Mountain Bike Suspension Linkage and Frame Design MQP

A Major Qualifying Project submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the degree of Bachelor of Science
March 18, 2021

Submitted by:

Macrae Benziger

Advisor:

Torbjorn Bergstrom Ph. D

Abstract

The objective of this project is to design and build a prototype mountain bike that uses a novel linkage design in order to improve ride characteristics on steep technical terrain while maintaining an efficient pedaling platform for ascents. Historically, downhill performance and uphill efficiency have been mutually exclusive features on mountain bikes. Currently, bikes that strive to maximize uphill and downhill performance will usually end up lacking in both. By designing a bicycle frame that incorporates modern geometry with a complex suspension linkage, I hope to create a mountain bike that excels at both efficient uphill travel and aggressive descents.

Contents

1 Introduction

1.1 Objective

The objective of this project is to design and build a prototype mountain bike that uses a novel linkage design in order to improve ride characteristics on steep technical terrain while maintaining an efficient pedaling platform for ascents.

1.2 Rationale

The sport of mountain biking has come a long way since its inception in the late 1970s. Mountain bikes originated as a fully rigid steel-framed behemoths and have steadily evolved into lightweight and incredibly capable machines. The rapid development of the sport can be contributed to several technological advancements, but the most notable of which is suspension design improvements. Modern bicycle suspension has made it possible for some athletes to ride over terrain that most people would have trouble traversing on foot. The growth of the sport has caused many different riding disciplines to form, and companies have developed bikes that are purpose built to perform under the specific riding conditions of each discipline. But recently companies have pivoted away from discipline-specific bikes and have started to offer multi-discipline “quiver-killer” bikes that do not force riders to invest in multiple bikes in order to ride various terrains. The creation of multi-discipline bikes has caused a new style of riding to form called “enduro” riding. An enduro bike needs to be capable of handling large impacts and maintain stability at high speeds on steep descents, while also providing a supportive pedaling platform and responsive handling while traveling uphill. Historically, downhill performance and uphill efficiency have been mutually exclusive features on mountain bikes. Current enduro bikes that strive to maximize both uphill and downhill performance end up lacking in both. By designing a bicycle frame that incorporates modern geometry numbers with a novel suspension platform, I hope to create a bike that excels at both uphill travel and aggressive descents.

1.3 State of the Art

There are many mountain bikes that can be described as “all-mountain” or “enduro”. Unlike purpose-built bikes such as the downhill oriented *Trek Session* or the lightweight and efficient *Specialized Epic*, enduro bikes are designed to perform well on all types of terrain. An example of an enduro mountain bike that has great performance on technical descents, but leaves the rider struggling to pedal uphill is the *Evil Insurgent.*

Figure 1: 2017 Evil Insurgent

The lack of performance on ascents can be contributed to two aspects of the *Insurgent's* frame design; not enough pedaling support and geometry numbers that favor downhill riding. Geometry of a bike refers to the position and angle of critical sections of the frame, and pedaling support is a characteristic of the linkage design where the suspension stiffens under pedaling forces. A high-pivot linkage, like the one used on the *Forbidden Druid,* is a slightly unconventional single-pivot suspension design that places the main pivot point farther above the bottom bracket than standard designs.

Figure 2: Forbidden Druid

This design typically provides a very stable pedaling platform thanks to the large amount of anti-squat. Though the downside to this type of linkage is that the chain growth that happens when the suspension moves through its travel induces a large amount of pedal-kickback. This is solved by placing an idler gear on the main frame pivot point.

Mountain bike geometry also plays a major role in performance and handling. Most modern mountain bikes have adopted “long, low, and slack” dimensions in their geometry. This means that the “reach” of the bike, or the horizontal distance between the bottom bracket and the top of the headtube, is longer that what was previously considered normal. The bottom bracket is also lower to the ground and the headtube angle is slacker, or farther from vertical. The move toward these geometry numbers have greatly increased the descending performance of mountain bikes, but this type of frame geometry also causes a bike to be difficult to pedal uphill. One way of solving this issue is to steepen the seat tube angle. A bike that uses a steep seat tube angle combined with “long, low, and slack” geometry is the *Transition Patrol*.

Figure 3: Transition Patrol

A steeper seat tube angle will place the rider more forwards on the bike and improve uphill performance. This combination of geometry allows a mountain bike to maintain its downhill performance while increasing the climbing capabilities of the bike.

