Best Practices

FOR SELECTING AND SIZING GUIDE WHEELS

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Introduction

For over 40 years, Bishop-Wisecarver has been developing best practices for matching guide wheel systems to customer requirements based on engineering and empirical experience. By sharing this knowledge and experience, selecting a guide wheel with the properties best-suited for a given application becomes easy and results in a system that reduces design costs and engineering changes, as well as lower warranty, assembly, installation and mounting costs.

Linear guide systems are chosen for an application based not only on their precision and speed characteristics, but also on a host of other operating conditions such as environment, length, speed, duty cycle and temperature, to name a few. Guide wheel systems should not be overlooked; in many applications and environments they have notable advantages.

Well-known for their ability to outperform re-circulating ball technology in harsh environments due to their completely enclosed ball bearings and raceways, guide wheel sys-
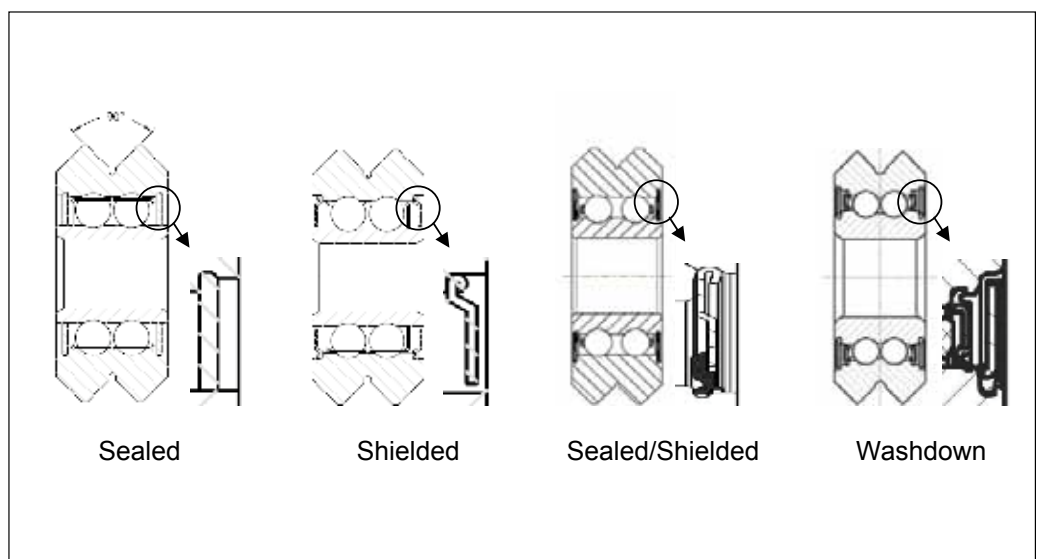

| Sealed | Shielded | Sealed/Shielded | Washdown |

Figure 1—Application environment determines the type of required guide wheel bearing protection.

tems also have other lesser-known yet distinct advantages. They routinely operate in environments with low noise level requirements, high (up to 500° F) or low (as low as −94° F) operating temperatures, wash-down practices, high humidity and/or very long travel lengths. They can meet flatness, parallelism and straightness tolerances as tight as ± 0.001" (± 0.03 mm), and, compared to other linear guide systems, guide wheels have less friction, are much faster to assemble and are very cost-efficient.

By matching the component properties of a guide wheel system to a given application, engineers can ensure trouble-free operation over the system's predicted lifespan—as well as reduced costs, lead time and field failures. The types of wheel and track selected must be matched to all application requirements, including environment, loads, accuracy, life cycle and cost. Bishop-Wisecarver has developed the following process for ensuring the best match of guide wheel system to application, beginning with the operating environment to calculate the required size of the wheel.

Bearing Type Selection

The environment determines the type of guide wheel bearing protection required.

Sealed. Environments with heavy concentrations of liquid or fine/powdery particulates can displace and/or change the properties of the bearing lubricant, causing premature wear and failure of the bearing balls and raceways. Specifying a sealed bearing for this operating environment can prevent damage to the bearing elements, ensuring the predicted lifespan of the system.

