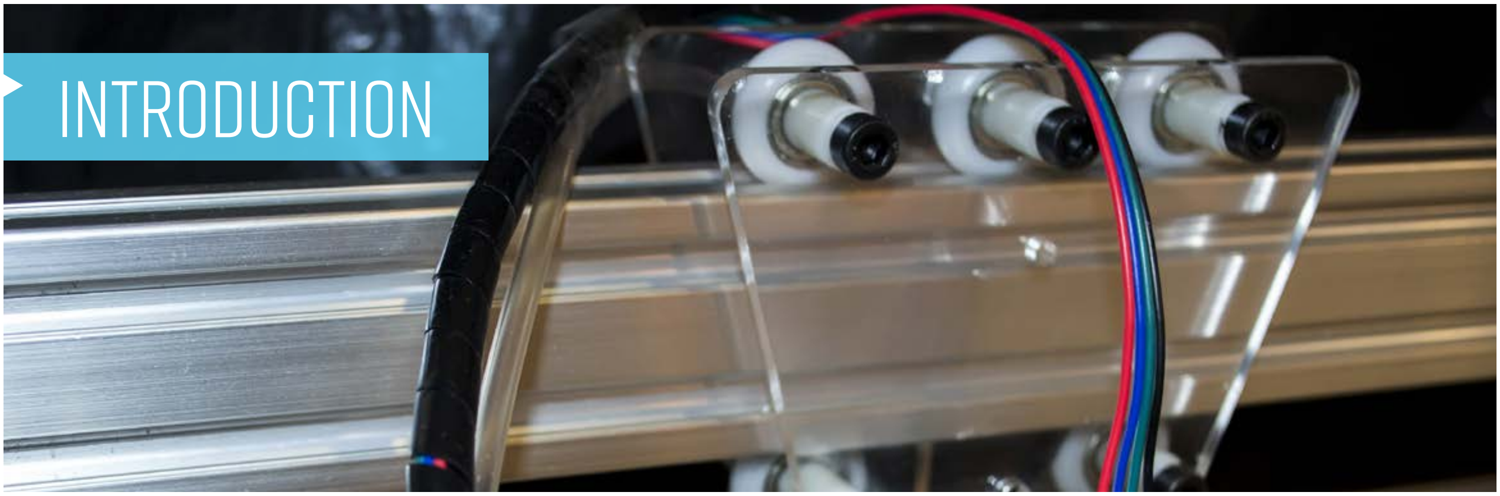
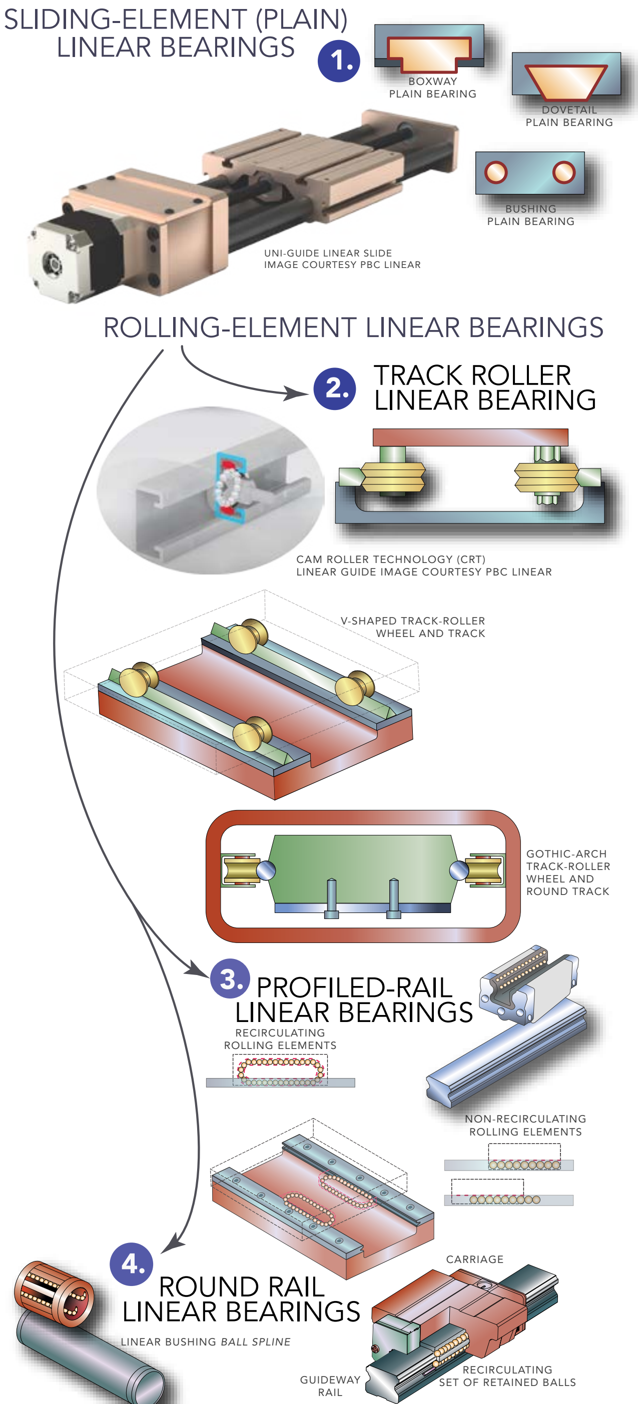


INTRODUCTION



Linear bearings are included in linear actuators and the axes of other motion systems to guide and support machine assemblies and payloads over the linear stroke. All linear bearings fall into four categories:

1. A carriage or comparable table rides on a linear rail or track via plain (sliding) elements
2. A carriage rides on linear rail via wheel-type track rollers
3. A carriage rides on a profiled linear rail via carriage-contained arrays of ball bearings or cylindrical rollers
4. A bushing studded on its inner diameter with rolling elements rides on a round shaft

The interrelated functions of these linear-motion components to both support (bear) loads and guide loads is the core reason why they're called both *linear bearings* and *linear guides* — depending on which function is being emphasized by the source. Both terms are so generic that they can refer to any products from the four categories listed above — including such disparate designs as plain linear bearings, ball bushings, and recirculating-roller linear bearings. Confusing matters is the fact that industry makes inconsistent use of even more specific linear-motion terms. For example, the term *slide* is often used to refer to the carriages of linear bearings based on rolling (not sliding) bearing elements. The term *rolling-contact guide* is often used to refer to profiled-rail linear bearings even though track-roller linear guides also include rolling contact (at their track wheels).

That said, *linear guide* often indicates a standalone guide rod, ball slide, or mechanism solely for guiding loads. The term *profiled rail* nearly always indicates some linear bearing with roller or ball elements. Many manufacturers use the terms *linear slide* (whether based on rolling or sliding action) and *linear rail* (whether plain, track-roller, or profile) to indicate a linear-motion guide element that's incorporated into a build complete with some mechanical drive. Though the terminology surrounding plain linear bearings is probably the most consistent, various manufacturers use *plane bearing* (as in one dimension in 3D space) instead *plain bearing*. While the two terms are often used interchangeably, the American Bearing Manufacturers Association encourages use of the term *plain bearing*.

The term *linear stage* generally implies a design has guided elements as well as some mode of mechanical linear actuation and reinforced body — often sans inclusion of the motor.

Motorized rails (more commonly called linear actuators) abound — though the distinction here is that there are countless linear actuators sold without any linear-guide element. That's useful for OEMs aiming to employ some specialized linear guide or omit guides altogether.

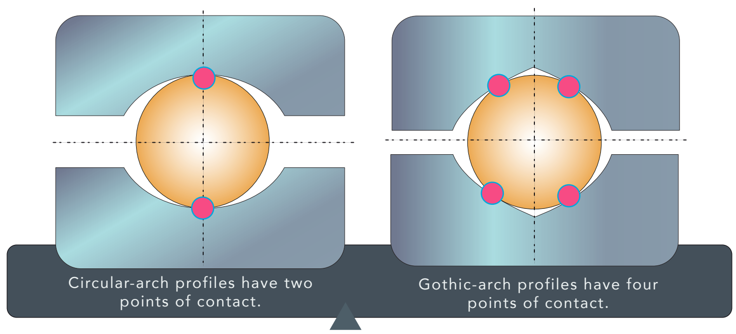
BASICS OF PLAIN AND ROLLING-ELEMENT LINEAR BEARINGS

While many linear-motion applications absolutely demand either plain linear bearings or rolling-element linear bearings, the majority are well satisfied with either.

Plain linear bearings (on low-friction aluminum or steel shafting or rails) can outperform rolling-element linear bearings on vibrating, hot, or short-stroke axes — and on axes needing very low friction coefficients (μ) even down to 0.12.

In contrast, rolling-element linear bearings (with μ down to 0.001) are often indicated on high-speed axes (running to many meters per second) and those involving high moment loads.

For other applications, it's left to the design engineer to determine which options offer the most advantages (including cost, life, and friction characteristics) for full design optimization.



Above are the Gothic arches at the historic Cloisters of Glasgow University in Scotland. Gothic arches in civil engineering provide loftier reaches and half the (compromising) side thrust of Roman arches. In mechanical engineering (and more specifically in bearing designs) Gothic arches increase clearance and roller-to-raceway (or track) contact.

Plain bearings are the simplest type of linear guide, relying on sliding contact between two surfaces. Their construction can be boxway, dovetail, or shaft and bushing.

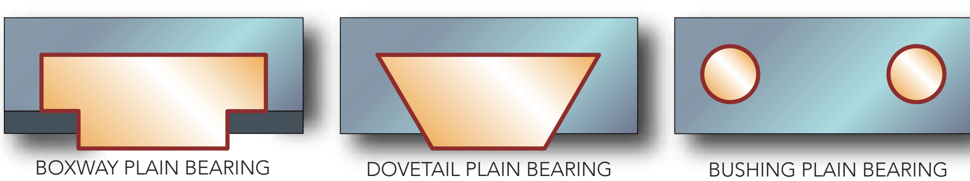
Boxway bearings can carry the highest loads, while dovetail designs allow less precise machining and assembly.

Plain bearing bushings are simple to manufacture and install, though any unsupported shafts can limit load capacities and risk issues from deflection.

Plain bearings with metal surfaces provide the highest stiffness and load capacities. In contrast, plain bearings made of plastics or composites offer high corrosion resistance and self-lubricating properties. No matter the design, sliding contact should always be between dissimilar materials, with one element harder than the other. This concentrates any wear in the softer element.

Plain bearings can withstand shock loads and vibrations without significant working-surface damage. Plain bearings are also less sensitive to contamination and rarely fail catastrophiccally. The catch is that plain bearings have higher friction coefficients (typically 0.05 to

LINEAR-BEARING DESIGNS BASED ON SLIDING CONTACT



Plain bearing linear guides can be boxway, dovetail, or shaft and bushing designs.