1.4 Approach

In order to design an enduro mountain bike that maximizes uphill and downhill performance, I plan to combine features from various other bicycle designs. I will use a suspension design software specifically created for mountain bikes called *Linkage X3.* This software will be used to create a 2D simulation of a suspension design created to have the optimal amounts of bottom out resistance, pedaling support, and small bump sensitivity. The frame will be designed around components that I already own, such as a 205x65 trunnion mounted rear shock, 650b wheels with 12x148 hub spacing, a 170mm travel suspension fork with a standard tapered headtube, and a 73mm BSA threaded bottom bracket shell. I plan to use a modified version of a high pivot suspension linkage that somewhat resembles the design used by *Forbidden Druid* but increase the travel to around 160mm. I also plan to incorporate geometry numbers similar to those of the *Transition Patrol* because I have ridden many bikes in the enduro category, and the *Patrol* has the ride characteristics that I prefer. After I have created a 2D simulation of the desired linkage, I will begin to model it in *SolidWorks*. I plan to use a manufacturing method similar to that used by the company *Atherton Bikes* in which the tube intersections and smaller suspension links are manufactured out of metal, and then are later bonded to carbon frame tubing in order to complete the frame. Instead of modeling an entire bicycle frame, I will model individual tube intersections and then derive the necessary tube lengths required to achieve the required frame specs and suspension geometry. I plan to 3D print a proof of concept to test fitment and smooth operation. Then I plan to machine the tube intersections out of aluminum and then bond them to carbon tubing in order to make a functioning prototype.

2 Methods

The method section below describes the general procedure that I followed in order to build my prototype mountain bike. Some of the processes were iterated multiple times as the project progressed. Research was done to come up with new solutions to solve problems that arose throughout the project.

2.1 Research

In order to fabricate an effective full suspension mountain bike frame, I conducted extensive research on existing frame and linkage designs. This involved finding bicycles that had desirable ride characteristics, then analyzing the frames to understand the design aspects that were responsible for said ride characteristics. I used the results of this research in conjunction with my own personal experience riding mountain bikes in order to generate a list of features that I wanted to integrate into my design.

2.2 Brainstorming

I used a few brainstorming tools to facilitate the generation of ideas. The main process that I used was sketching potential frame designs in a notebook. This process allowed me to iterate and finalize an initial concept that I referenced throughout the project. This allowed me to visualize my ideas and eliminate ones that were either overly complex or had slim chances of functioning correctly. Sketching was also utilized in order to conceptualize how the frame linkage would be converted from the 2D model into 3D space.

2.3 2D Linkage Simulation

I used the *Linkage X3* frame design software to create an analyze my conceptual design. I used this software to come up with dimensions the final frame and linkage geometry. Once my frame design was constructed within the software, I could use the frame analysis features to fine-tune suspension curves and compare suspension parameters between my design and multiple existing designs.

2.4 CAD Model

Using the 2D model as a base, I constructed a 3D model using *SolidWorks.* This involved adding features that would allow standard bicycle components to be assembled onto the frame. I had to figure out the position and shape of each suspension link while ensuring that there was no interference between parts. Each piece of the frame was designed to be 3D printed using an FDM printer.

2.5 Prototype

The final step in my design process was to create a 3D printed prototype to validate my design. This would allow me to make sure that my linkage functioned as intended as well as test fit components on my frame to ensure proper fitment. The frame components that make up the prototype can be modified so that they can be machined out of aluminum to create the final functional frame.

3 Results

The results section describes what went into designing and building the frame prototype and contains a thorough analysis of my final frame design.

3.1 2D Linkage Design

The first step in my design process was to brainstorm ideas. I did this by sketching a variety of suspension designs in my notebook. I wanted to stay away from linkages that were commonly used in mountain bike frames, including 4-bar and Horst-link suspension designs. After many design iterations, I eventually settled on the design shown below (Figure 4).

