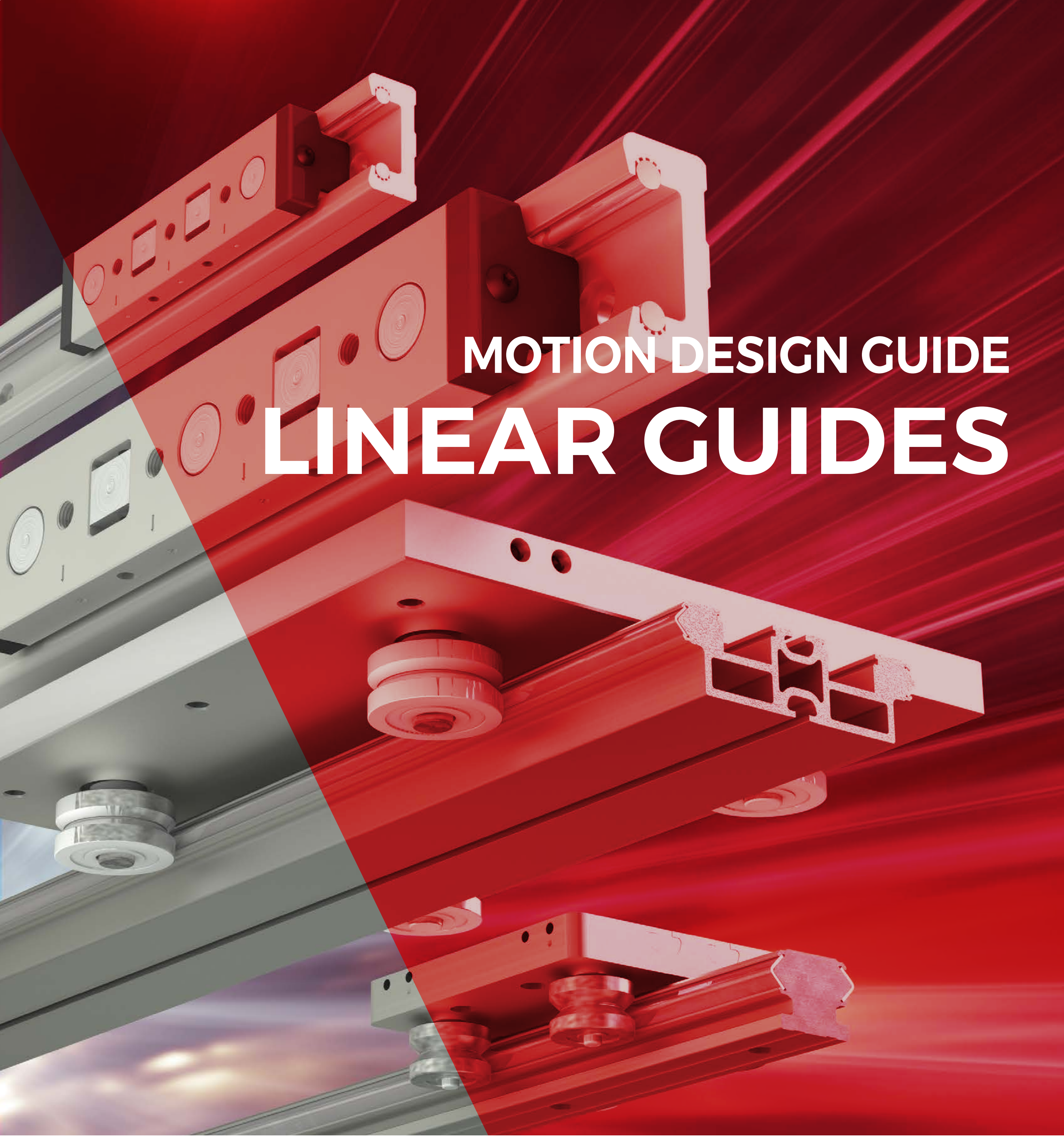

MOTION DESIGN GUIDE
LINEAR GUIDES

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LINEAR GUIDES DESIGN GUIDE

Linear-motion systems are essential in everything from manually operated industrial drawers and doors to advanced Cartesian robots. Mechanisms that include the former operate without power, using inertia or manual power to move loads. Components to complete the latter include ready-to-install drive and guidance designs in the form of self-contained motor-driven actuators or linear-motion machinery subsections. Some designs simply rely on the rotary-to-linear mechanism or actuator structure for total load support. However, most linear designs in industrial machinery (and elsewhere) have 1) pneumatics, linear motors, or motor-driven rotary-to-linear mechanisms to advance attached loads as well as 2) linear bearings or rails that guide and support the loads on the axis.

In this Design Guide, the editors of Design World detail the special case of track-roller linear guides and how they compare to other linear rails, slides, and ways to facilitate single and multi-axis linear motion — and the disparate ways these linear components integrate into machinery for top performance.

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DEFINITIONS AND COMMON LINEAR-MOTION VARIATIONS

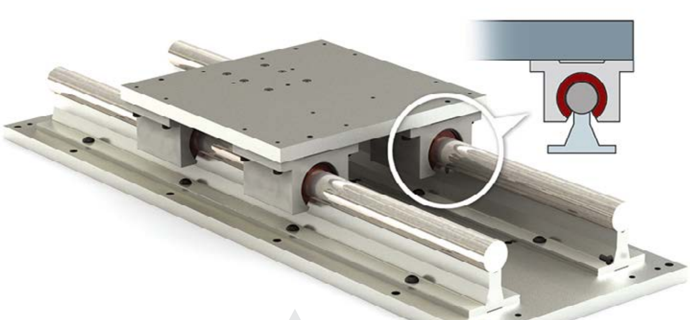
Typical linear-motion arrangements consist of rails or shafts, carriages (also called runner blocks, blocks, cars, or sliders), and some type of load-bearing element. Engineers differentiate these systems by the surface interaction (sliding or rolling) of their load-bearing zones and the type of contact points — as well as how the design's rolling-element recirculation works if applicable. In fact, linear guides are more advanced than ever, with advances in materials and lubrication (to help designs last longer in harsh applications), innovative rail geometries (to help designs withstand more misalignment and load than ever), and modular guide mounts (to boost load capacity and minimize deflection).

BACKGROUND LINEAR-GUIDE TERMINOLOGY

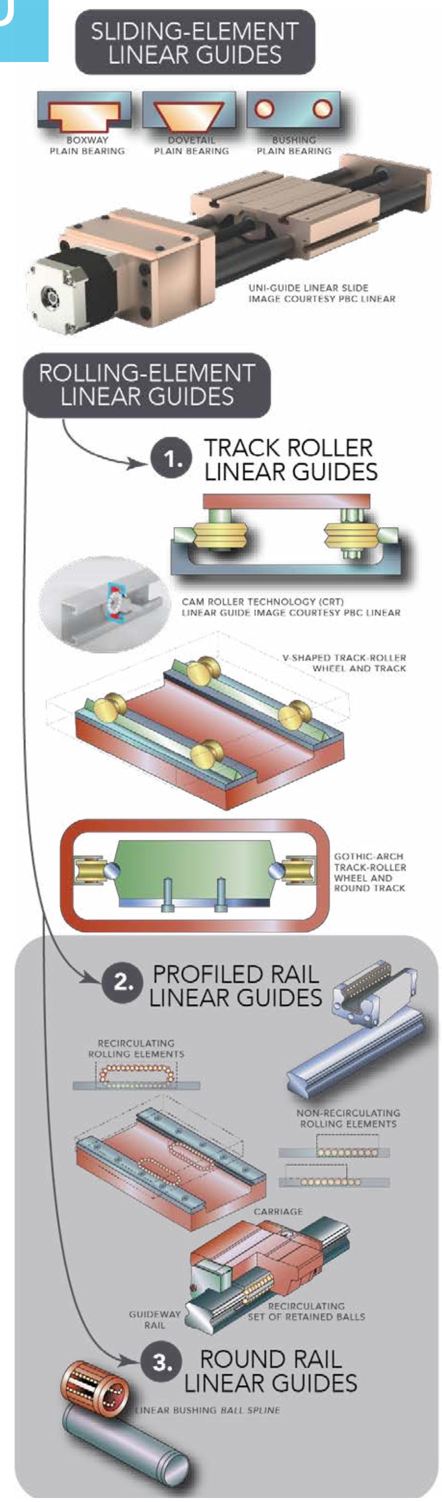
The term *linear guide* can refer to any one of several different component types depending on the context. Unlike plain-bearing linear guide taxonomy (which is fairly consistent) the terminology for ball and roller linear guides is quite varied. That said, the term *linear guide* **most often** indicates a standalone rod-based assembly, rolling-element slide, or other mechanism for guiding loads. In contrast, many (though certainly not all) manufacturers use the terms *linear slide* (whether based on rolling or sliding action) and *linear rail* to indicate linear-motion guide elements in builds complete with some mechanical drive. The term *linear stage* generally implies a design with linear-guide elements, a reinforced frame, and actuation components of some type — with or without motor.

One classic linear guide with sliding contact is a dovetail slide, and one classic linear guide with rolling contact is a rail-riding carriage rail with twin banks of recirculating balls. Sliding-contact linear guides are the more straightforward linear-motion component type. These consist of a carriage or slide (in many cases made of anodized aluminum alloy) that rides over a surface known as a rail, way, or guide. Sliding contact occurs when the moving part directly contacts the rail section.

Older versions of these sliding-contact rails generated considerable friction during



This Simplicity linear-guide assembly from PBC Linear is based on sliding contact between self-lubricating Frelon bearings (in red) and round rails.



Shown here is the tree of linear-guide families and subtypes. Note how the load-bearing elements in track-roller linear guides are inside the components' wheels — in contrast with the load-bearing elements in profiled-rail linear guides which have direct contact with the linear raceway. This aspect of track-roller design (among other things) makes the linear guide type particularly robust, even in extreme environments.

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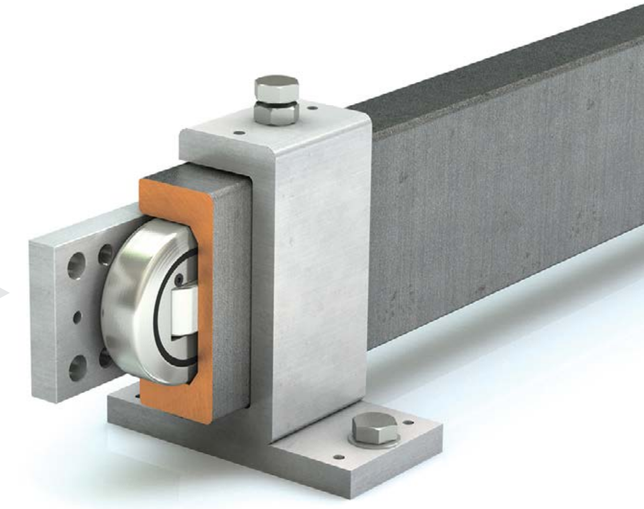
DEFINITIONS AND COMMON LINEAR-MOTION VARIATIONS



The steel rails of Hevi-Rail track-roller linear guides can do double duty — serving as guides as well as the support structures of linear axes. That's in contrast with linear guides based on profiled rail, which also require a machined surface for support and alignment ... as well as additional adjustments to deliver published parallelism values. Image courtesy PBC Linear

movement, so were only suitable for basic applications. However, newer versions have self-lubricating sleeves and other highly engineered features to maximize positioning accuracy and repeatability.

In contrast, linear-motion systems with rolling elements are either recirculating or non-recirculating …

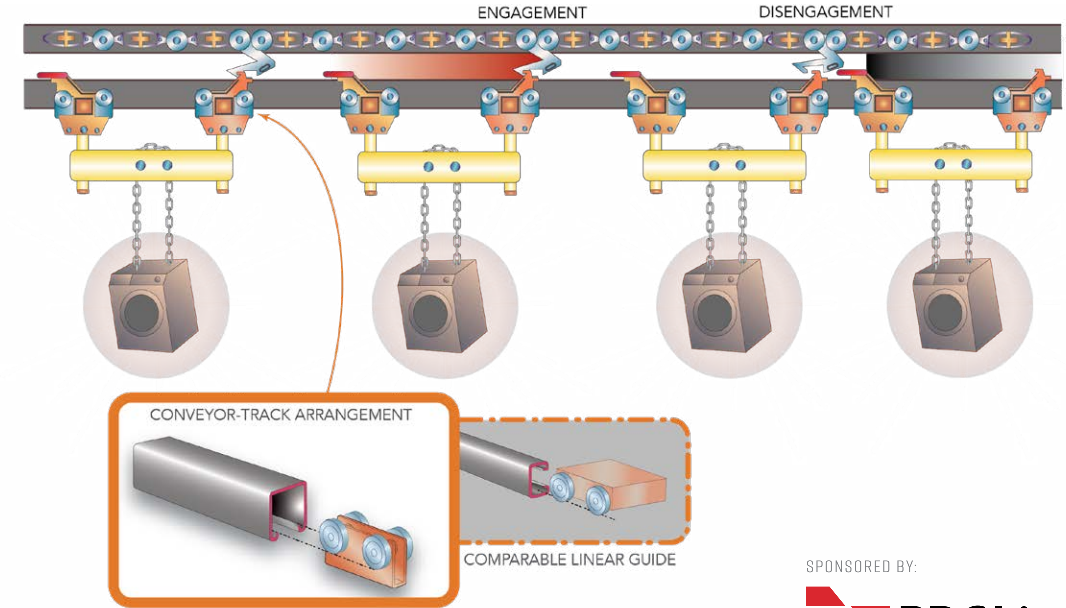
- Non-recirculating types use rolling elements such as bearing balls or rollers (usually held in a spaced array by a cage) for movement. For example, crossed-roller linear guides are a non-recirculating subtype in which cylindrical roller bearing elements are oriented in a crisscross pattern. Because the rollers don't recirculate, these linear guides have limited strokes — but provide high load capacity and good stiffness … with smoother motion than many comparable options based on recirculating bearing elements.

