Part I

Motivation

Background

The history of the bicycle goes back to the 1800's. Investigating the innovative changes in materials, changeable gears, wheel sizes and frame shapes over the past two hundred years is a whole different report in itself and will not be covered by the scope of this paper. The intent of this project is to analyze different types of modern off-road bicycles and determine their strengths and weaknesses through assessing their mechanical design and performance via test rides and computer analysis.

The off-road cycling community's birth place lies in Marin County, California. People would take their beefy cruiser bikes and ride them on the dirt fire roads of Mt. Temalpais. This trend of cycling was not called mountain biking when it began; these off-road bicycles had various names: Klunkerz, Ballooners, Bombers, Beaters and possibly many more. Avid cyclists began to catch on to the fun and exhilarating aspects of the off-road cycling sport; Joe Breeze, Otis Guy, Gary Fisher, and Tom Ritchey began designing custom mountain bikes in the 1970's that had bigger tires, flat handle bars, and a bigger wheel base that all provided more control in high speed off-road situations [1]. Although they were not the first to outfit bikes to be more suited for off-road use, these four men are truly the pioneers of the mountain bike industry we see today.

The remainder of this section will discuss the components of a bicycle and the information needed to understand the design innovations of modern mountain bikes. If you are well versed in the language of bicycles, it may be in your interest to skip ahead to the next section: Focus.

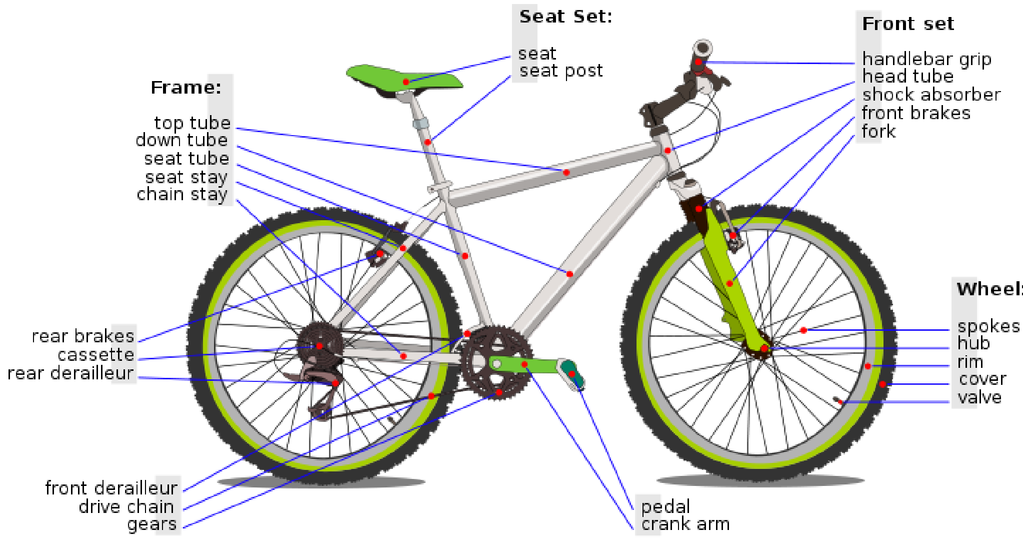

Figure 1: The components of a bicycle

Figure 1 is a diagram labeling the components of a bicycle. The pieces that make up the frame of the bicycle are the head tube, top tube, down tube, seat tube, chainstay and seatstay. Applying force to the pedal turns the crank arm which distributes the force through the drive chain and to the rear wheel. The derailleurs make it posible to move the chain up and down the cassette and front gears, hence changing the gear ratio. There are a few more vocabulary words specific to a bike with rear suspension linkage.

The names of the pieces of the frame are still similar-the seat stay and chainstay, but they are now connected to the frame and shock via pivot points and rockers, or linkages.

Focus

Implementing suspension into a bike frame is an obvious development path for the off-road bicycle. A well tuned suspension will create more traction and control in rough terrain. Although there is independent suspension for the front and rear wheels, the purpose of this experiment is to analyze the different designs of suspension for the rear wheel and identify their strengths and weaknesses. To do this, we must first answer the question: What constitutes an effective rear suspension?

Figure 2: Ideal axle paths

By analyzing Figure 2, we can see that the front axle path has a rearward and upward motion to its travel. Looking at the free body forces from the ground on the wheel, this direction of motion is ideal for absorbing impact. Therefore, it is in our interest to design a rear suspension which has an axle path that mimics that of the front.

Here is where things may begin to get tricky—the ground forces are not the only body forces acting on the wheel. There are forces on the wheel from the chain when the rider accelerates, and there are forces on the wheel from braking when the rider decelerates.

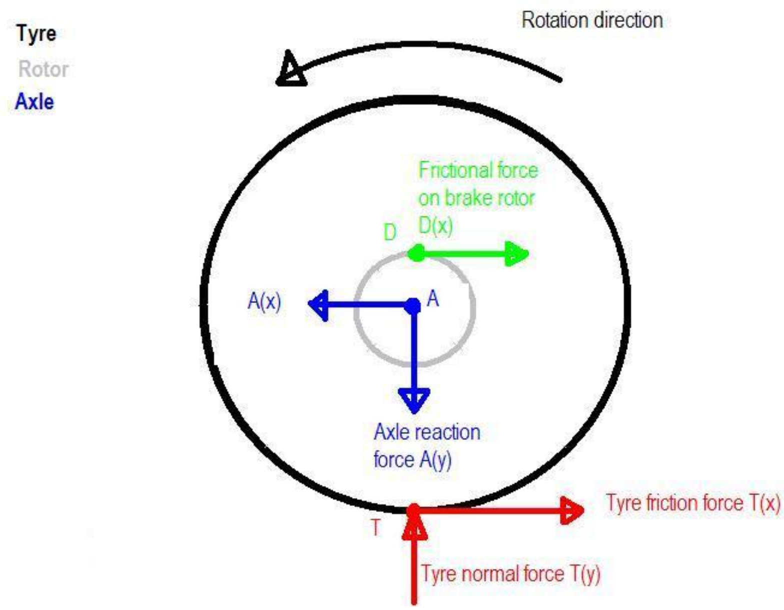

Figure 3: Freebody diagram of force on the rear wheel

Figure 3 is a free body diagram illustrating all the forces acting on the rear wheel. Different rear suspension linkages have different behaviors in each of these situations; braking while the wheel is trying to track through rough terrain may limit the amount of effective travel, and pedaling forces can also limit the amount of available travel. These properties of a rear suspension are known as “brake jack” and pedal feedback. Different rear suspension designs will respond differently to these forces based on brake caliper and pivot point placements.

Before we get into the nitty-gritty of the different suspension designs on the market today, we must understand some simple aspects of torque, leverage ratios, and the basic forces that act on the rear wheel.

A leverage ratio is simply the ratio of the lengths of a lever on each side of the fulcrum. Figure 4 is that of a lever, which is the same as a rocker that has a pivot which acts at the fulcrum.

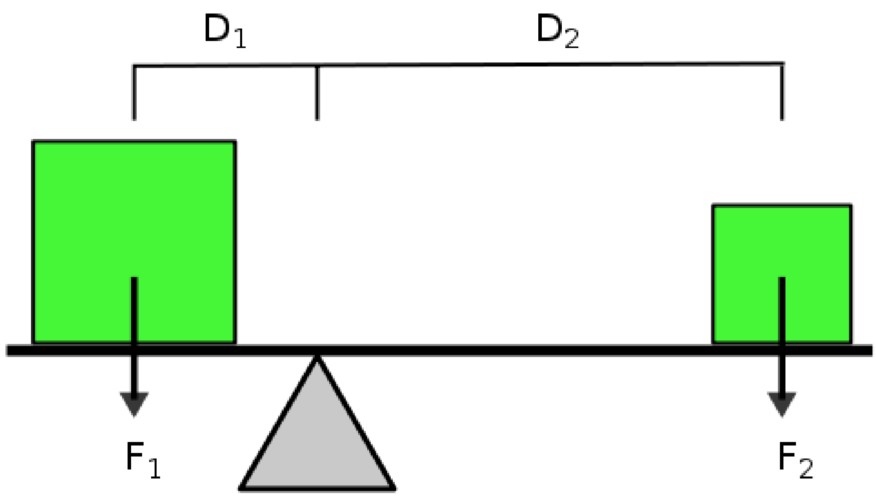

Figure 4: Rocker pivot (a simple lever)

We know the force on Point 1 is simply the force applied to Point 2 multiplied by the ratio of D_1 and D_2 respectively, which we can then consolidate to

$$F_1 = F_2 * \frac{D_2}{D_1}. \tag{1}$$

This is the reactant force on Point 1, F_1, from the force on Point 2, F_2.

Torque, τ, is given by

$$\tau = FD, \tag{2}$$

where F is the force perpendicular to the radius of motion, and D is the rocker length. The torque about a pivot point is the force on the link multiplied by the length of the link. From this we can derive a formula for the force on Point 1 (Fig. 4) as a function of the torque applied to the rocker pivot. Solving Equation 2 for F and plugging it into F_2 in Equation 1 yields

$$F_1 = \frac{\tau}{D_1}, \tag{3}$$

where τ is the torque about the pivot, and D is the distance from the pivot point to the force point.

The remainder of this paper will investigate the axle path, leverage ratio, pedaling forces, and mechanics of six different rear suspension designs. They will be reviewed in individual sections in order of technological hierarchy, starting with the simpler single pivot designs and ending with the more complicated linkages. The individual reports will then be followed by a conclusion section where we will consolidate what we have learned about already existing suspension designs into what is best for theoretical mountain bike design.

Part II

Experimental

Abstract

The following contains subsections where we will investigate each frame design individually. The images and plots used in each of the sections were generated using Linkage by Racooz Software.

The initial image is that of the frame design itself. This image aids in visualizing the shape of the bike and how the pivots and links are placed to achieve varying wheel paths and leverage ratios. Note, there are some numbers in the upper left of the image that can be ignored; they are simple measurements of frame distances, such as force on the wheel, bottom bracket height and wheel base, that will actively change when making a flash video of the suspension in action.

The first graph is a magnified image of the axle path. The graph is constructed by tracking the axle path as it moves through space. The x-axis is the amount of rearward or forward motion the wheel has (in millimeters) as it moves vertically along the y-axis (also in millimeters). Also note the axes have different scales.