Shielded. Generally, shielded bearings are used in environments with heavy concentrations of large particulates—such as metal flakes—that can work their way between the balls and bearing raceways. The larger debris can cause premature wear and damage—i.e., brinelling or spalling.

Sealed and shielded. Bearings that feature shields *and* seals offer the advantages of both sealed and shielded wheels. The shield protects the seal from damage by large particulates while the seal protects the bearing elements from the fine particulate and liquid that the shield is less effective against.

Special configurations. The wash-down bearing includes a patented inner seal and outer shield design. The design of the outer shield allows it to act as a momentary seal while pressure from high-velocity fluid causes the shield

to deflect and conform to the wheel's metallic surface. When the pressure is removed, the shield returns to its normal position, allowing any liquid and debris that entered between the shield and seal to drain out or be spun out by centrifugal force.

(Author's Note: In contaminated environments, a de-rating factor based on the severity of the contamination must be used for sizing. This is discussed later in Load/Life Equation—Sizing and Selection.)

Selection of Wheel, Track and Bearing Material

Wheels. Wheels are available in a variety of materials to suit a wide range of applications. The most commonly used materials are 440C stainless steel, 52100 carbon steel and polymer. Stainless steel materials should be used in humid, liquid and corrosive environments. Although highly corrosion-resistant, some corrosion can in fact occur with stainless steel, depending on the severity of the environment. Polymer wheels offer certain benefits, including chemical resistance, low friction and low noise. Polymer wheels have reduced load performance versus steel wheels, but polymer wheels are an economical choice for light-load applications and harsh chemical environments.

Track: Standard track materials include AISI 1045 carbon steel and AISI 420 stainless steel; other track materials include aluminum, which can be used with polymer guide wheels. The 1045 is a medium-carbon steel with good strength and hardness properties (53 HRC hardened; 22–25 HRC unhardened) that minimizes wear. The 420 stainless steel contains just enough chromium to limit corrosion, yet can be hardened up to 45 HRC (20–22 HRC unhardened).

Stainless or carbon steel track are equally effective in environments with heavy concentrations of large particulates and flakes, because contaminants are swept away when the wheel passes over the track. Since the wheel has a smaller diameter at its inner-V compared to its outer-V, the wheel's inner-V travels at a slower rate than the outer-V on the track. This creates a velocity gradient that pushes the debris outward, resulting in an especially clean track.

When selecting the track material, it is generally advised not to specify a material softer than the wheel material, as this can result in the track material galling onto the wheel, damaging the track, wheel and payload, and

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requiring time-consuming and expensive repair of the system. However, a notable exception to this rule is that it *is* acceptable to use hardened steel-track material with steel wheels—despite the track having marginally less hardness than the wheels.

Operating Temperature and Lubrication

As stated, guide wheels can accommodate up to 500° F for operation in environments with high temperatures, and as low as −94° F for operation in low-temperature applications.

If accuracy is crucial, stainless steel wheels can be heat treated to the point where they become very thermally stable, thus minimizing growth. For example, carbon steel, stainless steel and polymer wheels all can withstand the temperature and duty cycle of autoclaving. To sterilize instruments and equipment, an autoclave must reach a minimum of 121° C (250° F) for 30 minutes.

Lubrication is key in maintaining a long service life and minimizing field failure. Internally, guide wheels are lubricated for life with an extreme pressure- and corrosion-resistant grease, but the lubrication of the wheel/track interface is the responsibility of the user. Lubricator assemblies prevent damage to bearings and help prevent corrosion—even in stainless steel systems. In our experience, most bearing failures are caused by either an inadequate, incorrect—or complete lack of—lubricant.