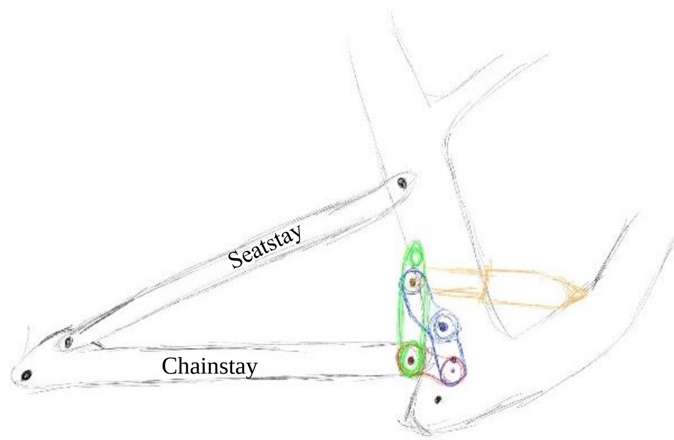


Figure 4: Initial sketch of suspension linkage

The next step was to put it into the linkage design software. *Linkage X3* is it powerful suspension design and analysis tool specifically built to be used for mountain bike frame design. In order to create a new frame in the software you have to start with a template. There is a template for every common frame type, but since the linkage that I designed is unlike anything else on the market I had trouble finding a template to start with. After experimenting, I discovered that it was possible to create my linkage by choosing the *"4-bar w/ Shock linkage"* option, then switching the position of the chainstay and seatstay. For this reason, I have decided to refer to my linkage as an "*inverted 4-bar with shock linkage"*. After I input values for the frame geometry and linkage points the frame could be visualized in the software (Figure 5). I could now use the analysis tools within *Linkage X3* to begin to tune these values.

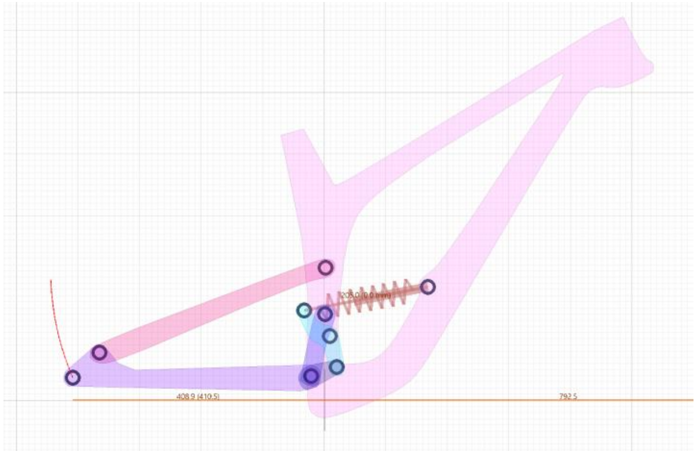


Figure 5: Frame design in Linkage X3 software

3.2 Frame Geometry

The geometry of a bicycle frame has a large impact on the performance and feel of a mountain bike. In order to come up with the geometry values for my bicycle frame, I used a combination of research and personal experience riding mountain bikes. Having owned and extensively ridden the *Evil Insurgent* (Figure 1) and the *Transition Patrol* (Figure 2), I tend to prefer bikes with similar geometry. As such, I chose geometry numbers that were relatively similar to both of these bikes. Based on this, I have decided on the final frame geometry shown in the table below (Figure 6).

Frame Geometry (mm)	
Reach	460
Stack	614
Effective TT Length	547.1
Seat Tube Length	440
Seat Tube Angle	78.8
Head Tube Length	100
Head Tube Angle	64.8
Chainstay Length	423.7
Wheelbase	1201.4
Bottom Bracket Height	318.9
Fork Offset	37
Front Travel	170
Rear Travel	160
Fork Axle To Crown	562
Wheel Size	650b
Shock Length	205
Shock Stroke	65

Figure 6: Table of frame geometry values

Some geometry values affect the ride characteristics more than the others. The 78.8 degree seat tube angle moves the rider forward when pedaling, which is a better position for climbing uphill. The 64.8 degree headtube angle gives the bike stability at high speeds and makes the bike more predictable on extremely steep terrain. 460mm of reach is relatively long, which gives the rider more stability while descending. The 423.7mm chainstays are quite short, which makes the bike very maneuverable and gives the bike a more "flicky" feel. "Flicky" is a term used to describe how the bike makes it easy to transition between turns. The frame also is designed to have a suspension fork with the shortest available fork offset, which is 37mm. The short fork offset brings the front wheel closer to the rider and helps to counteract the low-speed lack of handling that a slack headtube angle typically causes. This combination of frame geometry will allow my design to function well both while descending and while pedaling uphill.

3.3 Suspension Kinematics Analysis

Using the tools within *Linkage X3* I am able to perform extensive analysis on my frame design. The software graphs various suspension curves and can simulate various loads on the frame.

