



# The Recumbent Trike Design Primer

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*Version 8.0*

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## Introduction

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Back in 1993 I embarked on a project to design and build a recumbent tricycle. In those days the internet was still a novelty and specific information on recumbent trike design was dismal at best. Regardless, I set out to experiment. After 3 unsuccessful designs and 250 lbs of scrap aluminum, I finally built a trike that was almost road worthy. During my experimentation, I kept meticulous shop notes and when I wasn't tinkering in my garage I was spending time at the city library doing research.

Further refinements eventually produced a road worthy design which I placed into production. After producing three revisions and two product lines, my recumbent trike was now a force to be reckoned with. Unfortunately, my passion for recumbent trikes was eclipsed by my engineering career and family.

With my closed operations I focused my free time in transforming my shop notes into a recumbent trike primer and releasing it free to the world as a resource. The original document was released in 1997. Over the years I have added a few items, but it wasn't until recently that I took the time to completely clean it up and re-edit the original content. The document is clearly more legible and I'm certain that you will enjoy reading it.

This document focuses on the basics of recumbent tricycle design. In order to keep the concept elementary I have simplified many of the terms and explain the technology in detail at a level that most people will enjoy reading. If the explanations contained in this document do not address your concerns or doesn't present the 'big picture', please email me (Rick) at [trikesrcool@yahoo.com](mailto:trikesrcool@yahoo.com).

Offering plans for building a trike will only teach you how to build one. However, once armed with the information on making a great trike; you will appreciate the compromises and risks associated with designing your own trike.

If your desire is building a trike from a set of existing comprehensive plans, check out my Thunderbolt /Spitfire recumbent trike plans at <http://www.hellbentcycles.com>

## Tadpole and Delta Recumbent Trike Designs

Recumbent tricycles come in two configurations; the Tadpole having two wheels forward and one aft (2F1R), and the Delta having a single wheel forward and two aft (1F2R). Each of these configurations has their advantages and weaknesses.

### The Delta Configuration



*Above is the Anura Delta trike by Greenspeed*

#### Pros:

- Easy to design, concepts follow that of a standard bicycle
- Lower cost to manufacturer, uses standard bicycles components

#### Cons:

- Quick moment of inertia causes excessive roll. This condition can be corrected using a lean steering mechanism.
- Braking is compromised by a single front wheel which must provide the majority of braking for the vehicle.

### The Tadpole Configuration



*Above is the Innesenti tadpole trike built in the UK*

#### Pros:

- Two wheels in front offer excellent overall braking
- Overall excellent handling

#### Cons:

- Steering systems are more complicated and require unique parts
- Design is complicated and dependent on many contingencies

Before elaborating on the design overview, it is appropriate to offer some reasons why I prefer the two wheels front, one wheel aft design commonly referred to as the 'Tadpole' configuration. The most common tricycle design is the single wheel in front, two-wheel aft configuration (1F2R) referred to as the 'Delta' configuration. Although a well-designed Delta trike has many merits such as reduced cost, and complexity, it does not have the handling characteristics of a Tadpole design. Without going deep into physics to explain this comparison, I'll only mention that it has something to do with the Moment Of Inertia. In layman terms, a Tadpole trike's front-end exhibits less acceleration (less G forces) than the rear end when turning. This allows the trike to negotiate corners at great speed and stability. On the other hand, a Delta trike exhibits the opposite condition; where the vehicle's front-end exhibits a higher degree of momentary acceleration in comparison to the rear. This condition results in over-steering and can compromise the handling performance of the vehicle. Although the overall handling characteristics are dependent on the actual design of the vehicle, the Tadpole design comes out as the winner as for handling.

As for stopping, again the Tadpole has the major advantage. During braking, a vehicle weight displacement and force goes forward. This is why on all vehicles the major braking is performed on the front wheel(s). On a delta, only a single wheel exists. It doesn't take a rocket scientist to figure out that stopping with two front wheels is more effective than a single wheel.

A tadpole configuration uses the same steering geometry design principles as an automobile. Geometry considerations such as Caster, Camber, and Toe-End exist for this trike design just as they do on an automobile. In contrast, a Delta design uses geometry similar to that of a bicycle. The design objective for the Spitfire is to create a 'Cycle-Car', not a bicycle with a third wheel.

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## Tadpole Trike Variations

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**A**lthough a small niche market, recumbent tadpole trikes come in a plethora of configurations. In this section I have compiled a short list of features and technologies that describe the various types of tadpole trikes.

### Front Steering vs. Rear Steering

One gimmick that pops up periodically is a rear steering HPV. The rear steering concept has been applied to both Tadpole and Delta trike configurations without any staying success.



*Above is a rear-steered Sidewinder Pro cruiser*

Although the virtues of rear wheel steering include a simplistic design, lighter weight, a smaller turning radius, and an exhilarating and fun riding experience. However, the fact that the trike drives like a forklift makes it a losing proposition every time. Since people have a fascination with gimmicks, the rear steering trike will always have a place in the HPV industry.

### Lean Steering

A lean steering trike is a three wheeled vehicle that steers by virtue of leaning the rider's body into the desired direction of the turn. Although several variations exist, the most notable implementation is where the seat moves in relation to the frame causing the vehicle wheels to turn or alter the wheel geometry. A stationary horn or tiller is fixed to the frame (this can also be a U-bar) allowing the rider to lean the seat left or right (the seat is linked to a steering mechanism), hence steering the vehicle. Since the rider leans into the direction of the turn, the center of gravity is optimized producing a trike with excellent low speed handling. The concept is similar to steering a bicycle with one obvious exception: the leaning is linear to the steering and not by the G forces applied. Consequently, the steering in this implementation is not optimized for higher speeds. Please note that the example explained here may not be characteristic with all lean steering tricycles.

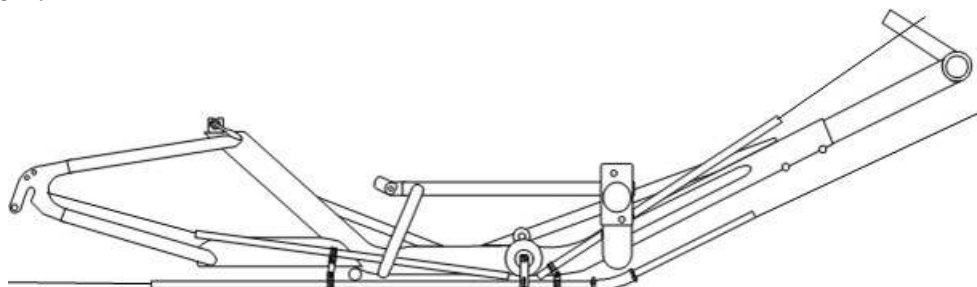


*Above are two examples of Lean Steer technology. The left image is a Tiefflieger trike. On the right is the front view image of a Tripendo.*

Lately, there have been other implementations of the lean steer trike that allow the front wheels to lean into the direction of the turn. Not only does this enhance the handling characteristics of the trike, it also relieves the wheels from side-loading allowing larger diameter wheels. As with most emerging technology this concept is relatively new, requiring future improvements to make it practical. The main premise of a trike is to provide a stable platform that does not require balancing. Although lean steering has the potential of optimized handling at lower speeds, it does require equilibrium to master. As with rear steering, this is yet another gimmick that comes and goes. Those who are hopelessly hooked on two wheels will be glad to know that there will always be a lean steering trike in at least one incarnation or another.

#### **Front Wheel Drive and Rear Wheel Drive**

Most conventional rear drive systems use a long chain that requires a series of idle wheels or tubes to route the chain from the forward mounted cranks back to the rear wheel. A typical trike may require a chain that is up to 3 times longer than a conventional bicycle chain. An efficient chain management system is judged on the least amount of friction imposed on the chain. This may include a reduction in the number of pulleys or the use of Teflon tubing used to route the chain. Regardless of the chain management used, the sheer mass of the chain adds unwanted dynamic weight to the drive train. In recent years some companies have experimented with light-weight belt and cog systems (Gates Carbon Drive), but this solution has so far produced more problems than it solves for recumbents. There are other chainless solutions on the horizon, but none have proven to be a viable replacement for the venerable chain system.



*The drawing above illustrates the complexity of a chain management system used of the Spitfire and Thunderbolt trike. On the drive (high tension) sides of the chain, an idler wheel is used to route the chain around the frame. The chain tubes on the passive chain side also route the chain, but also act as a chain guard; preventing dirt from spoiling the chain.*



One of the virtues of the recumbent industry is the ever-evolving, innovative change being made. The recumbent trike market is undergoing even more changes. The recent technology making news is front wheel drive systems. The main virtue of a front wheel drive system is superior traction and a localized drive train. The first commercially available front wheel drive recumbent trike was developed in Russia (S32) back in 1996. The Zenit S32 and AS Engineering S327 trike designs were both plagued with reliability, weight, and performance issues that prevented them from becoming instant successes. To date, these issues have not been resolved and both companies have closed operations only to open again with improved offerings.



*Above are images of the AS Engineering's S327. Details of the fwd system are shown in the left two images.*

Although logic dictates that a localized drive train should have these attributes as virtues and not liabilities, this particular design implantation was killed by these flaws:

- A simple freewheel instead of a limited slip differential placed power to the inside wheel during turning which compromised performance.
- Four separate sets of universal joints complicated the design by adding more Dynamic weight and extra cost.
- The cantilevered force placed on the inside knuckle axles required high friction, heavy weight bearings that compromised reliability and performance to the drivetrain.

Perhaps in the near future, these problems can be worked out, making it a desirable alternative to the conventional, long-chain and idlers of the rear drive system.

## Suspension

A recumbent trike uses smaller wheels (I'll get into this later) than a standard bike. The problem with smaller wheels is that they provide a harsher ride than larger diameter wheels. The first compact, foldable bikes created by Alex Moulton solved this problem by using a compressed rubber elastomer as a shock absorber. Thanks to the ever evolving technologies of the mountain bike, we now have shock absorbers that rival those in automobiles. A well-designed suspension system can offer a featherbed ride regardless of the conditions of the road. Up until recently, most implementations have been limited to rear suspension, as it was extremely easy to implement, and it doesn't pose any restrictions to handling or steering geometry. With easy-to-route chain management systems, and the cranks being so far forward from the swing arm, it's obvious to see that rear suspension can be easily adapted to a tadpole-configured recumbent trike with little compromise.



*Above is the Optima Rider shown with rear suspension. The larger rear wheel defeats the need for suspension, as it already gives a smoother ride.*

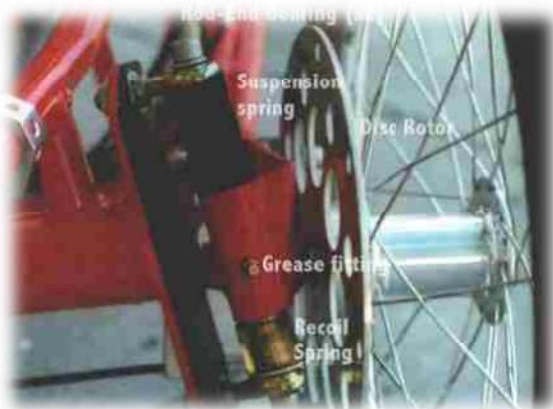
However, the virtue of a rear suspension system is refutable, as the rear wheel delivers less than 1/3 of the total shock felt by the rider. Secondly, the swing arm designs currently employed on these trikes are all more susceptible to side-loading forces than conventional triangulated rear ends.

Front suspension is more effective in reducing shock than rear suspension. After all, 60% of all the shock is produced by the front wheels. Although effective, front suspension does have its own problems; a lightly dampened front suspension system has the propensity to cause excessive sway which compromises handling.



More sophisticated suspension designs use a parallelogram configuration that reduces brake dive, while others go even further adding an anti-sway bar. Regardless of implementation, a high performance front suspension system requires a high level of engineering prowess and sophistication.

*At the left is an image of the suspension system of the sophisticated Pirol Trike (Germany). Do you wonder what would happen to the bottom A-frame mount if it encountered a large protruding rock?*



Somewhere in between there are some like me that have a simplistic and practical approach to front suspension and avoid corner sway by restricting the shock travel to less than 25 mm (1 inch).