In high-temperature operating environments, lubrication is especially important. Friction caused by the wheels rolling across the
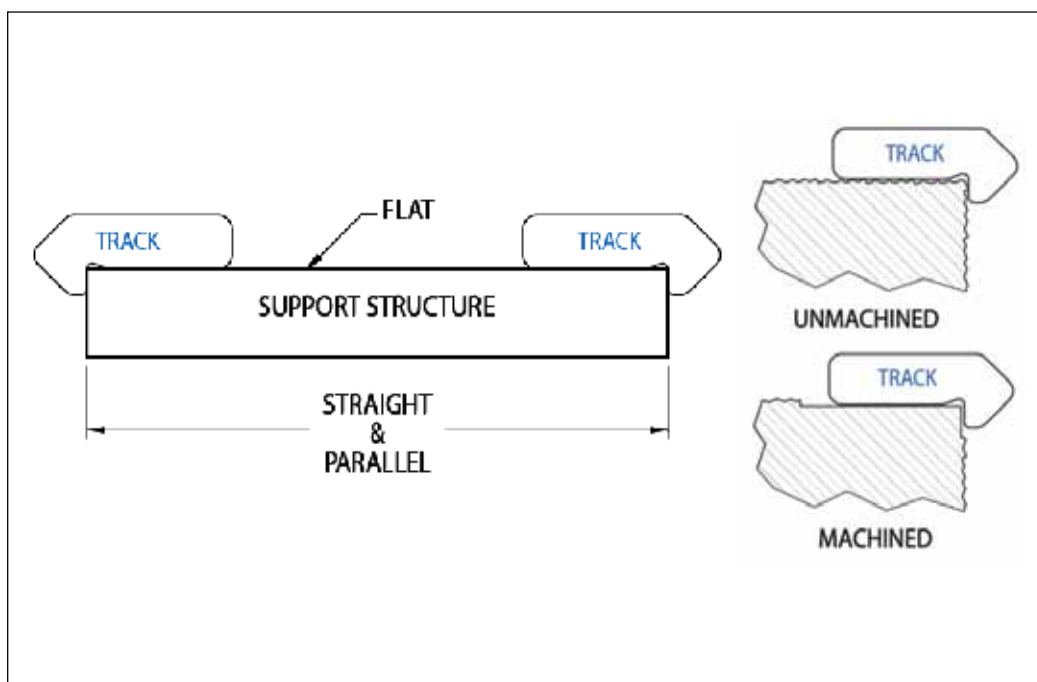

Figure 2—Cold-finished or extruded bar plate is accurate enough to serve as the support structure for most applications, although greater accuracy can be obtained by machining the surfaces on the support structure used for mounting the track.
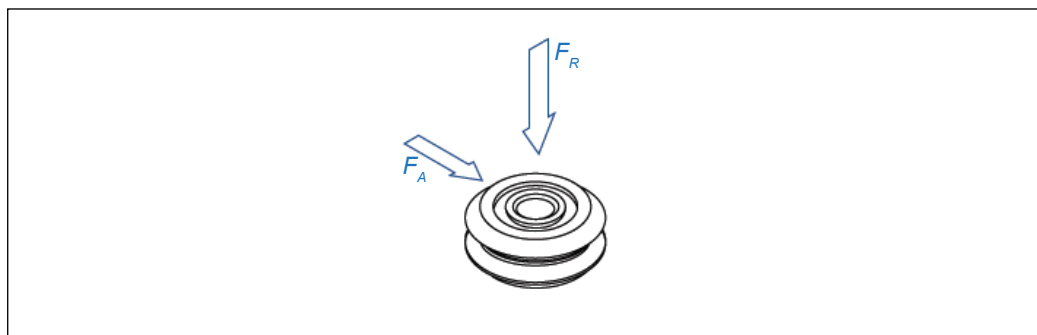

Figure 3—Service life of a properly designed guide wheel system is limited to that of the most heavily loaded wheel bearing. In typical scenarios, start with determining whether the loads are radial and/or axial.

track generates additional heat at their interface that can lead to excessive heat buildup in the wheel and cause the contact surfaces to gall. This potentially leads to excessive brinelling or spalling on the rolling contact surfaces—and eventual premature failure of the system. The use of guide wheels with high-temperature grease and proper track lubrication will help decrease friction-generated heat buildup and protect against premature system failure.