3.3.1 Shock Compression

Shown below (Figure 7) is a graph of the suspension compression curves. The blue line represents shock compression versus wheel travel, while the red line represents the motion ratio. The motion ratio is the relationship between the movement of the shock and the movement of the rear axle. It is calculated by dividing the shock compression by the wheel travel at every individual point in the suspension travel. The motion ratio (red) line is the inverse of the leverage ratio, which has a major influence on ride feel.

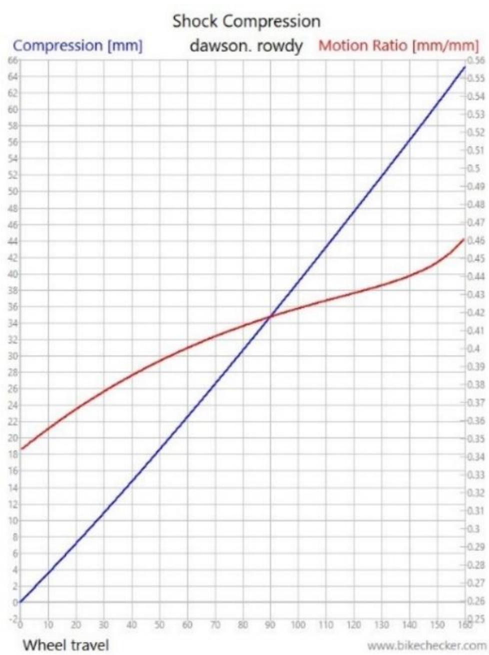


Figure 7: graph showing the shock compression and motion ratio

3.3.2 Leverage Ratio

The graph below (Figure 8) represents the leverage ratio of the suspension. The leverage ratio is just the inverse of the motion ratio. The steepness of this line represents the progressivity of the suspension. A progressive suspension platform is desirable because it provides a greater resistance to bottom-outs, which sometimes happens during large impacts and is where the suspension reaches the end of its travel and harshly stops. A progressive suspension design will stop this by effectively stiffening up the suspension closer to the end of its travel. The steeper the slope of the leverage ratio, the more the suspension will stiffen up. This affects the overall “feel” of the bike. As you can see, my linkage design is quite progressive. In the first half of the travel, the suspension will feel fairly linear. At about 40% into the travel the suspension gets slightly stiffer. This helps provide a more stable pedaling platform for the rider and it helps eliminate pedal-bob, which happens when a rider stands up to pedal and the suspension compresses with every pedal stroke. This is inefficient because energy that could have gone into moving the rider forward are now going into compressing the suspension. Near the last 20% of the travel, my suspension stiffens up greatly. This aggressive suspension ramping will help reduce bottom-outs and keep the rider in a more usable travel range.

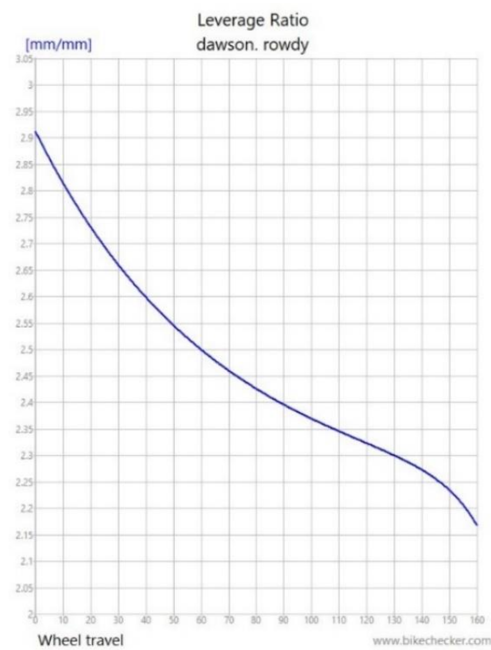


Figure 8: graph of the rear linkage leverage ratio

3.3.3 Forces

The forces graph (Figure 9) generated by *Linkage X3* is the calculation of the relationship between the vertical forces acting on the rear wheel and the shock compression that it causes[1]. The slope of the wheel rate, which is the red line, better shows the real progressivity of the suspension linkage. The program creates this graph by simulating a force that is applied vertically to the rear wheel and measuring the resulting shock compression. This more accurately simulates actual riding conditions. The progressivity of the shock compression can be tuned, but for this example I left it as is. As stated before, I set out to implement a large amount of progressivity into my suspension design. This graph allows for a better understanding of how the suspension of my mountain bike frame will behave while riding. The ramp up at the end of the travel is far more aggressive on this graph then it is on the leverage ratio graph. This graph more accurately depicts how the suspension will behave.