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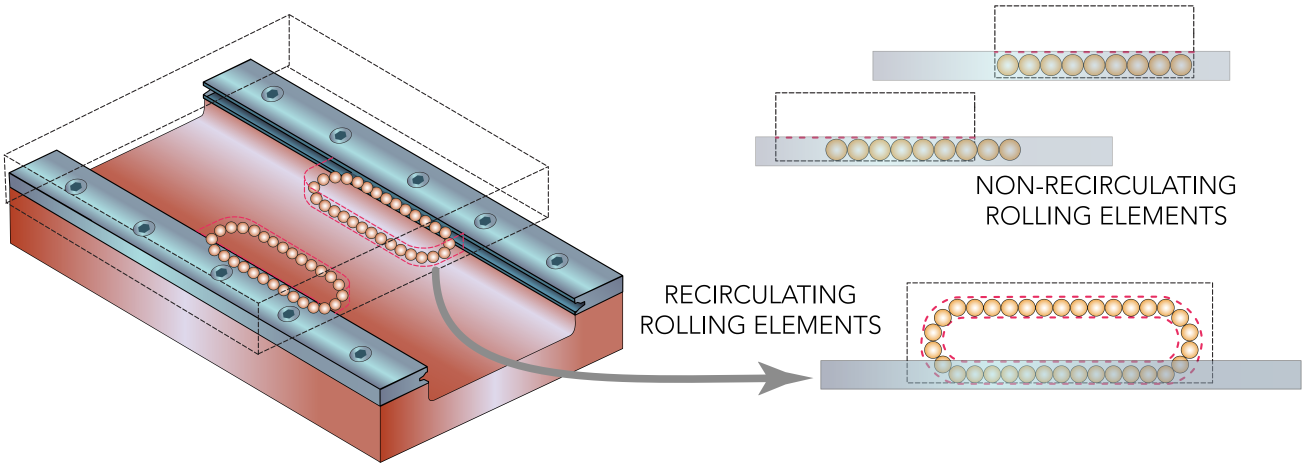
BASICS OF PLAIN AND ROLLING-ELEMENT LINEAR BEARINGS

RECIRCULATING AND NON-RECIRCULATING ROLLING-ELEMENT LINEAR BEARINGS



0.1) when compared to rolling-element linear bearings.

Rolling-element linear guides use balls or cylindrical rollers between the two bearing surfaces. These rolling elements can setup to recirculate (as in profiled-rail bearings or linear bushings or linear bearing guides) or not recirculate — as in certain track-roller guides and crossed-roller slides. Recirculating designs allow unlimited motion along the guide rail or shaft length ... and non-recirculating designs have strokes limited by the rolling-element assembly length.

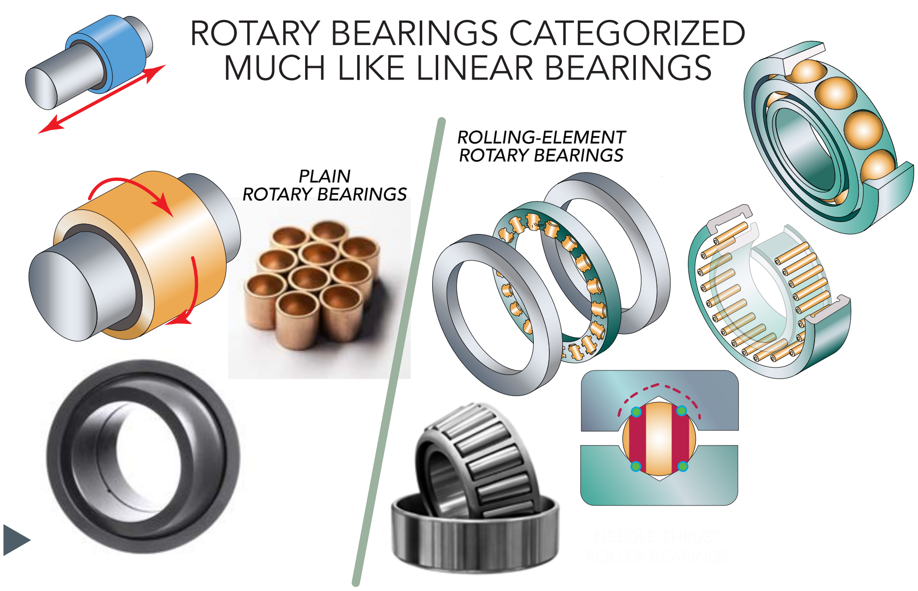
One advantage of rolling-element linear guides is their low coefficient of friction — typically 0.005 to 0.01. Because the rolling elements are typically made of bearing steel, they also offer high load capacities and the option to accept preload for high rigidity. However, preload increases friction and may necessitate upsizing of the rolling-element linear guide during specification.

While plain linear bearings can be made from a wide variety of materials, profile-rail rolling-element bearings come in the most diverse track geometries and raceway arrangements. Profiled-rail track geometry defines how rolling elements contact the raceways:

- **Circular arc** contact provides lower friction
- **Gothic arch** contact yields higher moment capacities.

In addition, the arrangement of the raceways on the profiled rail can be either face-to-face or back-to back. The face-to-face arrangement has equal load capacities in all directions, while the back-to-back arrangement gives greater torsional moment capacities.

Determining the life of rolling-element linear guides is done by calculating the L_{10} bearing life — a theoretical but statistically formulated prediction of the distance a linear bearing can travel before it reaches its fatigue life. L_{10} life depends on loading type and magnitude, although environmental factors such as shocks, vibrations, and contamination can reduce the life of rolling element bearings.



Though beyond the focus of this Design Guide, rotary bearings (like linear bearings) are categorized by whether they're based on sliding or rolling motion.

(continued)

BASICS OF PLAIN AND ROLLING-ELEMENT LINEAR BEARINGS

TRIBOLOGY BASICS FOR LINEAR BEARINGS

Tribology is the study and application of the principles of friction, lubrication, and wear between two surfaces in relative motion. In linear bearing systems, those two surfaces are the bearing element and the guide raceway.

The term ***wear*** generally refers to deterioration. However, when discussing tribology principles in relation to linear bearings, ***wear*** refers to material loss on bearing surfaces. Wear is an inevitable outcome of use caused by the load, speed, and other operating conditions that the bearing experiences. The life of a linear bearing — whether recirculating or plain type — is determined by the amount of wear on the bearing surfaces.

The primary cause of wear in bearing applications is friction. Bearings are designed and manufactured (and finished and polished) to have extremely smooth surfaces, but they'll inevitably have microstructures called asperities or rough spots where the material dips and protrudes — much like the peaks and valleys of a mountain range.

As two bearing surfaces such as a raceway and a ball, for example — move past each other, the peaks on each surface collide. This not only creates friction as the surfaces interfere, but the peaks can also break and release as particulates that abrade the bearing surfaces (through friction), causing premature fatigue failure.

By separating the bearing raceway from the rolling or sliding element (ball, roller, or plain bearing surface) lubrication reduces friction between the surfaces ... which in turn reduces wear and lowers the amount of heat generated. Lubrication also inhibits corrosion of the bearing surfaces and protects them against contamination.

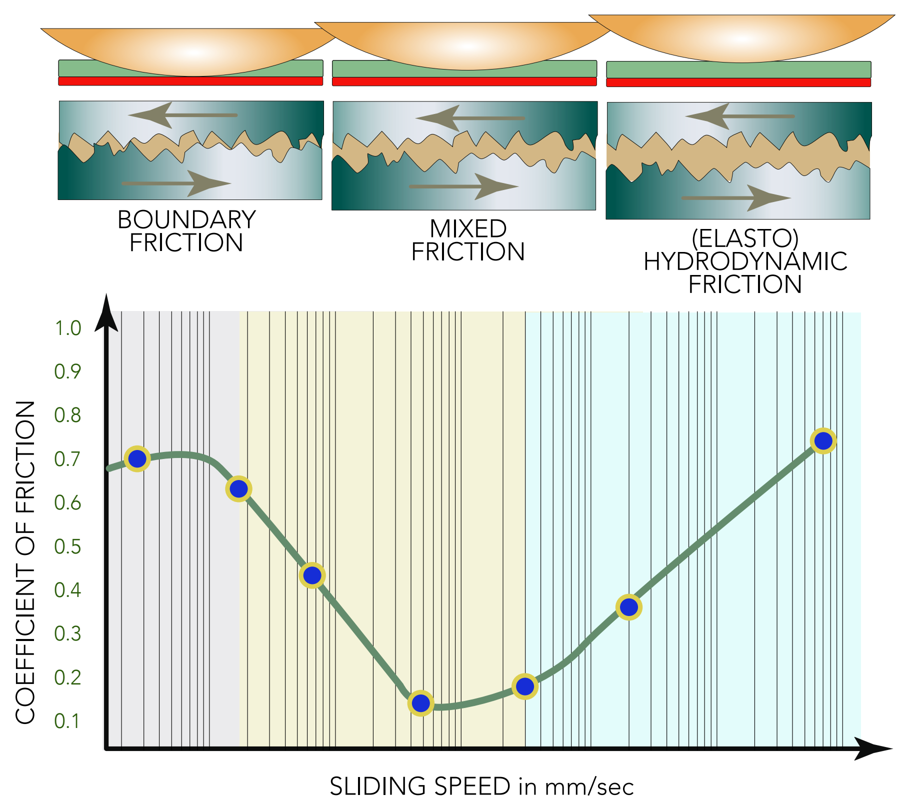
Most people are familiar with friction as the force that impedes the movement of two bodies relative to each other (a book and a table, for example). But friction takes two forms: static (also referred to as breakaway) and dynamic (also referred to as kinetic). Static friction is caused by molecular bonding when two surfaces are in contact. Dynamic friction is caused by surface roughness. Lubrication plays a role in reducing both static and dynamic friction.

TRIBOLOGY VISUALIZED: THE STRIBECK CURVE

Different levels of lubrication develop between bearing surfaces, based on the lubricant's viscosity, the pressure between the surfaces, and the speed of the bearing. The development of the lubrication film and the change in friction are shown on a

A Stribeck curve shows the development of the lubrication film and the resulting change in friction. As velocity increases, the bearing surfaces draw in more lubricant, creating a thicker lubricating layer under higher pressure, which results in higher viscosity.

Finally, the layer becomes thick enough to separate the asperities of the surfaces … and the viscosity provides sufficient film strength for the lubricant to support the load.



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BASICS OF PLAIN AND ROLLING-ELEMENT LINEAR BEARINGS

Stribeck curve. When a bearing is stationary, lubrication is essentially squeezed out of the space (or lack thereof) between surfaces. Friction is high in this phase, due to the interaction between the two surfaces. This is called boundary lubrication or boundary friction.

As the bearing begins to move, lubrication is pulled into the space between the surfaces. The pressure between the surfaces causes the lubrication's viscosity to increase, and a thin lubrication layer develops between the bearing and the raceway. In some places, the lubricating layer separates the two surfaces, but in other places the peaks of the two bearing surfaces still contact. Friction is reduced, but it is not yet minimized. This is referred to as mixed lubrication or mixed friction.