*The image on the left shows a simple front suspension system deployed on a Zephyr Mk III (circa 1996) that allows the steering knuckles to travel on the same angle as the caster. Although this low cost system appears as a novel idea, the system was prone to brake dive.*

## Basic Trike Frame Design

In this section, I discuss the basic elements of a Tadpole trike design and the hierarchy of each as they apply. The objective here is to educate you in understanding that any trike design is actually a compromise of all of these elements.

### Weight Distribution

The weight distribution is the ratio of the horizontal weight displaced between the forward and aft wheels. It dictates how a trike handles and how stable it will be. The more weight on the forward wheels, the better the cornering and less over-steer. However, too much weight on the front wheel causes the rear wheel to be too light. This can lead to rear wheel wash-out during hard cornering or cause the trike to end-over during braking. Too much weight on the rear of the trike causes it to capsize even during mild handling as the single wheel has the majority of weight. A trike with 70/30-weight distribution is optimum.

### Center of Gravity

If weight distribution is the ratio of horizontal weight, than Center of Gravity is the ratio of top to bottom vertical weight. Center of gravity is as crucial as weight distribution for optimum trike handling characteristics. However, unlike weight distribution, the center of gravity has



*The above image is a Masa Slingshot (circa 1975). This low slung trike placed the CG close to the axle and weight distribution front 40%, rear 60%. The 36" wide wheel track aided in giving this monstrosity mediocre handling. However, the low visibility and impractical size and weight quickly led to its demise.*

no handling or stability compromises when its ratio is lowered. If all the weight is placed well below the axle, the trike is going to have excellent handling regardless of weight distribution. Obviously, a low slung vehicle does have several disadvantages including visibility, safety, comfort and practicality. For practical reasons most road worthy trikes will have most of the weight above axles.





*The image on the left is a Greenspeed SLR racing trike. When it comes to pure performance this machine pulls no punches; the low CG permits a narrow 26" wheel track and the 20° angled seat allows this trike to cut through the wind at phenomenal speeds.*

### Wheelbase

In regards to a recumbent trike, the length of the wheelbase influences the steering, stability, weight distribution and overall comfort. The wheelbase is the length between the rear wheel axle and front wheel(s) axle. In my experience, wheelbase is based on other trike requirements; it is never a requirement in itself. Example: I want a trike with a very steep angled seat with a 700c rear wheel, and a 70/30 weight ratio. When all these requirements are tallied I end up with a 45 inch wheelbase trike, but is this number good or bad? There really isn't a good or bad number, as both long and short wheelbases both have their pros and cons.

### Short Wheelbase (under 40")



*With only a 33 inch wheelbase and a tight 13.8 ft turning circle, The Catrike Dash is one of the shortest trike offerings.*

#### Pros:

- Creates a tighter turning radius
- Faster and sportier handling
- Smaller, more compact frame (stiffer and lighter)

#### Cons:

- Rider's position has more effect on overall weight distribution
- Reclining of seat position is limited due to rear wheel clearance



### Long Wheelbase (over 40")



*Measuring in with a 45 inch base and an 18.4 ft turning circle, the ultra-fast Catrike 700 has one of the longest wheelbases of any contemporary trike. BTW-I scaled this photo and horizontally transposed it so that it has a direct size relationship with the Dash trike above.*

#### Pros:

- Rider's position has less effect on weight distribution than SWB
- Seat has more clearance for reclining, even with a larger diameter rear wheel

#### Cons:

- Longer frame lends to higher weight and flexing
- Larger turn radius

So what is a happy medium? If I took a wheelbase consensus of all the production trikes on the market, they would average between 38 to 41 inches. This variation takes into account wheel sizes that can vary from 20 inch to 700c. When designing a trike never allow the wheelbase to be the limiting factor, as a short wheelbase, steep seat angle, and large rear wheel combination cannot all exist. This statement is repeated when I discuss wheel size and seat angle, so remember it.

#### Wheel Track

The wheel track is the width between the two front wheels. The wider the wheel track the less susceptible the vehicle is to capsizing during cornering. However, if too wide, the vehicle becomes impractical on most bike lanes. A 32-inch wheel track offers excellent handling and is practical for all bike roads too. Several manufacturers have released compact trikes that have reduced wheel tracks under 29 inches. The overall widths of these trikes allow them to pass through a standard 32 inch doorway. Other trikes like the Spitfire RS have a negative camber (we'll discuss camber later) that allows a wider wheel track but the overall width is compact enough to fit through a door way.

Another consideration for wheel track width is the front wheel diameter, as the turn radius is dependent on the lock to lock travel of the steering system. Larger diameter wheel will interfere with the rider's legs while turning, thus limiting the lock to lock travel of the steering and ultimately dictating the turning radius. This also applies to basic ergonomics; as the wheel track decreases, so does the space and comfort in the trike.

## Steering Geometry

The quality of the steering system and steering geometry also dictates the performance of the trike. The steering geometry is so complex that I have devoted an entire chapter for this topic in this primer.

## Frame Design

The last element in basic trike technology is the frame design. There are several issues here that affect efficiency and handling. The most important issues of the frame are weight and rigidity. Along with rigidity comes stability, as any frame or wheel flex is always undesirable especially at high speed. Beyond these basic requirements are other elements that should be equally noted. Reliability, cost, ergonomic and convenience are but a few requirements that the designer must consider. However, these considerations go beyond the scope of performance.

For excellent performance and reliability a 3-dimensional space frame is an excellent choice (e.g., Greenspeed/Catrike/Spitfire).

These types of frames all have triangulated chain stays that use the seat as part of the structural frame. The result is a frame that has reduced flexing which enhances stability and reliability. Even better is a frame that also includes web-gusset to reinforce the bottom bracket boom and cross-members (e.g., Thunderbolt III or Spitfire II). This type of frame reduces the effects of pedal steering caused by uneven cadence and boom flex.

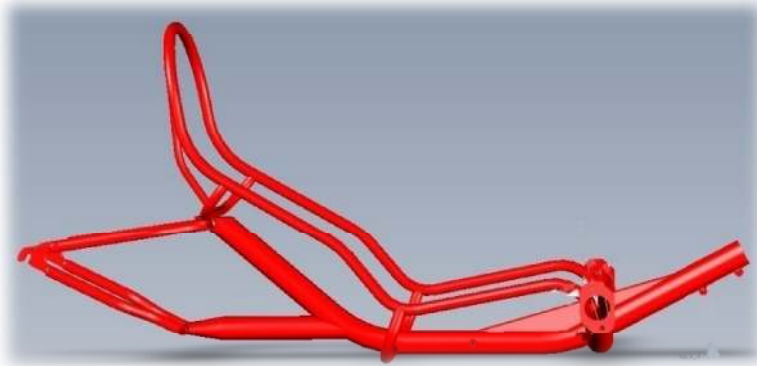


Above: A Greenspeed trike frame assembly complete with steering and bottom bracket shows how the seat is an integral part of the trike frame adding stiffness to the rear end.



Above is a Catrike frame assembly with chain management attached. This 3-D space frame implementation cleverly doubles the seat frame tubes as the Seat Stays.

Although stiffer, these 3-D frames are not necessarily lighter since they require more frame components and have several weld joints.



The lightest and least expensive trike designs use a standard cruciform frame that does not include seat stay support or an integrated seat. Although the least rigid and reliable, these trike are also the easiest to design and build.

Above is a Spitfire/Thunderbolt Mk III frame that includes a 3-D integrated seat and frame and also sports a gusset on the boom to reduce pedal flex.

### Summary

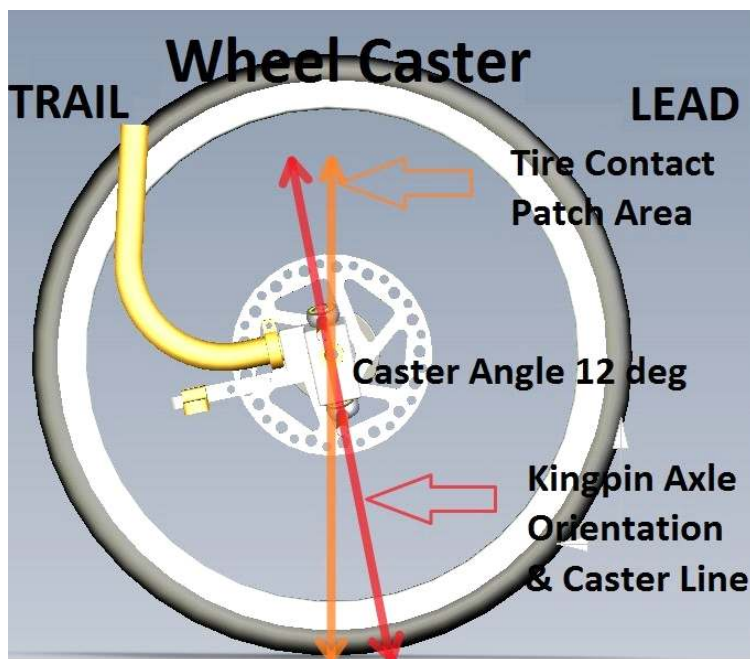
The success of a recumbent tricycle design is a careful mixture of Weight Distribution, Low Center-of-Gravity, Wheelbase, Wheel-Track, Steering geometry and Frame design. In most cases the design will be a compromise of all these attributes.

## Trike Steering Geometry

A recumbent trike is only as good as the steering, as it behaves similar to an automobile. As similar to an auto, the steering system is inherently complicated, as more than a single geometry is used to define it. In this section, I'll discuss the fine art of steering geometry.

### Caster Angle

The first geometry is the caster angle. This angle is the kingpin plane relationship to the wheel contacting the road (contact patch). Refer to the drawing below. As the drawing illustrates, the kingpin points down in front of the tire's contact patch.

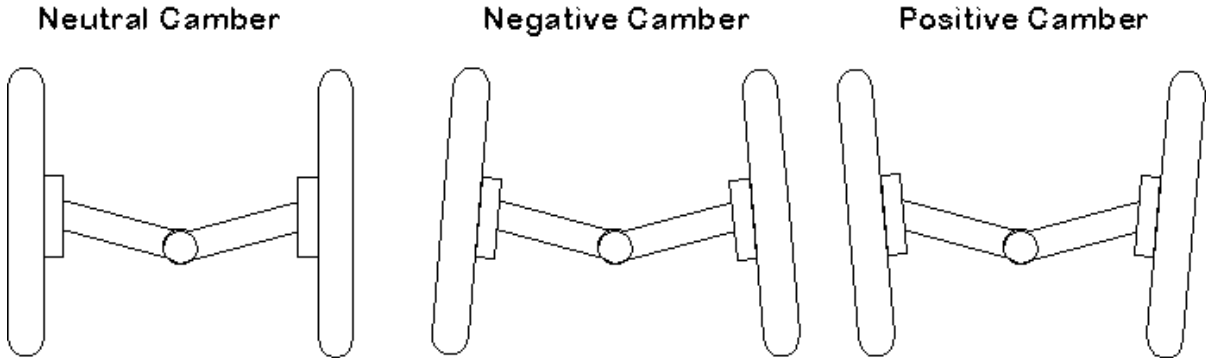


Since the steering system rotates on the Kingpin plane, the relationship between the contact patch and the kingpin forces the wheels to point inward as weight is placed on the wheels. Increase the kingpin angle, and more force is applied to bring the wheel inward. The resulting effect forces the steering system to return back to a neutral (or straight) position. We use a 12° caster on the Thunderbolt project. As a footnote, a standard automobile uses a 4-5° caster and a race car or go-cart gets much steeper.

### Camber

The next geometry is the camber angle of the front wheels. If the wheels are at exact right angles to

the ground (90 degrees) or the distance between the top of both wheels equals the distance between the bottom of both wheels, the camber is said to be neutral. If the distance between the top of both wheels is shorter than the bottom, the camber is said to be negative. And, if the distance between the top of both wheels is longer than the bottom, the camber is said to be positive. Normally, a negative or neutral camber is desirable. The Thunderbolt project has adjustable camber so that you can adjust it to your satisfaction.