The second graph displays the leverage a force applied to the rear axle has on the shock at a given point in the vertical travel, also known as "the leverage at the rear wheel." This ratio is unitless and in the y-axis, and changes with respect to the x-axis—the position of the axle in the travel measured in millimeters. Calculating the leverage of a single pivot can be simply done using Eqn. 3. For example, find the torque about the main pivot due to a force on the rear axle, then that torque may be used to solve for the resulting force at any lever arm distance. However, calculating the leverage ratio for 4-Bar linkages is very complicated and is where Linkage suspension software becomes very useful. When multiple

pivots and links are involved in the apparatus, angles of forces, thus leverage ratios at the rear wheel, are constantly changing. The way Linkage calculates leverage ratios for the more complicated linkages (VVP, Maestro, etc.) is by deriving the instantaneous center (IC) of rotation of the rear axle, and calculating the leverage of this "virtual" single pivot at each point throughout the travel. This can be done by drawing a line through both pivots (not where the shock is connected) of an individual rocker, and then finding where the lines from the two rockers in the linkage intersect.

The third graph illustrates how many degrees the pedals rotate as the suspension is compressed. The x-axis represents the distance through the rear travel (in millimeters), and the y-axis represents the rotation (in degrees). This is directly related to the chain growth, but this graph allows us to analyze where and how fast the chain growth inhibits the pedaling forces. When riding, it is the pedal feedback that the rider notices as the negative effect of the chain growth.

Single Pivot

Apparatus:

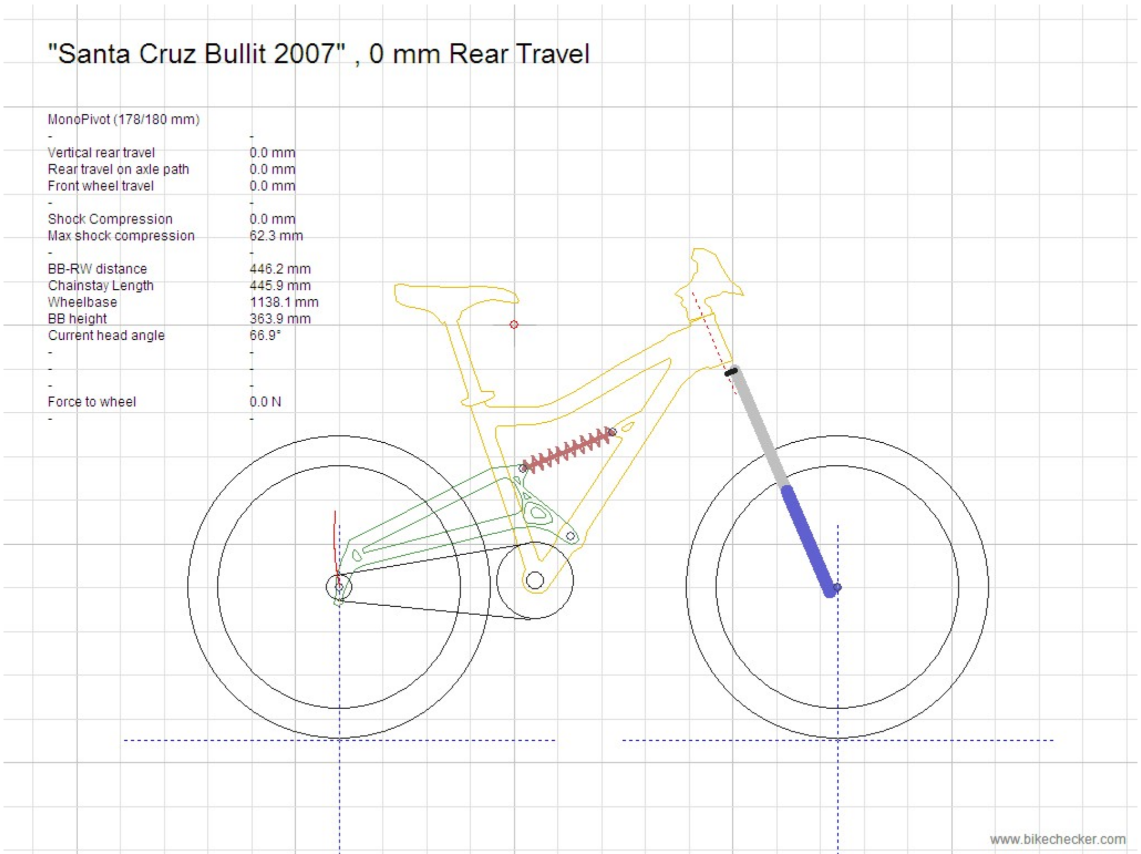

Figure 5: Single pivot on a Santa Cruz Bullit

Figure 5 is a diagram of a Santa Cruz Bullit, a single pivot designed dual suspension mountain bike. Single pivot suspensions are the simplest type of rear suspension. They have a fixed pivot point, which makes the rear wheel pivot along the fixed arc of the swing arm. A linkage, or rocker, may be used to attach the swing arm to the shock to achieve a changing leverage ratio as the wheel moves through the travel. However, the best property of a single pivot rear triangle that connects directly to the shock is that it creates a linear leverage ratio, which can be great for short travel small bump compliance.

Design:

There are also some flaws to the simplicity of the single pivot design. Since the path of the rear wheel is restricted to the arc of the swing arm there is immense chain growth as the wheel moves further through the travel. A rider standing on the pedals going through extremely rough terrain can feel these chain growth forces in the pedals. By consulting Fig. 5 we can see the higher the pivot is placed, the more the pedaling forces will oppose that of the wheel travel. If the pivot point is placed lower we see the opposite—pedaling forces will cause the suspension to stay compressed. Also, since the brake caliper is attached to the end of the swing arm, there are immense amounts of brake jack. As the wheel tries to move through the arc of the swing arm, braking forces oppose this motion and effectively limit the activity of the rear wheel.

Results:

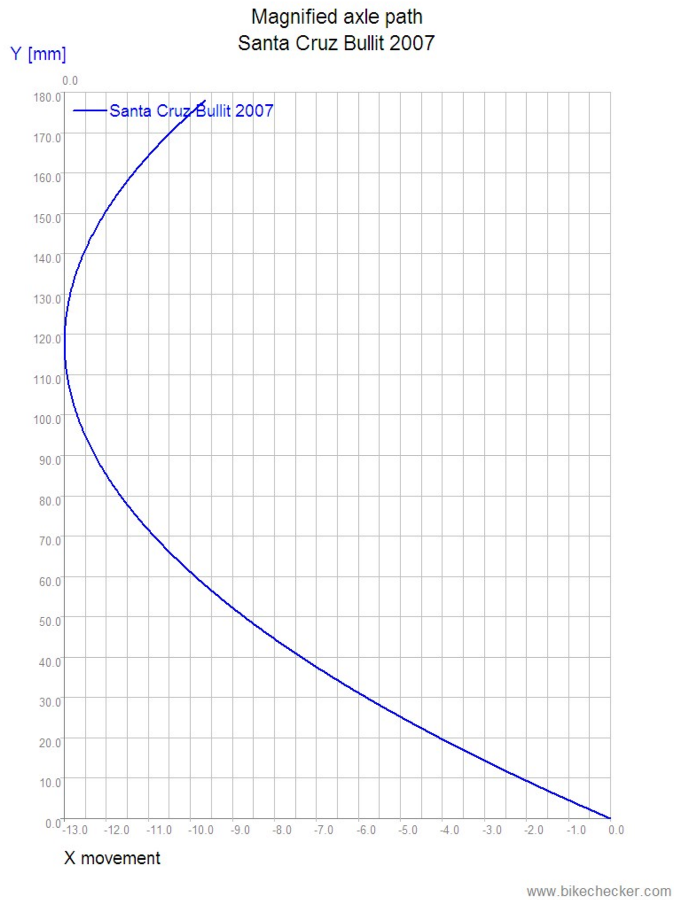

Figure 6: Magnified Axle Path (Santa Cruz Bullit)

Figure 6 is a graph showing a magnified wheel path of the rear wheel, where the x and y-axis are the movements of the axle in millimeters. Notice through most of the travel the wheel is moving rearward and upward, an ideal path for smooth bump absorption. We can also see from Fig. 7 that the variance in leverage ratio is very minimal, it is not linear, but the curvature of the leverage ratio is exagerated due to the accuracy of the leverage ratio in the y-axis. As the wheel moves through the travel (x-axis) the leverage ratio remains nearly constant.

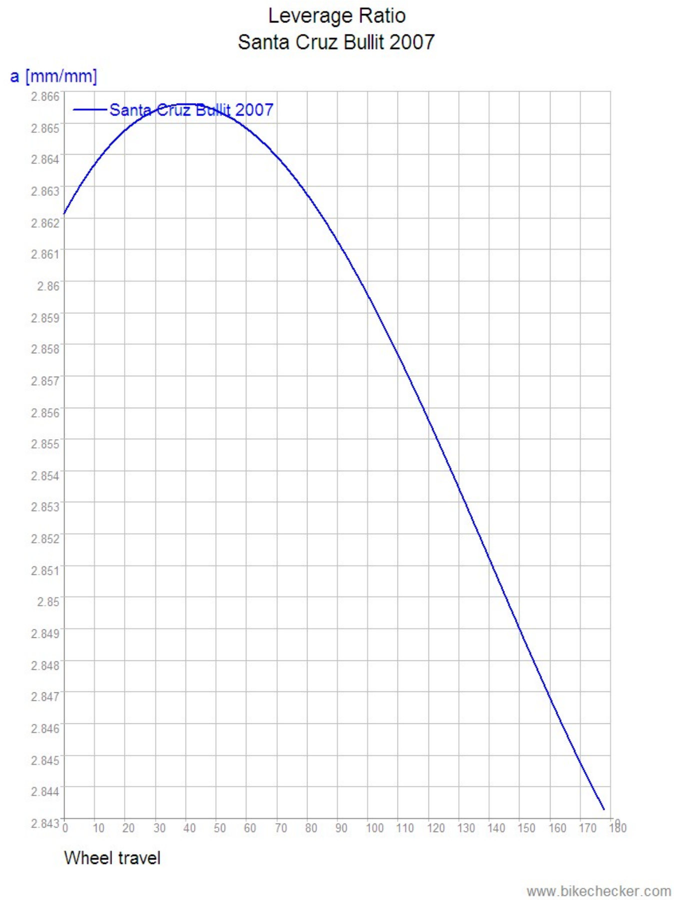

Figure 7: Leverage Ratio (Santa Cruz Bullit)

However, Figure 8 reveals the flaw of the single pivot design. Although the wheel path and leverage ratio are ideal, the chain growth is unavoidably large due to the pivot of the swing arm being placed high above the bottom bracket. This causes immense amounts of pedal feedback. As the wheel moves through the travel (x-axis). At the end of the travel, the cranks have moved 17 degrees from their position at zero travel. Although the pedal feedback is linear, it is so drastic that big bumps are very perceptable through the drive train.