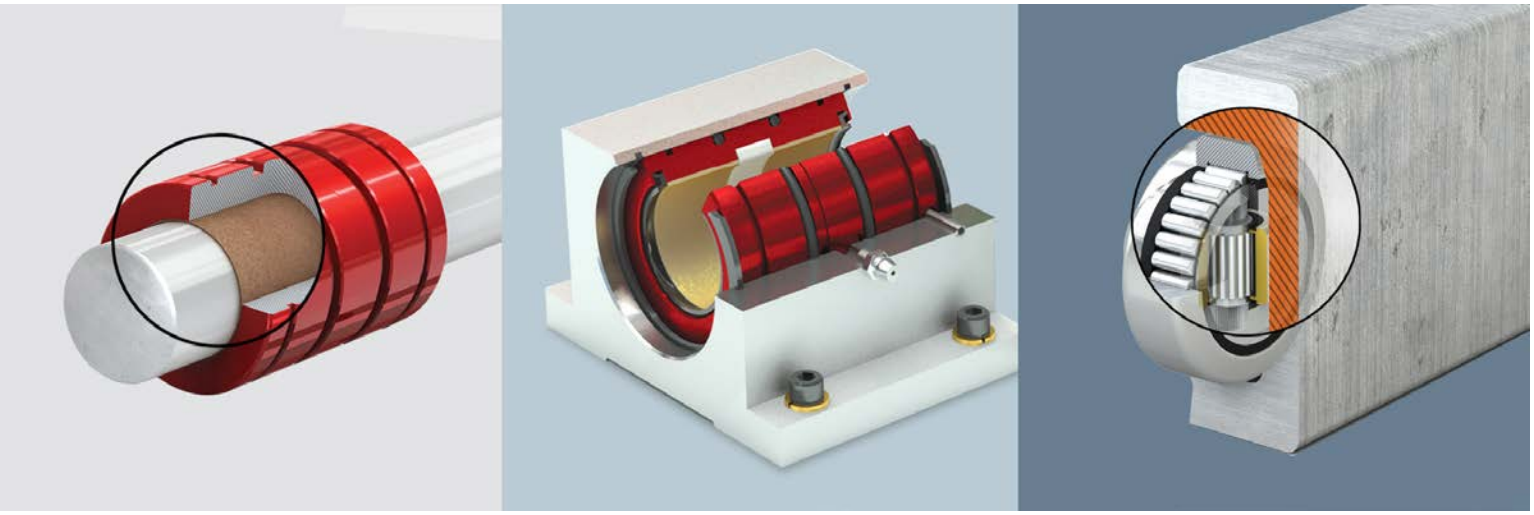
Once the speed increases enough, the lubricating layer completely separates the bearing surfaces. In this phase of operation, friction is caused by shear of the lubrication rather than by surface interferences. This is referred to as elastohydrodynamic lubrication or elastohyrdrodynamic friction.

LUBRICATION OPTIONS FOR LINEAR BEARINGS

Linear bearings that are not solely self-lubricating are typically lubricated with either oil or grease. Grease adheres to surfaces better and lasts longer than oil, making grease the more common choice for rolling element bearings, such as recirculating ball and roller bearings. And because of speed's influence on the development of the lubricating film, low-speed applications typically require grease since it provides better protection under the conditions of boundary lubrication and mixed lubrication, which are prevalent at low speeds.

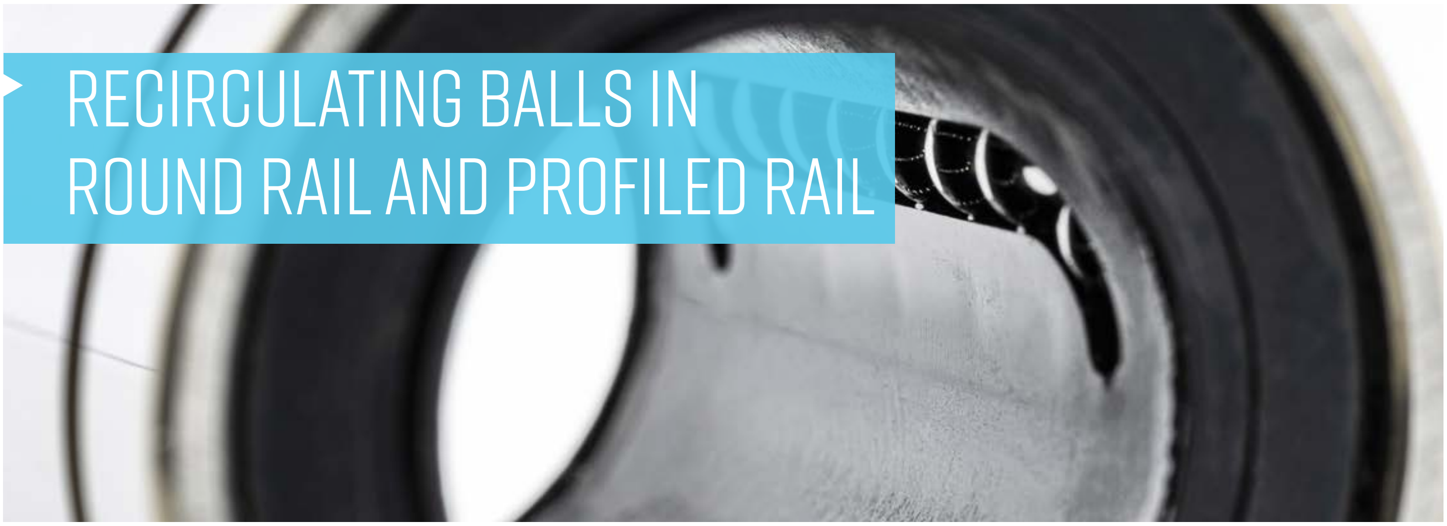
Oil on the other hand dissipates heat better than grease, making it more suitable for high-speed applications where heat generation is especially problematic. Oil can also be circulated through an external lubrication system that cools the oil and filters out any debris. It also flows more readily, making it better at lubricating complex structures and surfaces. But because of its low viscosity, it may not be a suitable choice for vertical surfaces, due to its tendency to pool at the lowest available space. An oil mist can address this problem, but adds cost and complexity to the bearing system.

Plain bearings are often made from (or impregnated with) self-lubricating materials such as PTFE (Teflon), Delrin, or nylon. One caveat is that in some applications, the release of lubrication from these materials can be inconsistent … and the sliding contact between the plain-bearing surfaces can produce friction and heat. So while it's possible for many plain bearings to be operated without lubrication, using external lubrication can be beneficial … even for bearings that use self-lubricating materials — especially when the application involves high loads or high speeds.



PBC Linear offers Simplicity plain bearings with self-lubricating Frelon® liners, internally lubricated bearings such as their Hevi-Rail brand, or optional zerk fittings for complete raceway lubrication.

RECIRCULATING BALLS IN ROUND RAIL AND PROFILED RAIL



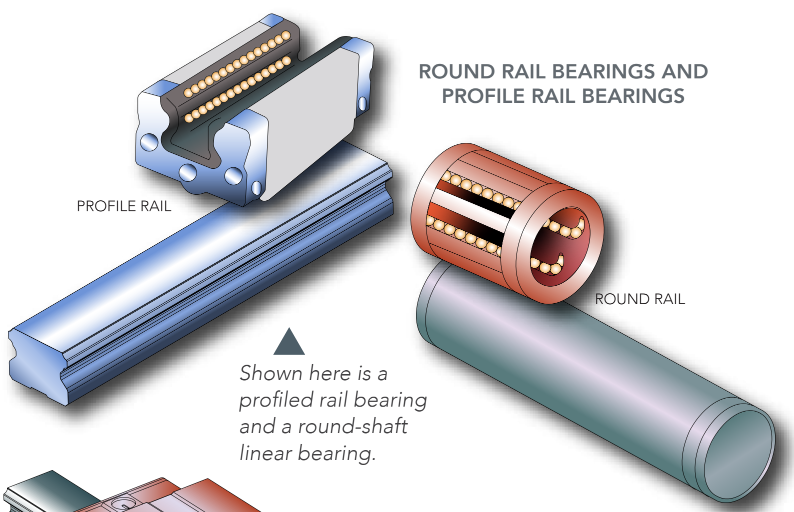
There are two main types of recirculating-ball linear bearings — one based on round shaft and one based on profiled rail. Because both types use recirculating ball circuits, the terminology to describe them is very similar and often overlaps.

Round-shaft recirculating-ball linear bearings are also called linear bushings, ball bushings, bushes, or just *ball bearings*. The latter is the least descriptive and most problematic (as it can cause confusion with rotary ball bearings) but it's quite common … so just know that in the context of linear guides, *ball bearing* almost always implies a round-shaft linear bearing. This design includes two basic components:

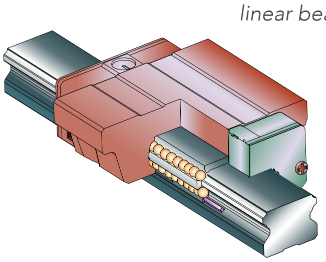
- A hardened shaft having a round or modified circular cross section
- A sleeve-shaped cylindrical nut (usually called a bushing) having captive circuits of recirculating balls.

The bushing (via its ball-bearing elements) rides along this hardened shaft (usually made of specially engineered steel) to provide low-friction linear guidance.

ROUND RAIL BEARINGS AND PROFILE RAIL BEARINGS



Shown here is a profiled rail bearing and a round-shaft linear bearing.



Profiled-rail linear guides are also called guideways or just profiled rails depending on the context, manufacturer, and industry.

Linear bushings were first patented in 1940s and became commercially available in the 1950s. Until the profiled-rail linear guides came onto the motion-control scene in the 1970s, these linear bushings were the primary form of linear-motion bearing support for applications not requiring the high load capacities and accuracies delivered by machined linear ways. But make no mistake: As linear-bushing designs evolved over the decades, their increased load capacities and new self-aligning capabilities have meant they've endured as a top choice for linear guidance in motion applications.

Round-shaft recirculating-ball linear bearings offer a distinct mounting advantage: Unlike profiled rail needing full support and mounting along its whole length, round-shaft linear bearings allow for support only on the ends — even on lengths up to 20 times the shaft diameter. Round shafts also don't require machined surfaces for mounting, because ball bushings inherently compensate for some misalignment — reducing cost and time for designing and preparing mounting surfaces.

Today linear-bushing shaft sizes range from the miniature (to just a couple millimeters in diameter) to 100 or more millimeters — allowing application in packaging, paper processing, assembly, and general-automation applications.

The other type of recirculating-ball linear bearing is profiled rail … also called guide rails, linear guides, LM guides, and profiled-rail guideways. These have a grooved squarish-shaped linear rails … and rail tracks on on which the balls ride are specially machined for performance and longevity. Profiled-rail recirculating guides have high load capacities and rigidity and excel in everything from simple pick-and-place applications to semiconductor equipment and machine tools.

With ground raceways and reference edges, profiled rails commonly achieve travel accuracies that are an order of magnitude better than round shaft guides. In these criteria, round-shaft linear bearings are more commonly valued for their ability to handle inaccuracies (self-aligning) than for travel accuracy.

HERTZ CONTACT STRESSES IN LINEAR BEARINGS

Linear bearings that use balls or rollers to carry a load (as opposed to plain linear bearings) are subjected to Hertz contact stresses. This is a type of material stress that significantly impacts bearing load capacity and fatigue life.