**Toe-In**

The Toe relationship is somewhat similar to Camber, but at a 90° from the axis of the kingpin (longitudinal axis). Positive Toe or Toe-In refers to the front wheels pointing inward towards each other at the forward end and away from each other at the rear. This inward relationship is relatively very small. With most vehicles a ‘Toe-In’ relationship is a desirable trait in that it provides greater straight line stability at the cost of efficiency and sluggishness on cornering response. In practice, a recumbent trike requires little if any Toe-In. A Toe-In of no more than 0.1" is sufficient. trajectory intersect

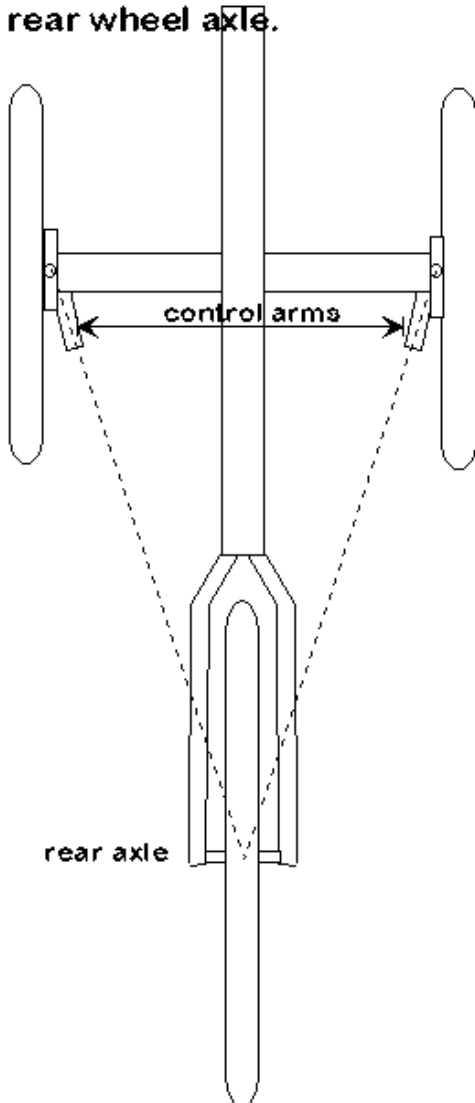
**Ackerman Steering Compensation**

The Ackerman steering compensation provides a way for a vehicle to turn without the front wheels scrubbing. In layman's terms, this means that when the vehicle is steered in either direction, the inside wheel shall always turn sharper than the outside wheel. Let's look at this with an example: My Thunderbolt can turn around a 15-ft. circle. This means that the outer tire is pointing at a particular angle that follows the 15-ft. circle. However, the inside wheel, which tracks 32 inches closer to the inside, must turn at a sharper angle so that it can follow a 9.5 ft circle. Obviously, if both wheels turned at the exact angle, they would scrub when the vehicle turns. Not only would this wear out the tires, it would also cause the vehicle to drastically slow-down when turning.

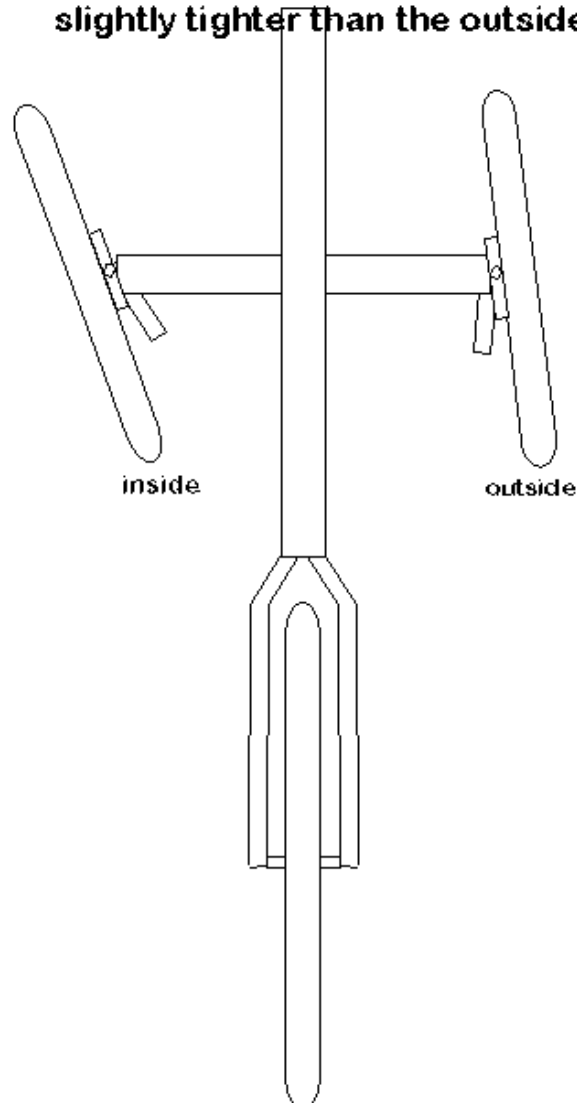


## Ackerman Steering Compensation

The Ackerman compensation is established by aligning the steering knuckle control arms so that they both point to the rear wheel axle.



The result of the ackerman steering compensation is shown below. Note that the inside wheel is turned in slightly tighter than the outside.



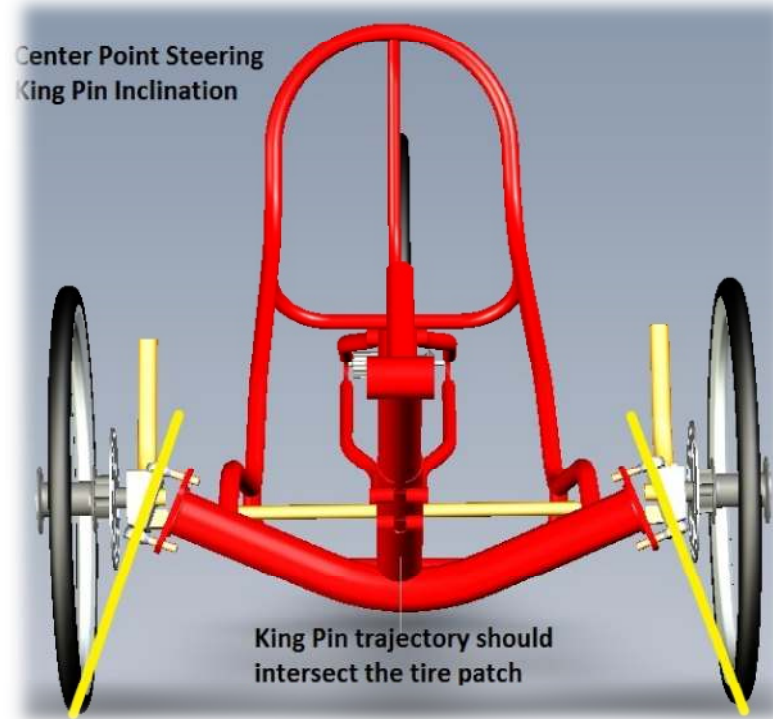
There is some consideration concerning Ackerman that must be understood. First, perfect Ackerman does not mean always yield the best performance. Secondly, the accuracy of the Ackerman compensation is dependent on the type of steering system used on the trike design. Peter Eland has created a couple of spreadsheets that accurately calculate the Ackerman Steering based on the steering linkage type, wheel base and wheel track.

As mentioned, perfect Ackerman steering compensation does not guaranty the best performance. In some cases it is desirable to reduce the Ackerman during large radius turns as it makes the steering less sensitive and less prone to over-steering. This Anti-Ackerman actually prevents over-steering at high speeds. An Anti-Ackerman is actually a partially compensated Ackerman implementation and allows a small amount of scrubbing when turning a

large radius, but it follows the full compensation during smaller radius turns. The exaggerated result is a vehicle that slows down in the corners, but allows the trike to sustain faster speeds without steering instability. My personal T-bolt could sustain speeds greater than 50 MPH without steering instability, as it uses a 2° Anti-Ackerman offset. Therefore, perfect Ackerman is up to the rider. Again, I strongly recommend using Peter Eland's spreadsheet.

**Kingpin Inclination (Center Point Steering)**

The inclination of the Kingpin allows the steering axis to turn precisely on the center patch of tire contacting the pavement (hence the name Center Point Steering). This imaginary intersection is commonly referred to as the Scrub Patch. Because the steering axis rotates directly over (and front of) the contacted patch of tire, the steering is less affected by defects



in the road, hence reducing 'bump steering' and allowing the full effects of the caster to work. Another by-product of kingpin inclination and Caster allows the camber to change in relationship to the wheel steering angle. This compensation allows the wheels to lean into the corner in which they are turning. Ultimately, this dynamic orientation modifies the wheel geometry resulting in slightly enhanced handling. The kingpin inclination is at a 90-degree plane in relationship to the caster angle.

*Above image shows the projected King Pin angles highlighted yellow.*

**Deviations of King Pin Inclination**

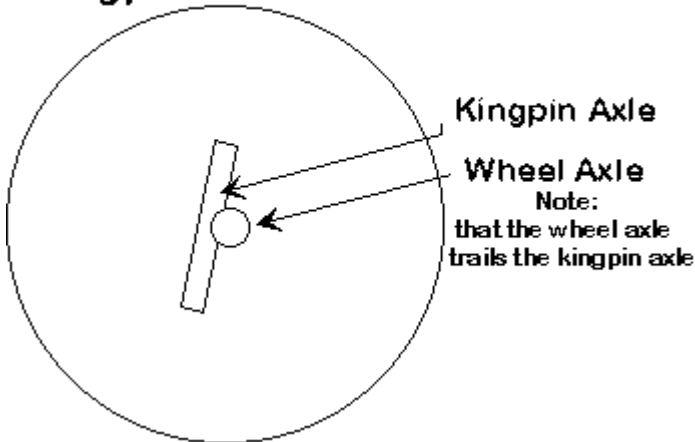
Most automobile designers purposely reduce the Kingpin inclination angle so that the projected intersect line falls short of the center of the tire patch. This is done to give the steering an enhanced 'road feel'. On the other hand, some trike designers extend the angle so that the projected intersect line falls outside the center of the tire patch. This over-compensation further reduces the effects of brake pull, but can also cause over-steering. In my humble opinion (and for what little it's worth), if concerned trike manufacturers used a balanced braking mechanism, this practice could be avoided altogether.

Some manufacturers refuse to implement center point (Pointe for you over the pond) steering into their designs. In some cases the designer has placed the King Pin axis so close to the wheel that the king pin centerline becomes very close to the tire patch and therefore inclination is not necessary. However, in most cases the designers or builders are just plain ignorant, as their designs completely ignore this concept.

### Kingpin to Wheel Axle Orientation

The placement of the wheel axle, in relationship to the kingpin, drastically affects the steering. If the wheel axles are placed in front (lead) of the kingpin axles, the 'caster effect' is defeated making the steering unpredictable and extremely unstable. However, if the wheel axles trail too far behind the kingpin, the steering may be influenced by road shock and brake steering. Again, this occurrence is referred to as bump steering and brake pull. Ultimately, the wheel axle and kingpin should intersect or be within 0.5 inches trailing.

### Wheel axle to kingpin orientation




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## Steering Mechanisms and Linkage Systems

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This chapter focuses on both steering mechanisms and steering Linkage systems. The steering mechanism is the method upon how the vehicle is steered (input device for you nerd) and the steering linkage system is how the device controls the wheels.

### Steering Mechanisms

Steering Mechanisms come in a few basic flavors: Over Seat Steering (OSS), Under Seat Steering (USS) and Direct Knuckle Steering. Each of these steering systems has several configurations and has its advantages and disadvantages.

#### Over Seat Steering- OSS

##### Pros:

- Lower weight
- Lower complexity
- Allows a narrow track wheels configuration
- Lowers overall frontal area, improved aerodynamics

##### Cons:

- Rider cannot use the tiller for support, requires a seat with lateral support to keep the rider from falling out.
- Not as popular as Under Seat Steering, due to arm fatigue or lack of intuitive design.
- Fatigue level is higher than an Under-seat steering system.

**Over Seat Steering- OSS (cont)**

The Over Seat Steering (OSS) system is normally configured as a 'T' or 'Y' bar Single Handle Tiller. As for the better steering handle configuration, it is a matter of personal preference. From an inconclusive observation, the Single Handle Tiller (or 'Y' bar) is geared towards sport riding, as the rider's arms have limited support, but tight control. The 'T' bar fits the more traditional role as it is both user-friendly and a bit more comfortable than the 'Y' bar. Whatever the preference, the design of the OSS mechanism is a science. On higher quality trikes, the steering column rotates freely using a universal joint (U-joint). The U-joint allows the steering mechanism to move with the rider's body, as to allow body English. On cheaper trikes, the steering column is either fixed or restricted to a single axis movement.