- Profiled-rail recirculating types (sometimes called recirculating linear guides) use some type of moving platform that houses a bearing block. This bearing block or carriage contains small internal raceways in which rolling elements run to let the block move along a profiled linear rail with little friction.

Another recirculating-element option is based on a cylindrical sleeve called a *ball bushing*. This bushing nut is lined with recirculating bearing balls … and this nut rides along a round rail or shaft to allow axial movement.

History lesson: In 1946, ball bushings were introduced and established the basic mechanism of rolling-element linear-motion bearings. In today's designs, the bushings may also have

Track-roller assemblies are useful in a broad range of applications … even beyond those for precision linear motion. One heavy-duty use is shown here — that of a power-and-free conveyor. In such systems, an upper track is powered by a chain and the lower track is unpowered. Track-roller trolleys (four of which are shown here) ride on the lower track and are driven by devices on the powered track called pusher dogs that engage with and disengage from the trolleys. These designs differ from those for linear guides in several ways — two of which being how the conveyor wheels ride on lips flanking the track-channel opening … with that opening facing downward to accommodate the items hanging off the trolley centers. In contrast, linear-guide designs based on these components tend to have the track channels sans lips and open to one side (on a vertical axis) with the track-roller wheels riding on a wider interior surface of the track channel.



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DEFINITIONS AND COMMON LINEAR-MOTION VARIATIONS

integral flanges to support axial loads. In fact, the term *profiled rail* (to indicate the linear-guide subtype having recirculating elements riding on specially shaped and engineered bar) serves in part to differentiate this option from *round-rail* ball-bushing-based options.

Of course, profiled-rail linear guides have their limitations: They're generally too costly for consumer-grade products such as those having linear door and drawer slides, for example. Most profiled-rail linear guides also necessitate machined mounting surfaces to deliver on published travel-accuracy values and prevent carriage-block binding and skidding. Typically, only nominal amounts of rail cantilevering is acceptable. Linear guides based on cam follower or advanced *track roller* assemblies (the focus of this Design Guide) don't have these limitations. They're generally more cost effective than profiled rail, and they can deliver smooth-running linear strokes that avoid the notchy action of some lightly loaded guides' cyclical raceway-to-bearing-element contact. As we'll explore, track-roller linear guides also excel in actuated applications consistently exposed to debris during operation, as they're rugged and have geometry that tends to plow contaminants off the tracks.

One last note on classifications: The categorization of profiled-rail linear guides as recirculating or non-recirculating is less relevant that it is for profiled rail linear guides, as the former have load-bearing elements that qualify as non-recirculating (as their wheels remain fixed at given attachment locations on the system carriage) or recirculating (as the bearings inside each wheel assembly course round and round).

VARIOUS OTHER TERMS FOR TRACK-ROLLER LINEAR GUIDES

Further complicating classification is that there are several names for track-roller linear guides. Terms found to be predominant in a given technical reference or data sheet depend on the manufacturer and market. In addition, reorganization of linear-motion industry taxonomy is afoot as new distribution channels such as Amazon (as well as established distributors such as McMaster-Carr) have come to influence how young engineers in particular reference various technologies. For example, Amazon currently categorizes linear motion components into six different subcategories under the Power Transmission Products section of its Industrial & Scientific category.

Linear track roller is a very common and unambiguous variation of the "track roller linear guide" term predominantly used in this Design Guide.

Track-roller linear guides are systems that pair profiled wheels with precisely mating tracks — usually V-shaped, rounded, or having a C or U-channel shape — to impart guide and load-bearing functions to actuated linear axes.

Guide wheel and linear guide wheel and roller guide are all common terms for track roller linear guide systems and their wheels. Some of these terms are used to emphasize the accommodation of misalignment as a primary function of the linear guide. Manufacturers will often indicate the wheel material or shape when using this convention — nylon-12 crowned guide wheels or steel wheels, for example.

Skate-wheel linear guide is a term that is specific to manual and gravity conveyors as well as the DIY CNC maker community. It often (though not always) implies an arrangement for which the track is beneath a carriage's load-bearing wheels. The term references the fact that these wheels either closely resemble or actually are consumer-grade components sold for use on products such as skateboards. Though most are entirely inappropriate for industrial use, skate wheels provide surprisingly decent accuracy when assembled into hobby-grade CNC systems to serve as basic track-roller linear guides.

Profiled wheel or wheel-based linear system is a slightly less common term usually used to emphasize some beneficial aspect of the wheels' radial geometry (and to a lesser extent the mating track geometry). The use of the word profiled also serves a marketing function emphasizing to design engineers that track-roller linear guides are a highly engineered and viable alternative to profiled rail linear guides.

Square linear-guide rail usually refers to flat-wheel track-roller designs that pair with C-channel tracks. Many such designs include arrays of wheels in different orientations on a carriage to engage multiple interior track surfaces.

Cam-roller guides and idler-roller guides are other names for track-roller linear guides. However, there is some ambiguity with the term cam roller, because it also refers to the cam-follower-based rollers found within large mechanical indexing tables so common in automotive assembly and beverage-bottling applications.

AMBIGUOUS LINEAR-GUIDE TERMS CLARIFIED

So far, we've covered the main types of linear guides and the standard industry terminology to describe them — and we've put track-roller linear guides into context. However, there is one last group of linear guide phrases and words having multiple meanings. Here we differentiate several technical definitions as they relate to track-roller linear guides and profiled-rail linear guides.

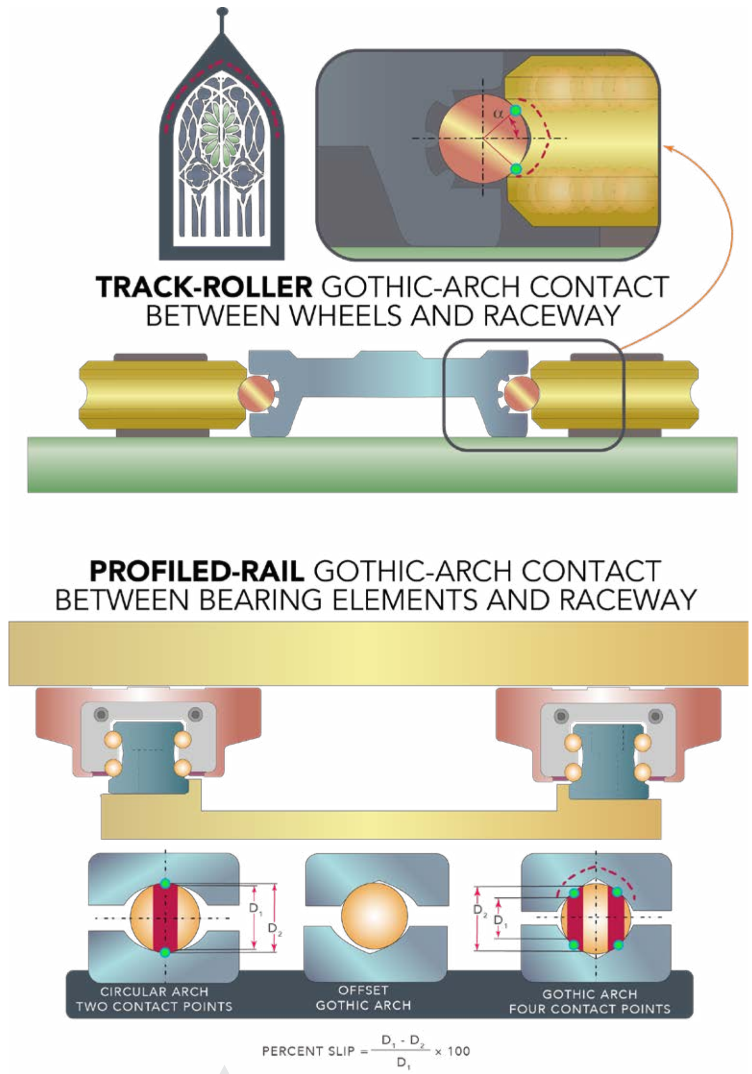
TWO MEANINGS FOR GOTHIC-ARCH LINEAR BEARING

Gothic arches originate from civil engineering. They're an adaptation of round-top Roman arches having a pointed shape resulting from the intersection of two circle-arc segments — called springing points when they're extensions of straight (and vertical) arch segments. In civil engineering, the benefits of Gothic arches are that they provide loftier arch reaches and half the (compromising) side thrust of Roman arches. In mechanical engineering, Gothic arches allow more clearance and greater roller to rail (or track) contact than other options.

Track roller linear guide: *Gothic arches* in the context of track rollers refers to the roller wheel's outer working-surface shape — and the mating geometry of the linear track it rides. Gothic arch wheels have a highly engineered radial surface with a concave profile. That's in contrast with flat rollers, crowned (rounded) rollers, vee-shaped (notched) rollers, chamfered rollers, and flanged rollers which we cover later in this Design Guide. In Gothic-arch linear guides, the track is:

- A machined and treated surface on a section of standard rail
- A round hardened steel race embedded in a section of standard rail — with the latter often made of lightweight anodized aluminum.

When the ends of the build are obscured, these can visually resemble profiled-rail linear guides. Strength and straightness to ±0.5. mm per 300 mm. The wheels' Gothic arch geometry ensures



Raceway geometry affects axis stiffness, friction, and moment load capacity in both profiled rail linear guides as well as track-roller linear guides. In both linear guide types, Gothic arch geometry (on the raceway for profiled rail and on the track-roller OD for track rollers) provides four-point contact instances between the linear guide element and the rolling subcomponent. Gothic arch geometry can make for load capacities that are lower than other options, but also enables exceptional linear accuracy.

Redi-Rail from PBC Linear is a low-profile option — with a 19-mm height for tight spaces that preclude other linear-guide types. Anodized aluminum rail sports hardened steel races upon which Gothic-arch wheels ride. The linear guides handle loads beyond 100 lb.

(continued)

AMBIGUOUS LINEAR-GUIDE TERMS CLARIFIED

the wheels securely and smoothly ride these races … and many pre-engineered variations boost performance by integrating three, four, or even five gothic-arch rollers that are offset and trapped between the races of the linear track.

One final note: Track-roller wheels with Gothic-arch external profiles often contain double-row angular-contact ball bearings within. That allows them to bear the axial loads induced from both sides of their OD — as well as high radial forces with its tread — the wheels' thick OD working surface.

Profiled rail linear guide: *Gothic arches* in the context of profiled rail linear guides are found in the geometry of the linear rail raceways — not the carriage or rolling elements. In fact, profiled rail raceways usually have either circular arch grooves or Gothic arch grooves. These groove geometries (both of which are associated with guides employing ball-bearing elements) arose from industry innovation aimed at boosting linear-guide load capacities. Circular arch grooves contact ball bearings at two points. Gothic arch grooves contact the ball bearings at four points. Though beyond the scope of this Design Guide, a third option called an offset Gothic arch is also available.

Gothic arches in profiled rails offer multi-axis load bearing and high moment load capacities. Their main drawback is the tendency to fall out of pure rolling with differential slip resulting from speed-varying disparities in the elliptical contact areas between ball and raceway — as well as an increase in sliding friction. More dramatic differentials between ball and arch diameters (as well as increased contact area) makes for more differential slip. The relationship between this slip and contact area means the effect also puts a limitation on allowable preload.

PBC Linear Redi-Rail consists of aluminum rail integrated with hardened steel races for a strong yet lightweight design. Carriages are sealed against contamination and engineered with double-row bearing rollers that glide over particles.

Profiled rail linear guide: *Roller bearing* in the context of profiled rail refers permutations that use cylindrical or barrel-shaped rollers instead of spherical balls for the carriage's load-bearing elements. These are particularly common in machine-tool applications … though rollers' performance benefits are worthwhile in other industries as well. Roller-based designs have higher load capacity, rigidity, and power density than comparable ball-element designs … making them excel on gantries and other multi-axis arrangements that benefit from compact linear components. The main caveat here is that they can be costlier.