Noise

Industrial environments generally tend to be forgiving of loud noise. However, noise is an issue in applications that are in proximity of the general public. For example, patients can be unnerved when in contact with noisy medical devices; noisy guide-way systems for CAT scans and MRI equipment can make patients needlessly uncomfortable. Guide wheel technology can effect a 20% noise reduction, as compared to square-rail or round-rail systems.

The ball bearings in a guide wheel follow a constant radius raceway path, while the ball bearings in square rails follow an oval raceway path with widely varying radii. A square rail has straight sections with radii at the ends, and thus a 180° arc. The ball bearings move along alternating straight and semi-circular paths, forming a complete circuit. The sudden change in the ball's trajectory when transitioning from the straight to the semi-circular section precipitates heightened noise and vibration. Occasionally, polymer cages are used to reduce the noise of the ball bearings, but they are not completely effective.

Tolerances and Track Mounting

The track does not require additional, costly grinding and finishing operations to achieve tight tolerances. The flatness, straightness and parallelism of the support structure surface on which the track is mounted or bolted determine the accuracy of the linear guide system. As such, designs requiring less accuracy will also require less surface preparation and, therefore, will result in significant time and cost savings.

For example, if only ±0.004-in. tolerances are required, a guide wheel system can be bolted to a less-than-even surface; surface preparation is minimal and installation time and costs are low. However, for systems requiring ± 0.001 in., better mounting-surface preparation is required.

Loads

The service life of a properly designed guide wheel system is linked with that of the most heavily loaded wheel bearing. Therefore, loads must be evaluated to predict lifespan and minimize warranty and in-field repair costs. However, load evaluation can be fairly tricky; it therefore is extremely important to understand *exactly* the conditions under which the guide wheel will be used.

Generally, we start with determining whether the loads are radial and/or axial:

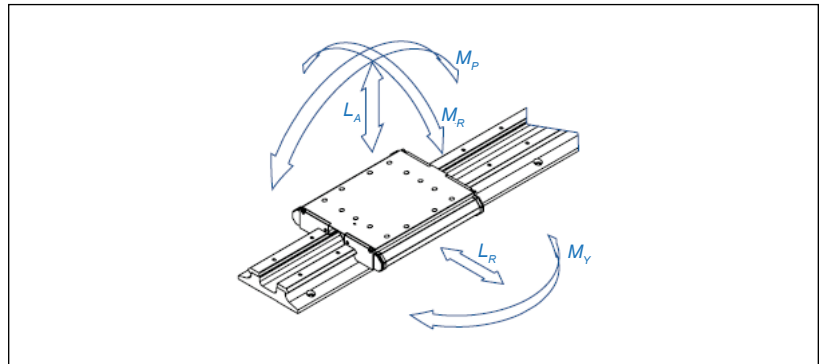F_R: Radial load refers to the load applied in a direction perpendicular to the axis of

Figure 4—Systems with guide wheel-equipped wheel plates can be used in both linear and moment loading conditions.
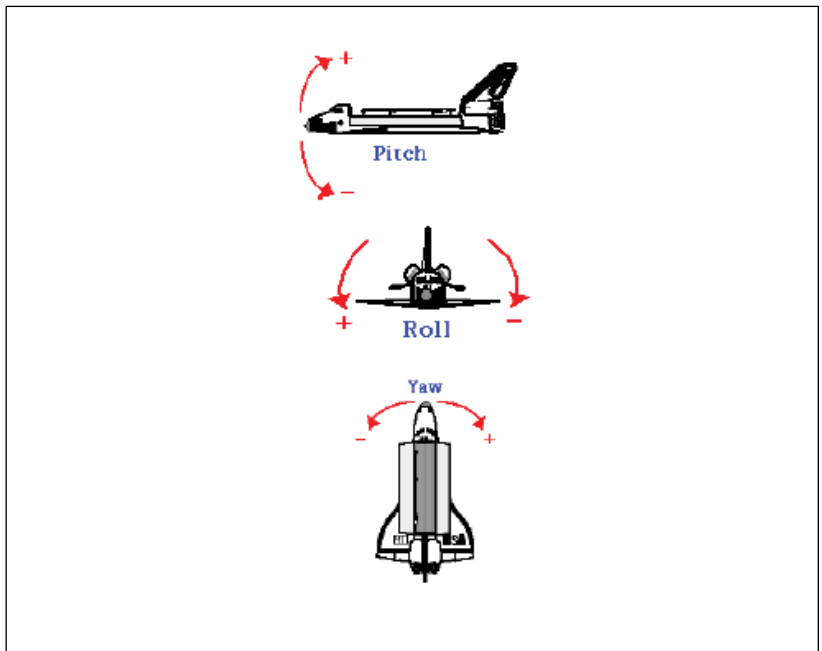