*Above is a OSS steered Spitfire Trike*

**Under Seat Steering-USS**

Pros:

- Intuitive control makes it easier to master
- Provides comfortable support for arms
- Gives the rider support during high G turn, precludes the use of lateral seat support.

Cons:

- Heavier weight compare to OSS
- Increases the Frontal Area making the trike less aerodynamic.
- Places the riders hands dangerously close to the wheels or ground
- Requires ample room for U bar clearance that may compromise wheel track or seat width.

The actual steering mechanism for Under Seat Steering is either a U-bar configuration or dual lever design. Again, the choice is up to the rider, as to which configuration is better suited.



*Above is a USS steered Spitfire*

The dual lever design is best suited for ultimate comfort, while the U-bar gives the vehicle a sportier and lighter feel. Additionally, the U-bar system tends to be simpler and cheaper as it requires fewer parts for operation. However, the expensive, dual-lever system offers superior linearity and better flexibility for adjustment.

**Direct Knuckle Steering**

Pros:

- Simple and inexpensive implementation, uses single tie-rod system
- Provides comfortable support for arms
- Gives the rider support during high G turn, precludes the use of lateral seat support



Cons:

- Side to Side motion is counter intuitive to some
- Increases the Frontal Area making the trike less aerodynamic.
- Places the riders hands dangerously close to the wheels or ground
- Requires ample room for U bar clearance that may compromise wheel track or seat width.

The Direct Knuckle Steering system is rudimentary, but brutally effective. Designs that use standard bicycle head set for the steering knuckles benefit most from this system since they can use existing bicycle components. Unlike the rotational movement used by other steering systems, this type is described as a left to right motion. Consequently, it is not as intuitive as other steering systems. The low cost and least amount of weight makes this steering a winner for many.

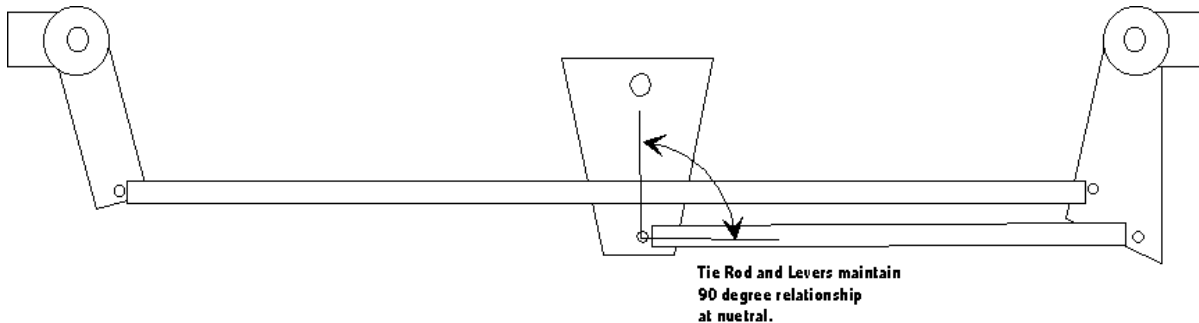


*Above is a Catrike Road Trike with direct Knuckle Steering*

**Steering Linkage Systems and How They Work**

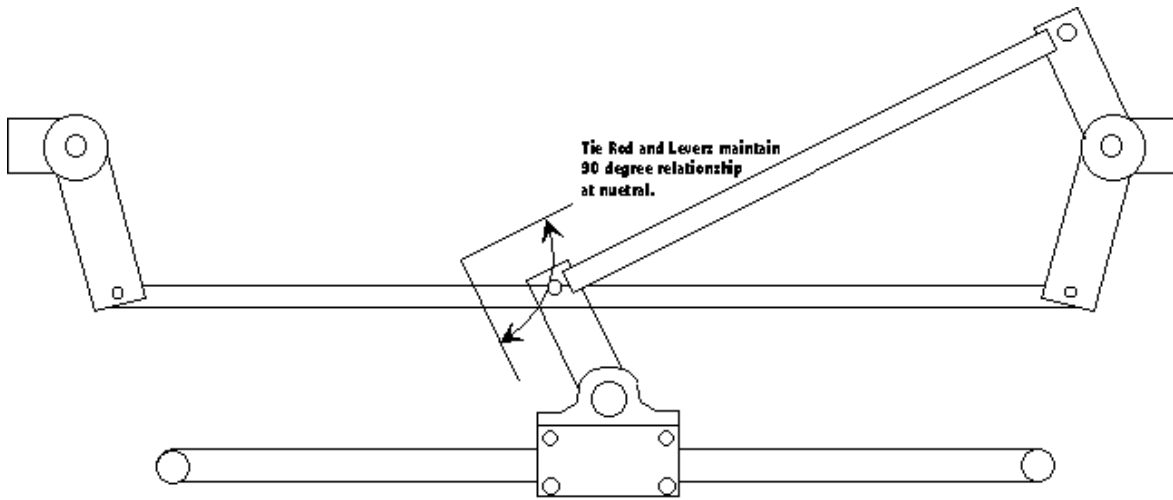
The steering linkage is another factor in the equation. Although more than a dozen steering systems exist, I'll mention a few widely used steering linkage systems as they would apply to the Thunderbolt. These are shown and explained below:

**Single Tie Rod and Drag Link System**



This type of steering system was common on early automobiles and eventually found its way to farm tractors. A knuckle-to-knuckle Drag Link provides continuity between the wheels, while the Tie Rod provides linkage to a Bell Crank (Pitman Arm). The best attribute is that the main linkage consists of only two rod-end bearings. This allows the steering to remain relatively tight. Although this system uses more parts than the other two steering systems, it provides superior flexibility for adjustment and provides adequate Ackerman compensation. However, the system weighs slightly more than the other two systems mentioned. Misalignment of the Bell Crank orientation (caused by the Tie Rod deviating from 90°) causes a slight non-linearity throughout the steering range. This is compensated by applying Ackerman to the steering knuckle control rod that links it to the Bellcrank.

The drawing on opposite page depicts an application for OSS (Over Seat Steering). For USS (Under Seat Steering U-bar), the drawing below applies.

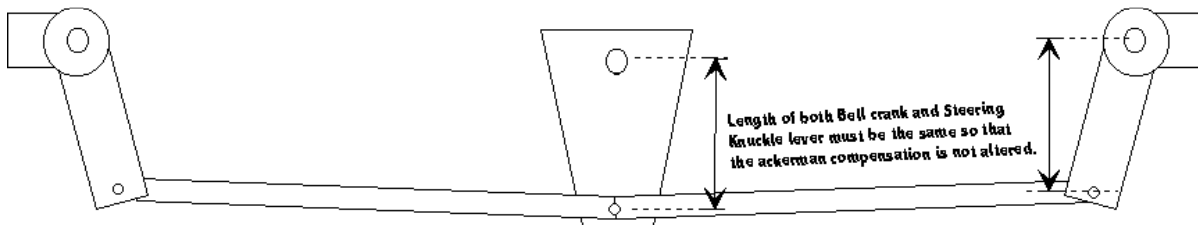


As with the first example, this design also offers good Ackerman compensation.

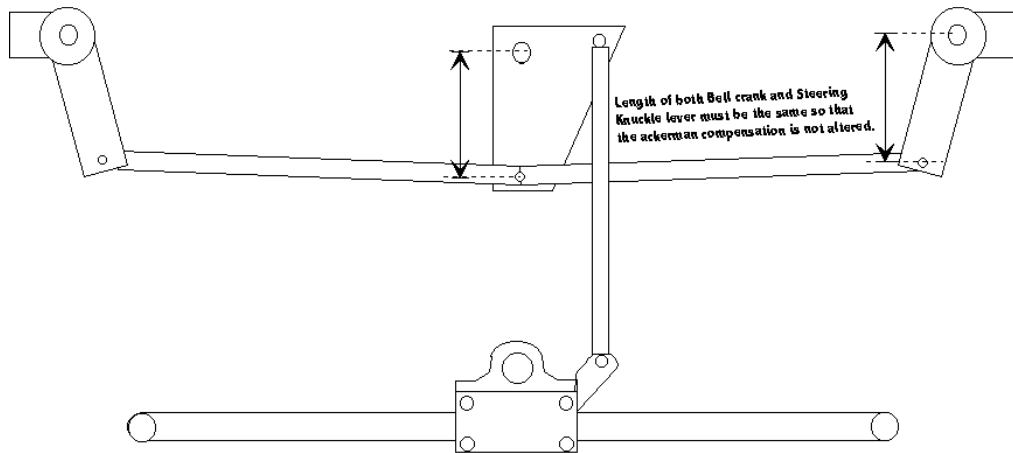
### Dual Drag Link System

#### Note

*The illustration below refers to the geometry relationship as it applies to the Thunderbolt. As depicted, the bellcrank axle does not align with the kingpins. Obviously, a shorter bellcrank arm can be adapted with success if the bellcrank axle is moved aft so that the both control arms are almost parallel. However, the shorter length lever shall have some affect on the overall Ackerman.*

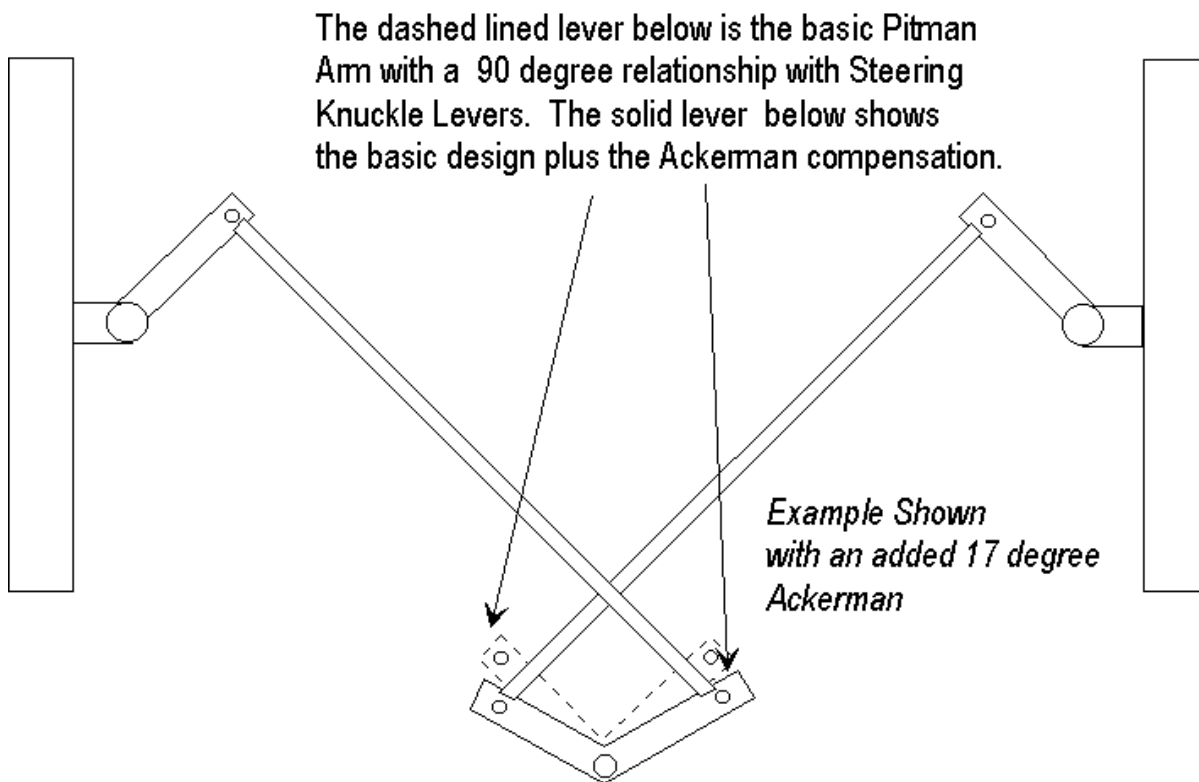


This system offers lower weight, less parts than the Single Idler Arm system and is optimized for Over Seat Steering, as the Bell Crank is mounted almost at the kingpin plane. The major advantage to this system is that it provides near perfect Ackerman compensation. This design was used on the Volkswagen Bug over 50 years ago. The Bell Crank orientation and length must remain constant to maintain proper Ackerman. Adapting a USS steering system requires a U-bar mounted aft of the king pins. Unfortunately, the steering linkage becomes increasingly complicated as a second Pitman Arm (Bell Crank) and Tie Rod are required (refer to the drawing below). The Bell Crank length (from arm pivot to axle) must equal the Steering Knuckle Lever length (measured from the arm pivot to kingpin axle). Deviations to this relationship can diminish the Ackerman compensation.