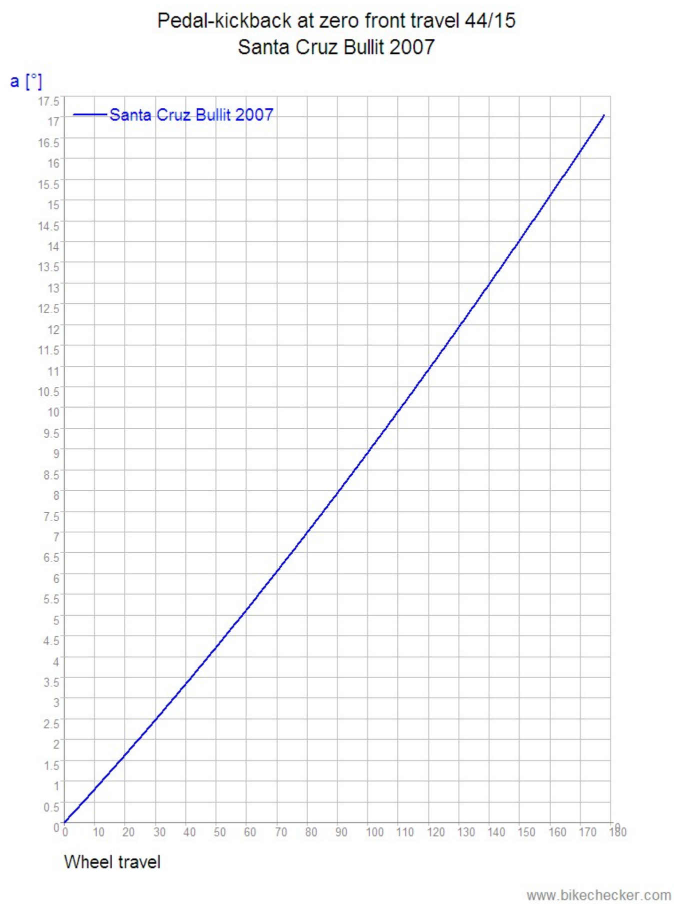

Figure 8: Pedal Feedback (Santa Cruz Bullit)

4-Bar Link

Apparatus:

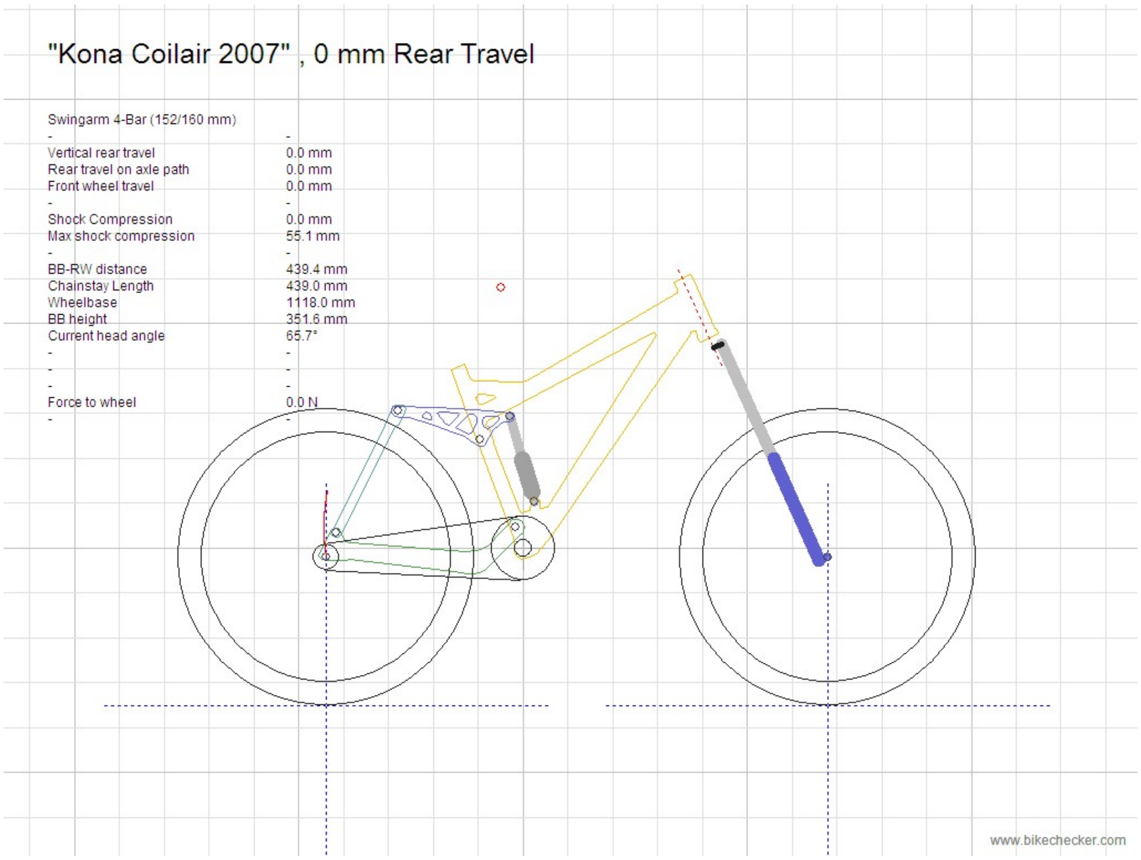

Figure 9: Standard 4-Bar Link on a Kona Coilair

Figure 9 is a diagram of a Kona mountain bike. Their whole line of bikes uses this standard 4-Bar link to provide nonlinear leverage ratios. Looking at the linkage in the diagram it is apparent that the axle of the rear wheel is still following the arc of the chain stay, hence, it is essentially still a single pivot suspension design.

Design:

This design has the same problems under chain forces and acceleration/deceleration. Because the linkage has a pivot on the chainstay, which is also where the brake caliper is attached, braking forces have the same effect as all single pivot bicycles—it will lock out the travel causing brake jack. Also, with the location of the pivot point the chainstay low and near the bottom bracket, pedaling forces will tend to pull the rear wheel through its travel. This pedal feedback is unavoidable when using a 4-Bar link or single pivot, but is not always a problem—to some people it has become preferred. The problem comes from chain growth, and becomes more of a problem when chain growth is not linear. If the chain growth is nonlinear large changes in terrain will make the pedal feedback much more noticeable to the rider. A completely linear chain growth is ideal and much less noticeable.

Results:

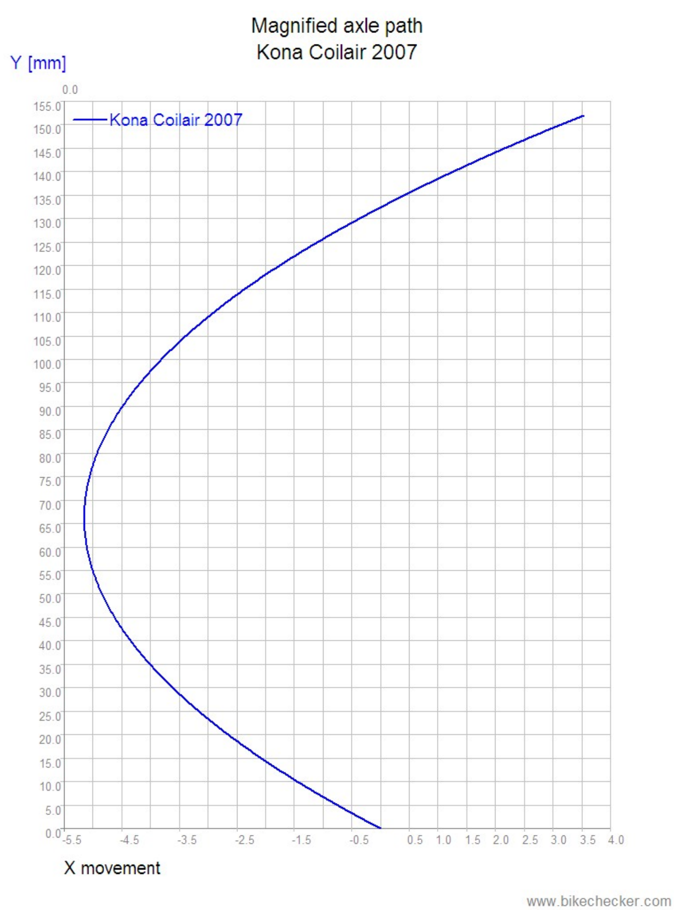

Figure 10: Magnified Axle Path (Kona Coilair)

Figure 10 is a graph showing a magnified wheel path of the rear wheel, where the x and y-axis are the movements of the axle in millimeters. The axle path of the 4-Bar link cannot maintain a rearward axle path for as much of the travel because the pivot point of the rear swingarm is positioned low and close to the bottom bracket. However, this was not the main design goal of this linkage. The 4-Bar is really a single pivot, but the linkage creates a leverage ratio that naturally stiffens as the bike sits deeper in the travel. This changing leverage ratio will provide even more traction in small bumps, and will feel more forgiving under big impacts when compared to a standard single pivot.