TWO MEANINGS FOR ROLLER BEARING

In mechanical engineering, the term roller bearing with no other context refers to rotary bearings with cylindrical roller load-bearing elements instead of spherical ball load-bearing elements. Rotary bearings are common components in motion systems. They're used in gearboxes, motors, pulleys, fans, and pumps … and in fact, virtually any time a shaft is rotating, rotary bearings are there to reduce friction and support radial and often axial loads.

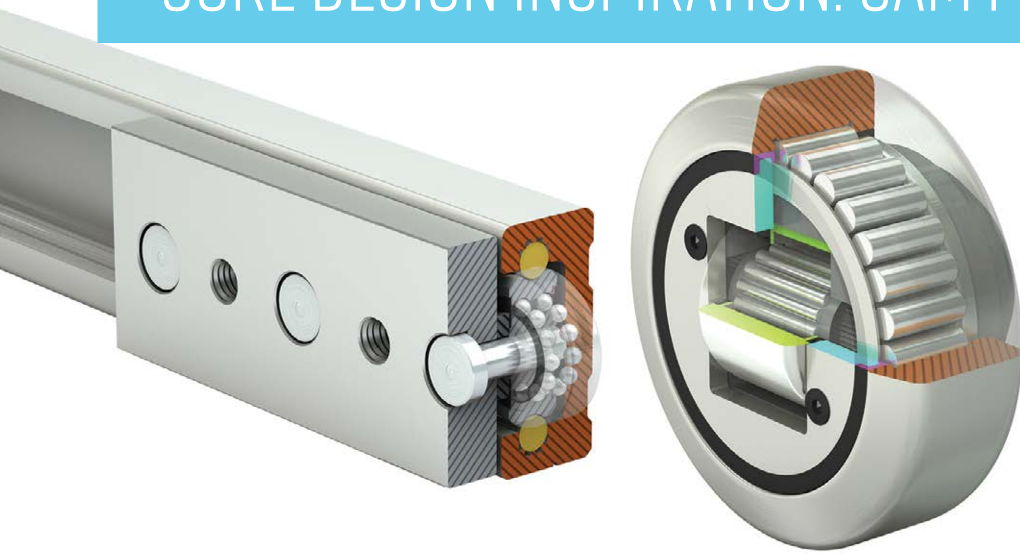
Track roller linear guide: *Roller bearing* in the context of track rollers can refer to the entire linear-guide design or just the rolling wheel or cam follower of the design. Case in point: PBC Linear RediRail products are often called *roller bearing linear guides* or rail guides. In fact, the wheels in track-roller linear guides can incorporate cylindrical rollers, though they usually incorporate ball-bearing elements.

TWO MEANINGS FOR RAIL

Track roller linear guide: The term *rail* is often just a more casual way of referencing the technology known as track-roller linear guides. Some manufacturers put the term in their product names: For example, Redi-Rail from PBC Linear can serve as an appropriate alternative to profiled rail in moderate-load designs needing high speed and precise linear strokes — especially in automation and machine-transfer applications. In other contexts, rail might specifically imply the track geometry and its surfaces that serve as the wheel raceways.

Profiled rail linear guide: Often the term *rail* in the context of linear motion does in fact imply profiled rail — paired with a carriage block recirculating or nonrecirculating rollers as described above.

CORE DESIGN INSPIRATION: CAM FOLLOWERS



Just like cam followers, the wheels used in track-roller linear guides contain ball bearing elements or cylindrical bearing elements … with both sold in a variety of arrangements. Shown here are cutaways of wheels from PBC Linear [Redi-Rail](#) (left and shown assembled into the mating track) as well as [Hevi-Rail](#) (right). In addition, carriages can include three, four, and five track-roller wheels having various preload-adjustment capabilities.

The wheel designs used in track follower linear guides are at their core much like cam followers. Recall from basic mechanical engineering that cam followers are power-transmission devices with a rotary bearing core to bear load (both radial and axial) while serving as the interface between independently moving machine sections — maintaining a physical separation between these sections to minimize rotational friction. Applications include those on rotary indexing tables and turntable conveyors, long-stroke robot transfer units (RTUs), and an array of highly customized machinery.

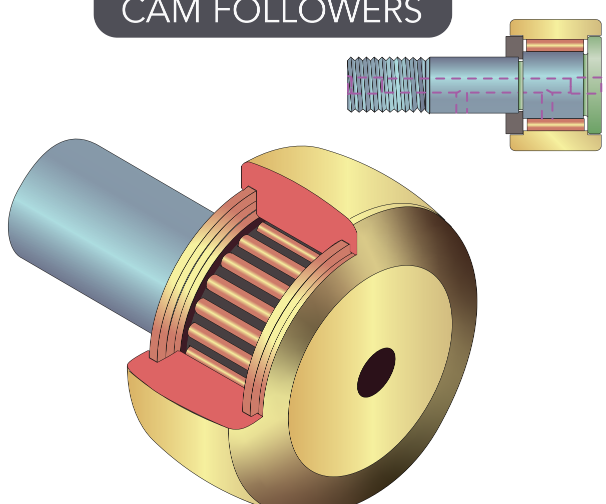
The outer diameter (OD) of the cam-follower bearing assembly is its working face — typically made of steel, nylon, urethane, polyamide, or other engineered material. This OD mates with some machine surface … traditionally this was a mechanical cam of some type — such as the precision barrel of an indexing table. Such mechanically automated indexing tables have a motion profile cut into a cam drum that engages the followers, which in turn transmits the power to an output.

Cam followers also find use in assemblies that pair them with linear tracks and other engineered paths on customized assemblies.

Cam followers assemble onto machines in one of two ways. Stud-type cam followers include a partially threaded shaft fixed to the follower inner diameter (ID) for assembly onto a machine frame with a nut or similar fastening device. Yoke cam-follower variations (identifiable by their open ID) often mate to machine frames via press fit at a hardened inner race usually held by the follower's end plates. Because they're not a cantilevered design, yoke followers exhibit minimal deflection. But stud cam followers are indispensable in an array of applications — including those that are subject to high loads.

The most common cam-follower design employs thin cylindrical-shaped needle rollers to carry high radial loads; where applications require the axis to run at high speeds, a cage can separate the rollers. Otherwise, where loads are particularly

CAM FOLLOWERS



Cam-follower variations have features specific to application speed and more.

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CORE DESIGN INSPIRATION: CAM FOLLOWERS

high and the axis needs high dynamic load capacity, cam followers often include twin rows of standard ball-bearing elements.

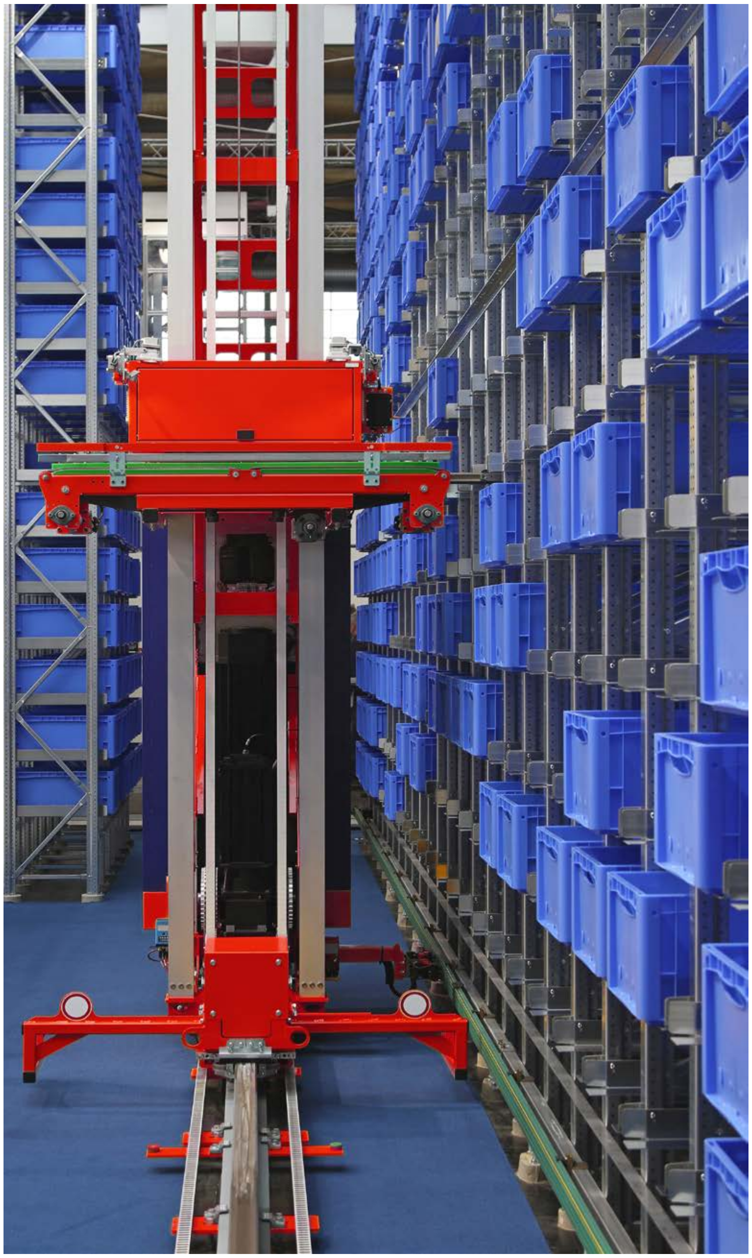
Other cam-follower variations are based on bearing designs with barrel, spherical, spindle, and tapered geometries. Though beyond the focus here, some light-load cam followers are even built around simple plain (sleeve) bearings.

Note that cam followers differ from their roller-bearing cousins in a few ways. Because the latter are typically interference fit into assemblies, they get circumferential reinforcement from the surrounding machine frame or housing. In contrast, the outer race of a cam follower must be thick to prevent deformation … especially under the localized line of loading. In addition, many cam followers include lubrication ports and more ruggedized surface finishes to withstand exposure to environments during operation — especially those that operate exposed on unprotected machine sections.

Many cam followers have flat outer diameter (OD) profiles, while others (especially those for linear-motion applications) include crowned, edge-flanged, or vee-shaped ODs to engage tracks and rails that are engineered with mating geometry.

Crowned cam followers can compensate for ten times the misalignment that traditional flat-profiled cam followers.

Some cam followers serve as track followers by engaging rails to deliver linear motion. These designs are increasingly common in automated storage and retrieval systems (AS/RS) and seventh-axis RTUs mentioned earlier. That's because cam-follower-based track follower linear guides outperform the linear bearings known as profiled rail guides … especially where compactness and ultra-high accuracy are less important than ruggedness, quick and forgiving installation, high-speed reversals, and long life.



Automated storage and retrieval systems (AS/RSs) make copious use of track-roller linear guides.

TRACK-ROLLER LINEAR GUIDES: WHERE THEY EXCEL

Track-roller linear guides excel in dirty leather and textile-cutting applications that can quickly harm other linear guides.

With so many linear guide choices, deciding which technology to specify for a given application can be difficult. On one hand, not every application requires machine tool rigidity and the ability to move a small car. On the other hand, most applications require a guide that can withstand high duty cycles in an industrial environment. Among linear-guide technologies that excel in more challenging motion applications are track-roller linear guides. Linear guides based on track rollers often serve in two challenging application types:

- Long-stroke linear-motion axes such as those driven by belts or rack-and-pinion sets
- Linear systems in harsh environments subject to hot and humid conditions, extremely cold temperatures, washdowns, abrasive materials, extreme loading, and corrosive chemicals.

However, other uses abound. Here we list five benefits that track-roller linear guides offer for applications ranging from light industrial off-highway designs to large-scale material handling.

Design engineers should specify track-roller linear guides when the applications will benefit from high speed, low weight, and the ability to withstand harsh environmental conditions … and when the design requires an economical linear guide that's easy to assemble and mount.

Speed of track-roller linear guides: Because track rollers are based on radial rather than recirculating bearing elements, they can travel at higher speeds than ball or roller-based profiled-rail guides. Track-roller linear guides can commonly reach speeds beyond 10 m/sec. Standard acceleration limits are 50 m/sec2 although higher accelerations are possible by increasing the preload of the track-roller wheels to avoid slipping. For applications such as pick-and-place or assembly, track-roller linear guides offer the highest speeds of virtually any linear guide.

Weight of track-roller linear guides: Track-roller assemblies benefit from weight that's far lower than that of other linear-guide options. As mentioned, one typical track-roller linear guide construction consists of an aluminum rail with steel guide inserts and an aluminum carriage block with steel rollers. In contrast, recirculating bearing carriages and rails must be made almost entirely of steel for higher load carrying capacities, which improves rigidity … but greatly increases weight. The lower weight of track-roller linear guides enables the increased acceleration limits already discussed and is beneficial in highly dynamic applications — especially those with multiple axes.