When two surfaces of different radii are in contact and a load is applied (even an extremely small load) a small contact area is formed — and the involved regions experience very high stresses. These stresses are known as Hertz (or Hertzian) contact stresses. In rolling-element linear bearings, Hertz contact stresses occur on the balls (or cylinders) and the raceways.

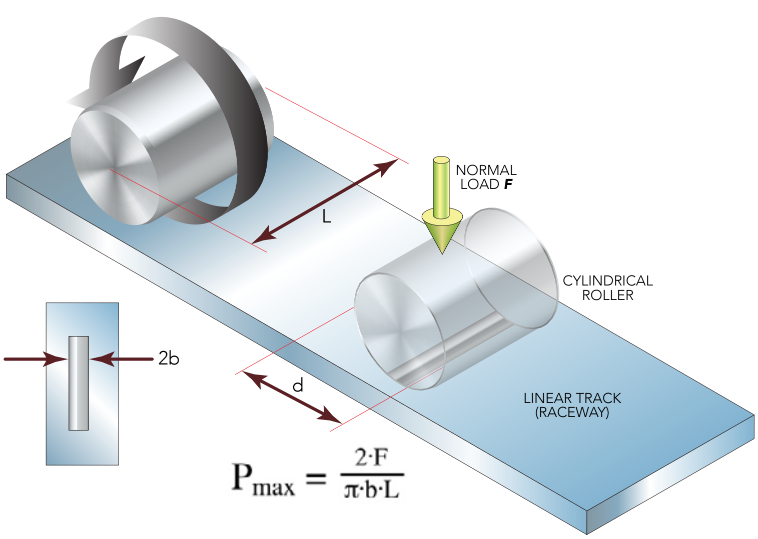
In theory, the contact between two spheres occurs at a point, and the contact between two cylinders occurs as a line. In either case — point or line contact — the resulting pressure between the two surfaces would be infinite and the surfaces would experience immediate yielding.

In real-world applications, when two surfaces are pressed together with a force, some elastic deformation occurs at each surface ... and a contact area forms. The stresses occuring on the two surfaces may still be very high (sufficient to initiate spalling or other forms of failure) but not actually infinite.

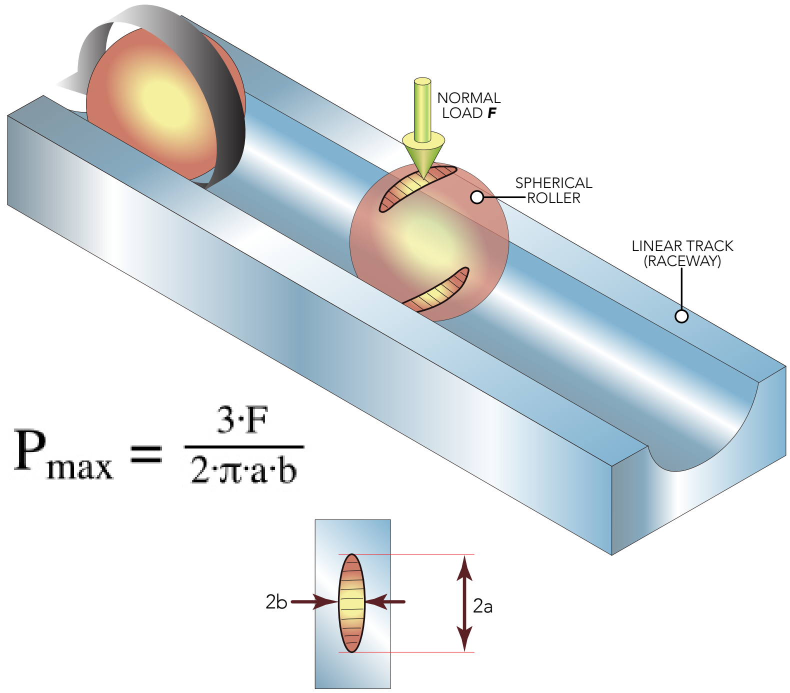
Analysis of Hertzian contact stresses relies on four assumptions:

- The surfaces are smooth and frictionless
- The bodies are isotropic and elastic
- The contact area is small relative to the contacting bodies' sizes
- Strains on the bodies are small and within the elastic limit

Hertzian stresses are present when any two surfaces with different radii are in contact — even if one surface is flat or if one surface is convex and the other is concave — the case for rolling-element bearings. In this case, the ball or roller is convex, and the raceway is concave. In the analysis of Hertz contact stresses, a convex surface (the ball or roller) has a positive radius, and the concave surface (the raceway) has a negative radius. Of couse, flat surfaces have an infinite radius.



$$P_{max} = \frac{2 \cdot F}{\pi \cdot b \cdot L}$$



$$P_{max} = \frac{3 \cdot F}{2 \cdot \pi \cdot a \cdot b}$$

Because the surfaces have different radii, the contact area between a spherical ball (or a cylindrical roller) and a bearing raceway has an elliptical shape. Under these conditions, the maximum pressure between the two surfaces is given by separate geometry-based equations.

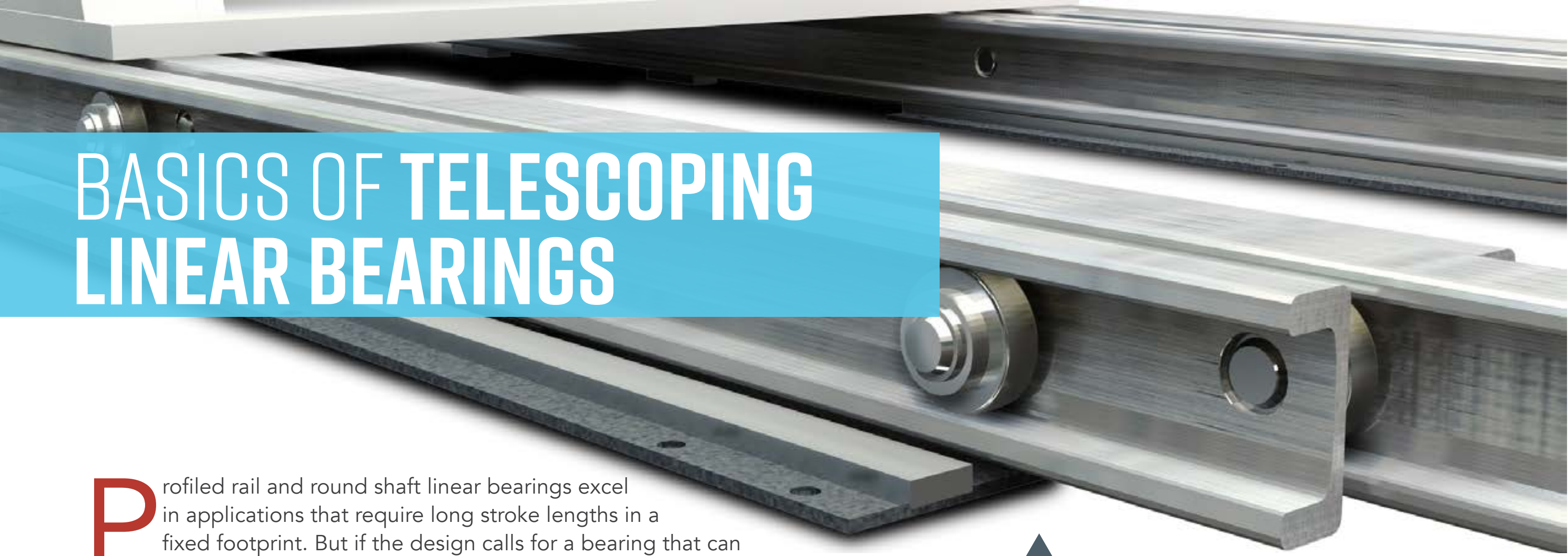
HERTZ CONTACT STRESSES AND LINEAR BEARINGS

Hertz contact stresses have a significant effect on bearing dynamic load capacity and L_{10} life. Shear stresses, which cause fatigue — a primary mode of failure of rolling elements — are proportional to the maximum Hertz pressure between the two bodies.

Hertz contact and the resulting deformation of surfaces is also what causes bearings to skid rather than roll. This is because the Hertz contact areas have different diameters than the rolling elements themselves, so the rolling elements slip. Hertz contact has implications for bearing preload as well. Preloading the rolling elements gives them a larger — and finite — Hertz contact area, which increases stiffness. But the increased contact results in high heat generation.

That's why a preload amount of just 8% is considered high preload for linear bearings ... and preload greater than 10 to 15% being extremely rare. Plus because Hertz contact is nonlinear, a small amount of preload can provide a significant increase in stiffness without resulting in unacceptable slip, friction, and heat.

BASICS OF **TELESCOPING LINEAR BEARINGS**



Hevi-Rail® linear bearings from PBC Linear can provide telescopic or cantilevered solutions in high-load applications such as racking systems, warehouse handling, and horizontal lifts.

Profiled rail and round shaft linear bearings excel in applications that require long stroke lengths in a fixed footprint. But if the design calls for a bearing that can retract to move away from the process or to allow access to a working area, a fixed rail or shaft won't do. In these applications, telescoping bearings can provide high load capacity and high rigidity in a retracting footprint.

For many people, the term telescoping bearings brings to mind drawer slides — as those found in our kitchens and offices. But industrial applications that require telescoping motion are common, and manufacturers produce telescoping slides with high rigidity in a wide range of material and coating options for harsh industrial use.

In fact, telescoping bearings offer partial, full, and over-extension stroke options. It's key for design engineers to identify the extension needed and not just go with the longest possible (or practical) stroke option. Here's why: Partial extension refers to an extension length less than the closed length – typically 50 to 65% or better in select cases. Full extension means the extended length is equal to or 100% of the closed length. Over-extension means the bearing's extended length is greater than its closed length — up to 150% in most cases.

Telescoping rails also come in dual-stroke or double-stroke configurations, which allow the load to be moved in both directions while maintaining the same closed length. One problem with this configuration is that the intermediate element does not always return to its closed position. To counter this, some manufacturers include a driving disk in the intermediate element to bring the assembly back to the correct position.

Telescoping linear rails are often mounted on their side, as they can withstand higher loads that way: Radial load capacity is greater than the axial capacity.

Static load capacity tends to be more critical than dynamic capacity because the nature of telescoping applications is to execute a move and remain in that position for an extended time.

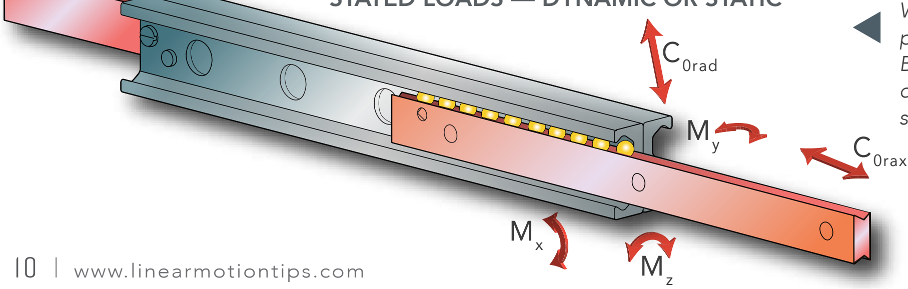
Minimizing deflection is paramount though: Aluminum rails excel in lightweight designs, and stamped steel is an economical choice, but with limited load capacity and ability to withstand vibrations and shock. Cold-rolled steel is another economical option … but then the balls riding the rails are harder than the rail and slider — ultimately resulting in pitting and denting of the raceways. So hardened cold-rolled sliders and raceways (while costlier) are recommended. They avoid the above issues and allow preload for greater rigidity and less deflection.