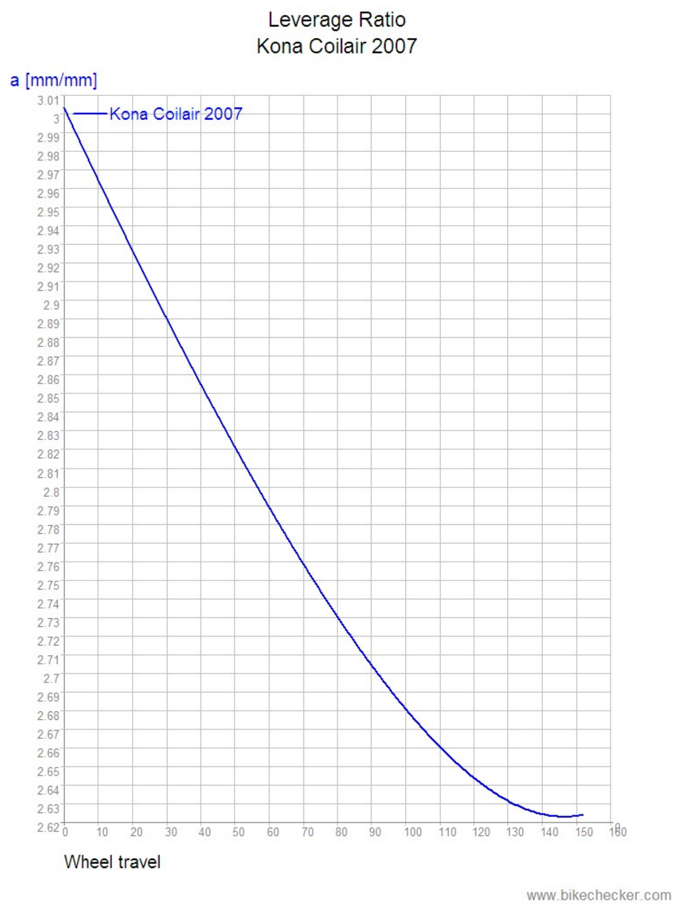

Figure 11: Leverage Ratio (Kona Coilair)

Figure 11 illustrates the effectiveness of the 4-Bar linkage. In the beginning of the travel the wheel has a 3:1 leverage ratio, and as the wheel moves through the travel its leverage on the shock decreases giving the bike a suspension that “ramps up” which provides better traction and an endless feel to the travel. The fact that the pivot of the rear swing arm is positioned so close to the bottom bracket allows for a suspension design with minimal chain growth. Figure 12 is a graph of the pedal feedback influences by movement through the rear travel.

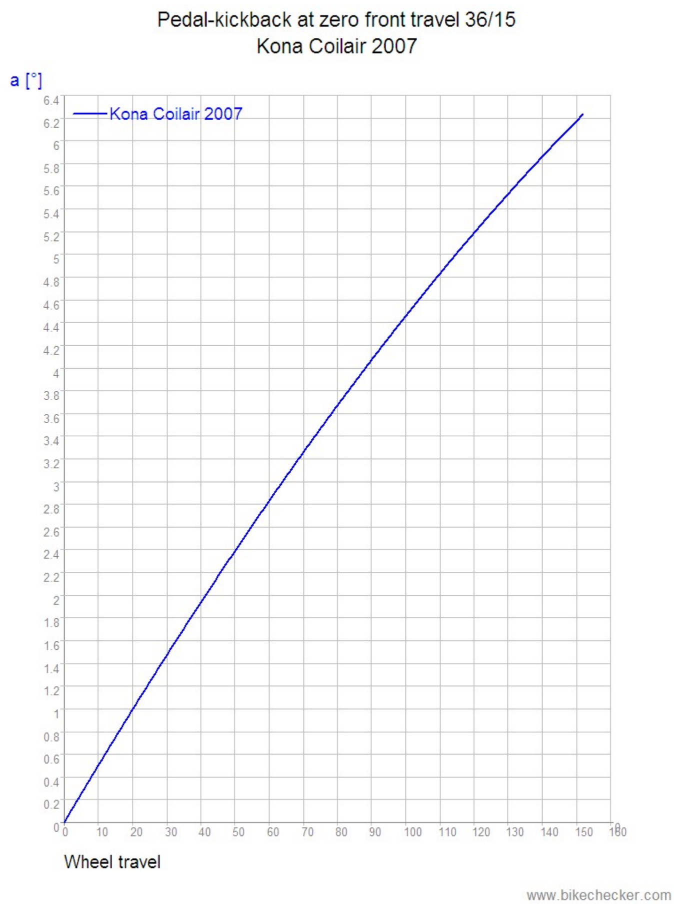

Figure 12: Pedal Feedback (Kona Coilair)

The 4-Bar link does a much better job of minimizing feedback through the drivetrain because of that rear swingarm pivot placement. As the wheel moves through the travel the pedal feedback is less than half of the feedback felt through a single pivot with a higher main pivot.

4-Bar Horst Link (FSR by Specialized)

Apparatus:

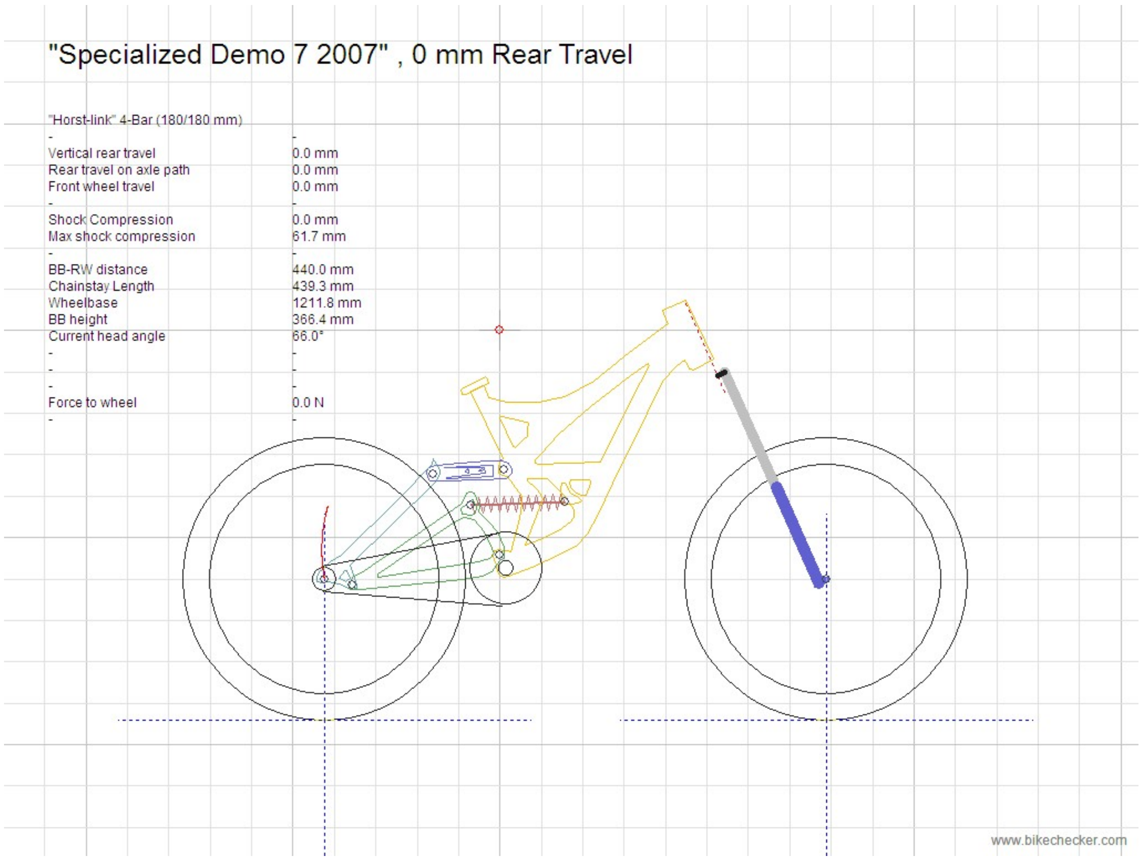

Figure 13: 4-Bar Horst Link (FSR) on a Specialized Demo 7

Figure 13 is a diagram of a Specialized FSR suspension bike. The Horst link modifies the wheel path of the standard 4-Bar link by moving one of the pivot points from the seatstay to the chainstay. Placing the pivot point in front of the rear axle (on the chainstay) allows the path of the rear wheel to be more complex and not simply following the arc of a swing arm. This allows for a fully active suspension under braking and pedaling forces.

Design:

Because the brakes and wheel are attached to a "floating" seatstay, braking forces no longer inhibit the linkage from being active. The pivot points on the chainstay and at the top of the seatstay are always free to move and compress the shock. The position of the pivot points in an FSR linkage provides full control over the rear wheel path.

Results:

The 4-Bar Horst link proves to be very similar to the standard 4-Bar link. Figure 14 shows the axle path as the wheel swings through the travel. It maintains rearward motion through the beginning of the travel for small bump compliance, and has similar shape to that of the standard 4-Bar linkage. However, the FSR design has the rear pivot on the chainstay rather than the seat stay which drastically changes how the wheel reacts to pedaling forces.

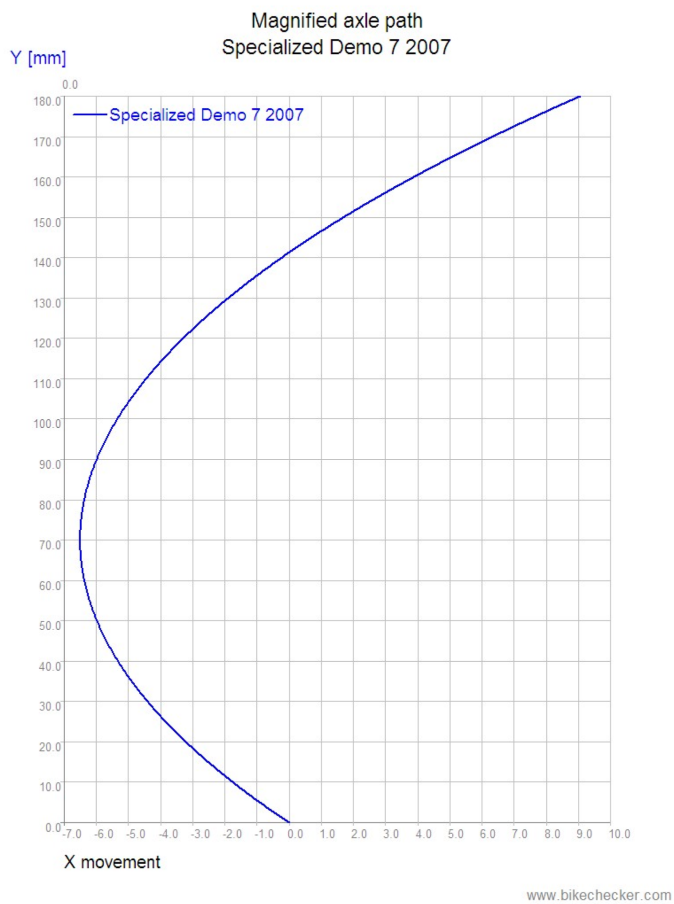

Figure 14: Magnified Axle Path (Specialized Demo 7)

Figure 15 shows the leverage ratio is also similar to that of 4-Bar; it has a ramping nature in which the travel stiffens progressively through the travel.