The example above was initially used on the production Thunderbolts back in 1996. Obviously, you can see why we are using the Single Tie-Rod steering system.

### Crossed Dual Drag Link



The Crossed Dual Drag Link is optimized for a USS (U-bar system), as the Bell Crank (Pitman arm) is placed behind the steering Kingpins. This linkage system is used on Ian Sims' Greenspeed Recumbent Trike and many other inspired designs. Note that this is the only example rendered of a Leading Lever steering system. The Crossed Dual Drag Link system can be adapted for OSS by moving the Bell Crank forward. However, an Aft Lever Dual Drag Link steering system is better suited for an OSS configuration.



### Crossed Dual Drag Link (cont)

The science of maintaining a linear rod linkage system requires the application of the Right Angle Rule. The Right Angle Rule requires that both rod ends maintain a 90° angle to each linked lever arm when the wheels are in a neutral, forward position. Not only does this practice insure that both rods maintain a linear arc throughout the full range of motion, it also insures the stability of the linkage. As the rod ends approach an angle close to 0° or 180° in relationship to either of the lever arms, the linkage rod loses its ability to hold and control the arm. The Right Angle approach guarantees the steering linkage force is optimized throughout the 90° arc of steering travel. This principal is applied to the Crossed Dual Drag Link steering configuration shown above. To achieve the 90°-angle relationship with the above example, the two drag link rods require separate mounts on the Pitman Arm. To prevent tire scrubbing during turning, these mounting locations are angled back further on the Pitman Arm to provide the necessary Ackerman compensation.

Greenspeed has used this system for several years and has only recently changed it to a dual draglink system for better stability for braking.

### Summary

As mentioned in the preface, each steering system has its advantages and disadvantages depending on its application. My choice is an aft lever system using a Single Tie Rod and Drag Link System. My decision is based on cosmetics and practicality.

Peter Elands has created a comprehensive spreadsheet that calculates all the steering combinations that are discussed in this chapter. It's worth the time and effort to experiment with spreadsheet to dial in a steering design.

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## Trike Rear End Design

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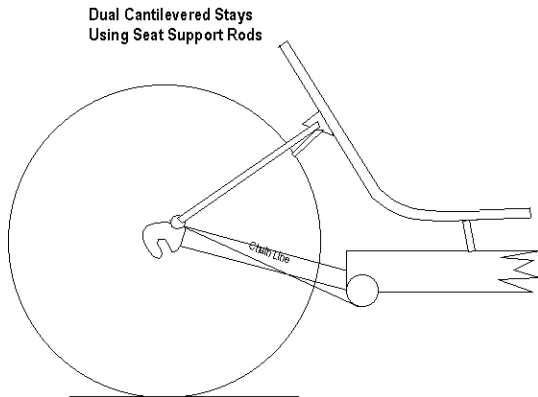
In this section, I address the stay reinforcement issue by referring to a Seat Tube. The name originates from descriptions intended for the standard diamond frame bicycle. Beyond this discussion are other types of designs. Additionally, in terms originating from the diamond frame bicycle, we refer to the 2 sets of tubes that support the rear wheel as Chain and Seat stays. The chain stays are normally oriented close to a horizontal plane; where else the seat stays are normally oriented 30 to 70 degrees in relationship to the chain stays and intersect at the wheel drop-outs. Recumbents are weird, as these conventions sometimes do not apply.

### Designing Rear Stays for a Trike

The rear-end structure of a trike requires a balanced combination of reinforcements to overcome direct vertical weight loading, chain loading and torsional side loading. Each of these forces is dynamic and some directly interacts with each other. The designer or builder must make provisions to address each of these loading forces as they play a critical part in the trike's overall design.



## Vertical Weight Loading



As mentioned, only 25 to 35% of the total weight of the vehicle is placed on the rear wheel. Therefore, the need for designing rear wheel stays for vertical weight loading is not a chief concern. Most trike designs that do not include triangulated seat/chain stays (Dual Cantilevered stays) still use seat support rods that attach to the chain stays. Although this does not remedy torsional flex caused by side loading, it does offset some of the vertical force applied to the chain stays.

*Left: Image shows a typical dual-cantilever stays design rear-end. The aft seat support rods also reduce vertical weight loading.*

## Chain Loading

Chain loading is the pulling action that occurs when high tension is applied to the chain causing frame components to flex from forces transferred from the crank arms to the rear wheel. The pulling action of the chain causes either a compression action or cantilever action to the rear wheel stays. If the chain stays are relatively parallel with the chain line, the energy exerted as a compression force. If the chain stays are angled in relationship to the chain line (e.g., the base of the stays are above the chain line), the stays undergo a cantilevered force instead of compression force. As the angle increases so does the tendency for this type of flexing. The vertical weight load on the stays helps offset some of this energy.

The effect of chain loading is less predominated with a fully triangulated rear assembly. Furthermore, well-calculated placement of a chain idler wheel also reduces the effects of chain loading. In summary, the chain stays oriented to the chain line handle the compression loading with more predictability than stays that are angled away from the chain line.

## Side Loading

Side loading is the affect of the rotational side force placed on the rear wheel (although the front wheels exhibit this too). This force is exerted during cornering or swaying of the trike; hence a torsional force is applied to the rear wheel stays. The most common method of counteracting this type of force is to triangulate the stays using a combination of seat and chain stays. Both sets of stays require mounting to a firm seat tube (a term used to describe the base tube that both sets of stays attach to) with a minimal space between each stay at the base. The angle between the seat and chain stays is arbitrary as other compromises exist. If the seat tube were a non-flexing structure, the optimum angle of the stays would approach 90 degrees with the chain stays parallel with the chain line. However, the seat tube is an integral part of the trike frame and is also subject to flexing. Consequently, added reinforcement is necessary for the frame to accommodate this configuration. A compromise would be to lower the angle so that minimal reinforcement would be required for the seat tube.

Another method for reducing side loading forces on the stays is to use a smaller rear wheel. Since a smaller wheel has a reduced radius, the side forces have reduced leverage on the wheel axle. Additionally, the smaller radius allows shorter chain stays decreasing the side loading effect even further. On the down side, a smaller rear wheel makes the ride of the vehicle harsher and may require special gearing from higher gear/inch range.

An Angled Cantilevered Stay is yet another method for reducing side loading. I will discuss this design later.

### Rear Stay Examples

Many rear stay configurations exist, so I have compiled together a study of a few basic designs that summarize this section’s discussion. These designs are compared and rated as **Bad**, **Average**, **Good**, and **Excellent**.

### Dual Cantilevered Stays

The rigidity of a trike’s rear-end increases both reliability and performance. Many trike designers choose to use only dual cantilevered chain stays (or a single stay with a stub axle). Although this is a violation of my trike design principle, it does reduce the overall cost and weight of the trike. Furthermore, reducing the size of the wheel makes this approach more attractive, as it reduces the cost and weight further and increases the stiffness and reliability. Many manufactures use BMX forks as chain stays, further assuring that stresses are kept in

check. It is my opinion that the overall weight and cost penalty outweigh the penalty for sacrificed performance and reliability when used with a 20 inch wheel.



Left is the Terratrike Sport 2.0

Vertical Weight Loading: **Average**  
 Chain Loading: **Good**  
 Side Loading: **Bad**

Pros: Simple and Inexpensive

Cons: Susceptible to side and vertical loading

### Angled, Dual Cantilevered Stays

Triangulated stays are not the only solution. Back in 1995, I met Bill Haluzak who was displaying a new, lightweight version of his popular short wheelbase Horizon recumbent bike. Instead of using a triangulated rear stay, Bill opted to use a single chain stay rear-end design using a modified BMX fork. At first glance I thought the rear wheel would be susceptible to severe side loading. However, after careful inspection I concluded that the rear end was adequately firm proving my first impression absolutely wrong. What made Haluzak’s rear frame design so rigid that he could use a single stay design? The answer lay in the geometry in which the stays were designed.

The best way to explain this configuration is to use the standard front wheel and fork as an

example. The fork blades point towards the ground in a vertical fashion. The supported wheel transfers all the side loading forces to the fork crown. A dual cantilevered stays design is identical to a standards fork assembly, except it’s mounted horizontally instead of vertically.



Above is a Challenge Ligfietsen Trike that uses angled dual cantilevered stays. The mark-up shows where the stress is concentrated.

### Angled, Dual Cantilevered Stays (cont.)

Vertical Weight Loading: **Good**  
 Chain Loading: **Bad**  
 Side Loading: **Good**

**Pros:**

- Simplicity and lower cost
- Good side loading qualities

**Cons:**

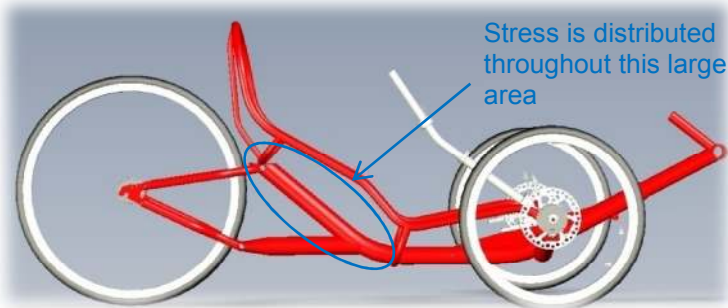
- Susceptible to chain loading
- Focuses torsion and cantilever stress at one point
- Requires an additional seat tube

Let us compromise and move the fork/stays to 45 degrees. We now have stays that can handle side-loading forces. This is what the Angled, Dual Cantilevered Stays are all about. This approach can be implemented for a trike, provided that a seat tube is added to compensate for the low CG required for a tricycle design.

For any type of structure, the price for rigidity is weight. The low CG required for a trike makes it difficult to maintain angled chain stays without increasing the amount of main tubing material. This can be seen in the Challenge Ligfietsen example. Another penalty that must be paid is chain line routing. If the chain line routes directly from the main tube to the rear wheel, the chain stays would flex under the demanding loads of the chain. Consequently, either the angle of the stays must be reduced or conventional triangulated stays must be employed. In the case of the Ligfietsen trike, the stay angle is compromised to reduce chain loading.

### Full Triangulated Stays

This classic design has been in use for over a century. No surprises here, it works and there has not been a tube design since that can rival the strength and reliability. Any trike manufacture



worthy of praise would design a trike rear end with full-triangulated stays. This design solves all loading problems as well as chain and vertical loading. The drawbacks of a fully triangulated rear end are that it complicates the design, costs more and adds weight to the trike. However, these issues I regard as trivial.

*Above is a 3D model of the Thunderbolt Mk III/Spitfire Mk II. Note that the rear design uses both chain and seat stays. The main tube and seat are integrated providing excellent stiffness.*

### Full Triangulated Stays (cont.)

Vertical Weight Loading: **Excellent**  
 Chain Loading: **Excellent**  
 Side Loading: **Excellent**

**Pros:**

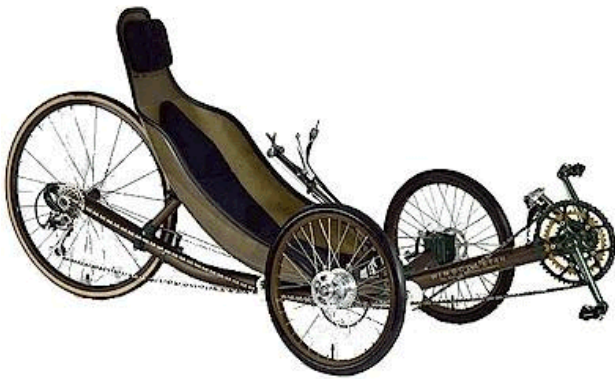
- Distributes stress throughout the frame
- Excellent stiffness and reliability

**Cons:**

- Requires the addition of an extended seat tube (main tube)
- Adds complexity, cost, and weight

### Single Cantilevered Stay

The Windcheetah, AS32, and the Rubicon all use a Single Cantilevered Stay design. In comparison to the Dual Cantilever Stays, the rear wheel is supported on only one end of the axle. This chain stay in most implementations is an extension of the main frame tube. Although I have little experience with this design, I can confidently remark that the chief redeeming feature is aesthetic quality and certainly not performance. As with the dual cantilever stays configuration, the design is void of any side loading support. Additionally, the single end support of the rear wheel axle is subject to added cantilever forces. Again, a smaller rear wheel reduces these problems, but does not eliminate them.