When employing telescoping linear rails, the load's center of gravity should be placed as close to the mounted rail as possible. It should also be centered about the moving element to allow for even load distribution among the balls. Load calculations are normally made assuming that the load is properly distributed.

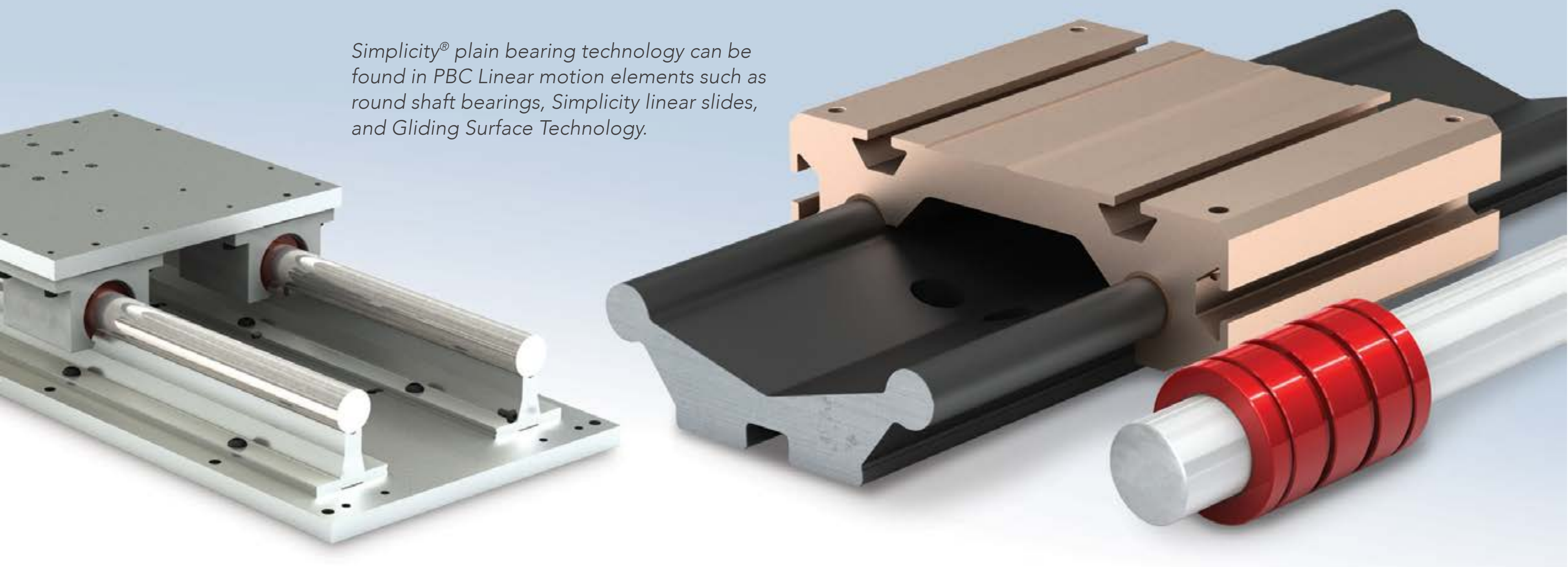
Like a profiled rail bearing, the primary function of a ball cage in a telescoping bearing is to maintain ideal ball separation — ensuring a more even distribution of the load. Without a ball cage, the balls could gather at one end or the other of the stroke, limiting the overall stroke available. Note that the ball cages in telescoping bearings are typically stamped steel … so unlike those in profiled rail bearings, they do not reduce noise.

Some final tips: When sizing a telescoping bearing for continuous duty, be sure to use the proper life calculation and the dynamic load capacity. Some manufacturers publish load and deflection specifications based on the slides being used in pairs (as they often are), while others declare the load capacity per single rail.

Also some manufacturers provide static load capacities and calculations rather than dynamic capacities and formulas. Make an effort to understand how the slides are rated and what specifications the manufacturer is providing.



With telescoping linear bearings, load placement is an important factor in deflection. Be sure to understand whether a stated load is dynamic or static and whether it's based on a single rail or a pair of rails.



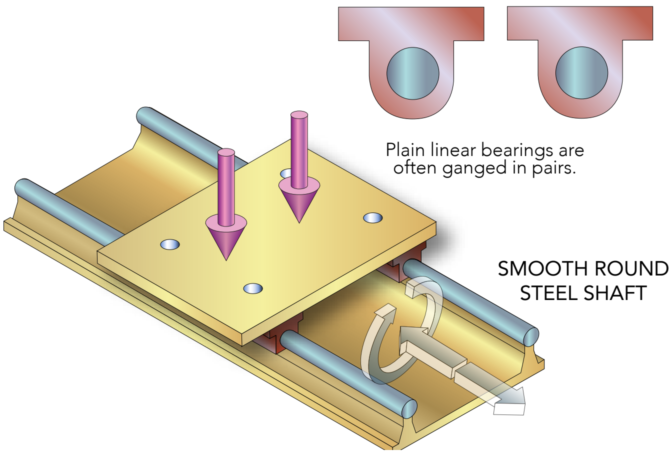
Simplicity® plain bearing technology can be found in PBC Linear motion elements such as round shaft bearings, Simplicity linear slides, and Gliding Surface Technology.

MORE ON PLAIN SLIDING-ELEMENT LINEAR BEARINGS

Today's plain sliding-element linear bearings are advanced motion components that showcase how material science has enabled new technologies for everyday and niche applications.

As mentioned in an earlier section of this Design Guide, plain linear bearings rely on highly engineered surfaces instead of rolling elements to minimize friction.

In short, a monolithic cylinder sleeve — the load-bearing element of the assembly — has an inner diameter surface of some specialty nylon, bronze, graphite-plugged bronze, Babbitt alloy, impregnated polymer, or other proprietary material. That monolithic cylinder bearing rides on a carefully engineered round rail (shaft) that's commonly made of steel or stainless steel to avoid the softness issues of aluminum and the abrasiveness of certain ceramics.



Of course, aluminum, ceramic, and even engineered polymer materials are all used in the construction of plain linear-bearing rails where they offer essential benefits.

In all round-shaft linear bearing systems (including plain linear bearings) the shaft acts as the inner raceway of the bearing — so has a significant impact on the performance and life of the system. Ground and polished shafts have fewer surface imperfections to cause friction and wear in plain linear bearings. On the other hand, overly smooth surfaces in plain linear bearings that rely on lubrication (whether supplied externally or from the bearing's self-lubricating properties) won't allow oil to adhere to the shaft … and will likely cause wear to occur more quickly.

Some industry sources categorize plain linear bearings by whether the load-bearing sleeve:

- Needs continuous application of some external oil or other lubricant
- Has an inner-diameter surface that is impregnated with slowly depleted lubricant to operate for reasonable number of strokes before necessitating replenishment or (more common) bearing replacement
- Sports a permanently lubricated inner diameter for exceptionally long life and reliability

As mentioned earlier in this Design Guide, one key benefit of plain linear bearings is how their construction practically prohibits catastrophic failure. Instead, wear is either imperceptible or quite gradual. Of course, the amount of wear that indicates failure (or foundering to perform as needed) in one application may be perfectly acceptable in a different application. This variability makes it important to understand what constitutes normal wear and the factors that might cause unacceptable depletion of service life.

(continued)

MORE ON SLIDING-ELEMENT LINEAR BEARINGS

Plain linear bearing wear is a measurement of the amount of material lost from the internal diameter of the bearing. That inner diameter is always made of a material that's softer than the shafts or rails on which they ride, so are the sacrificial element of the assembly … wearing more (or faster) than the shaft.

PLAIN LINEAR BEARINGS — COMPOSITE ELEMENTS

Plain linear bearings with composite cylindrical elements are capable of operating in settings to 120° C and handling loads inducing up to 350 MPa. Friction coefficients are around 0.25.

Some composite bearing elements feature an inner-surface lining that contributes to a low coefficient of friction and provides self-lubrication. These bearings are better able to dissipate heat than plastic bearings and have better dimensional integrity in high-temperature applications — which in turn helps prevent excessive wear due to reduced clearances.

Some monolithic composite plain linear bearings (made of various engineered polymer and additive formulations) withstand regular exposure to moisture with minimal absorption. The caveats here are that thick-wall composite linear bearing elements can prevent dissipation of heat; exhibit cold-flow distortion; necessitate extra clearances; and (because they don't envelop particulate) allow debris to scratch the linear raceways.

PLAIN LINEAR BEARINGS — PLASTIC ELEMENTS

Plain linear bearings having load-bearing cylindrical elements made of plastic have good wear resistance because they are generally soft enough to let particulates embed in the bearing ends — and avoid getting trapped between the bearing and shaft.

LINEAR-BEARING ELEMENTS MADE OF PLASTIC ARE SOFT ENOUGH TO CAPTURE FINE DEBRIS TO PREVENT BEARING AND SHAFT ABRASION.

They're also self-lubricating and can maintain a very low coefficient of friction between the bearing (cylindrical element) and the shaft during startup and continuous operation. Both of these attributes contribute to good wear resistance. No wonder monolithic plain linear bearings made of nylon and myriad other self-lubricating (and corrosion-free) materials excel in oscillating applications. One caveat is that heat can cause expansion and reduction in clearance between the bearing (cylindrical element) and the shaft — which in turn increases friction and wear. With some (though not all) plastic linear-bearing elements, moisture and chemicals can warp and degrade the bearing (cylindrical element) in other ways as well.

Designers specifying these plain linear bearings should carefully evaluate the involves axis temperature and load to specify sufficient assembly clearance as needed … though that can decrease the bearing's positioning precision.

PLAIN LINEAR BEARINGS — LINED METAL ELEMENTS

Plain linear bearings based on metal cylinders permanently bonded with thin Teflon ID working surfaces excel in dynamic heavy-load applications such as those in large-scale packaging equipment and overhead gantries for material handling — capable of self-lubrication and supporting loads to 20 MPa even to 560° C. They're typically unsuitable for precision machinery (as in the semiconductor industry) and shouldn't be chosen for consumer-grade or manually actuated designs.

Heat readily dissipates from these bearings, allowing running clearances to 0.012 mm with zero risk of catastrophic failure.

PLAIN LINEAR BEARINGS — BRONZE ELEMENTS

Bronze linear-bearing elements (just as their rotary-bearing counterparts) feature solid or powdered-metal bronze to resist corrosion while bearing loads inducing up to 300 MPa for standard offerings. These plain linear bearings are commonly found on linear axes involving pivoting or oscillating strokes. The metal-to-metal contact between bearing carriage element and raceway makes for higher coefficients of friction than other options as well as the need for proper lubrication.