Figure 15: Leverage Ratio (Specialized Demo 7)

The efficiency of the Horst link (pivot on the chainstay) achieves even less pedal feedback because it further minimizes chain growth. Figure 16 shows the pedals only change position by a few degrees as the suspension is compressed. This makes for an outstanding ride through extremely rough terrain at high speeds. It is simply the small change in location of pivots that allows the FSR or 4-Bar Horst link to achieve a travel that is more active under chain and braking forces.

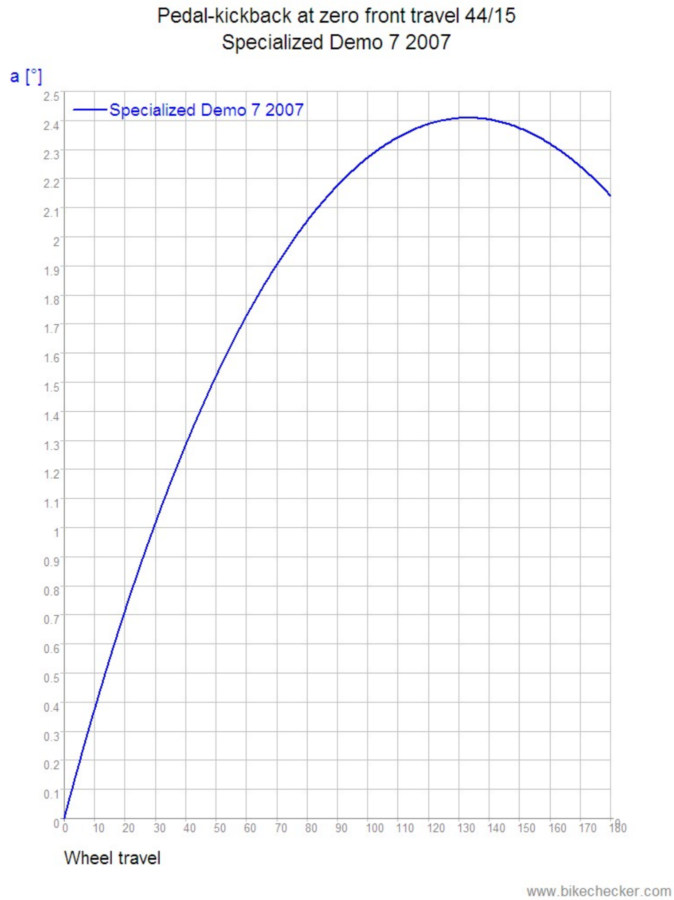

Figure 16: Pedal Feedback (Specialized Demo 7)

Virtual Pivot Point (VPP by Santa Cruz Bicycles)

Apparatus:

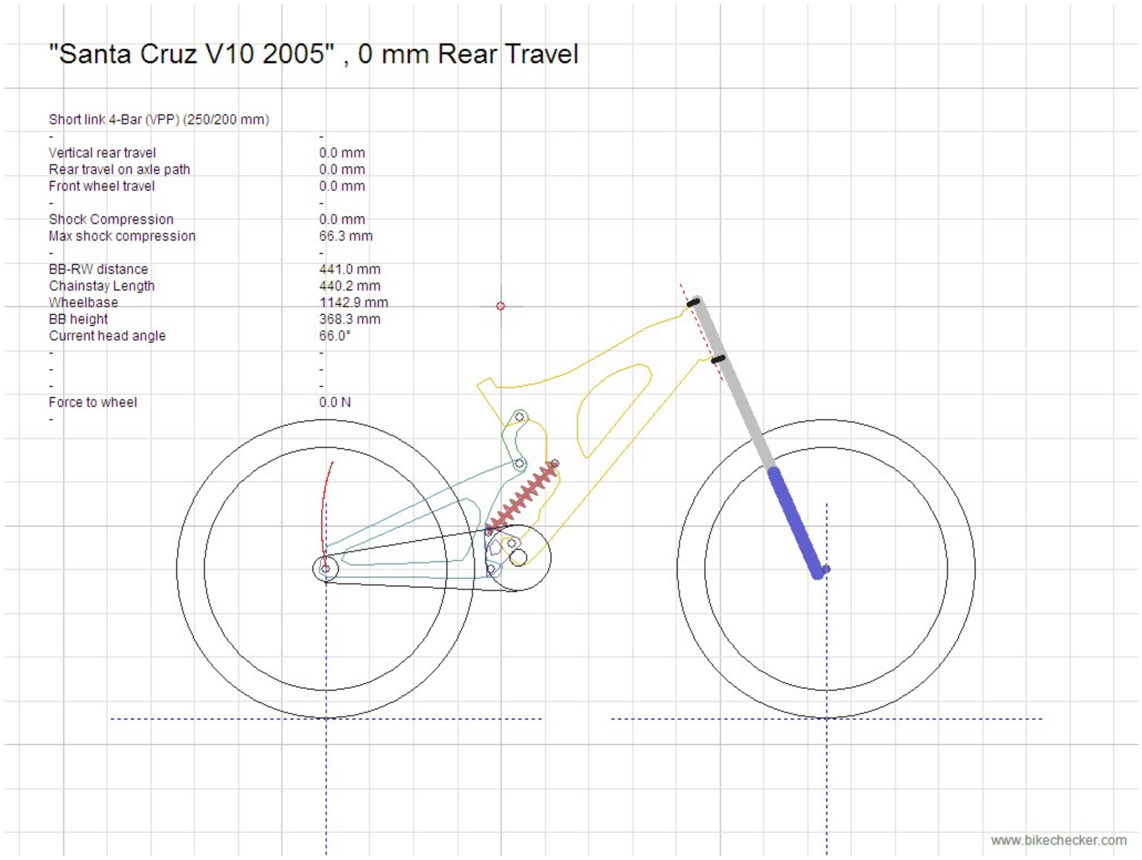

Figure 17: VPP on the Santa Cruz V10

Figure 17 is a diagram of a Santa Cruz V10, a large travel downhill bicycle, which utilizes a unique frame design which minimizes the effects braking and pedaling forces have on the suspensions effectiveness. The Virtual Pivot Point (VPP) is a linkage system that is designed to maintain an active suspension through all the different forces the suspension receives. The main accomplishment of the VPP is that pedaling forces act on the suspension in such a way that it actually counteracts pedal feedback, hence, reducing bobbing through the suspension when pedaling without compromising bump absorption. The VPP linkage is very similar to the 4-Bar linkage, except it uses a solid rear triangle with much shorter rocker links (rather than the long chainstay and big rocker that connects to the shock) connecting it to the frame. At a glance, it is still a linkage that uses four pivot points, but because the two pieces linking the rear triangle to the frame are constantly moving, there is no fixed pivot point. The pivot point is constantly changing based on the positions of the axel path and linkages, hence the name: Virtual Pivot Point.

Design:

The system uses chain growth to its advantage. Designed to work with a sufficient amount of sag, so the bike with a rider on it sits in a position that maintains positive and negative travel, the forces of pedaling are used to keep the VPP suspension from bobbing. However, because of its constantly changing "virtual" pivot point there is a period through the travel where the wheel path changes directions from rearward to forward. This causes a point in the travel where pedaling forces can indeed prohibit the suspension from being fully active. But for the most part, the design of the VPP accomplishes the goal of a linkage that pedals efficiently.

One major part of the solid rear triangle is the short rockers need to be extremely strong to withstand the forces on the rear wheel, which leads to the need for heavier more burly components on the bicycle. These small rockers also create lots of stress on the bearings making the longevity of the components not as prolonged as, for say, the single pivot design.

Results:

The VPP is still a 4-Bar link, but the solid rear triangle and smaller rockers allow for an even more customizable suspension build. Figure 18 displays the axle path of the rear wheel. Notice it is still similar to the 4-Bar and FSR linkage systems. Engineers have found that an axle path of this kind is the most desirable to mountain bike riders, in designing the VPP Santa Cruz bicycles was interesting in designing a suspension linkage that creates a changing leverage ratio and works with chain growth to improve pedal efficiency.

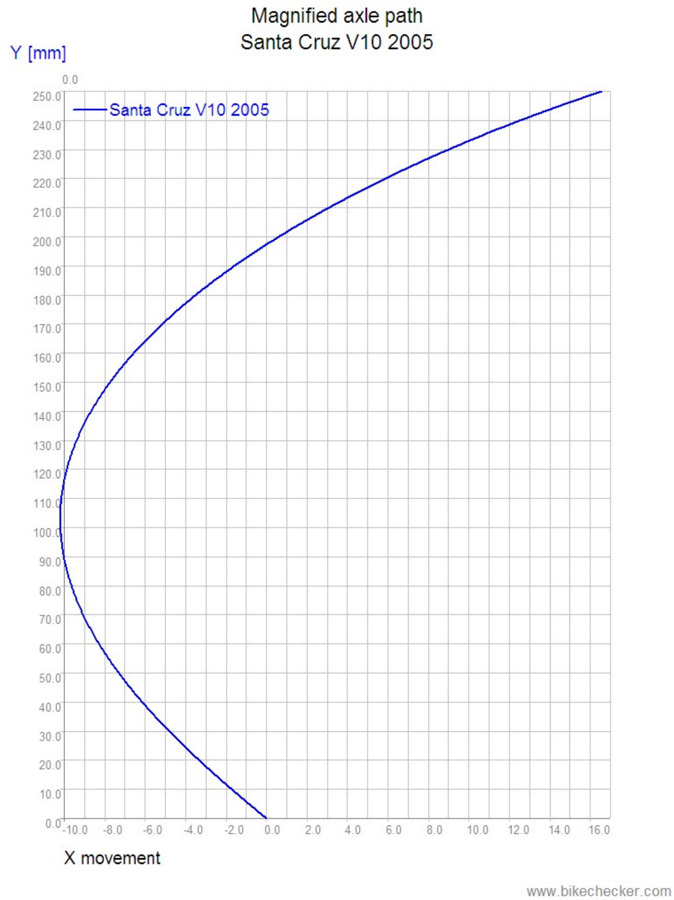

Figure 18: Magnified Axle Path (Santa Cruz V10)

Figure 19 shows the extreme ramping nature of the VPP, and the almost near infinte leverage on the shock at zero travel. The purpose of this design is to use the pedal feedback, shown in Fig. 20, and the ramping leverage ratio to minimize the bobbing associated with pedaling a large travel bicycle. The pedal feedback maintains a pedaling platform against the leverage ratio. In other words, as the leverage ratio drops, the pedal feedback increases to resist suspension bob.