Robustness of track-roller linear guides: Contamination that destroy the recirculating bearings of profiled rail is less detrimental to track-roller linear guides, so even the harshest environments rarely call for special sealing or protective coverings. That said, harsh washdown or corrosive applications benefit from guide rails and carriage bodies constructed of noncorrosive materials or coatings for additional protection.

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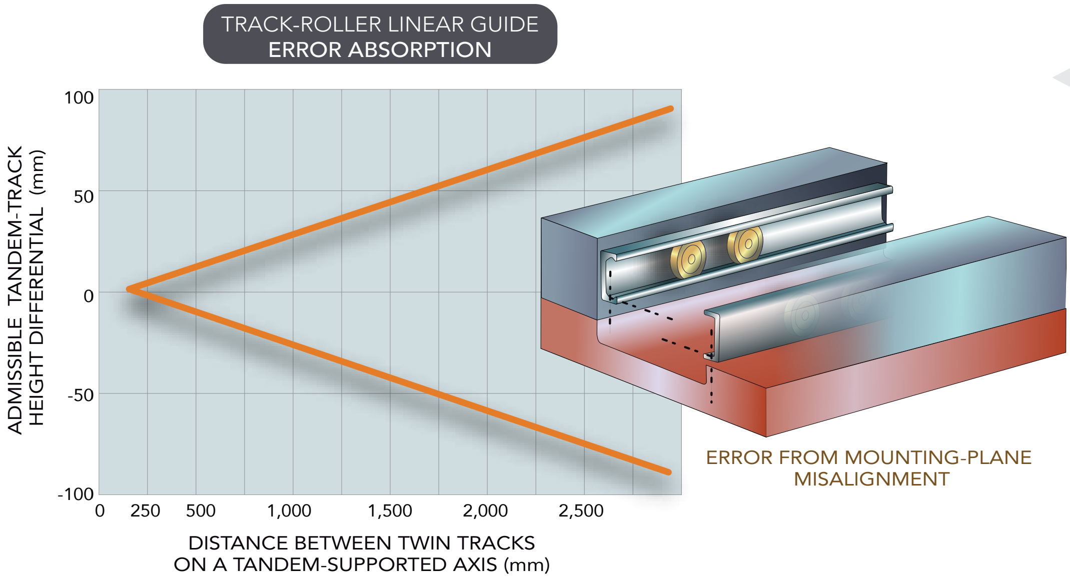
TRACK-ROLLER LINEAR GUIDES: WHERE THEY EXCEL



Track-roller linear guides are indispensable on extended-stroke applications, where they can compensate for slight geometrical inconsistencies that are quickly magnified into significant errors by lengthy axis stretches.

Also: While recirculating bearings live and die though proper lubrication, the radial bearings that support track-roller linear guides are oftentimes fully sealed and lubricated for life — especially smaller variations. Manufacturers may recommend a light oil or grease application between the track-roller wheels and the guide rail or offer lubrication ports or wipers to extend relubrication intervals … though in almost all cases, the lubrication requirements are far less stringent than those for profiled rail. That's another benefit of having the working load-bearing elements encased within the track-roller wheels.

Track-roller linear guide servicing: Unlike recirculating bearings having a set preload typically determined by ball or roller selection, most track-roller linear guides accept preloading adjustments by the user during installation. That means as application conditions fluctuate or components wear, preload can be further adjusted to maintain rigidity, speed, and performance. This also simplifies replacement, because adjustable preload means that bearing blocks and guide rails are interchangeable.

Mounting track-roller linear guides: For profiled rails with recirculating bearing elements, error in alignment degrades bearing preload accuracy and induces uneven loading as well as premature wear. This is not the case for track-roller linear guides, because carriage preload is adjustable — making mounting requirements for track-roller assemblies much less stringent than those for profiled rails. In most cases, mounting a track-roller linear guides rail doesn't require a reference edge, even when mounting two guide rails in parallel. Because many track-roller linear guide rails are aluminum, mounting them to aluminum substructures (such as extruded profiles, requires no special preparation or machining for flatness or straightness. This makes track-roller linear guides a good choice for self-assembled linear actuators.

Taking this forgiving mounting feature a step further are some track-roller linear guides in large-scale printing and slicing applications. Many of these can even accommodate imperfect machine-frame geometry. Here, track-roller linear guide pairs with complementary geometry accommodate the changing direction of the force vectors resulting from machine-frame misalignments. More specifically, such track-roller linear guide pairs might include:

- One guide with a C-shaped track having a flat raceway surface — to impart lateral freedom to a couple millimeters or more
- Another guide with a track that constrains the track-roller wheels on one flank while permitting slight rotation on the other flank — to impart angular freedom to a couple degrees or more

Together the linear guides work well even on nonmachined out-of-parallel surfaces for linear strokes sans excessive friction. In contrast, traditional linear guides in such applications register misalignment as additional load that (due to no DOFs in the mounting surface or linear guides) causes tensile force within the guide assembly — even to the point of binding. That's an especially distinct possibility on very long machine axes where even small assembly errors cause rather dramatic effects over the course of strokes that are multiple meters long.

HOW TRACK-ROLLER WHEEL DESIGN AFFECTS LINEAR-GUIDE PERFORMANCE

Track-roller wheels can be customized to the application at hand through their internal bearing-element arrangements; sealing; and outer tread geometry and material makeup. As mentioned earlier in this Design Guide, *treads* refer to the wheels' thick OD working surface, just as in automobile tires. We covered the internal features of track-roller wheels in this Design Guide's previous section on their similarities with cam followers. The environment dictates which track-roller wheel-sealing options are most suitable.

Wheel treads and internal subcomponents are typically manufactured out of carbon steel, high-alloy steel, stainless steel, performance polymers, and even aluminum in some cases. Consumer-grade and simple medical-device applications may benefit from polymer track-roller wheels to minimize noise. Where a linear axis is subject to light debris or washdowns, sealed bearings are necessary — as are stainless-steel wheel sections. Steel track-roller wheels (and even heat-treated variations with engineered high-temperature lubricant) may also be necessary in or near ovens and other hot applications exposing linear axes to 200° C and beyond. Machine-tool applications and other designs subjecting the track-roller wheels to more copious or detrimental debris (such as metal shavings) may necessitate track-roller wheels with fully sealed and shielded bearings to prevent brinelling, spalling, and premature failure.

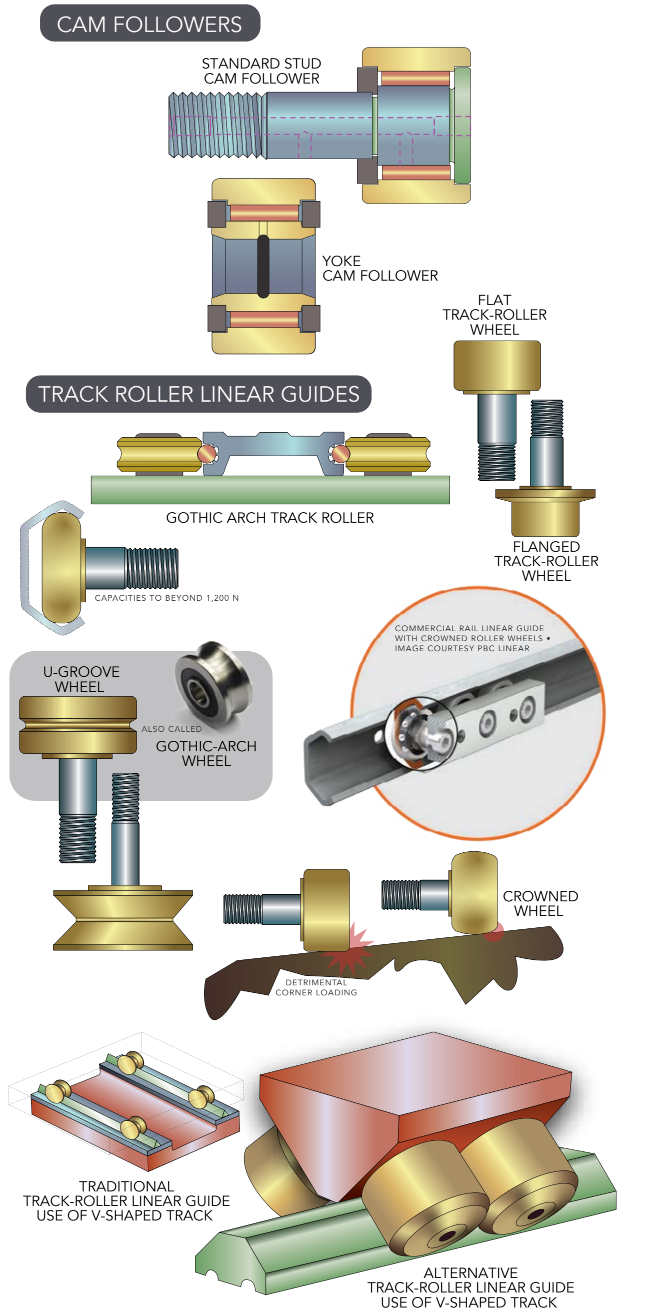
As mentioned earlier, some track-roller wheels are supplied from the manufacturer lubricated with lithium grease. Larger variations may have a relubrication port at their inner ring.

In regard to their geometries, track-roller linear guides include variations employing flat track rollers, crowned (rounded) track rollers, vee-shaped (notched) track rollers, chamfered track rollers, and flanged track rollers.

Flat track-roller wheels are just as they sound — simple flat-treaded wheels. Many of these wheels also include treads machined of alloy steel and case hardened to Rockwell hardness of Rc 55 and beyond for tread wear resistance complemented by a softer (and tough) inner core.

Flat track-roller wheels pair with various linear tracks — including simple bar and square tracks as well as hollow-box tracks. They are indispensable in heavy-duty automation, energy, and material handling applications.

Crowned (rounded) track-roller wheels include a slightly rounded radial profile on their OD. This geometric feature incurs additional cost but compensates for modest misalignment between the track-roller wheel and the track on which it rides.



Cam followers and track-roller linear guides are two technologies from the same origin. However, track-roller linear guides rely on advanced wheel arrangements and track integration for maximal linear-motion accuracy and reliability.

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HOW TRACK-ROLLER WHEEL DESIGN AFFECTS LINEAR-GUIDE PERFORMANCE

Such accommodation in turn helps avoid corner loading that would otherwise occur on the sharp shoulders of flat wheel profiles — and that minimizes thrust loading on the load-bearing elements contained inside the wheel. Crowned track-roller wheels (which are usually hardened steel) also minimize thrust loading during circular motion, such as that which can occur on curved sections of specialty track-roller linear guides. Speed is limited to a meter per second or so.

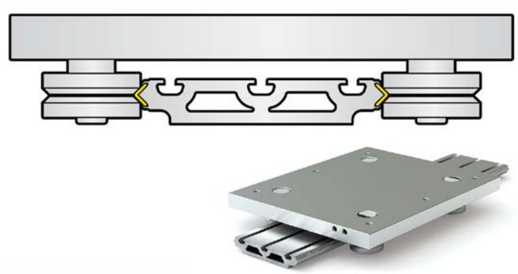
Note that crowned wheels can be ganged into concentric track-roller wheel pairs (to bear load) with one eccentrically mountable track-roller wheel to complete the carriage. The eccentrically mountable wheels are adjustable to impart preload and hold the load-bearing wheels firmly against the working track — so all the wheels on a carriage thus outfitted will roll without skidding or slipping. In fact, wheels accepting eccentric adjustment can also serve to compensate for wheel or track wear over time. Key to this arrangement are the designs of fixed bushings (for the load-bearing wheels for the radial load direction) and adjustable bushings (for the adjustable wheel).

Crowned track-roller wheels are most common in designs with modest accuracy requirements — often paired with tracks that are simply welded onto the machine frame. These designs include those in certain office equipment as well as packaging and HVAC applications. Elsewhere (in exceptionally rugged power-transmission applications) crowned wheels setup to ride on the surfaces of structural beams. Slightly more precise designs may pair the wheels with generic metal framing — long sheet metal or bar sections formed into C and U-channel tracks — such as those standardized by metal-framing supplier Unistrut USA of Atkore International Inc.

Chamfered track-roller wheels are wheels that often include other geometries described here (such as V-shaped profiles) or tapered profiles. Chamfering serves the same purpose of crowning — avoidance of corner loading — which is useful in heavy-duty applications such as fork trucks and other lifts.

V-shaped (sometimes called notched) track-roller wheels include a V-shaped radial cutout to mate with a track having a male V-shaped protrusion. These wheels are often wide enough to incorporate ground double-row or deep-groove angular contact ball bearings … or (in even larger iterations) tapered roller-bearing elements. V-shaped track-roller wheels operate on low to very high-accuracy axes; mounting greatly influences their overall precision. Benefits of these V-shaped wheels include the ability to resolve radial and thrust loads as well as the tendency to shed debris — especially when the contaminants first land on the sloped sides of male V-shaped track. Track-roller linear guides with steep side angles are especially good at clearing debris.