Load-bearing cylindrical elements made of bronze for plain linear bearings can be self-lubricating under some conditions, but often require external lubrication. Where such plain linear bearings rely on the warmth of normal operating temperatures for the release of lubrication from the bronze inner working surface, there can be suboptimal performance (and accelerated wear) should the linear run at a slower than expected speed. If sufficient lubrication isn't maintained, metal-to-metal contact will occur … and along with it high friction, high heat generation, and excessive wear. Complicating matters is how external lubrication can attract and trap particles that accelerate wear between the bearing and the shaft or raceway it rides.

A design related to bronze linear-bearing sleeve elements is split metal-backed linear bearing elements having a thin bronze layer to carry loads inducing up to 350 MPa. These self-lubricating linear

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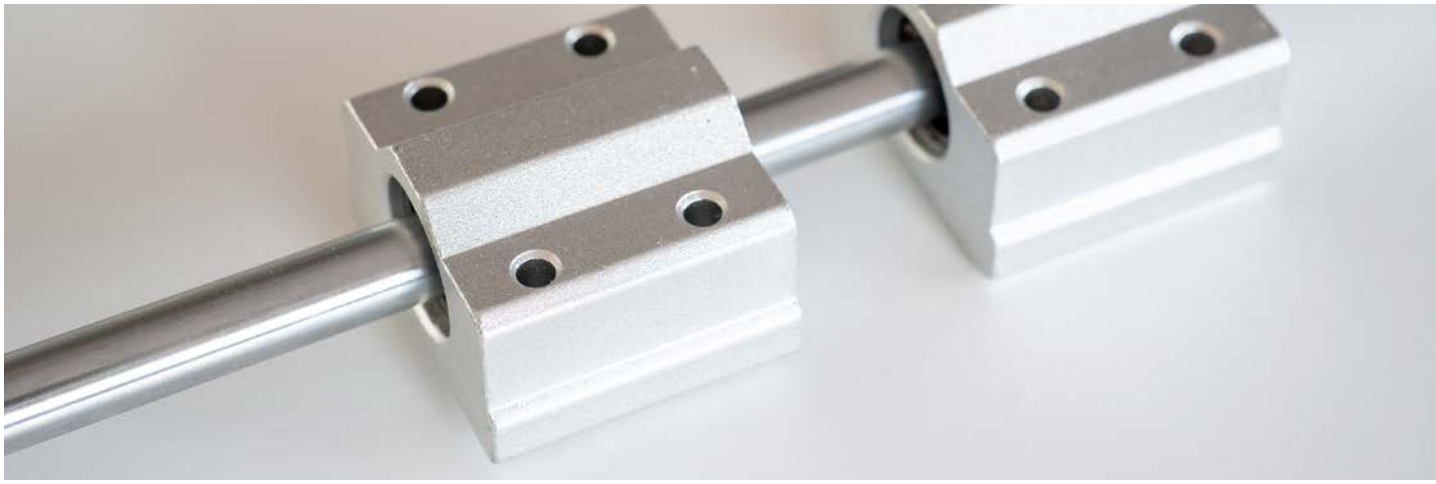
MORE ON SLIDING-ELEMENT LINEAR BEARINGS



bearing elements often press fit into carriage bodies destined for linear axes in relatively clean settings — though may need external lubrication on continuous-motion or oscillating axes. A relatively high friction coefficient (even to 0.25 for example) can cause lining wear that eventually yields to metal-to-metal contact. Nonrepeatable running clearances and dimensional instability are other issues. That's why the most common uses for these metal-backed linear-bearing elements are on consumer-grade products and forgiving motor-driven designs such as automatic doors not needing a lot of precision.

OTHER SLIDING-CONTACT RAIL GEOMETRIES

Though this Design Guide section primarily focuses on round-rail plain linear bearings, it is worth remembering that sliding carriage-and-rail setups come in two other variations — boxway and dovetail linear slides. Manufacturers of these designs typically incorporate ground grooves into an otherwise rectangular track geometry — to serve as a working surface.

Rails with a boxway or square shape are simplest. Square-rail plain linear bearings are compact and excel at carrying large loads in all directions without a lot of deflection. Manufacturers often preload these plain linear bearings ... it's worth noting that linear systems based on square rails do not self-align.

Plain linear bearings with a dovetail shape (or twin rail) have male track geometry that securely engages female saddle (moving bearing element) geometry. That boosts stability and load capacity, even in unusual orientations or applications with unsteady loads.

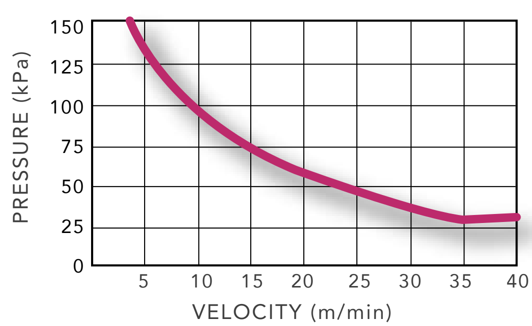
Round rails covered in this Design Guide section deflect the least under load. In addition, systems based on round rails are inherently self-aligning so are easier to install than other options. But no matter the type, all these rails come in myriad sizes and lengths.

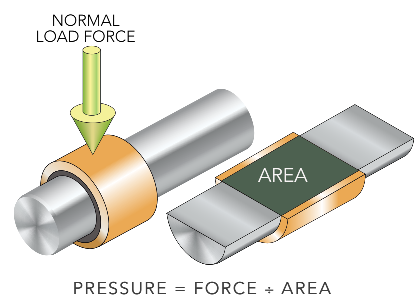
PLAIN LINEAR BEARING SPECIFICATION

When applying plain linear bearings, design work usually begins with accurately defining the axis load (along with its orientation and distribution) and stroke requirements. Load capacities of plain linear bearings are generally in reference to a pressure-velocity (*PV*) value fully detailed later in this Design Guide — more specifically, as a radial force divided by the linear bearing's

PRESSURE × VELOCITY (***PV***) CURVE FOR PLAIN BEARINGS

PV values are one tool for sizing plain linear bearings. Shown here is one representative chart for an engineered-plastic linear-bearing assembly. Read more about the derivation of PV values later in this Design Guide.





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MORE ON SLIDING-ELEMENT LINEAR BEARINGS

area of contact with the raceway upon which it rides. With plain linear bearings, axes bearing light loads allow faster running speeds than those bearing heavier loads. That's because friction *f* = Load × friction coefficient μ.

PV RATINGS PARTIALLY QUANTIFY PLAIN LINEAR-BEARING PERFORMANCE BY DEFINING MAXIMUM PRESSURE AND VELOCITY COMBINATIONS … LIMITATIONS IMPOSED BY HEAT GENERATION IN THE BEARING … AND THE BEARING ABILITY TO DISSIPATE HEAT.

Plain bearings may also necessitate a slighter more powerful motor on the axis to compensate for a friction coefficient that could reach 0.1 or 0.2 with some designs, which is higher than that of rolling-element linear bearings. That said, some plain linear bearings (especially those with polymer liners for working surfaces) actually exhibit lower (better) friction coefficients after they've operated for some time … thanks to a microscopic filling (smoothing) of the raceway surface with plain-bearing material.

Another consideration is ambient temperature and temperature rise due to demanding duty cycles. Estimating the effect of the latter on a plain linear bearing is usually through some calculation of the maximum surface-speed average over some number of minutes.

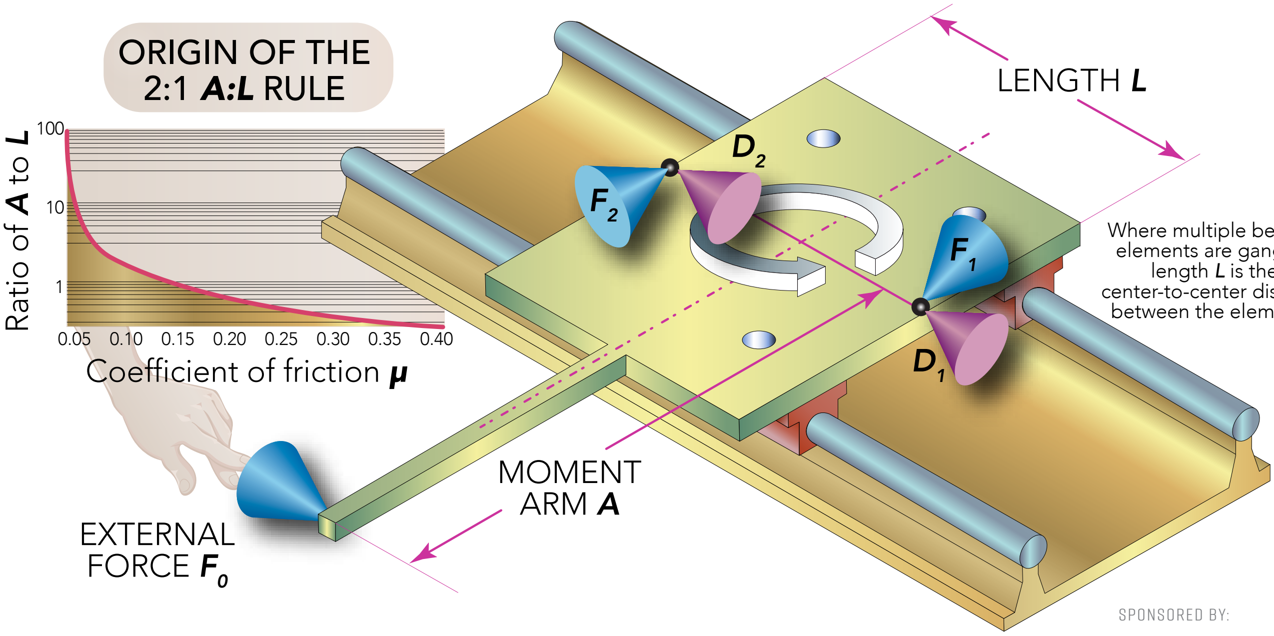
Ultimately, design engineers should verify the performance of any plain linear bearing with prototyping and testing on axes replicating the final design — and enlisting testing laboratories for verification as needed.