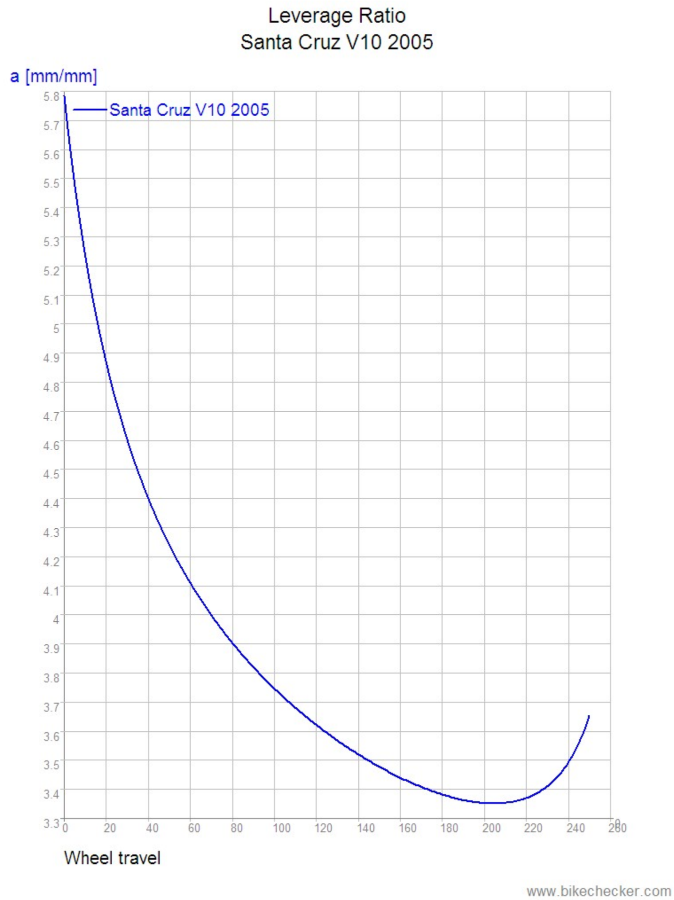

Figure 19: Leverage Ratio (Santa Cruz V10)

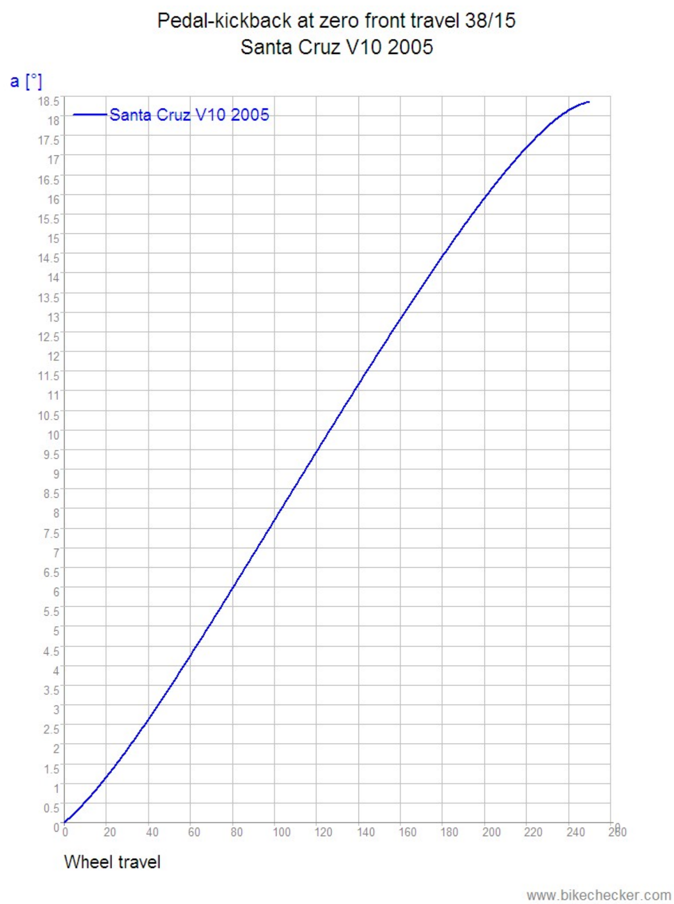

Figure 20: Pedal Feedback (Santa Cruz V10)

Maestro Link (Giant Bicycles)

Apparatus:

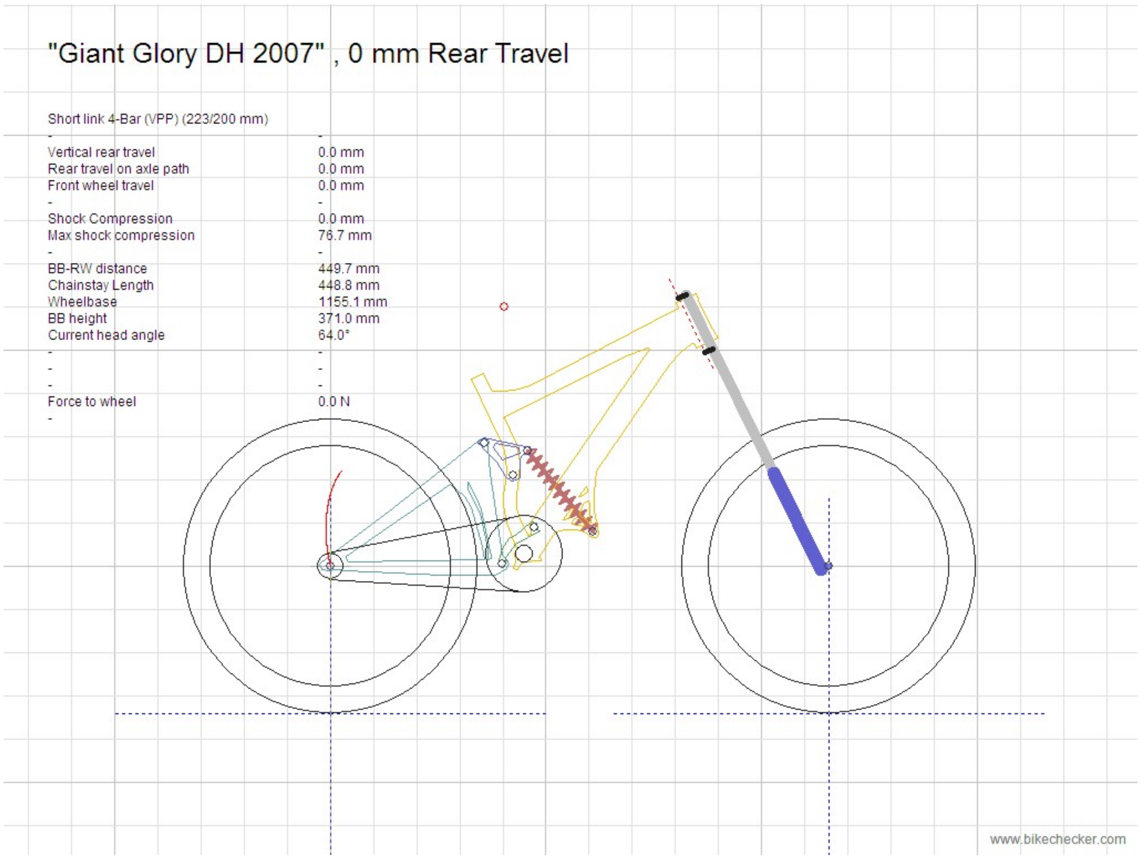

Figure 21: Maestro Link on a Giant Glory DH

Figure 21 is a diagram of Giant's large travel downhill bicycle. The Maestro link by Giant is very similar to the VPP and DW link designs—that it has a solid rear triangle connected to the frame and shock via 2 rockers. The goals of the Maestro link are to increase pedaling efficiency and maintain an active travel under braking and pedaling forces. Where this design differs from the other two similar linkages, the VPP and DW link, is that it maintains a constantly decreasing leverage ratio providing great small bump traction and a suspension that stiffens as the wheel moves further into the travel, creating a suspension that feels endless.

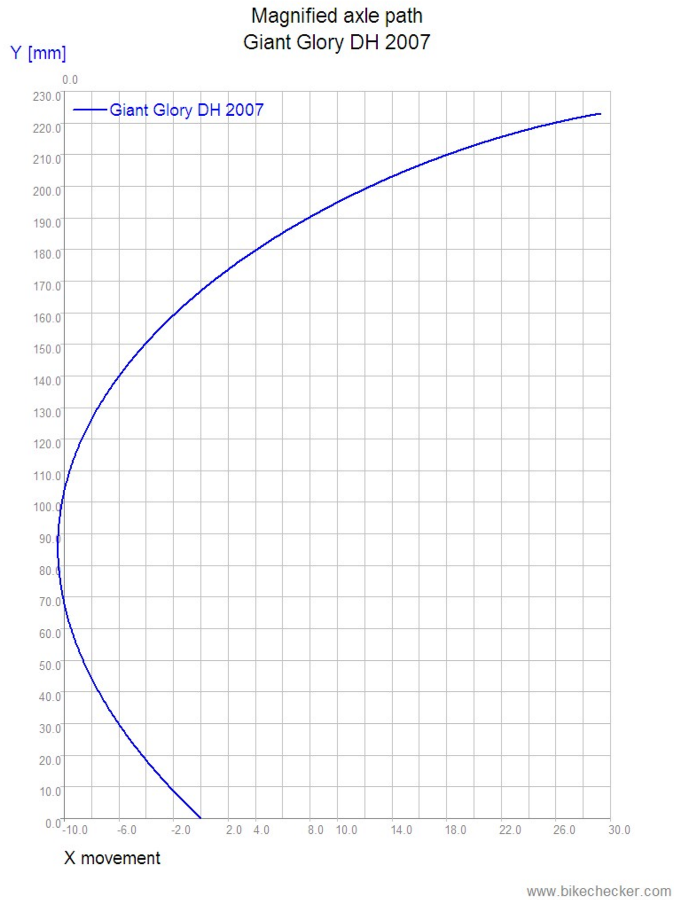

Figure 22: Magnified Axle Path (Giant Glory DH)

Design:

The differences in the Maestro link are results of key pivot point and rocker placements. It is able to maintain complete suspension activity under pedaling forces and total braking independence.