*Above is the legendary AVD Windcheetah trike. The 23 year old design uses a brilliant cantilevered single stay rear end.*

Vertical Weight Loading: **Good**  
 Chain Loading: **Excellent**  
 Side Loading: **Bad**

**Pros:**

- Elegant Styling
- Easy chain routing

**Cons:**

- Susceptible to side loading
- Expensive unique hardware required

### Summary

As with all aspects of the trike, the rear end design is based on the builder's requirements. All the design examples mentioned here all deserve worthy praise, as each design fills a specific purpose whether it is low cost, performance, or aesthetics. Furthermore, many of the shortcomings mentioned can easily be overcome by using smaller rear wheels. My favorite is the time honored, fully triangulated rear stay design, as it offers the best performance, especially for larger rear wheels.

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## Wheel Size Consideration

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**T**adpole-designed trikes come in a wide variety of wheel size configurations. If the center of gravity were not an issue, I would be bold to mention that wheel size has little affect on handling (provided the rear wheel stays are sturdy enough). Chiefly, wheel size affects efficiency, weight, ergonomics, and quality of ride.

During the testing of my first prototype, I discovered that 700c diameter front wheels were too weak and tended to fold (taco) easily during hard cornering. BMX 20-inch wheels (ERTRO 406) were tried and found to work without any problems. I also discovered that smaller wheels in front allowed for sharper turn radius, as the larger wheels tended interfere with the rider. Since the rear tire is under less side loading, I was able to use 26-inch wheels that offered excellent rolling resistance and made the ride significantly smoother than a rear 20-inch BMX wheel.

The chief advantage of a small rear wheel is that it offers better reliability and lighter weight than a large wheel. The reliability aspect of a smaller wheel system is that they tend to take side loading better than larger wheels. The lighter weight virtue is obvious, as a smaller wheel is lighter than a larger diameter wheel and the wheel stays are smaller, too.

It should be pointed out that both front and rear tire size selections have much different requirements. On the Front wheels, the size is restricted to maintain a smaller tract, tighter turn radius and aerodynamics. On the Rear wheel, the size may be restricted to maintain rear end stiffness, but needs to be large enough for adequate gear/inch range.

The chief advantage of larger wheels is that they provide better Roll-Over resistance and offer a stable, more comfortable ride. Additionally, a large rear wheel does not require special gearing (such as an oversized chain ring and extra chain). However, this case applies to the rear wheel only.

My preference is using a 26 inch or 700c rear wheel, as it allows an excellent high gear inch range, provides a softer ride and has superior “roll over” qualities that give it an overall performance edge over a 20” rear wheel. For the front I prefer to use 20 inch (ERTRO 406), as these have average roll-over resistance, adequate leg clearance, and good aerodynamics.



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## Seating

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### *Note*

*I do not have quantitative data that specifically addresses this subject. However, I have conducted numerous experiments in sling/webbing and rigid back seat design.*

Seating is a preference. Basically, an HPV seat is divided into two types: Mesh or Rigid. In some incarnations, a combination of the two can be had. Each has its virtues and disadvantages. Some people indicate that foam-back rigid seats have the greatest efficiency, but none have substantiated their claim. The same applies to mesh seats.

### **Performance Criteria**

The critical performance issue of an HPV recumbent seat is the provision for firm support of the rider's lower back. Deflection for the lower back of the seat should be less than 1.5 inches. Deflection for the buttocks and upper back can be exaggerated without much efficiency loss. Please note that this performance criteria may not apply to low angle seating.

Another important performance issue is seat weight. Lately, graphite composite materials have made rigid seats as light as the nylon mesh on aluminum frame seats.

A lower seat angle allows better aerodynamics. Aerodynamics play a critical role in an HPV's overall performance. With a low slung seat, the trike rider can cut through the wind like a hot knife through butter....right smack into a car! Low slung seats compromise the rider's vision, so beware!

### **Comfort Criteria**

As for comfort, take your pick. My personal preference is a Mesh Sling seat. The fabric is breathable and is void of uncomfortable hard spots. A well designed, quality made sling seat has several adjustments that can fit the most discerning buttocks.

The virtue of a rigid seat is that it can provide firmness. However, in my experience, they have been scorned by many racers, as they retain heat and moisture and many are not adjustable. Easy Racer has addressed some of these problems by using a set of contoured pillions. These pillions are designed for minimized area, but allow maximized support and comfort.

Seat angles and head rests are subjective topics. As for an efficiency advantage (disregarding aerodynamics), I have heard pros and cons from each camp. As for head rests, they're great. However, bicycle helmets are designed for upright bicycles and not for recumbent trikes. Consequently, back rests and helmets don't seem to get along these days.

### **Side/Lateral Support Criteria**

A trike seat is unique in that it must provide lateral support for the rider. However, this is not always true. In many cases nylon mesh (simple potato sack) is stretched over the seat frame without a seat area and therefore, no lateral support to keep the rider in place. In this design, the Under Seat Steering 'U' bar provides the lateral support for the rider. In other cases lateral support is built into the seat. A primary example is the Windcheetah. The Windcheetah or Speedy was designed as a narrow track, Over Seat Steering configured trike. Thus lateral support is required to keep the rider in the cockpit during high G turns.

As mentioned, everything is a compromise, even the seat.

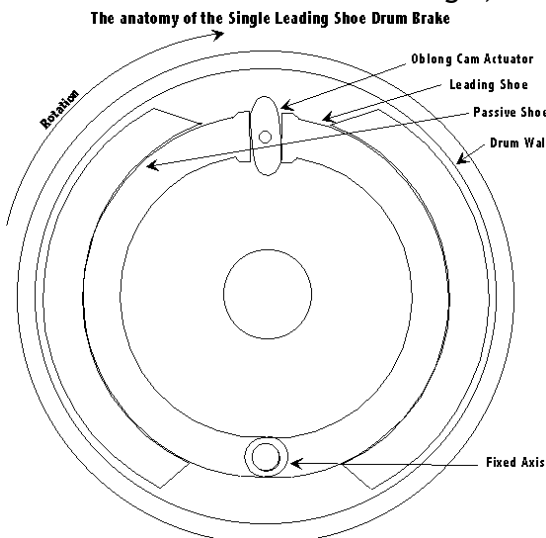
## Brake Systems

Before I go off the deep end on this subject, I must mention that most tadpole trikes use only front brakes. A back brake is rarely used. Therefore, this discussion focuses on front wheel brakes. I'll elaborate on the rear brakes later.

Basically, three types of braking systems are employed: Drum, Disc, and Caliper.

### Drum Brakes

The standard drum brake used for the majority of recumbent trikes is the Sachs VT5000. This drum brake is classified as a single, leading shoe brake. The basic drum brake uses two brake shoes inside a cylinder drum. When the brakes are applied, an actuator rotates an oblong cam that forces both brake shoes outward against the cylinder drum. See the illustration below.



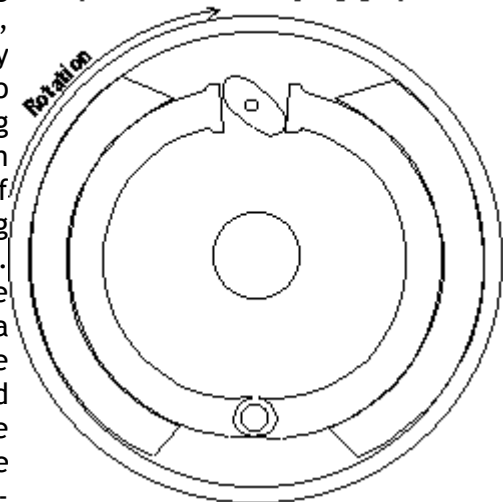
### Drum Brakes, Pros and Cons

The major advantage of the drum brake is that it provides solid and reliable braking and is optimized for Tadpole trike designs. The disadvantage is that a drum brake performs poorly in wet weather conditions (if moisture gets into the drum) and is susceptible to heat fading. Additionally, the self-energizing drum brake action is nonlinear and may be slightly unpredictable.

### Single Leading Shoe Drum Brake

The single leading shoe drum brake is a self-energizing brake system. The principle behind the self-energizing brake is that when the brake shoe is applied to the drum, the brake mechanism diverts some of the rotating energy and applies it to the shoe for additional contact force to the drum, hence more friction and stronger braking force. In essence, the self-energizing mechanism operates as a positive feedback system. The chief component of the self-energizing system is the leading shoe. As mentioned, the shoe moves on a stationary axis. On the opposite end, a cam is used to push the shoe against the drum. The leading shoe is designed in such a fashion that when the cam pushes that shoe against the rotating drum, the initial friction grabs the shoe and forces it even harder against the drum. As the name implies, only one of the two shoes is self-energized. The direction of rotation dictates which shoe is leading (self-energizing). In most cases, the drum brake manufacturer designs the leading shoe slightly larger and heavier than the passive shoe. The Single Leading Shoe Drum Brake is widely used for bicycles and HPVs.

Single Leading Shoe Drum Brake  
(with brake shoes fully engaged)



### Dual Leading Shoe Drum Brake

The dual leading shoe self-energizes both brake shoes. In this configuration, the stationary axis is replaced with another Cam. The Cam profile is changed from an oblong shape to a half-crescent. This applies to both cams. The new shape allows each cam to operate a single brake shoe. The rounded portion of the crescent shape cam acts as a stationary axis for one shoe while the flat portion of the cam actuates the other shoe. In summary, the leading shoe is the near pinnacle of drum brake design. Unfortunately, the Dual Leading Shoe has not found an application on production bicycles or HPVs.

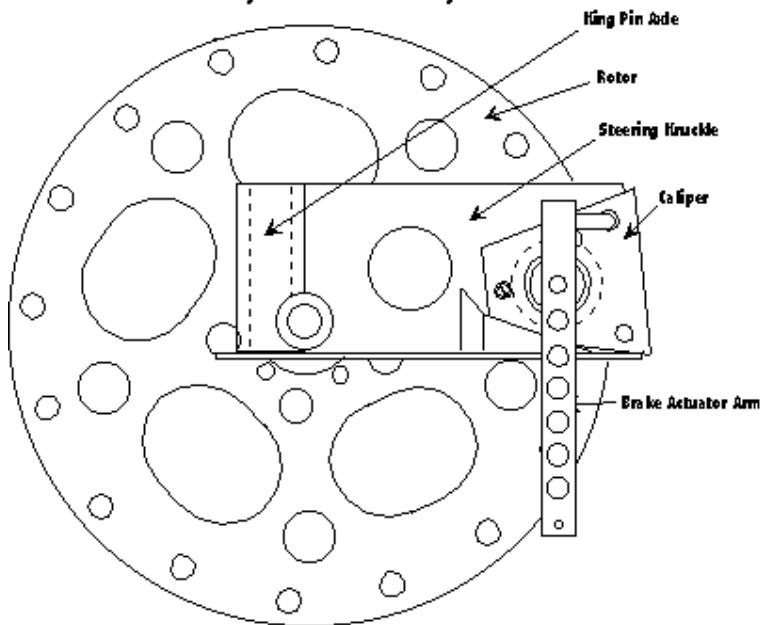
### Drum Brake Fading

Brake fading is the degradation of braking power over a defined time of constant usage. An example is traveling down a steep and long descent, applying the brakes constantly to maintain a safe speed. During the descent, the brakes may appear weaker, requiring extra force.