SATISFYING (AND BREAKING) THE 2:1 RULE

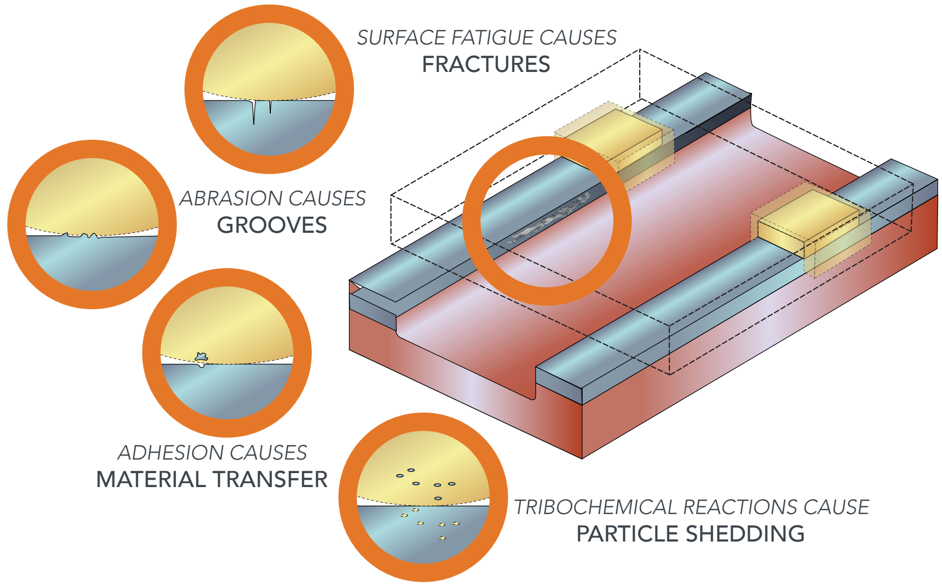
One rule of thumb in linear-motion engineering is that any moment arm ***A*** associated with a load acting on a linear bearing's body or carriage assembly shouldn't be longer than twice (2:1) that bearing's length ***L*** … or else jerky stick-slip motion or even binding will occur. In fact, the actual ratio for a given linear bearing in an application may be somewhat more or less than 2:1. Reaction forces as well as statics and dynamics dictate the ultimate value.

Linear bearings have only one degree of freedom, so resist forces to spur motion in other directions. To illustrate: Assume for the sake of simplicity that force F_0 acts on a single plane parallel to a linear bearing's allowable direction of motion. This F_0 on the bearing at distance ***A*** from the bearing center creates a moment force — and two resultant forces F_1 and F_2 that resist the moment. Multiplying by the bearing's friction coefficient μ (with static μ and dynamic μ assumed one) this in turn generates D_1 and D_2 drag forces. If the magnitude of the latter exceeds the force driving the axis, motion ceases. Said another way, the externally applied force F_0 must exceed the total D_1 plus D_2 drag force to move … with acceleration (motion) > 0 → F0 > D1+ D2. Other calculations and plotting values can yield the values of this acceleration for a given arrangement.

In fact, the 2:1 rule (or an equivalent limit on the magnitude of moment-arm loading) applies to all linear bearings. The reason the rule isn't one set universal ratio is that the friction coefficients of linear bearings vary so widely. So the ratio for a rolling-element linear bearing that rides on an array of ball rollers might allow a ratio as high as 400:1 or even more. Any excessively ***A*** to ***L*** ratios can be corrected by reducing moment arm ***A*** or bearing friction; counterbalancing or increasing bearing length; or reducing F_0 applied load.



THE CAUSES OF PLAIN BEARING WEAR



Fatigue failure of bearing raceways is one factor that limits life.

For rolling-element bearings, the L_{10} life calculation is an easy way to determine the bearing's expected travel life. But for plain bearings, determining life expectancy is not so straightforward.

Plain bearing life is based on the amount of wear the bearing experiences, which depends on factors that are unique to each application, such as the bearing material and operating conditions. In addition, the amount of wear that indicates failure (or failure to perform as needed) in one application may be perfectly acceptable in a different application. This variability makes it important to understand what factors cause plain bearings to wear, and therefore, reduce service life.

The most significant factor in plain bearing wear is material. Plain bearings are made of softer materials than the shafts or rails they ride on and are ***sacrificial*** — meaning the bearing will experience more (or faster) wear than the shaft does. Common bearing materials include plastics, composites, and bronze.

Which materials are better at resisting wear? Plastic bearings have good wear resistance because they are generally soft enough that particulates will embed themselves in the bearing, rather than becoming trapped between the bearing and shaft. They're also self-lubricating and can maintain a very low coefficient of friction between the bearing and the shaft during both start-up and continuous operation. Both of these attributes contribute to good wear-resistance.

However, as heat is generated in the bearing, the bearing can expand, which reduces the clearance between it and the shaft ... causing additional friction and wear. Another vulnerability for plastic bearing materials is moisture, which can cause certain plastic linear bearings to expand. Exposure to chemicals can also change the material properties of inappropriately specified bearings (typically decreasing the material hardness) which accelerates wear.

CAUSES OF PLAIN BEARING WEAR INCLUDE INSUFFICIENT LUBRICATION, EXCESSIVE HEAT, AND OVERLOADING.

Composite bearings are often constructed with an internal lining that contributes to a low coefficient of friction and provides self-lubrication. Like plastic bearings, composite designs are susceptible to decreased hardness when exposed to some chemicals. But they are better able to dissipate heat than plastic bearings and have better dimensional integrity in high-temperature applications, which helps to prevent excessive wear due to reduced clearances.

Bronze bearings can be self-lubricating under some conditions, but often require external lubrication. If sufficient lubrication isn't maintained, metal-to-metal contact will occur, which results in high friction, high heat generation, and excessive wear. And this external lubrication can attract and trap particles, causing increased wear between the bearing and the shaft.

What role do shafts play in plain bearing wear? Shafts are typically made from aluminum, steel, or ceramic. Ground and polished shafts have fewer surface imperfections to cause friction and wear in bearings. But if the surface is too smooth, lubrication (whether supplied externally or from the bearing's self-lubricating properties) won't adhere to the shaft, and wear will occur more quickly.

What does PV rating have to do with plain bearing wear? A bearing's PV rating, which defines the maximum pressure and velocity combination the bearing can withstand, is based on heat generation inside the bearing and the bearing's ability to dissipate this heat. Exceeding the PV rating will result in too much heat being generated (or the bearing won't be able to sufficiently dissipate the heat), and excessive wear will occur.

Solutions in washdown applications include stainless steel and ceramic coated shafting, Frelon®-lined Simplicity® bearings, and Gliding Surface Technology from PBC Linear.

PREVENTING **LINEAR-BEARING CORROSION**

Corrosive environments can include anything from detergents and chemicals for washdown (the high-pressure cleaning of equipment) to acid baths and their related vapors, to chemicals in food processing. Because profiled linear rails, round shafts, and ball screws are made primarily from steel components, they're highly susceptible to corrosive agents, which can quickly cause rust, pitting, and degradation of the critical bearing surfaces.

There are measures that designers and engineers can take to protect these components from corrosion.

Probably the simplest solution is to consider bearings made from polymers. But polymer bearings can't provide the same load capacity, rigidity, or running accuracy that their steel counterparts can. When the application calls for high load carrying capability, high stiffness, or high travel accuracy, steel components are the best technical solution. In these cases, there are three factors that designers and engineers can consider in order to protect components from corrosion and ensure optimal bearing life.

MOUNTING AND HOUSING

Possibly the lowest-cost option that designers can employ to protect against bearing corrosion is to mount the components in a way that minimizes the corrosive agents from getting on the critical surfaces. For most linear bearing components or systems, this means mounting them upside down or on their side. Depending on the direction of the spray or splash, mounting the components above the work area can also minimize the amount of contact they receive with corrosive liquids. That said, where acids are the main concern, vapors may be as harmful as actual liquid contamination. In this case, because vapors typically rise, mounting the components below the work area may be best.

For linear systems that are enclosed in a housing, it's generally better not to employ a cover if the system is mounted upside down, so that any liquid that gets into the housing can drain out. When an enclosed system is mounted upright, the addition of drain holes in the housing can help prevent liquids from standing inside the actuator.

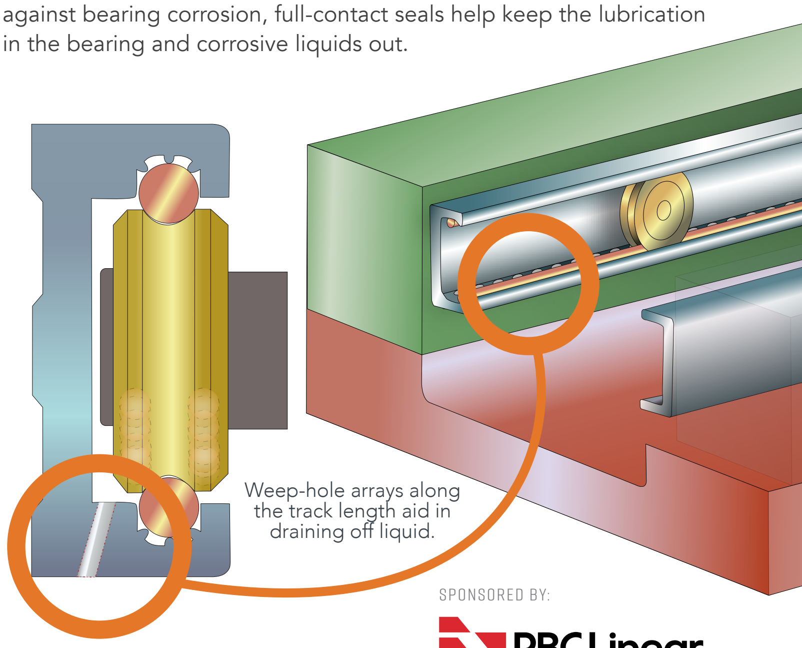
MATERIALS FOR LINEAR BEARINGS AND DRIVES

The first thing that probably comes to mind in terms of materials for corrosive environments is stainless steel. However, stainless steels can't be hardened so have lower load carrying capabilities than bearing steel ... and may be unsuitable for some applications.