Results:

Figure 22 shows the axle path of the rear wheel in the Maestro linkage has more of a vertical path in the beginning of the travel rather than rearward. This is similar to the axle path of a standard 4-Bar linkage with a pivot near the bottom bracket, but the geometry of the Maestro linkage allows it to achieve a progressive leverage ratio.

As shown in Figure 23, the leverage ratio severely drops as the bike moves further through the travel, and at the end of its travel the ratio drops off to a near infinite slope. This design achieves the most ideal ramping leverage ratio compared to any of the linkages reviewed in this report.

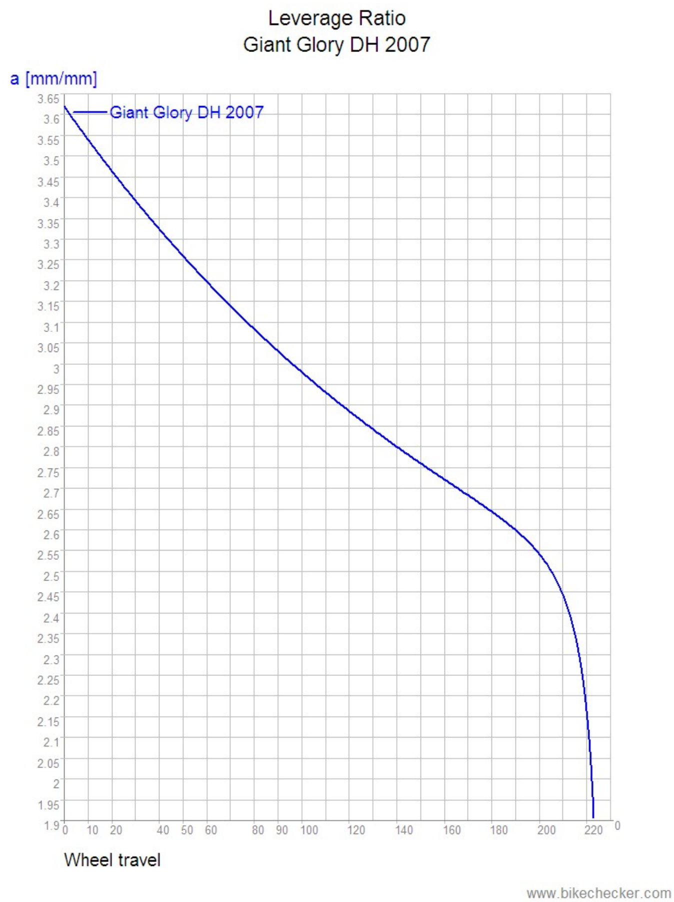

Figure 23: Leverage Ratio (Giant Glory DH)

Figure 24 shows the change in angle of the pedals as the axle swings through the travel. The pedal feedback has been minimized while still maintaining a large amount of travel with a progressive leverage ratio.

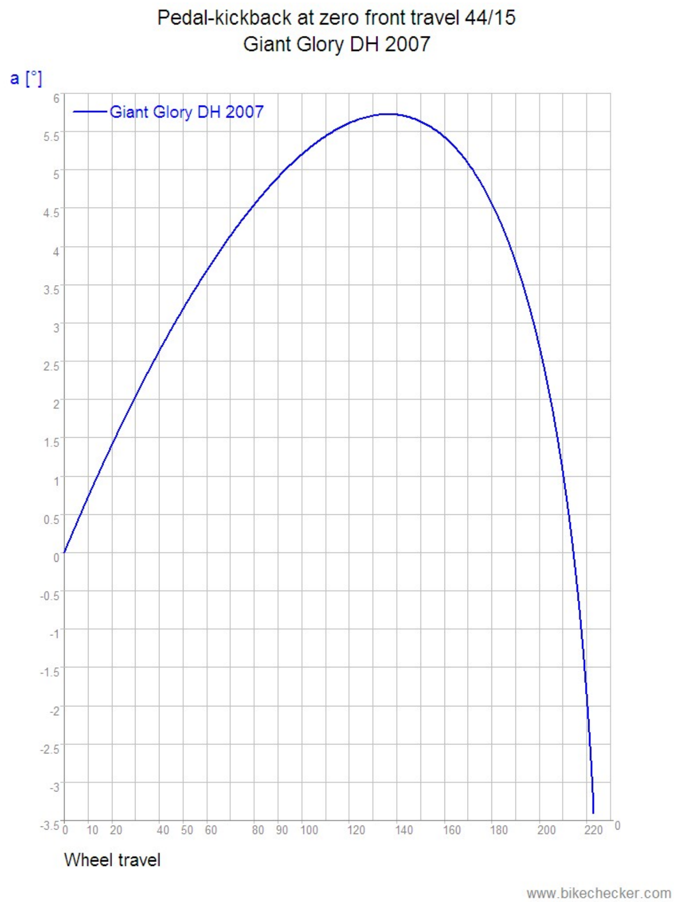

Figure 24: Pedal Feedback (Giant Glory DH)

DW-Link

Apparatus:

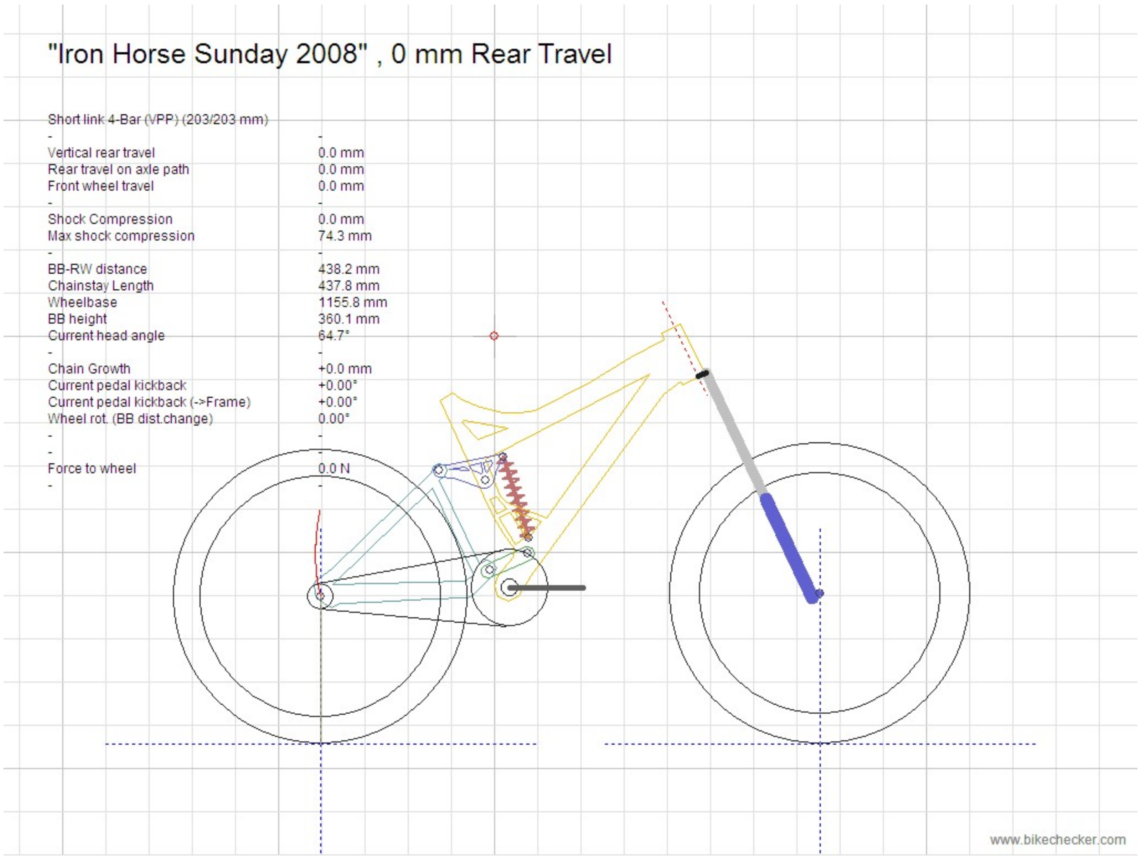

Figure 25: DW-Link on an Ironhorse Sunday

The DW link, designed by Dave Weagle, is similar to the VPP and Maestro link designs—that it has a solid rear triangle which connects to the frame and shock via two rockers. The difference with the DW link is that the pivot points and rockers have been engineered to focus on wheel axle path rates and equalize pedaling forces and rider weight distribution to minimize the effects of pedal feedback and bob.

Design:

When a rider accelerates, we know from Newton's 3rd law that the opposite reaction is the rider's weight shifting towards the rear of the bike. The DW linkage provides a virtual pivot point that responds perfectly to oppose that rear transfer of weight and prevent the bike from "squatting" into its suspension—this also increases the over efficiency of the bicycle by maintain more traction and sensitivity.

As talked about earlier in this report, pedal feedback becomes extremely noticeable with rapid changes in chainstay length, and hence chain length. The DW link has a positive linear growth of the chainstay which makes pedal feedback almost imperceptible. As the rear suspension reacts to rough terrain, the "virtual" axle path of the changes to an ideal location based on the amount of bump compliance needed, achieving a balance of traction and stability under hard braking that is unmatched by other suspensions. In the initial stages of the travel, the pivot point is high providing a rearward wheel path which provides great small bump absorption. In the middle of the travel, the leverage ratio decreases giving the bike a natural tendency to extend and provide more traction. The end of the axle path strengthens the leverage ratio slightly and provides even more dampening making the suspension seem almost endless.