Contrary to popular superstition, brake fading is caused by the expansion of the brake shoes and drum that occurs during extreme heat. When brakes are cold or at room temperature, the brake shoe fits flush against the drum. When both of these components get warm, they began to expand. Consequently, the brake shoe no longer fits flush against the drum and braking is

impaired. The brake shoe material does not compromise due to heat, and hence does NOT cause brake fading! Over the last century, scientists and engineers have perfected several composite materials that stand up well to excessive heat and wear. Braking is a science, not voodoo magic.

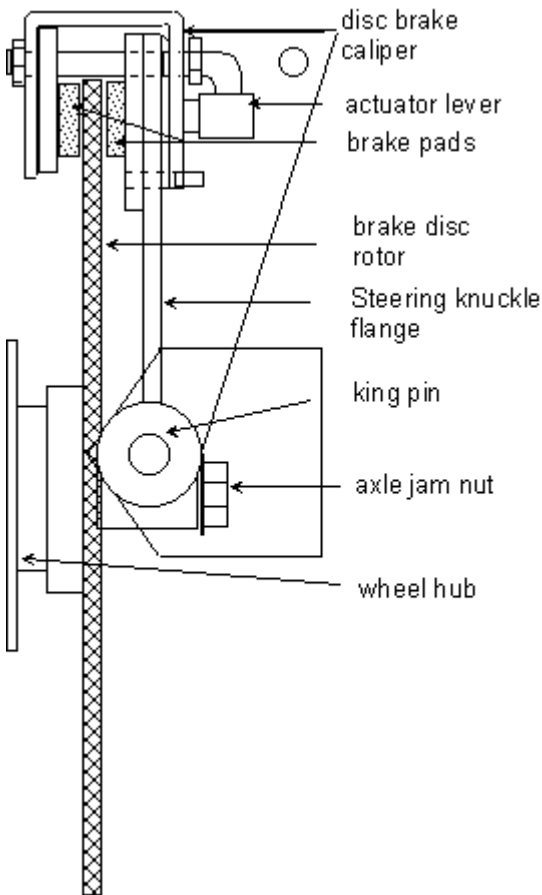
**The anatomy of a Disc Brake System**



## Disc Brakes

The problems with brake fading and sensitivity to moisture have both been remedied by the advent of the Disc Brake system. The disc brake applies a set of flat pads on opposing sides of a revolving rotor. Since both brake pads and rotor surfaces are flat, the brake is infallible to fading or moisture buildup.

### Disc Brake Pros and Cons



The major advantage of a Disc Brake is that they provide excellent and reliable braking and are optimized for Tadpole trike designs. The disc brake action is proportional and provides smooth braking even during the harshest weather conditions. As for disadvantages, the majority of disc brakes are heavy as compared to drum brakes. Lighter disc brakes are available, but are very expensive. Performance reliability for disc brakes is another problem, as most disc brakes are prone to rubbing. Not only is this rubbing an annoyance, it is also a performance robber.

In recent times, the disc brake systems adapted for bicycles have advanced dramatically. In the past, the bicycle disc brake had a negative reputation as being heavy, noisy and having lackluster performance. However, due to many technological breakthroughs (chiefly in material science), disc brakes are now smaller, stronger, and quieter.

### Disc Brake Characterization

Several variations of the disc brake exist. A disc brake is categorized by Actuation and Execution.

#### Actuation

Actuation is how the brake is activated. Three types exist: Mechanical Cable, Hydraulic, and Hybrid.

**Mechanical Cable Systems** use much of the same hardware as a standard bicycle caliper brake. The brake is actuated using a conventional handle and cable/housing. A levering or cam system constricts two brake pads against the rotor in order for braking. On the Avid disc brakes, a cam and ball bearing system is used for even braking. The advantage of a mechanical disc brake is that the cabling is simple and parts are always readily available. The major disadvantage of this system is that the inherent cable-stretch and cable housing compression reduces the overall effective force that can be applied to the brake mechanism.

**Hydraulic Systems** rely on a Master and Slave cylinder system to provide the actuation. As with all hydraulics, the medium is light-weight oil that is moved through a semi rigid line from the brake handle (Master Cylinder) to the disc caliper which can have one to four slave cylinders. The amount of force developed by the Master Cylinder depends on the cylinder's displacement. The direct force that can be applied by a hydraulic system is awesome! However, no system is without its problems. Replacement parts are difficult to find, and if you don't like the handles that came with your brakes, well... too bad.



The **Hybrid System** uses standard brake cables, but actuates a mechanism that contains both Master and Slave cylinders. The reason for this system is it allows a cable linkage system to be optimized by the caliper. Additionally, the hydraulic actuator provides better performance than a total mechanical system. As a mixed blessing, conventional cabling and brake handles can be used. This type of disc brake is rare to find and is slowly being phased out due to the unneeded complexity.

### Execution

The mechanics of a disc brake are simple: Squeeze two brake pads against a turning rotor and voila! However, preventing the brake pads from rubbing against the rotor (when the brake is not engaged) has always been a problem. I'll describe two methods how this is accomplished.

In the **Floating Rotor** design, a Caliper containing the actuator and brake pads is situated in a fixed position (e.g., mounted to the steering knuckle). The Rotor is mounted to a spline shaft on the wheel hub where it has restricted horizontal movement. When the rotor is rotating, it can brush up against either of the two opposing pads. When this occurs, the rotor bounces off the pad and is resituated (hopefully) in a position where it is not touching either pad. The premise of this design is that rotor and pad rubbing cannot be avoided, but can be reduced to a tolerable level.

Advantage: No calibration or adjustment and the system is light and simple.

Disadvantage: Always slight rubbing and the spline is prone to wear out quickly.

We can be thankful that these types of brakes are all but obsolete.

In a **Floating Caliper** design, the caliper is either floating or is biased to a location where neither pads contact the rotor. On the Practical Innovation's disc brake, the caliper was designed so that it was in a fixed or biased position during no braking. During braking, the caliper became free-floating so that both pads could contact the rotor with identical force.

Advantage: least susceptible to rotor/pad rubbing.

Disadvantage: Many adjustments and weight penalty.

As with the floating rotor, this design is quickly sinking to obscurity.

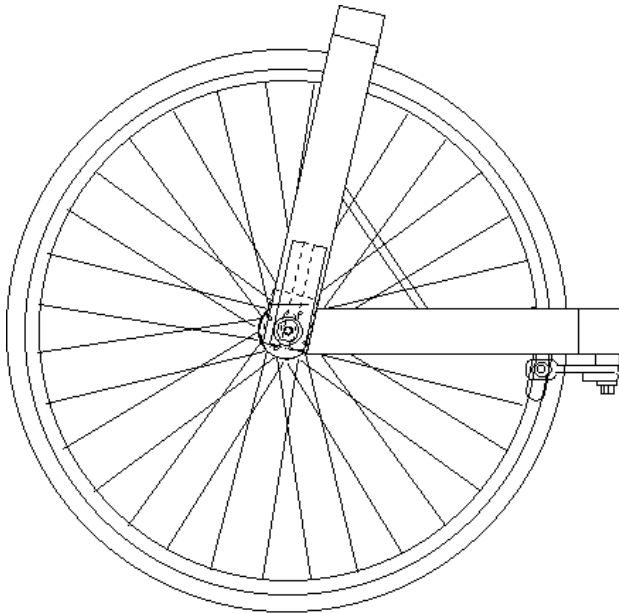
The **Fixed Caliper** design is built around the assumption that the rotor is perfectly true and will remain so. As the name implies, this caliper design is stationary mounted using either a concentric washer or spacers to make the final adjustments. Once adjusted, the pads should not touch the rotor until the brake lever is actuated.

Advantage: Adjust and forget, very light weight

Disadvantage: Shimming and adjustment is difficult

These disc brake systems are used for both mechanical and hydraulic and are usually the lightest and most common system available.





### Caliper Brake System

The venerable caliper brake offers adequate performance and reliability. Since several books exist on this subject, I will not elaborate much. The caliper brake system can only be used with the Steering Stirrup that supports a standard BMX wheel. This additional ancillary can compromise weight constraints. However, the caliper brake is readily available and so are the BMX standard wheel sets. The economy and practicality of this system makes it a very attractive alternative for the home builder.

*Left is a stirrup knuckle with a caliper brake.*

### Summary

As a designer and innovator of disc brake systems for tadpole trikes, my opinion stands as an authority on this subject. Currently, I feel that the drum brake is the most practical choice (not always the best) for recumbent trikes. The drum brake is inexpensive and easy to adapt to tricycle needs. In addition, the wheel can be easily removed. Even though the hydraulic disc brake beats the drum in almost all categories, the price is normally higher for most people.

### Side Note

*As the former owner of Practical Innovations, my mission was to produce a product that was technologically ahead of its time. I spent many months and thousands of dollars developing a practical disc brake system. My first two generations of disc brakes were utter failures. However, perseverance prevailed and I finally developed a high performance disc brake system that was reliable. The disc brake was the main selling point for all models of Zephyrs sold. Although there are now disc brake systems that offer better performance than my own, I remain the only manufacturer that has successfully implemented a proprietary brake and linkage system to a recumbent.*

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## Wheel Bearings

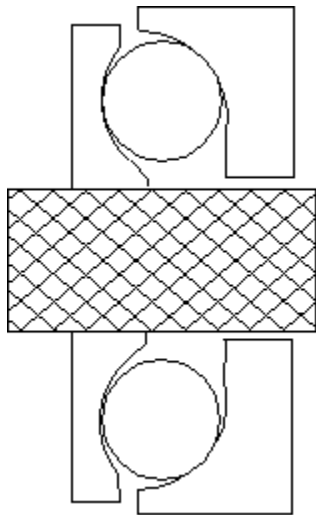
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The biggest misunderstanding in designing a recumbent trike is the requirement for both front and rear hub bearings. For years we have been tantalized by all the great custom hubs built by Phil Wood and countless other manufacturers. Most of these hub builders use sealed cartridge bearings. When we hear the word "Cartridge Bearing" we think of performance, quality, and reliability. What we are not told, is that sealed cartridge bearings are specifically designed for radial loading and not optimized for axial loading.

**Radial loading** is the amount of weight placed vertically above the axle. Sitting on a trike places an axial load on the bearings. The drawing below is a cross-sectional view of a radial bearing.

Axial or **Thrust loading** is the amount of force placed against the horizontal plane of the axle. Negotiating a tight corner at high speeds places a radial load on all three wheels. A cross-sectional view of a cup-and-cone axial bearing is shown below.

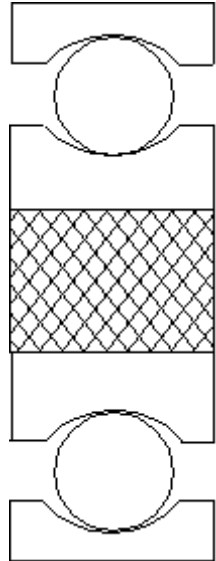
Although all bicycles use a combination of both axial and radial loading, the recumbent tricycle places much more emphasis on axial loading. Therefore, the venerable cup-and-cone bearing arrangement is still the most effective.



If an axial load rated bearing is the best, why are they less reliable than the sealed cartridge bearing? It turns out that the seal makes the biggest difference in the cartridge bearing. If a similar seal existed for the axial cup-and-cone bearing, the longevity would exceed that of the cartridge bearing.

Another advantage of the cartridge bearing is the easy serviceability. In most axial bearings, the cup is an integral part of the hub and cannot be replaced.

*Left: is a Axial bearing*



**Summary**

Although the cartridge bearing appears attractive, it is not always the ultimate solution. A recumbent trike produces heavy side loading which requires a bearing to have an adequate axial load specification.

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## Chain Line Management

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Chain management was lightly touched in a previous chapter, as the disadvantage of most recumbents is the long, hard to manage chain. A recumbent chain is managed using either a tube, a Chain Pulley or mid drive system. This section will explain all of these solutions.

### Polyethylene Tubing

In today's trike market, the polyethylene garden sprinkler tubing is widely accepted as the standard. This tubing is light, offers a slick surface, and is inexpensive. Another important feature about this tubing is that it protects the chain from grime and dirt, hence extending its longevity. However, efficiency can be compromised if the wrong lubricants are used on the chain. It's best to use very thin oil when using this tubing, as it offers the least amount friction between chain and the polyethylene surfaces.