Just like crowned track-roller wheels, V-shaped track-roller wheels also lend themselves to mounting in sophisticated arrays on their carriages … including eccentric adjustment to compensate for system wear. Or some designs may include tandem linear guides with one employing V-shaped track-roller geometry … and its parallel twin employing crowned track-roller geometry to resolve other loads and machine-frame imperfections.



IVTAAQ linear guides excel on axes to beyond three meters long. Image courtesy PBC Linear

Track-roller linear guides are suitable for strokes even to many feet long. The MultiCam V-Series plasma-cutting table uses track-roller linear guides having V-shaped track-roller wheels and tracks.

(continued)

HOW TRACK-ROLLER WHEEL DESIGN AFFECTS LINEAR-GUIDE PERFORMANCE

IVT image courtesy PBC Linear

As mentioned, V-notched track-roller wheels ride on ridged tracks having sloped angles matching their own notch angles. Tracks and wheels from different manufacturers aren't designed to be interchangeable.

Where the raceway ridge is simply machined onto an extruded bar and plate, the design's parallelism, flatness, and straightness tolerances are not particularly tight … so deliver accuracy to about ±100 μm … though such designs do make for exceptionally cost-effective solutions. Some manufacturers offer V-tracks that are induction hardened and polished on the surfaces destined to serve as the working raceways, but then leave the rest of the track untreated to make it easier to drill with holes for mounting.

At the other end of the spectrum, track-roller linear guides with V-shaped wheels on precision engineered raceways with drawn, hardened, and ground steel surfaces can deliver accuracies to ±0.025 mm or better. Professional installation is necessary to maintain this and other precision values. Such tracks are offered in various grades of stainless steel to withstand harsh environments.

Note that there are other linear guides that leverage the benefits of V-shaped geometry. Instead of V-shaped track-roller wheels, these designs employ flat track-roller wheels mounted on V-shaped carriage to ride the two sides of a larger V-shaped track. Read more about this setup in this Design Guide's next section.

On **flanged track-roller wheels**, one or both axial sides have a wide flare. This serves as yet another mode of centering (tracking) the wheels on linear raceway.

U-groove track-roller wheels have a scooped (rounded) channel around their treads' radial profile to securely ride on round-profile shaft. Most of those for motion applications are made of high-carbon chromium alloy steel that is hardened and ground — and sealed and lubricated for life. In fact, the exact geometry of this U groove is highly engineered for secure and smooth traversal of the track races. Though not typically suitable for heavy-duty applications, U-groove track track-roller wheels maintain exceptionally reliable guidance on reciprocating axes as well as vertical lifts and those subject to shock loading.

As described in a previous section of this Design Guide, U-groove track-roller wheels are also called Gothic rollers. They're often paired with hardened and ground steel raceways having a round profile and securely press fit into engineered receptacles on aluminum-alloy extrusions. Lengths are to several meters.

One final note: Beyond profile geometries, track-roller wheels also allow customization in how they're arranged and mounted on their carriages and other movable machine sections. Above we briefly covered how gangs of wheels sometimes include a track-roller wheel that serves as an eccentrically-mounted take-up wheel. Elsewhere, carriages with gangs of four, five, or even more wheels per side deliver exceptional linear-guide accuracy.

HOW TRACK AND CARRIAGE INSTALLATION AFFECTS LINEAR-GUIDE PERFORMANCE

The tracks and carriages of linear guides also provide innumerable options for tailoring performance features to the application at hand.

Typically the tracks of a track-roller linear guide are harder than the wheels that ride them … as that helps prevent failure due to galling. For example, medium-carbon steel for tracks might be hardened to 53 HRc or 420 stainless steel hardened to 40 HRc. In contrast, tracks can be made of aluminum if they are destined to pair with engineered polymer track rollers bearing relatively light loads.

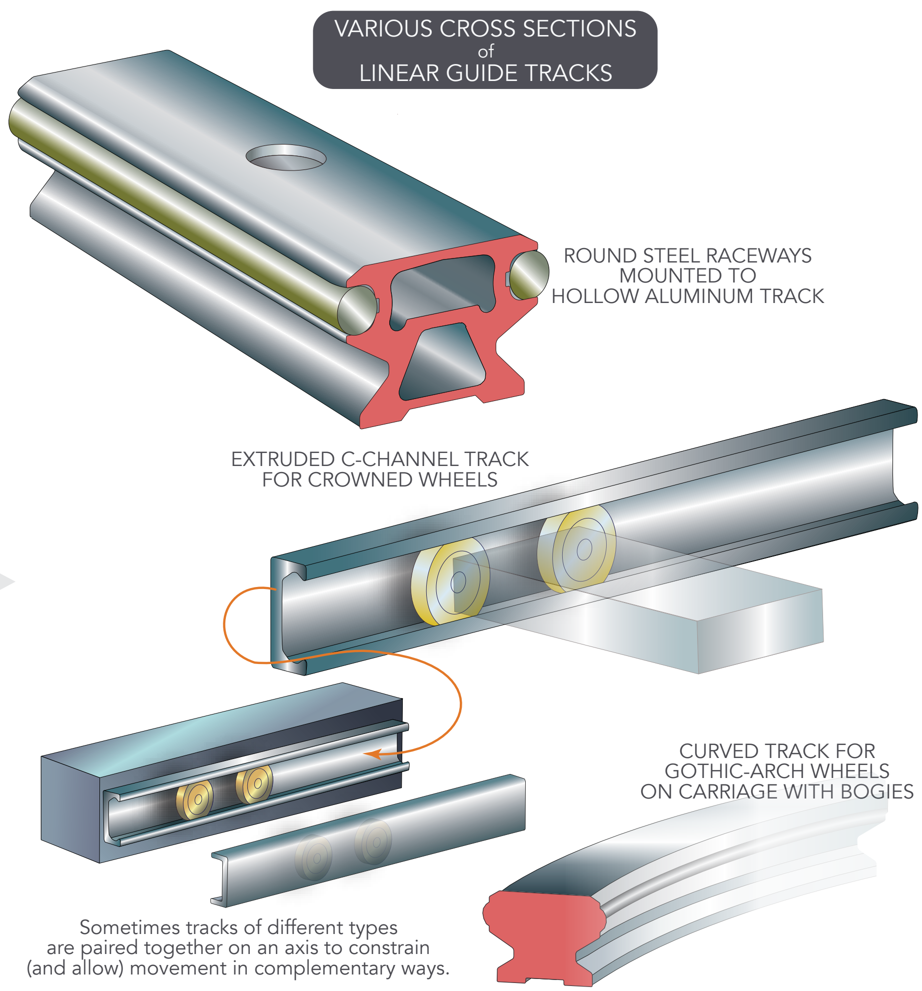
The straightness, flatness, and parallelism of the plate or other machine section to which the track is bolted determine system accuracy. That said, linear guide tracks can bolt to moderately inconsistent surfaces without exhibiting running issues during operation — even if the axis necessitates twin tracks in tandem.

Note that preload can eliminate play between load-bearing wheels and track. The main rule is that preload never exceed the wheels' radial load capacity — minus any other radial load from the installation on the wheels. Preload equals the ratio of breakaway force to the coefficient of friction … minus applied load. Two other caveats are that:

- Applying preload can in some instances shorten linear-guide wheel life
- Preload should never be used to compensate for assembly deflection.

Some track raceways require lubrication — either through manual application or through wiper ends on the linear-guide carriage. Many manufacturers offer oil-soaked felt inserts as an optional carriage feature. Otherwise, carriage designs may eschew these traditional felt inserts for low-friction oil-impregnated plastic wiper ends … in some cases, complemented by ultra-high-molecular-weight polyethylene (UHMW) spring-loaded seals. These extra subcomponents are often accompanied by an add-on port or nipple to allow occasional lubricant replenishment with an oil of some prespecified viscosity.

Dirty settings and continuous-duty axes necessitate more frequent relubrication at an interval that's often fully determined only after the machine goes into service.



Shown here are various cross sections of track-roller linear guide rails and raceways.

Bottom: Some large-scale machine designs with multiple axes benefit from the use of track-roller linear guides that come in pairs for each axis. Here a common solution is to use a rigid linear guide on one side of an axis and a compensating linear guide on the axis' other side — with the latter employing a carriage capable of slight pivoting within its track to prevent the axis from binding.

Other linear-guide options force design engineers to specify prohibitively expensive or impossibly high machine-frame parallelism … or oversized (and subsequently inefficient) linear actuators capable of powering through potential jamming zones.

(continued)

HOW TRACK AND CARRIAGE INSTALLATION AFFECTS LINEAR-GUIDE PERFORMANCE

What's the risk of insufficient track-roller lubrication on variations that require oil or grease? One problem that can arise it that of fretting corrosion on the linear track or the wheel treads. These rough and rusty-looking zones on the working surfaces of the linear guide can degrade operation and ultimately cause system failure.

TRACK MOUNTING AND ITS RELATIONSHIP TO MEASURES OF PRECISION

Certain subtypes of track-roller linear guides (such as those based solely on crowned wheels, for example) are famously forgiving of inconsistent mounting surfaces. But other high-precision track-roller linear guide installations necessitate rather stringent mounting-surface preparation and techniques to achieve published accuracy, straightness, and rigidity values. For these more precise designs:

1. The geometrical consistency of adjacent machine sections must have flatness and parallelism to within specified tolerances.

2. Assembly personnel must be familiar with the use of installation equipment such as calipers and dial indicators for the precise verification and location of surface, track, fastener, and mounting geometries. Precision track installation for designs not pre-integrated by the manufacturer into actuators or stages often requires the placement of linear-guide track against some reference surface or adjacent construction before initial hand tightening of fasteners; then follows additional alignment and clamping before final tightening of track fasteners to within specified torque values.

3. Mounting of the track-roller carriage onto track can be as easy as simply rolling the carriage onto the track from one end (for assemblies meant to have clearance) or rolling the carriage onto the track and then adjusting any eccentric wheel positions (for assemblies meant to prevent lost motion). Any track assemblies with side loading should be centered and secured before final tightening of brackets and other supports.

4. Where a track-roller linear guide may be subject to shaft creep (due to high accelerations and quickly alternating loads or slightly under-supported or cantilevered tracks) it's highly recommended that the installation include the use of endplates. Some manufacturers sell linear-guide tracks with these endplates premounted.

5. Wherever a design engineer anticipates that a track-roller linear guide may be subject to lateral loads, its carriages and tracks should be located against reference surfaces. In some cases, it's recommended that gaps between the track and adjacent machine surfaces be filled with epoxy or other synthetic resin.

6. Tandem mounting of linear guides requires special installation techniques. Many manufacturers recommend that the installer position and clamp the first track in place against a preset reference edge, and then tighten it in place… and next hand tighten the fasteners on its parallel twin track. Only after the wheels of the carriage are rolled onto the twin tracks and design clearance set should the second track be tightened the rest of the way down. Care must be taken to avoid the introduction of preload beyond any values published for the system — or else the linear guide will exhibit accelerated wear.

7. Note that track-roller linear guides come in **curved sections** to serve in indexing tables, gonio axes, or conveyors that trace oval paths through a facility. For the latter, some manufacturers sell track-joining accessories for precision joints with well-defined mounting procedures. Also refer to the section of the Design Guide below titled "the special case of track-roller bogie carriages" for more on this topic.

THE SPECIAL CASE OF TRACK-ROLLER BOGIE CARRIAGES

A bogie or truck in the context of motion-system engineering is a pivoting chassis fitted with a set of wheels. This subassembly in turn is pinned or mounted in some way to a carriage. The main purpose of a bogie in track-roller linear guides is to bear load while allowing wheels sets to stably ride on both straight and curved sections of track. In some cases, linear-guide carriage bogies may also include features to (much like those in railway applications) address vibration issues and minimize the impact of centrifugal forces when the train runs on curves at high speed; and Minimizing generation of track irregularities and rail abrasion.

Track-roller linear-guide manufacturers typically offer carriages with bogies in conjunction with curved track sections — to be used by design engineers in building circular and oval axes. Representative designs might include a steel carriage plate fitted with two swivel brackets (made of aluminum) with wheels to provide axial and radial load bearing.

(continued)

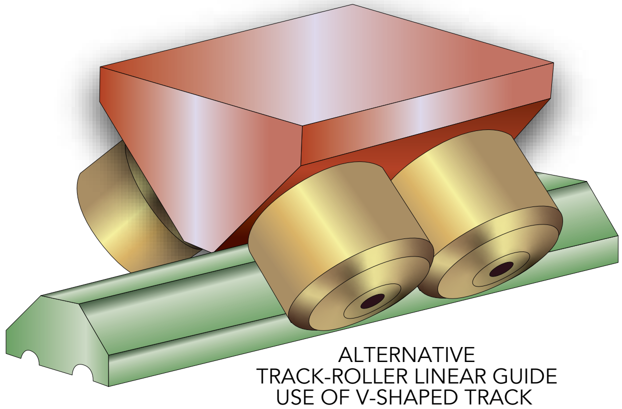
HOW TRACK AND CARRIAGE INSTALLATION AFFECTS LINEAR-GUIDE PERFORMANCE

V-SHAPED TRACK TO ACCOMMODATE A V-SHAPED ROLLER-STUDDED CARRIAGE

In the previous section of this Design Guide, we described linear guides employing V-shaped track-roller wheels. In fact, a related design uses flat wheels to engage the two sides of a V-shaped track — with the wheels mounted on a V-shaped carriage body. These carriages excel on heavily loaded axes and those run in continuous-duty machine operations. Such designs excel in exceptionally dirty environments (especially with abrasive debris) that also require the axis to make frequent reversals.