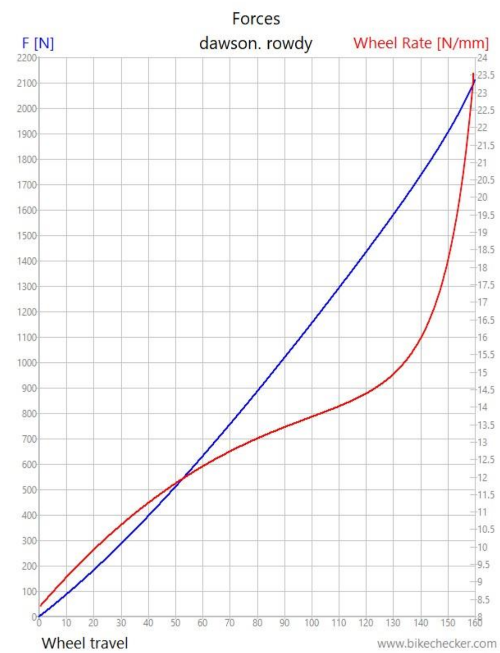


Figure 9: graph of vertical and axle-path tangential forces at the rear wheel

3.3.4 Axle Path

The graph below (Figure 10) depicts a magnified version of the path that the axle will take while the suspension moves through his travel. The wheel mainly moves rearward during the travel period this is significant because it affects how the suspension reacts two riding over bumps. This is because many obstacles on the trail will impact closer to the front of the wheel. This means that the impact force is more in line with the travel direction of the axle which improves the

---

[1] Roberts, Dan. "Enginerding: What Is Anti-Squat & How Does It Actually Affect Mountain Bike Performance?" Pinkbike, 20 Mar. 2020, www.pinkbike.com/news/definitions-what-is-anti-squat.html.

suspension's ability to react. The rearward axle path should give my design greater small bump sensitivity and eliminate harshness while riding over rough terrain. It should also improve grip. This is because the suspension will react quicker to obstacles on the trail and instead of the tire bouncing after hitting an obstacle, it will continue to travel down the backside and maintain contact with the trail. More contact with the trail means that the tires can better handle turning and stopping forces.

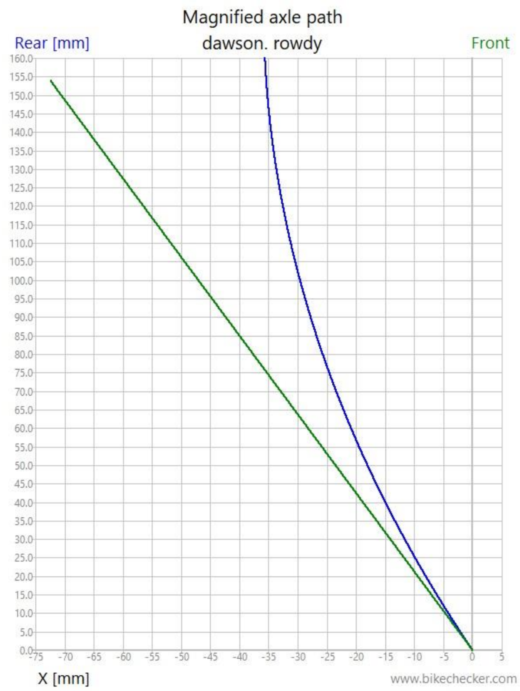
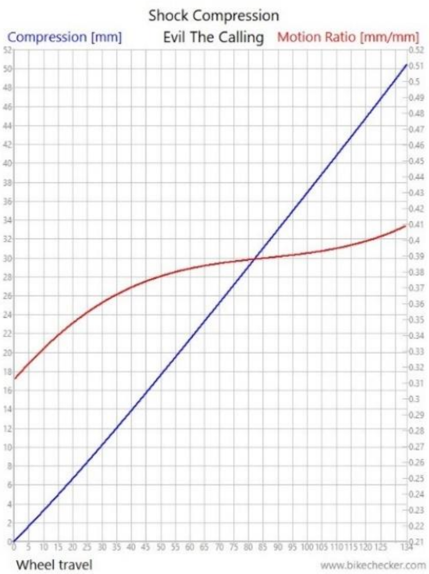