The reason why a chain can pass through this type of tubing with little friction is very elementary. In a straight path, only outside edges of the chain contact the polyethylene. What is important is finding the correct diameter of tubing to use, as three basic sizes exist, along with several thicknesses. If the tubing is too small in diameter, the chain surfaces have more contact with the tubing creating higher friction. A diameter of tubing that is too large makes the system heavy and allows too much chain slop. Polypropylene tubing with  $\sim .7$  OD and an ID of  $\sim .6$  inches seems to work the best. However, those who have an endless supply of money and resources can purchase the ultimate friction free solution; Teflon, tubing goes for \$5.00/ft. BTW- You can find this stuff on many recumbent websites.

The application of this tubing should be restricted to a straight chain line. This is especially important when applying the tubing to the drive side of the chain. On the non-drive side (the side of the chain where the derailleur pulleys take up the tension) routing the tubing in an arc may increase friction. If an arc is required, make it as gradual as possible, as to decrease the chances of friction. Another way of increasing the efficiency is to keep the chain tensioned, as to make it self-supporting so that it never has to rest fully on the inside of the tubing.

### Chain Pulleys

Ok, so they're actually skate board wheels. They work great if you get the right ones. Look for a durameter of at least 98 and a diameter of 50 mm. Almost every recumbent uses a chain pulley. In most successful trike designs the pulley is used almost exclusively on the drive side of the chain to change the chain line angle.



## Mid-Drive Systems

To my knowledge, Steve Delaire is probably the strongest proponent of the mid drive system besides myself. The mid drive system solve two problems with relative simplicity and efficiency; 1) Most recumbent trikes use smaller rear wheels that require higher gearing 2) The chain line angle needs to be altered. A mid-drive system handles both common problems, but requires a bit of consideration. First, two separate chains are used, and in most cases a second derailleur is needed (this is especially true when multiple gears on the mid-drive are used). With a second derailleur on the mid drive, the designer must insure that adequate ground clearance can be achieved. Lastly, an extra derailleur requires an extra shifter, this can complicate the ergonomics and design of the trike. My suggestion is to use a locally shifted type of derailleur (one that has an actuator built in) with a very short cage. This locally shifted derailleur will span only two extreme gears. This combination allows an extremely wide gear range, but benefits from a simplistic, convenient, inexpensive, and efficient system when compared to a Schlumph drive or SRAM 3X8 combination.

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## Performance Considerations

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The most frequently asked question I get is, “What makes a high performing recumbent trike?” This answer assumes we want ultimate efficiency and handling on both flat and hilly roads. The first and foremost criteria for performance are aerodynamics followed by weight and rolling resistance. I’ll elaborate each of these attributes and explain how they are addressed in a performance trike design.

### Aerodynamics

The majority of energy lost is through wind resistance. The science of aerodynamics is very complex and sometimes controversial. I confess that I only understand the basics of this field. However, applying these basics to an un-faired trike design provides 90% of what we need to know.

#### *Note*

*The mention of a front fairing and tail box has been omitted from this discussion. Although both accessories provide an ultimate solution to reducing aerodynamic drag, I don’t have the expertise to elaborate.*

Reducing the overall frontal area make the vehicle more aerodynamic. There are several ways to reduce the frontal area of a trike. I have provided a few of the major ones here:

- **Increasing the seat angle** provides an aerodynamic advantage. Most sport recumbent trikes have seat angles less than 35 degrees. Some have angles down to 25 degrees. As mentioned earlier in this chapter, a low angle seat does have controversy as it compromises comfort and visibility, not to mention a longer wheelbase.
- **Decreasing the wheel track** or the overall width of the trike is an obvious way of reducing the frontal area of the trike.
- **Tucking the rider’s arms in** towards their torso decreases the amount frontal area. This is accomplished using an OSS Joystick.
- **Use of smaller front wheels** reduces the frontal area. This is a paradox. Although reducing the wheel size down 20% (20” Vs. 16”) will obviously yield better



aerodynamics, the performance edge is completely eroded away by the decreased roll-over efficiency of the smaller wheel. I'll explain this later.

## Vehicle Weight

### Note

*In several periodicals and articles, I have found conflicting definitions of "Sprung" and "Unsprung" weight. In the automobile industry, Unsprung weight refers to the weight not supported by springs (e.g., wheels, steering linkage, etc.). People talking about bicycles have contradicted terms referencing both Sprung and Unsprung weight as the same. Consequently, I am avoiding the semantics of both definitions, as they officially do not apply to HPV's (according to my Webster's).*

## Frame Weight

As a preface, I wish to explain the virtues of weight or lack there of. A light-weight trike allows faster acceleration and the ability to climb hills much easier than a heavier trike. An out-of-shape, grossly obese rider on a light trike is like ordering a diet coke with a super size of fries and a triple cheeseburger. A light trike is best suited for an athlete, as they best benefit from this performance attribute. Obviously, a light weight trike will not compromise on stiffness or reliability.

## Dynamic Weight

The performance merit of any bicycle or HPV is based chiefly on gross weight; however, more important is where the weight resides. Weight or mass residing in the moving parts (e.g., wheels, cranks, chain) significantly compromises overall efficiency. This is what I refer to as Dynamic Weight. In simple physics, the larger the mass, the more energy it takes to alter its motion (and the more energy stored, too). Mass that maintains a constant velocity or subtle changes thereof, does not require as much energy to maintain its motion. The key phrase is altering or changing velocity. Obviously, it takes more energy to achieve a velocity than to maintain it. That is why the dynamic weight of the vehicle (the wheels, cranks, and chain) must be as light as possible.

Weight residing in non-moving parts (e.g., rider's torso, HPV frame, and accessories) presents less of a performance penalty, as it only plays a factor during acceleration, up-hill riding and added wheel resistance.

In summary, lighter wheels and drive train is the key to optimum performance. Weight loss in non-moving components should be of secondary concern.

## Decreasing Dynamic Weight

Throughout this chapter I mention that a trike design is the sum of many compromises. Consequently, lowering the dynamic weight of any HPV will be a fine balance of compromise.

## Lighter Components

Assuming money is no object, an ultra-light chain, Crankset, pedals, and wheels provides the most effective means of reducing Dynamic weight. Lighter tires are perhaps the most effective and cheapest way of reducing weight while switching to Titanium spokes provides the most expensive method.

## Smaller Rear Wheel

Decreasing the size of the rear wheel from 26" to 20" appears as an easy and convenient method of reducing the rotational weight of a trike. Although there is a 90 gram difference in





wheel weight, a smaller wheel requires a larger chain ring to achieve the high gear inch range as the 26" wheel. A 68 tooth chain ring increases the overall weight by at least 42 grams, not to mention 16 extra links of chain would add yet another 41 grams of weight (2.55 grams per link x 16). The total weight saved diminishes down to only 10 grams. The greatest attribute using a smaller wheel is where the weight is saved. After all, all weight is not created equal when we throw angular velocity into the equation. Are we confused? Let me explain:

I have two rear wheels that weigh 4 lbs ea. However, one wheel uses a heavy hub while the other uses a heavy rim. Which wheel has a higher rotational mass? The wheel with the heavier rim of course!

### **Rolling Resistance**

I may be splitting hairs on the hierarchy of this discussion. Some may claim that rolling resistance is more paramount than vehicle weight. Having three wheels instead of two may be a valid point to this claim.

Rolling resistance is a very touchy subject, as many people have their own strong preconceptions. Therefore, I'll present all the factors that affect rolling resistance, but will not place them in a hierarchy.

### **Tire Rolling Resistance**

Several years ago, Ian Sims built a rolling machine that was intended to test the rolling qualities of wheels and tires. Although his test could not measure the efficiency of a tire size, it was able to produce some interesting results with different brands of tires. More importantly, some European groups had also conducted empirical testing of tires with results that paralleled much of the results conducted by Ian. Some of the winners in this group of 20" size tires include Tioga Comp pools and Schwalbe Stelvios. Although the rolling resistance for some tires may be extremely low, it is best to consider other important factors too, such as tire weight, and application.

### **Roll-Over Resistance**

#### *Warning!*

*There are people that will always believe that small diameter wheels have a rolling advantage to larger diameter wheels. This article is not to evangelize, but to educate. Although my method and conclusion of research are open for debate, I don't spew self-serving propaganda to promote my product or design.*

Small tires small minds? Not exactly, up until 1995, almost all tadpole trikes used larger 26" or 700c rear wheels. The Greenspeed trikes became an almost instant success with their 20" rear wheel design. Not only did the 20" rear wheel make the trike slightly smaller and more convenient, but it made the rear much stiffer too. As the popularity increased, the question concerning the efficiency of a 20" rear wheel came under scrutiny. As mentioned previously, Ian Sims attempted to defend his position by using rolling test data that favored the 20" wheels. However, many discovered that the test methods used by Ian were only conducive at determining tire rolling resistance and not for comparing wheel size. At the time of these results I too, strongly questioned the validity of testing, as his test results for larger wheels greatly contrasted data generated from other empirical testing published elsewhere.

The subject of larger vs. smaller wheels is a very controversial subject. The answer to this is understanding the simple concept of Roll-Over Resistance. Roll-Over Resistance is the ability or inability of a wheel to roll over an uneven or aggregate surface. Example I have a skateboard that rolls fast over a smooth sidewalk, but doesn't roll well over the coarse

aggregate of asphalt. Apply this principal to trike wheels. Over a smooth gymnasium floor the difference between a 20" and 26" tire is very little. As the surface becomes increasingly coarse, the 26" wheels will roll better than a 20" every time.

Roll-Over Resistance is a measurement that can only be quantitated by comparing two wheel sizes over a known aggregate surface. Although rolling resistance of a tire can be accurately measured in a controlled laboratory experiment, Roll-Over Resistance is best measured by empirical road test methods. In my expert opinion, Roll-Over Resistance is as important if not more important as tire Rolling Resistance.

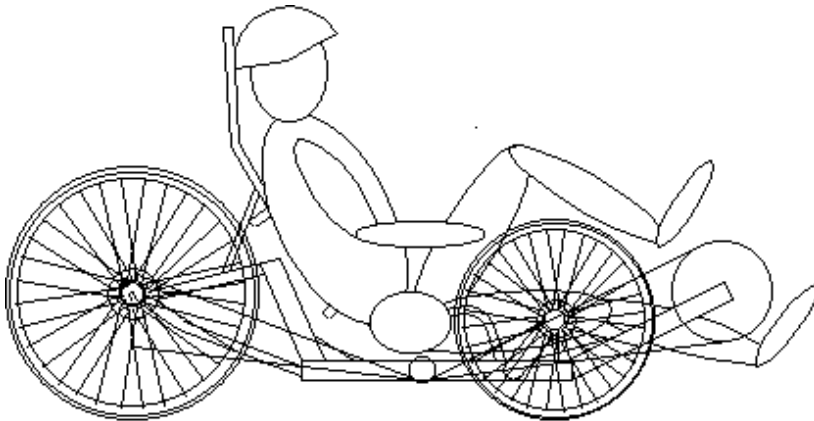
The problem applying this to a recumbent trike is that using smaller wheels in front is a requirement, as they reduce wind resistance, handle side loading, and allow adequate room for steering. The same applies to many recumbent bicycles, as a smaller front wheel allow easy foot clearance from the crank set and reduces wind resistance. However, on a trike we have three wheels instead of two. Since the front two wheels cannot change for the reasons mentioned, we have but the rear wheel to be concerned with. Consequently, changing the efficiency of one out of three wheels will not have the amount of success as that of a bicycle. Regardless a larger wheel will provide better roll-over resistance.

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## The Human Factor

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The basis for a recumbent style HPV is to provide comfort. Therefore, great care should be made to provide simple ergonomics such as the placement of key controls. The seat should be somewhat adjustable as to modify the orientation to suit the rider. In the case of a recumbent, the height of the bottom bracket should require deliberation, as it is a very important and subjective issue. It is best to use a neutral or conservative approach to



Concept drawing of the Thunderbolt used for establishing human requirements

ergonomics as a baseline. After your experimentation, the design can be changed to accommodate your special needs.

The key advantage of a tricycle recumbent is that the orientation of the rider has little impact on the handling characteristics or performance of the vehicle (*as long as weight distribution and CG are optimum*). A tricycle allows the designer greater flexibility

in the design so that more emphasis can be placed on the rider's ergonomics.