Figure 5—M_P is a "moment load" in the pitch direction. Pitch loading can be likened to an airplane climbing or descending. "Pitch moments" occur when a force wants to tilt the wheel plate up or down; M_R is known as "a roll moment." When an airplane banks left or right, this is considered movement in the roll direction. A roll moment occurs when the wheel plate is subjected to a load that makes the wheel plate want to tilt like an airplane banking; M_Y is a "yaw moment." Yaw occurs when an airplane turns left or right. The wheel plate is subjected to loading that impels the wheel plate to rotate left or right.

rotation.

F_A: Axial load refers to the load applied in a direction parallel to the axis of rotation.

We use a formula based on empirical data that is very easy to apply and reasonably accurate with regard to lifespan based on field experience. (*See* Load/Life Equation: Sizing and Selection.)

Standard bearing equations do not apply to wheels that are axially loaded, because the axial load is not uniform on the wheel. Axial loading will, in fact, result in a moment load on the wheel, causing uneven loading on the ball bearings—unlike a thrust bearing where the load is distributed equally on all the balls.

The wheel can accept higher moment loads by increasing the radial preload, but this leads to a much higher wear rate.

Systems with guide-wheel-equipped wheel plates can be subjected to both linear and moment loading conditions. Moment loads on a wheel plate are forces that cause torque loading around the wheel plate's coordinate axes.

Load/Life Relationship

Several factors influence the service life of a guide wheel system. We have devised a simple method to estimate the load/life relationship for a specific guide wheel system under defined loading conditions. This methodology accounts for the size of the bearing elements as well as

Table 1—Typical Guide Wheel Load Capacities: Steel & Stainless Steel							
Size		0	1	2	3	4	4XL
Axial F_A	N	123	252	625	1,701	4,001	6,552
	lbf	28	57	141	382	900	1,473
Radial F_R	N	650	1,220	2,650	5,900	9,700	14,300
	lbf	146	274	596	1,326	2,181	3,215

Table 2—Life Equation Adjustments	
Adjustment Factor (A_F)	Application Conditions
1.0 - 0.7	Clean, low speed, low shock, low duty
0.7 - 0.4	Moderate contaminants, medium duty, medium shock, low to medium vibration, moderate speed
0.4 - 0.1	Heavy contamination, high acceleration, high speed, medium to high shock, high vibration, high duty cycle

Table 3—Wheel Size/Life Constant L_C		
Wheel Size	Inches of Travel life	Kilometers of Travel Life
0	1.65×10^6	41
1	2.19×10^6	55
2	3.47×10^6	87
3	5.19×10^6	130
4	6.84×10^6	171
4XL	8.58×10^6	215

the relative spacing and load orientation, location and magnitude. The equation is based on clean, well-lubricated track conditions, so applications where lubrication is prohibitive require application of a de-rating factor.

It is important to note that secondary considerations such as maximum velocity; acceleration rates; duty cycle; stroke length; environmental conditions; shock and vibration; and extreme temperature ranges can all impact service life to varying degrees. As such, this sizing method is considered only as a guideline for guide wheel components and assemblies.

Load/Life Equation: Sizing and Selection

Load/life estimation requires a basic understanding of the principles of statics, the ability to work with free-body diagrams and the capacity to resolve externally applied forces on a wheel plate into the radial and axial reaction forces at each guide wheel in the design. The life of a guide wheel system is limited to the life of the most heavily loaded bearing in the design.