Contact between the carriage's wheels and the track is on two angled inclines. The strength of this arrangement is that the track-roller wheels' rotational axes are parallel to the track raceways for pure rolling without sliding friction. That in turn makes the assembly more efficient — and less affected by the scratchiness of debris in the environment.

Some designs offer extra protection against shock loading by allowing carriage flexing and temporary support of carriage overload at its center ridge by the track's peak; upon release of the overload condition, the carriage resumes its normal reliance on the track-roller wheels for load bearing. What's more, the linear-actuation mechanism can attach directly to the carriage body.

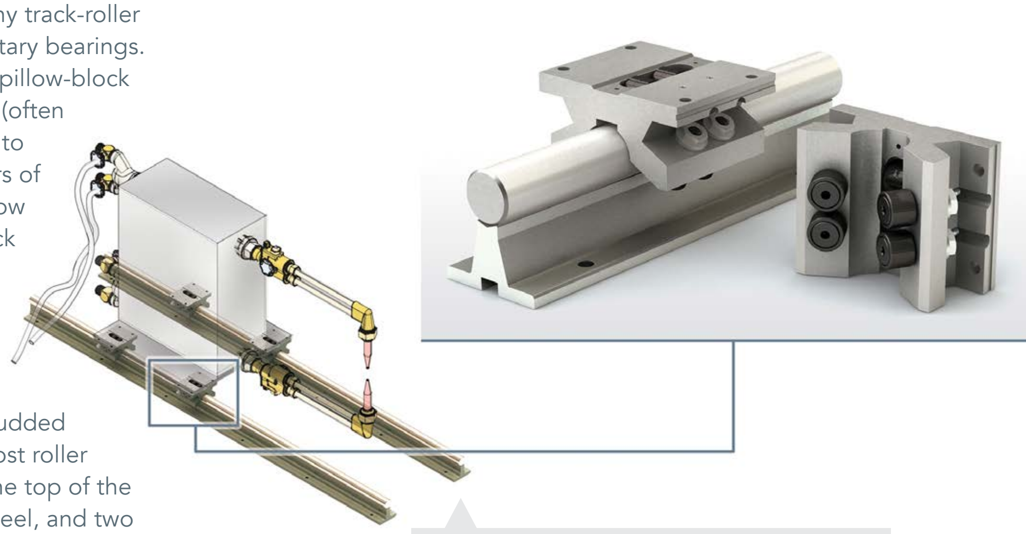


Some linear guides are based on track-roller wheels mounted to a V-shaped carriage.

SUMMARY OF ROLLER PILLOW BLOCK LINEAR GUIDES

Just as cam followers provide the basis for many track-roller linear-guide designs, so too do pillow-block rotary bearings. Recall from basic mechanical engineering that pillow-block bearings consist of a stationary pedestal block (often cast iron or steel) and a free-rotating assembly to provide friction-free support of a shaft. The ears of the pedestal bolt to a machine frame; split pillow blocks allow removal of the top cap of the block assembly even while the pedestal stays bolted in place.

In roller pillow block linear guides, the round tracks (the shafts in this arrangement) do the supporting — pairing with a carriage studded with wheels to support and guide a load. In most roller pillow block carriages, a track-roller wheel at the top of the carriage serves as the primary load-bearing wheel, and two or more track-roller wheels flank the carriage sides. In some cases, one or more side wheels can be adjusted to provide assembly preload or clearance.



Roller pillow block linear guides can deliver dynamic load ratings from 3,560 to 55,600 N ... and a low coefficient of friction allows speeds to 7.6 m/sec. Image courtesy PBC Linear

DYNAMIC LOAD AND STATIC LOAD CAPACITY FOR THE SPECIAL CASE OF TRACK-ROLLER LINEAR GUIDES

Load-capacity values are absolutely central to the specification of linear guides. As covered on linearmotiontips.com, all linear motion components with rolling elements (which includes many linear guides as well as ballscrews) have two load-capacity specifications — static load capacity and dynamic load capacity. These are based on different performance criteria … and are fully independent values. Let's explore.

Dynamic load capacity C is based on empirical data assuming a constant-magnitude load \ normal to the load-bearing surfaces for a defined travel distance (in the case of a linear guide) or number of revolutions (in the case of a ballscrew) without fatigue. Fatigue is reached when there's clear surface flaking of the bearing elements or raceways.

Dynamic load capacity defines the rated life of rolling-element bearings. The latter is called L10 life for how the prevailing standard is defined by the load and speed under which 90% of a group of identical bearings can survive for a set travel:

$$\text{Ball-element bearing life} = (C/F)^3 \times 100{,}000 \text{ meters}$$

$$\text{Roller-element bearing life} = (C/F)^{10/3} \times 100{,}000 \text{ meters}$$

Where F = Applied load.

Of course, these calculated life values often differ from true operating life — because the latter can be subject to accelerated wear or fatigue from track roller or raceway operating clearances that are overly large or small; challenging environments involving extreme temperatures, vibrations, shock loads, or contamination; short-stroke reciprocating motions causing false brinelling; and unanticipated damage during installation and mounting. That's why the study of previous applications similar to the one at hand can prove useful.

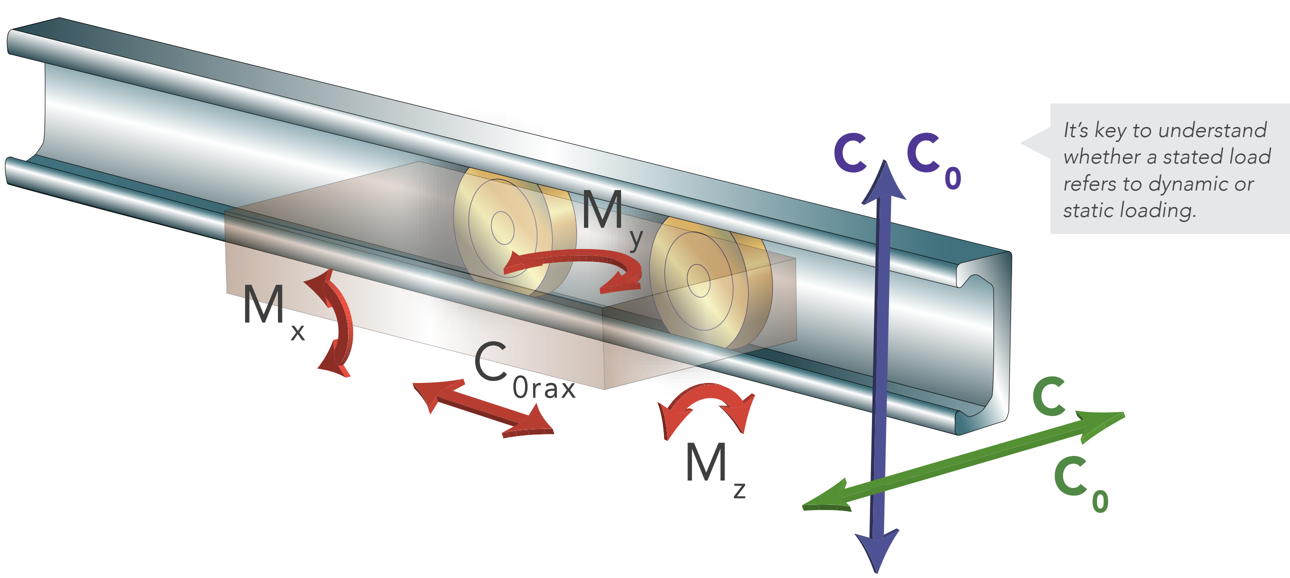
Now let's consider static load capacity C_0 — the amount of very slow or nonmoving load a bearing can withstand before total bearing element and raceway deformation equals 0.01% of the bearing element's diameter. Significant static loads in real applications can arise from shock loading. That's why many manufacturers recommend the specification of linear guides with a static safety factor to suit the application's actual operating conditions:

$$\text{Static safety factor} = \frac{C_0}{F_{0max}}$$

Where F_{0max} = maximum combined static load applied to the bearing. Typical safety-factor values range from two for very smooth-running axes (not subject to vibrations) to six for linear axes subject to extreme shock loading.

Note that the Rockwell scale hardness of the linear guide subcomponents is relevant here. Many raceways have a Rockwell scale Rc of around 60. Softer raceways diminish static and dynamic-load ratings.

STATED LOAD — DYNAMIC OR STATIC



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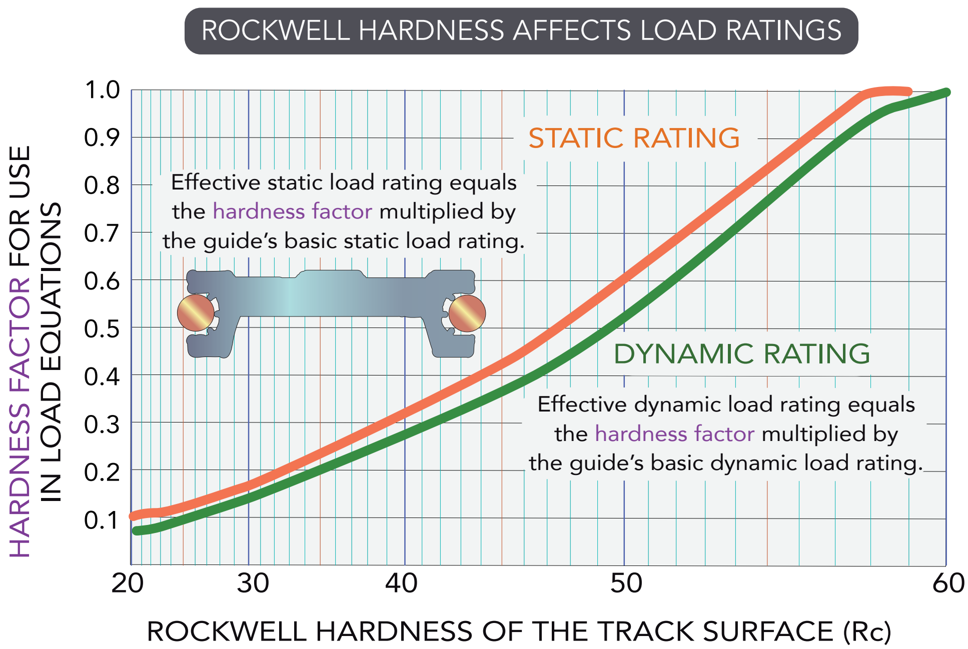
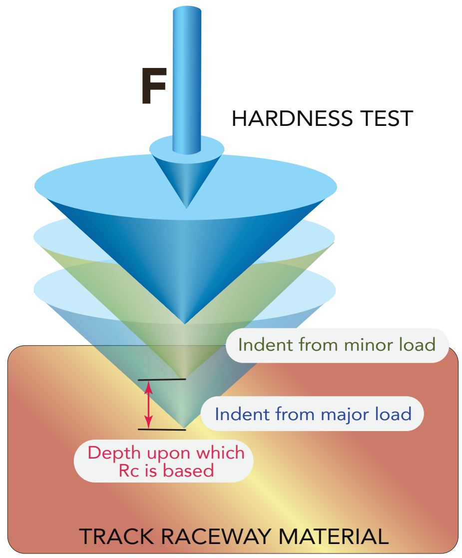
DYNAMIC LOAD AND STATIC LOAD CAPACITY FOR THE SPECIAL CASE OF TRACK-ROLLER LINEAR GUIDES

Note that the thick tread of track-roller wheels undergo elastic deformation under high radial loading. These wheels are subject to internal loading and OD bending stress that differs from those experienced by rotary bearings of otherwise similar construction. That's why the wheels are subject to permissible radial-load limitations .. and bending stresses must never exceed the tread material's strength values … or else fracture may occur. What's more, the basic load ratings of a track-roller wheel depend on its use on a track of specified surface finish and hardness. Use of any other track necessitates a modification of the assembly's load rating.

Track-roller life is calculated by the equations defined in DIN ISO 281 and then modified for loading, environmental, and safety factors for an adjusted life rating.

The Rockwell scale hardness of the linear guide subcomponents affects its ratings. Adjustments are required if the design (for one reason or another) necessitates softer raceways.