Just like the VPP, the DW link uses short strong rockers to attach the solid rear triangle to the frame and shock. These, and the Maestro link, are indeed very similar, but it is the unique layout of rocker size and pivot placement that makes the difference in performance.

Results:

Figure 26 is a graph showing the magnified wheel path of the rear wheel in a DW-Link, where the x and y-axis are the movements of the axle in millimeters. The wheel path is symmetrical, with rearward axle motion through the first half of the travel, and then forward motion in the second half. This shows how the virtual pivot changes location to maximize the efficiency of the leverage ratio, which Fig. 27 illustrates−that the Maestro link also achieves a ramping leverage ratio.

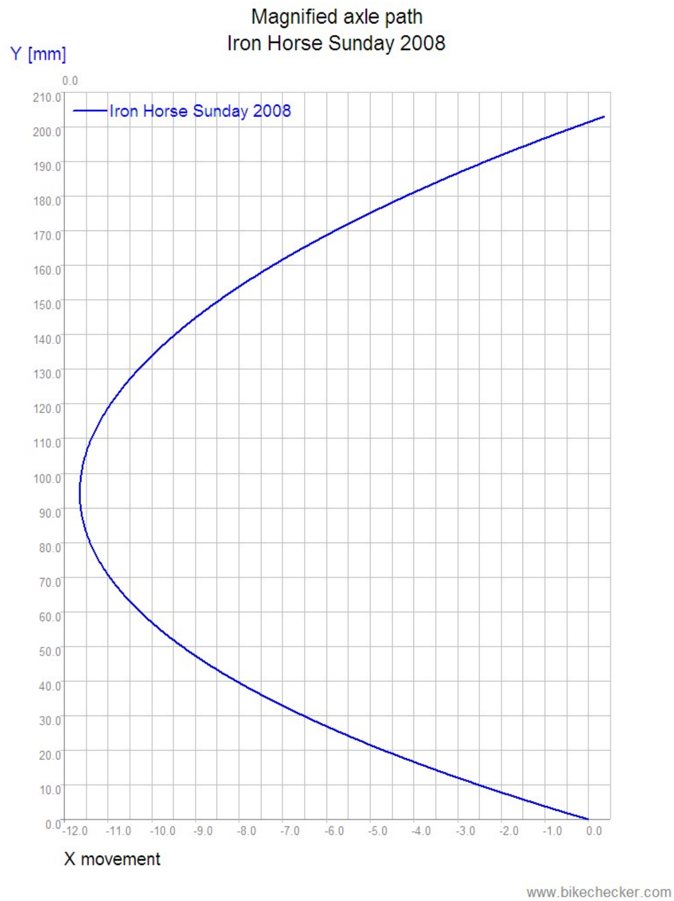

Figure 26: Magnified Axle Path (Ironhorse Sunday)

This ramping ratio works with the symmetrical axle path by providing more leverage through the rearward part of the travel making the bike more responsive to small bumps, and less leverage in the forward part of motion allowing big hit absorption to prevent the suspension from squating.

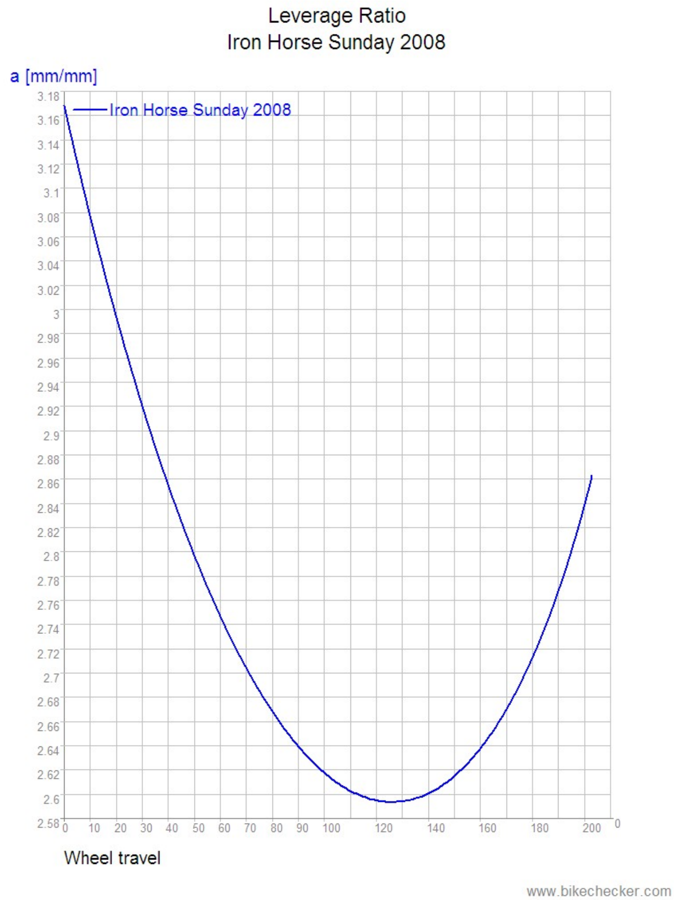

Figure 27: Leverage Ratio (Ironhorse Sunday)

The anti-squat aspects of the suspension are also compelled by the pedal feedback. Similar to the VPP, the DW-link uses the pedal feedback and chain growth to its advantage. Although Figure 28 shows a change over a 15 degree change in pedal angle, the pedal feedback through a DW-link is not as perceivable as compared to other linkages because of its linear chain growth and anti-squat properties.

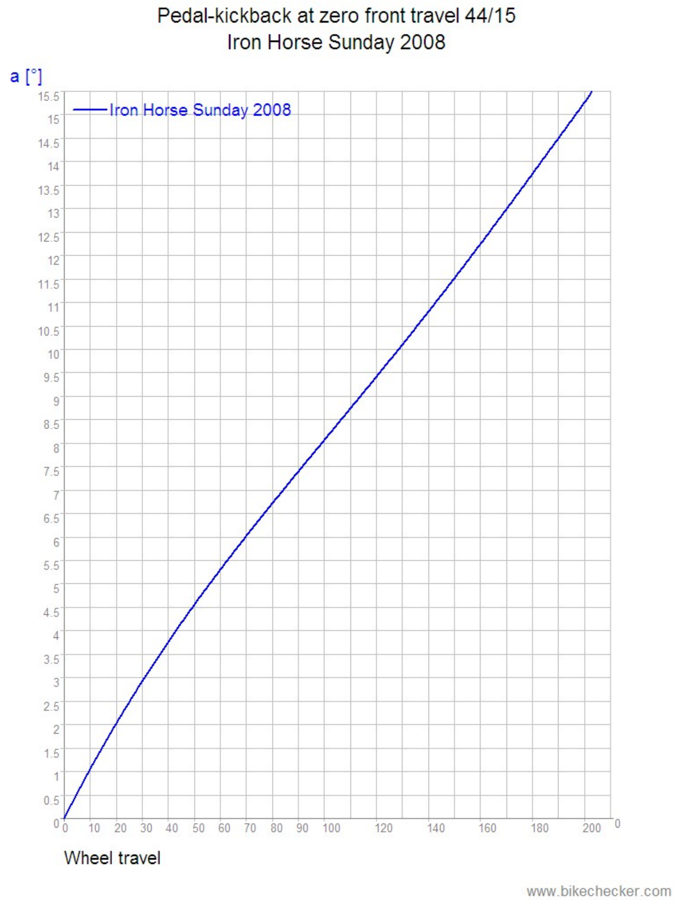

Figure 28: Pedal Feedback (Ironhorse Sunday)

Part III

Conclusion

The goal of this thesis was to the explore the different linkages used in mountain bike design in the industry today and gain an understanding of their individual behaviors.

Before concluding about the individual frame designs it is important to understand the linkage is not the only soldier in the battle. The properties of a shock greatly change how a suspension responds, and lots of research and development at bicycle companies also goes into deisgning a shock specific to the frame design. To design the most efficient riding suspension, dampening platforms and pedaling platforms in the shock absorber need to be designed side-by-side with the frame design in order to work the best. So, in the scope of this paper, there is no linkage that is the most effective rear suspension.

Starting with the most simple (and trusted) design, the single pivot, it was easy to see the need to design a linkage. The pivot needs to be placed high above the bottom bracket to achieve a rearward axle motion and braking forces and chain forces negatively contribute to the activeness of a suspension with a high single pivot point. The linkage allows for a much more customizable frame design and the ability to achieve a dynamic leverage ratio and axle path that deviates from the strict arc of a single pivot.

All the bike designs seems to agree that an initial rearward motion of the rear axle is ideal. However, the standard 4-Bar linkage can't achieve a rearward axle path, but it was the first to have a progressive leverage ratio. This linkage is very trustworthy, but with suffers from braking interference due to the pivot located on seatstay above the rear axle. The FSR (4-Bar Horst Link) perfectly modified the standard 4-Bar link to become a fully active suspension, even under braking through rough terrain.

The VPP, Maestro, and DW-link linkages are all very similar designs, but with different intensions. The VPP linkage's goal is to use pedal feedback as an anti-squating mechanism.

The Maestro, similar to the VPP but with the shock connected to the upper rocker, achieves the most ideal ramping leverage ratio. Unlike the VPP, which actually gains more leverage in the end of the stroke, the Maestro's leverage tends toward zero at the end of its stroke. This natural behavior of the linkage takes loads of stress off the shock, and makes for suspension that feels endless. The DW-link does a good job of maintaining linear chain growth to effectively anti-squat the suspension, which allows it to be more efficient when pedaling hard through rough terrain. The design of the DW-link accomplishes this through the constantly changing position of its "virtual" pivot point.

Images:

Figure 1: http://www.kleinbikes.com

Figure 2: http://upload.wikimedia.org/wikipedia/commons/thumb/8/8a/Bicycle_diagram-en.svg

Figure 3: http://rotorburn.com/forums/showthread.php?t=35572

Figure 4: http://en.wikipedia.org/wiki/File:LeverPrincleple.svg

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References

[1] Schubert, John. "The Klunkerz of Marin." Bicycling June 1982