Step 1: *Calculate the resultant radial (F_R) and axial (F_A) loads reflected to each bearing element in the linear guide design.*

All standard considerations involved in statics calculations must be accounted for, including inertial, gravitational and external forces such as tool pressure, bearing element spacing and magnitude/direction of the payload. Any external forces that generate a reaction through the wheel/track interface must be considered.
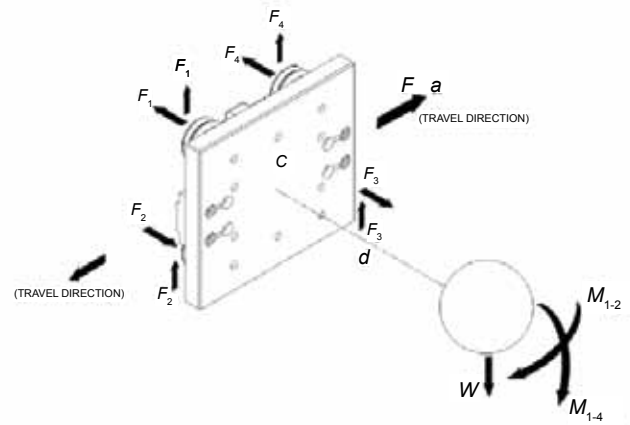
Step 2: *Calculate the load factor for the most heavily loaded bearing.*

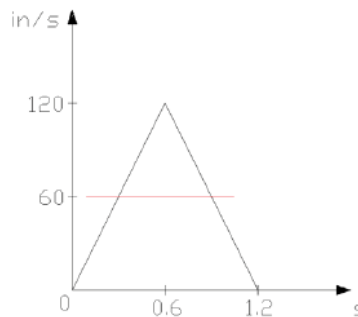$$L_F = \frac{F_A}{F_{A(max)}} + \frac{F_R}{F_{R(max)}} \qquad (1)$$

Where:

L_F	=	Load factor
F_A	=	Resultant axial load on guide wheel
F_{Amax}	=	Maximum axial working load capacity of guide wheel
F_R	=	Resultant radial load on guide wheel
F_{Rmax}	=	Maximum radial working load capacity of guide wheel

- Bearings should be sized such that $L_F \leq 1$
- The most heavily loaded bearing will have the highest load factor (See Table 1)

- Move 250 lb mass (24" x 12" x 12")
- Center of Gravity (CG) centered, *d* = 12.0
- 72" of travel in 1.2 seconds with a triangular velocity profile
- Orientation as shown with movement along the *Y*-axis
- Wheel spacing cannot be any larger than 10" apart in *Y* and *Z*-axis

V_{AVG} = 60 in/s
V_{MAX} = 120 in/s
Acceleration = (120 in/s) /(0.6 s) = 200 in/s^2 (0.52 G's)

Figure 6—Sizing DualVee guide wheels.

Step 3: *Calculate life by applying the load factor to the load/life equation below.*