FIVE THINGS TO CONSIDER IN VERTICAL APPLICATIONS

Mounting orientation is one of the core considerations when sizing and selecting a linear actuator. Depending on the type of linear guides used, some actuators can support higher downward or lift-off loads than side loads or can handle pitch and yaw moments better than roll moments. These are all important factors when evaluating an actuator for vertical duty. The type of drive mechanism also influences an actuator's suitability for vertical operation. Screws (whether ballscrews or leadscrews) are generally preferred over belts or linear motors for carrying loads vertically, but they do have some limitations.

The unique challenges of working against (and sometimes with) gravity go beyond just loading. Below are five factors that designers and engineers should consider when choosing a linear actuator for vertical duty.

LOADING IN VERTICAL APPLICATIONS

While load placement and orientation are two of the first parameters to examine in any application, it is worth emphasizing for actuators mounted in a vertical orientation. Because the actuator will be working against gravity during the upward stroke and will be assisted by gravity on the down stroke, the loads in each case will be different, regardless of the process (pressing, pulling, or transporting, for example). This will affect not only the bearing life of the guides and drive mechanism, but also the required motor torque. In addition, the force of gravity on the load when starting and stopping will influence the inertia of the system, which also influences suitable actuator selections and proper motor sizing.

In a vertical application, it's generally recommended that engineers specify two track-roller carriage blocks on each linear-guide track. This ensures that the assembly can support the pitch and yaw moment loads that arise during acceleration and deceleration.

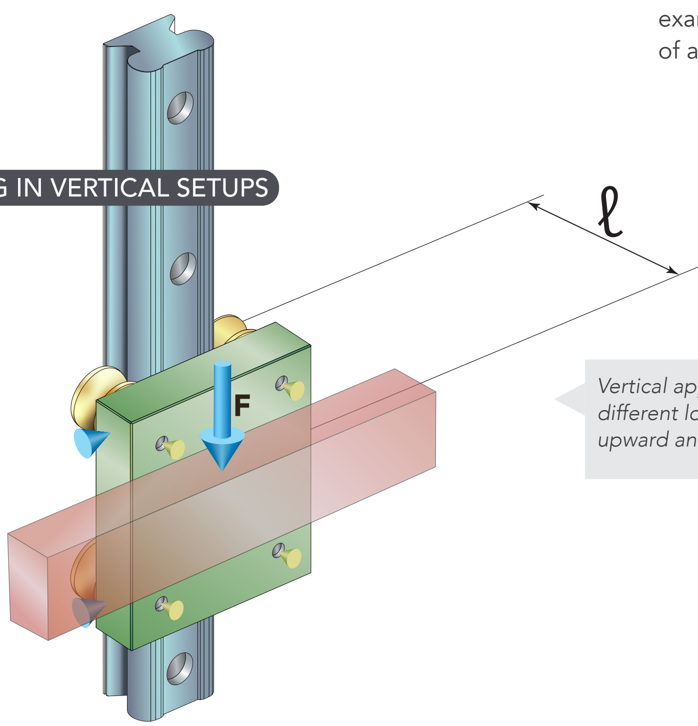
Similarly, using an actuator with two linear guides in parallel will enable the actuator to handle any roll moments that arise from a load that is not even distributed, or from external forces due to the process.

The best scenario if space allows is to choose an actuator that uses linear-guide tracks with two track-roller carriage blocks each.

LUBRICATION IN VERTICAL APPLICATIONS

As mentioned earlier in this Design Guide, track-roller linear guides have only modest lubrication requirements. That makes them excel on vertical axes that can cause detrimentally inconsistent lubrication on designs based on profiled rail, for example. That's because gravity can starve the highest portions of a linear guide (as well as its actuator's screw) of lubrication.

LOADING IN VERTICAL SETUPS



Vertical applications experience different loading conditions in the upward and downward strokes.

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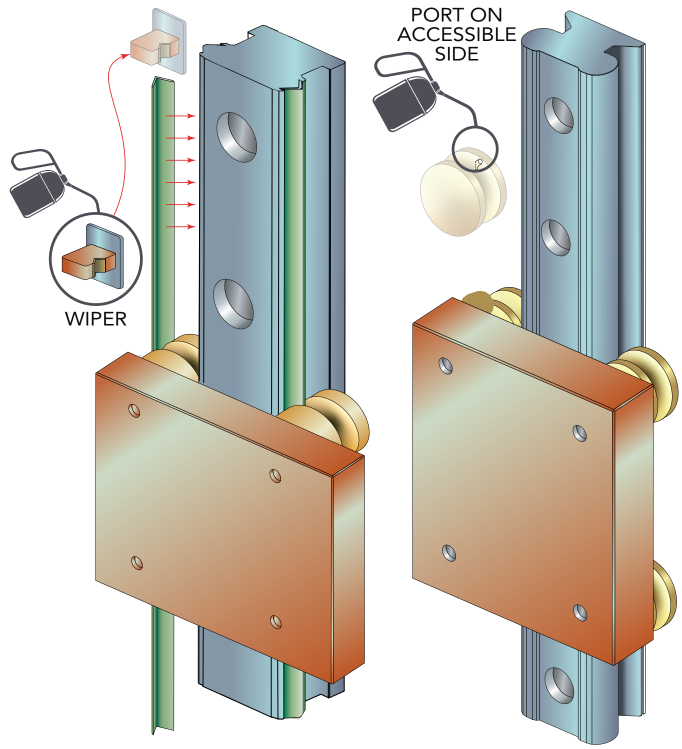
FIVE THINGS TO CONSIDER IN VERTICAL APPLICATIONS

Using the correct ports is critical for ensuring that linear guides and drives are properly lubricated in vertical applications.

LUBRICATION IN VERTICAL SETUPS



Where track-roller wheels destined for vertical axes do require lubrication, it's key that design engineers specify versions that will give plant personnel or other end users ready access to lubrication ports.

Manufacturers publish lubrication guidelines for vertical mounting. In many cases, these guidelines recommend against using oil. For grease lubrication, the assembly will often have specially metered lubrication pathways to ensure the grease reaches all critical surfaces.

BUCKLING LOAD IN VERTICAL APPLICATIONS

When using a ballscrew or leadscrew in a vertical application, the full load is experienced as an axial force, which can cause the screw to bend and eventually buckle under the load.

Buckling load is determined by the screw's root diameter, unsupported length, and end bearing arrangement. The end bearing arrangement has a significant influence on buckling load. The more rigidly fixed the screw assembly is, the higher its permissible buckling load will be. For example, a screw with a fixed-fixed bearing arrangement has 16 times the permissible buckling load than a screw with fixed-free end mounting.

$$F_c = f_b \cdot \left(\frac{d_1^4}{L^2} \right) \cdot 10^4$$

Where F_c = maximum compressive load (N)

f_b = End bearing factor

d_1 = root diameter of screw (mm)

L = unsupported length (mm)

Arranging the screw with the fixed bearing on the top will put the screw in tension, which in turn avoids excessive compressive forces on the screw. Most ball or leadscrew actuators are constructed with the fixed bearing on the driven (motor) end, but it's important to check the bearing arrangement and ensure the actuator is mounted in such a way that the fixed bearing is on the top.

BACK DRIVING IN VERTICAL APPLICATIONS

For safety reasons, screws are preferred over belts or linear motors in vertical applications, as they help prevent loads from catastrophically crashing if there's a loss of power to the motor. However, they can (and often will) backdrive. The odds of the latter occurring depend on the screw's friction, lead angle, and

(continued)

FIVE THINGS TO CONSIDER IN VERTICAL APPLICATIONS

efficiency. In general, leadscrews have a lower tendency to backdrive, due to their lower efficiencies.

The likelihood of a screw assembly backdriving can be determined by calculating the backdriving torque and comparing it to the friction force of the assembly (drag torque of the nut, friction from the seals, and friction from the end bearings). If the backdriving torque is less than the assembly's friction, the load is unlikely to cause backdriving.

$$T_b = \frac{\left(F \cdot P \cdot \eta_2\right)}{2\pi}$$

Where T_b = Backdriving torque (Nm)

F = axial load (N)

P = Screw lead (m)

η_2 = Reverse efficiency (0.8 to 0.9 for ballscrews)

Note that efficiency when backdriving is typically less than the efficiency for normal operation. Be sure to check the manufacturer's specification for the backdriving efficiency.

CONTAMINATION IN VERTICAL APPLICATIONS

Actuators in vertical orientations benefit from how liquid contamination typically drains away, reducing the risk of corrosion. However, very fine and light particulates such as fiberglass and ceramic powder on profiled rail in such arrangements are more likely to adhere to the rail surfaces instead of being pushed away end seals. That in turn can cause contamination buildup and increased risk of dirt ingress into the bearing's inner workings. So to ensure the best protection in vertical applications, linear guides with both front and side seals should be used.

Actuators with their own accordion coverings or full-contact seals (going beyond simple cover plates) are another option against both airborne and liquid contamination on vertical axes. Yet another option is to employ track-roller linear guides not vulnerable to contamination issues.

APPENDIX: ENGINEERING REVIEW OF REPEATABILITY, ACCURACY, AND INERTIAL VALUES

There are numerous ways to classify the performance of linear-positioning devices such as ballscrews, belts, and rack and pinion systems … but the terminology can be confusing. The two most common terms of accuracy and repeatability are often used interchangeably. So when someone says that a ballscrew is very accurate, they may really mean that it's repeatable. In fact, accuracy and repeatability are unrelated. A system can be very accurate but not very repeatable, or vice-versa. Here's the difference …

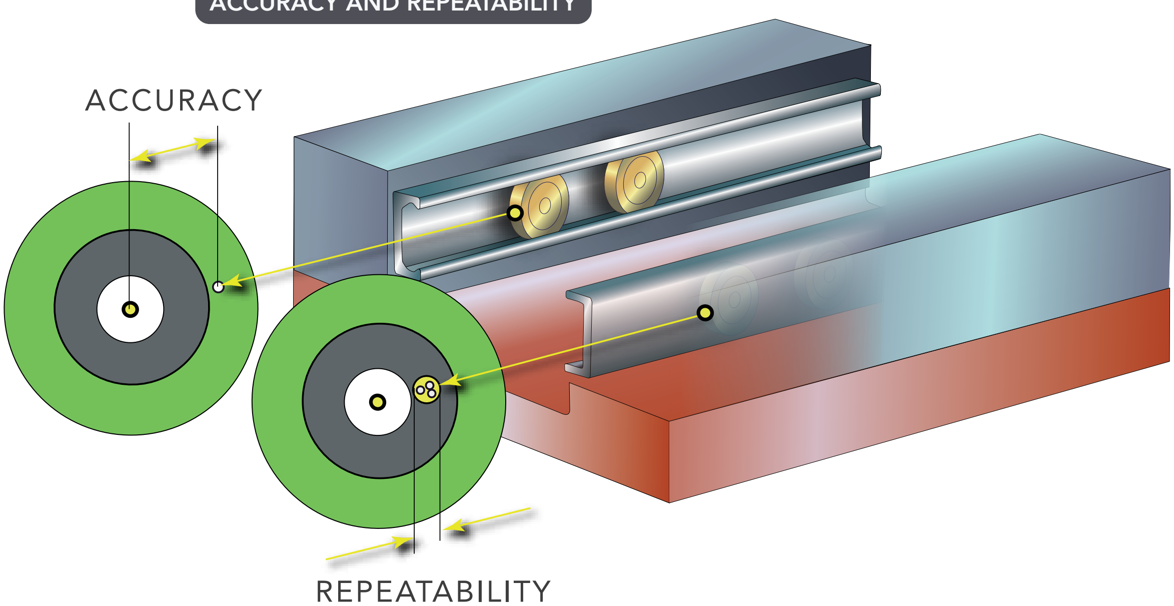
The formal definition of accuracy is the degree to which a measurement, calculation, or specification conforms to the correct or known value or standard. In relation to a linear drive system, this can be taken to mean the degree to which the final position matches the commanded position. So, if we command a rack and pinion system to travel 535 mm, its accuracy is determined by how closely it achieves 535 mm of motion. But how accurate is it? That depends on the amount of error you're able to accept. If the application will allow a result of 535 mm ±2 mm, then as long as the ballscrew achieves a position between 533 and 537 mm, it can be considered accurate.

Accuracy is most influenced by mechanical factors such as backlash, windup (lack of torsional stiffness), and flexing of components. On the electrical side, the bandwidth of the control system and the resolution of the measuring system (encoder or resolver) can also affect the accuracy of the drive's movement, since these components are responsible for commanding, reading, and correcting the actual position of the system.

Repeatability is a drive mechanism's ability to return to the same position multiple times under identical conditions. Repeatability can be defined as unidirectional, in which the point is always approached from the same direction, or bidirectional, in which the point can be approached from either direction. Unlike accuracy, which is somewhat subjective depending on the application requirements, repeatability is an absolute value.

For example, a ballscrew can be described as being repeatable to ±0 μm. Just as a system can be accurate but not repeatable, it can also be repeatable but not accurate. For example, if the specified movement is 535 mm ±2 mm, and the system consistently moves to 537.5 mm over several attempts, it is repeatable, but not accurate.