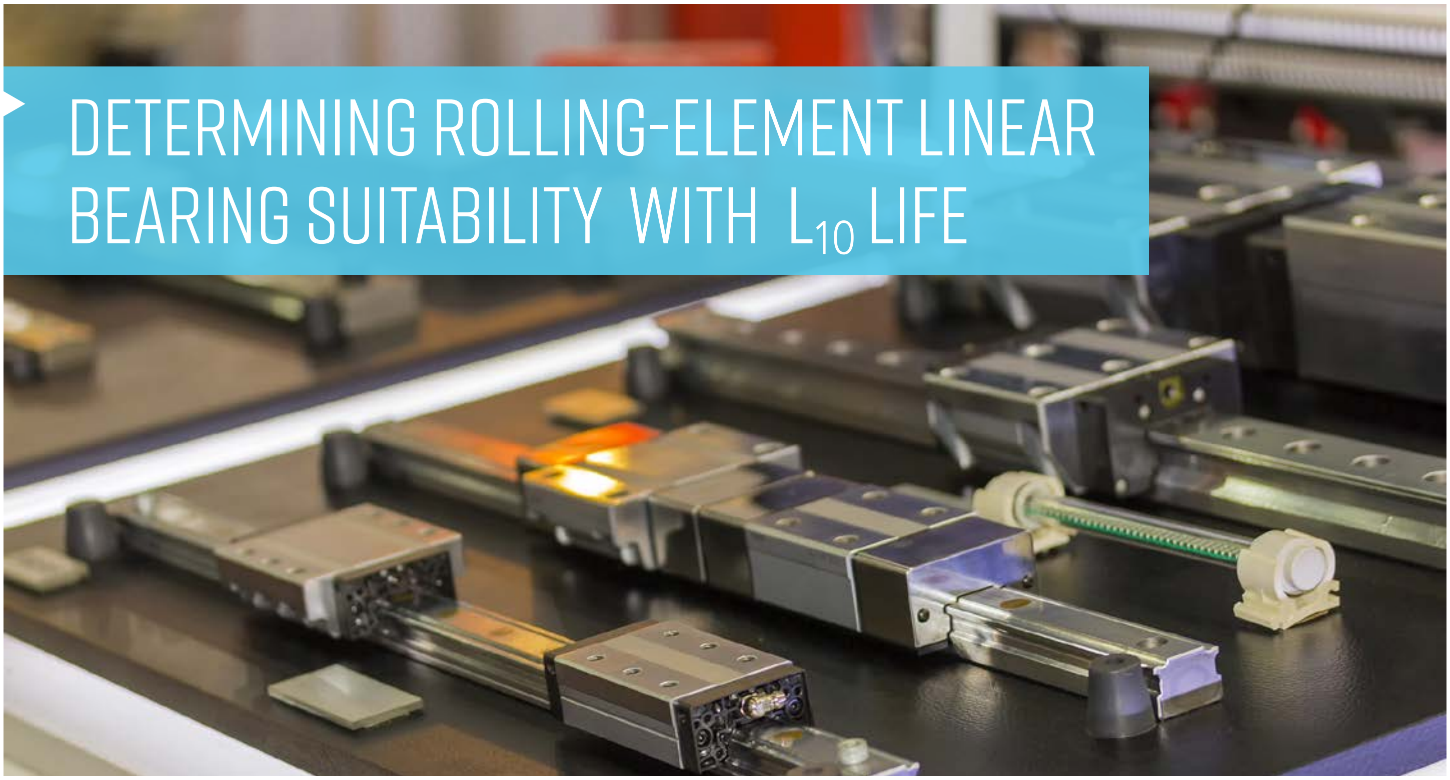
Even if stainless steel is acceptable from a performance standpoint, the range of linear-bearing products available in stainless or corrosion-resistant steel is limited. If stainless steel isn't an option, there are myriad platings and coatings for bearing steel (and for aluminum) that protect against virtually any corrosive agent.

LUBRICATION AND SEALING

The most common cause of bearing failure is a lack of lubrication, and while washdown processes (which are common in corrosive applications, especially in the food and beverage industry) rid the components of contamination, they can also wash away lubrication. When linear bearing components or systems are used in washdown applications, grease is the preferred lubrication, rather than oil, since grease is less likely to be washed away. For additional protection against bearing corrosion, full-contact seals help keep the lubrication in the bearing and corrosive liquids out.



DETERMINING ROLLING-ELEMENT LINEAR BEARING SUITABILITY WITH L_{10} LIFE



One of the fundamental steps in selecting a recirculating linear bearing, whether profiled rail or round shaft type, is to calculate the bearing life. But how is this calculation derived ... and what does it mean in the real world?

Bearing life for recirculating linear bearings, often referred to as the L_{10} life, is a value specifying the travel that a bearing can achieve before it reaches its fatigue life, which is the occurrence of the first signs of flaking on the raceways or the rolling elements.

The term L_{10} is used (rather than say, L5 or L25) because this is the distance that 90% of seemingly identical bearings — operating under identical conditions — can travel before fatigue occurs. In other words, the L_{10} life gives a 90% reliability that the bearing will achieve the specified travel. The calculation of L_{10} life for recirculating bearings with balls as the load-carrying elements, is given by:

$$L = \left(\frac{C}{F}\right)^3 x\, 10^5$$

… and for recirculating bearings with rollers as the load-carrying elements:

$$L = \left(\frac{C}{F}\right)^{\frac{10}{3}} x10^5$$

Where L = bearing life (m)

C = bearing dynamic load capacity (N)

F = applied dynamic load (N)

Although the bearing life equation is relatively straightforward, there are some nuances to determining bearing life of which design engineers should be aware.

First, the dynamic load capacity C of a recirculating linear bearing is determined by the manufacturer in accordance with ISO 14728-1. The ISO standard defines dynamic load capacity as the load — constant in magnitude and direction — at which the linear bearing (ball or roller) can provide 100 km (100,000 m) of travel before fatigue occurs.

ALTHOUGH STANDARD L_{10} LIFE IS BASED ON A RELIABILITY OF 90% IT'S POSSIBLE TO SPECIFY A HIGHER RELIABILITY LEVEL. THE BEARING-LIFE EQUATION IS SIMPLY MULTIPLIED BY A FACTOR CORRESPONDING TO THE DESIRED RELIABILITY.

Some manufacturers base the dynamic load capacity of their linear recirculating bearings on a travel of 50 km (50,000 m). The ISO standard acknowledges this difference and provides a dynamic load rating conversion factor that should be used when comparing bearings rated for 50 km with bearings rated for 100 km of travel.

In these cases, one of the following conversion methods should be applied:

- multiply dynamic load capacity of the 100 km bearing by 1.26
- divide dynamic load capacity of the 50 km bearing by 1.26

(continued)

L_{10} LIFE AND ROLLING-ELEMENT LINEAR BEARINGS

To see how the 1.26 correction factor is derived, check out this article.

Second, the ISO standard specifies that the bearing life applies to linear motion rolling bearings ***with contemporary, commonly used material and manufacturing quality and under conventional operating conditions*** — emphasis added. In the real world, many applications operate in conditions with high temperatures, shock loads, or other factors that will reduce bearing life — for which the bearing-life equation does not account.

To adjust for these conditions, manufacturers provide factors that either de-rate the dynamic load capacity or increase the applied load, reducing the bearing life accordingly. For example, if a bearing operates under heavy impacts or vibrations, the applied load would be multiplied by a factor between 2.0 and 3.0.

MANY APPLICATIONS OPERATE UNDER HIGH TEMPERATURES, SHOCK LOADS, AND OTHER EXTREMES THAT REDUCE BEARING LIFE … FOR WHICH THE BEARING-LIFE EQUATION DOES NOT ACCOUNT.

Depending on the manufacturer and bearing type, correction factors may be provided for designs involving:

- Shock loads and vibrations
- Special mounting situations (such as two bearings used with minimal spacing between them) shaft hardness (when it falls below HRC58)
- High temperatures or short strokes.

Although the standard L10 life is based on a reliability of 90% it is possible to specify bearing life at a higher reliability level. In order to do this, the bearing life equation is multiplied by a factor corresponding to the desired reliability. For example, the factor for bearing life with 95% reliability, which is denoted L5, is 0.62.

So the bearing life equation for 95% reliability is given as:

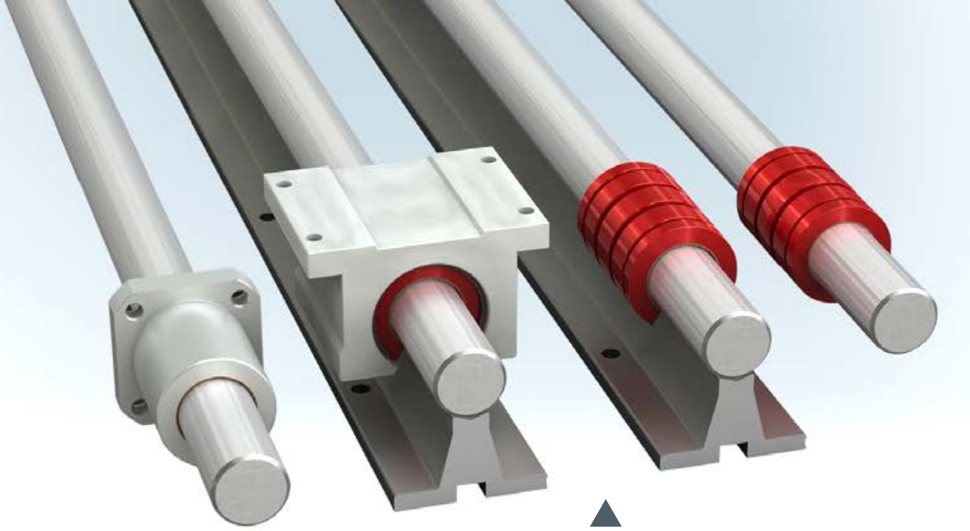
$$L5 = 0.62\left(\frac{C}{F}\right)^3 x10^5$$

The load on a linear bearing often changes during the course of its life, or even during the course of one move cycle. To accurately estimate bearing life under changing load conditions, the mean equivalent dynamic load F_m is used.

In the ideal world, a bearing would be selected by testing it under actual load conditions, but in the real world, this is almost never practical.

Although bearing life calculations are statistical predictions, and there are many factors that affect a bearing's actual service life, the dynamic load capacity ratings and life calculations provided by ISO 14728-1 are well-proven and accepted across the linear bearing industry.

DETERMINING PLAIN LINEAR BEARING SUITABILITY WITH THE PV RATING



Plain bearings from PBC Linear, such as pillow blocks and flange mounts, require calculation of the PV value to establish accurate loads.

When discussing bearing life, what comes to mind for most engineers is the standard L_{10} bearing life equation. But this equation (and a similar equation that exists for bearings that use rollers rather than balls) was developed for bearings with rolling elements.

For plain bearings having no rolling elements, determining the suitability of the bearing for a particular application requires an examination of technical and environmental factors — coupled with empirical testing and the experience of the manufacturer.

Of the factors to be considered, the most important are the pressure imposed on the bearing ***P*** and the bearing's velocity ***V***. These are combined to develop a PV rating that represents the highest combination of load and speed under which the bearing can operate properly. Pressure is determined by dividing the maximum load (force) on the bearing by the supporting area of the bearing:

$$P = \frac{F}{A}$$

Where P = pressure in N/mm^2 or lb/in.^{2}
F = Load on bearing in N or lb
A = Area in mm^2 or in.^{2}

For a round bearing riding on a shaft, the supporting area is simply the length of the bearing times its inner diameter:

$$A = l \times d$$

Where *l* = Bearing length in mm or in.
d = Bearing inner diameter in mm or in.

One of the critical performance characteristics of a plain bearing is its ability to dissipate heat. Heat affects a bearing in two ways. First, heat can degrade lubrication or the lubricating properties of the bearing. But more importantly, heat can change the clearances between the bearing and its housing or between the bearing and shaft. The result is increased friction, greater wear, and reduced bearing life.

A bearing's PV rating is related to heating caused by friction in the bearing, and takes into account multiple factors that contribute to the system's ability to transfer heat away from the bearing, including:

- The thermal conductivity of the bearing and the shaft (or rail)
- The difference between the maximum bearing temperature and the ambient temperature
- The coefficient of friction between the bearing and the shaft
- The thickness of the bearing

The plain linear bearing's maximum PV value is a key criteria — and often the starting point for choosing a linear bearing ... however, it's important to note that the PV rating isn't the only indicator of a bearing's suitability for an application.

The individual pressure and velocity values should also be kept within the maximum allowable limits, because some plain linear bearings perform well on high-load axes running at low speed ... while other plain linear bearings perform better on high-speed axes carrying relatively light payloads.

Environmental factors should also be considered when choosing a plain linear bearing and mating rail materials for an application.