Due to varying application load and speed parameters and environmental conditions, an appropriate adjustment factor must be applied to the life equation (See Table 2).
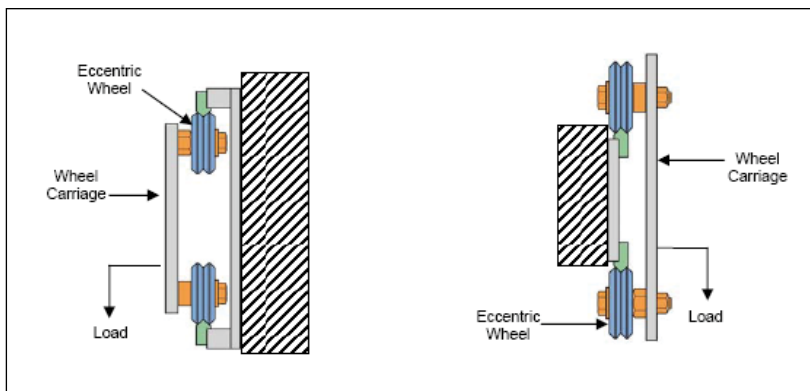
Figure 7—It is important to note that the optimal locations of the eccentric and concentric wheels relative to an applied radial load are dependent on whether the tracks are between or outside of the wheel plate's two rows of wheels.
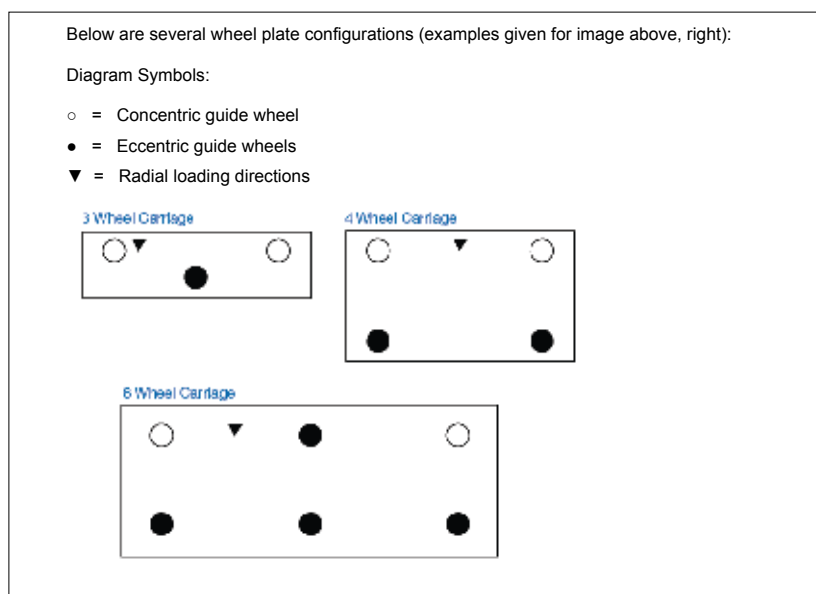

Figure 8—Wheel plate configurations for example shown in Figure 7/right.
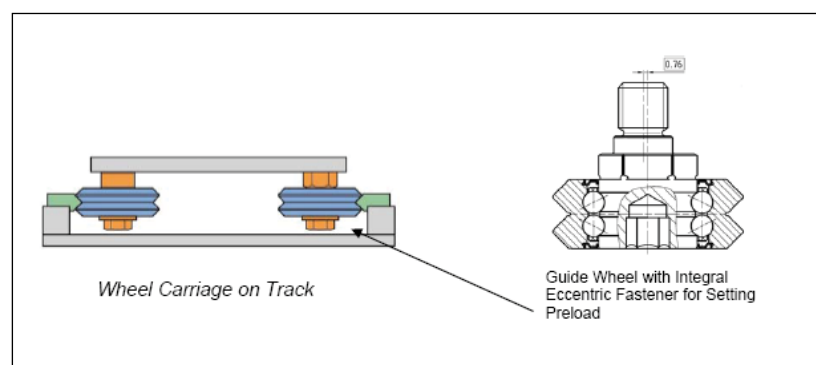

Figure 9—In assembling the system, the wheel plate should be placed on the tracks with no load attached and with the concentric wheels fully tightened and the eccentric wheels tightened just sufficiently to permit adjustment.

$$\text{Life} = \left(\frac{L_C}{(L_F)^3} \right) A_F \qquad (2)$$

Where:

L_F	=	Load factor
L_C	=	Life constant
A_F	=	Adjustment Factor

Calculation example (Table 3):

F_A	=	50 lbf
F_R	=	200 lbf
Wheel size	=	2
Environment	=	moderate shock loading and contamination with intermittent motion

Following the outlined procedure, we know the information from Step 1—radial (F_R) and axial (F_A) loads on each wheel—and are therefore ready to calculate that:

F_A	=	50 lbf
F_{Amax}	=	141 lbf
F_R	=	200 lbf
F_{Rmax}	=	596 lbf
L_F	=	50/141 + 200/596 = .69
$Life$	=	$3.47 \times 10^6 /(.69)^3 \times 0.6 = 6.33 \times 10^6$ inches of travel

Note that an adjustment factor of 0.6 was used due to the environmental influences.