ACCURACY AND REPEATABILITY



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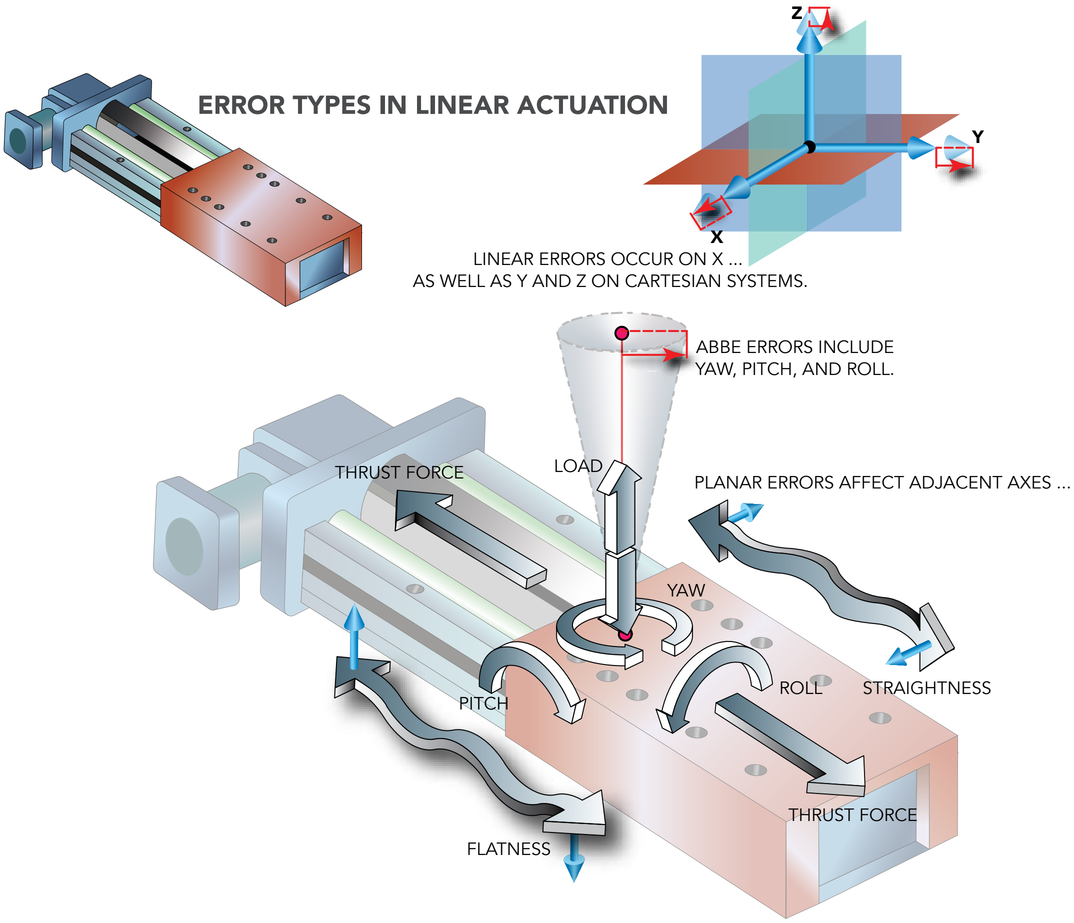
APPENDIX: ENGINEERING REVIEW OF REPEATABILITY, ACCURACY, AND INERTIAL VALUES



Factors that most influence repeatability are in the mechanics of the drive system — backlash in a rack and pinion system or lead deviation of ballscrew threads. Repeatability can also be affected by changes in the system such as expansion or contraction of components due to temperature fluctuations. While programming within the drive amplifier and control can generally compensate for a lack of accuracy, it generally can't correct for a mechanical system's lack of repeatability.

For an example from sports, let's consider a basketball player. If the player is accurate, he'll always get the ball close to the hoop. If his shooting is repeatable, he'll always shoot to the same location (hopefully, in the basket). The best players are both accurate (hitting the basket) and repeatable (doing it every time).

One last note: The term precision is often used to describe linear systems. However, precision is more applicable to measuring systems, where it refers to the variation between repeated measurements of the same quantity or subject. But when used in reference to linear motion systems, precision can reasonably be assumed to mean repeatability, although technically it is just a qualitative term in this context.

DIFFERENCE BETWEEN INERTIA AND MOMENTUM

The concepts of inertia and momentum are often confused — possibly due to the similarity of their definitions. Inertia is generally described as an object's resistance to motion, with momentum being the tendency of an object to continue moving. Both have implications for linear motion applications, but while inertia is a fundamental sizing parameter, momentum isn't directly addressed in system calculations. To distinguish between the two and find out why that is, we'll look at the definitions and uses of each.

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APPENDIX: ENGINEERING REVIEW OF REPEATABILITY, ACCURACY, AND INERTIAL VALUES

Inertia is resistance to change in speed: Inertia is a body's resistance to change in speed and is related to its mass and the distance of that mass from the axis of rotation. The classic illustration of inertia is a figure skater spinning on the ice. When her arms are outstretched, a part of her mass is far from the axis of rotation, and therefore she spins at a relatively slow speed. But if she pulls her arms in close to her body, her rate of spin increases, because her entire mass is now close to the axis of rotation $\mathbf{I = mr^2}$ where I = mass moment of inertia ($kg{\cdot}m^2$ or $lb{\cdot}ft^2$); m = mass (kg or lb); and r = distance from axis of rotation (m or ft).

Note that this is a general equation for the inertia of a point mass. Specific equations are available for various shapes, such as hollow cylinder, solid cylinder, disc, and so on.

Momentum is mass in motion: Momentum, on the other hand, is the product of an object's mass and velocity, and is sometimes referred to as mass in motion. While a change in shape — the distance of mass from the axis of rotation — will change a system's inertia, the momentum of a system cannot be changed unless an external force acts upon it. This principle is known as the conservation of momentum. The classic example of momentum is a game of billiards. Think of a moving ball, such as the cue ball, colliding with a non-moving ball. If the cue ball stops moving (v=0) its momentum has been completely transferred to the second ball. If the collision results in both balls moving, then the cue ball's momentum is shared by the two balls.

The equation of momentum for a linear system is simply:

P = mv

Where P = momentum ($kg{\cdot}m/sec$ or $lb{\cdot}ft/sec$)

m = Mass (kg or lb)

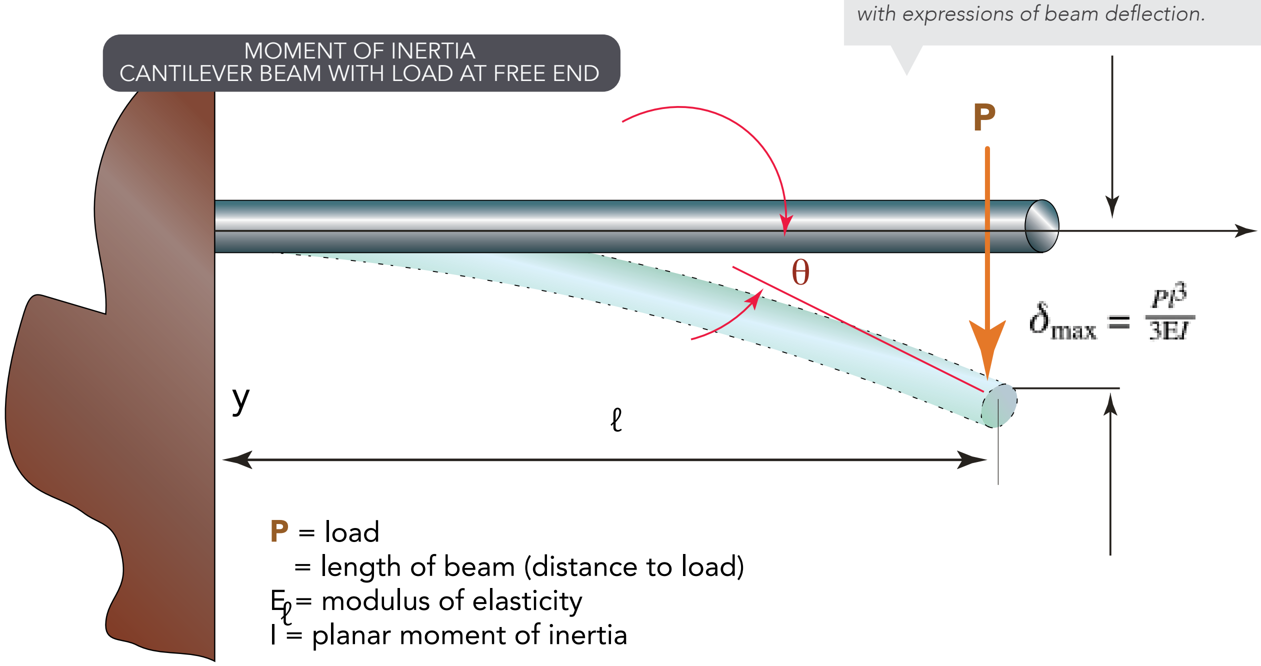
v = Velocity (m/sec or ft/sec).

This equation neatly correlates with the earlier description of momentum as *mass in motion*. But when the motion is rotational, the distance of the mass from the rotational axis comes into play. Therefore, angular momentum is expressed as the product of rotational inertia and angular velocity:

$\mathbf{L = I\,\omega}$

Where L = angular momentum ($kg{\cdot}m^2/sec$ or $lb{\cdot}ft^2/sec$)

This cantilever beam with a concentrated load at the free end shows the values associated with expressions of beam deflection.



(continued)

APPENDIX: ENGINEERING REVIEW OF REPEATABILITY, ACCURACY, AND INERTIAL VALUES

I = Rotational moment of inertia ($kg{\cdot}m^2$ or $lb{\cdot}ft^2$)
ω = Angular velocity (rad/sec)

For motion applications, inertia is an important factor in motor sizing calculations. If the motor's inertia is significantly smaller than the inertia of the load or system, the motor will have difficulty driving and controlling the load, and response time and resonance will be high. Conversely, if the motor inertia is much greater than the load or system inertia, then the motor is likely oversized, and the system will be inefficient.

Although momentum is not directly considered when sizing motion components, its effect is evident. Back to the ice skater example: it's the conservation of angular momentum principle that dictates that the skater's speed must increase when her arms are pulled in close to her body.

By reducing her inertia ($I = mr^2$ where r has been decreased) her angular velocity, ω, must increase in order for the angular momentum to remain constant.

MOMENT OF INERTIA — AREA OR MASS?

Moment of inertia is an important parameter when sizing and selecting a linear system. But it's critical to know which type of inertia (planar moment of inertia or mass moment of inertia) is given and how it affects the performance of the system.

Planar moment of inertia: Planar moment of inertia (also called second moment of area, or area moment of inertia) defines how an area's points are distributed with regard to a reference axis (typically the central axis) and therefore its resistance to bending. Terminology varies and sometimes overlaps for planar moment and mass moment of inertia.

If it's unclear which type of moment is specified, just look at the units of the term. Planar moment of inertia is expressed as length to the fourth power (ft^4 or m^4). I = ∫∫ x 2 dA where I = planar moment of inertia; x = distance to reference axis; and dA = element of area.

Second moment of area can be either planar or polar.

Polar moment of inertia describes an object's resistance to torque, or torsion, and is used only for cylindrical objects. The equation for polar moment of inertia is essentially the same as that of planar moment of inertia, but the distance used is distance to an axis parallel to the area's cross-section:

$$I = \int\int r^2 \, dA$$

Where I = polar moment of inertia
r = Distance to reference axis
dA = Element of area

The planar moment of inertia of a beam cross-section is an important factor in beam deflection calculations, and it is also used to calculate the stress caused by a moment on the beam. In linear systems, beam deflection models are used to determine the deflection of cantilevered axes in multi-axis systems. Unsupported shafts are also analyzed using beam deflection calculations.

MASS MOMENT OF INERTIA

Mass moment of inertia (also referred to as second moment of mass, angular mass, or rotational inertia) specifies the torque needed to produce a desired angular acceleration about a rotational axis and depends on the distribution of the object's mass (including a shape) around the axis. It has the same relationship to angular acceleration that mass has to linear acceleration. Mass moment of inertia, like planar moment, is typically denoted I but unlike planar moment, the units for mass moment of inertia are mass-distance squared — $slug{\cdot}ft^2$ or kgm^2.

The mass moment of inertia equation for a point mass is simply $I = mr^2$ where I = mass moment of inertia; m = point mass; and r = distance to axis of rotation.

For a rigid body, the mass moment of inertia is calculated by integrating the mass moment of each element of the body's mass $I = \int r^2 \, dm$ where I = mass moment of inertia; dm = element of mass; and r = distance to axis of rotation.

When sizing linear systems, the most important use for mass moment of inertia is probably in motor selection, where the ratio between the load inertia and the motor inertia is a critical performance factor.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