How to Size DualVee Guide wheels

The versatility of DualVee allows for an infinite number of wheel plate sizes; for this example we will restrict the size to a particular dimension (spacing between wheels). Many applications entail size limitations due to space constraints (Figures 6–7).

Force due to load:

$\Sigma M_{1,4}$	=	$10"(F_{2,3}) + 12"(250 \text{ lbf}) = 0$
$F_{2,3}$	=	$300 \text{ lbf} \rightarrow$
F_2	=	$F_3 = 150 \text{ lbf (axial)}$
ΣF_X	=	$F_{2,3} + F_{1,4} = 0$
$F_{1,4}$	=	$300 \text{ lbf} \leftarrow$
F_1	=	$F_4 = 150 \text{ lbf (axial)}$
ΣF_Z	=	$250 \text{ lbf} + F_{1,4} = 0$
$F_{1,4}$	=	250 lbf
F_1	=	$F_4 = 125 \text{ lbf (radial)}$

Force due to acceleration:

$\Sigma M_{1,2}$	=	$12" (250\text{lbs}) (0.52 \text{ G}) + 10" (F_{3,4}) = 0$
$F_{3,4}$	=	$156 \text{ lbf} \leftarrow$
F_3	=	$F_4 = 78 \text{ lbf (axial)}$
Σ_{FX}	=	$F_{3,4} + F_{1,2} = 0$
$F_{1,2}$	=	$156 \text{ lbf} \rightarrow$
F_1	=	$F_2 = 78 \text{ lbf (axial)}$

Total force on highest-loaded wheel:

F_4 = 125 lbf (radial)

F_4 = 150 lbf (static loading) + 78 lbf (force due to acceleration) = 228 lbf (axial)

Estimated wheel life under ideal environmental conditions:

L_F = $L_A / L_{Amax} + L_R / L_{Rmax}$

$Life$ = $L_C / (L_F)$

For a size-3 wheel (given working load capacity of L_A = 382, L_R = 1,326):

L_F = 228 / 382 + 125 / 1,326 = 0.691

$Life$ = 5.19×10^6 in / $(0.691)^3$ = 1.57×10^7 in

Wheel plate configurations. In designing a wheel plate, it is important to use the right combination of eccentric and concentric guide wheels, as dictated by the configuration. The linear systems should always have two *concentric* wheels while the remaining guide wheels should be *eccentric.* The eccentric wheels are used to eliminate play (clearance) between the wheels and tracks and allow preloading of all the wheels so that they roll smoothly rather than sliding or skipping on the track. If the wheel plate is loaded in the radial direction, the concentric wheel should support as much of the radial load as possible.

It is also essential to recognize that the optimal locations of the eccentric and concentric wheels—relative to an applied radial load—are dependent on whether the tracks are between or outside of the wheel plate's two rows of wheels.

Figure 8 displays wheel plate configurations relative to the sample shown in Figure 9/right.

Preload

Wheel plate preloading creates radial loading between the wheels and tracks that exists when the system is not loaded by another outside force, and serves to eliminate play between the wheel and track. Preload is determined by:

Preload = measured wheel plate breakaway force number of wheels x coefficient of friction

Preload adjustment is accomplished by gradually rotating the eccentric wheel bushing(s) until the tracks are held captive by the two sets of wheels on each side of the wheel plate—with no apparent clearance between the tracks and wheels and very light preload. Once this is accomplished:

- Fasten the eccentric wheel(s) so that they hold their positions.
- Next, check each wheel for correct preload by rotating the wheel with your fingers, while holding the track stationary. The wheel should skid against the track with a small amount of resistance, but should still turn without much difficulty. If rotation is not possible, the preload should be reduced accordingly by readjusting the eccentric wheel(s).

Caution must be used when applying preload because too much preload on the wheels can cause premature failure. The rated radial load should never be exceeded by the preload and subsequent radial loads that are applied to the wheel when in service. Note that preloading cannot compensate for large variations in track parallelism tolerances, which can occur in long travel length systems.

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