Figure 10: graph showing the rearward traveling axle path of my frame design

3.4 Suspension Comparison

In order to tune my suspension to attain a certain ride "feel", I referenced other frame designs that were available for *Linkage X3*. By looking at the graphs for other bikes and attempting to replicate their shape with my suspension design, I was able to attain the suspension characteristics that I desired. Shown below is the shock compression and leverage ratio graphs for the *Evil Calling*. This bike has a similar suspension feel to the *Evil Insurgent*, which is a bike that I have extensive riding experience with. The *Evil Calling* has the progressive suspension curve that I want to include in my design. From my experience writing I knew that I wanted a little bit more suspension ramp-up near the end of the travel so I decided to make the leverage ratio curve on my design steeper than the *Evil Calling* in the last 20% of travel.



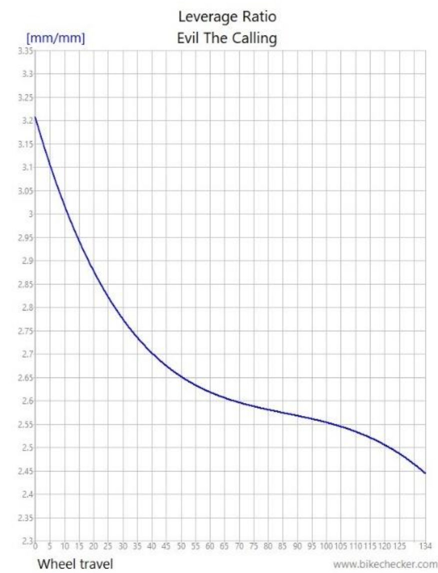
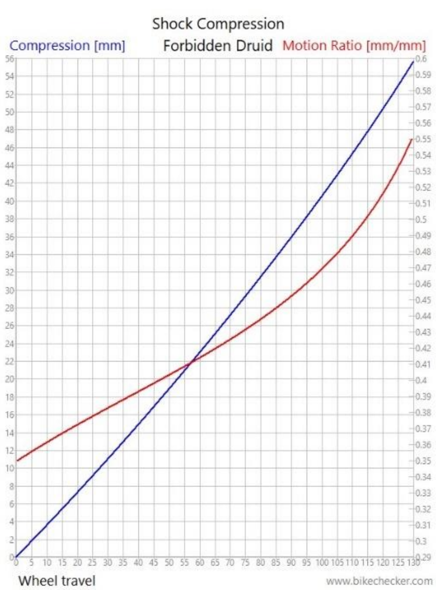


Figure 11 (left) & Figure 12 (right): Evil Calling suspension curves

The two graphs below show the shock compression and leverage ratio for the *Forbidden Druid*. The *Druid* has a similar suspension design to mine, and I was curious to see how the bike dealt with its travel. The *Druid's* suspension is more linear then mine or the *Evil's*, but it's still progressive. However, with the *Druid* lacks is ramp up near the end of the travel. Since the *Druid* only has 130mm of travel, the usable travel range would be reduced by greater amount if there was a significant amount of ramp up designed into the travel. My design has a more aggressive suspension curve then the druid that is better suited to more aggressive riding conditions.



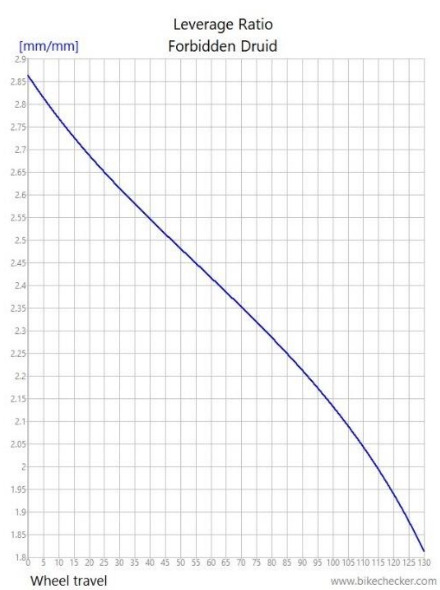


Figure 13 (left) & Figure 14 (right): Forbidden Druid suspension curves

3.5 CAD Model

Now that I had a 2D model of the suspension design and frame geometry, I now needed to integrate it into a 3D model (Figure 15). When designing the model, I decided to make the suspension links and tube intersections separate from the frame tubing. This makes the frame easier to manufacture and it gives me the ability to 3D print all of the pieces necessary to build a full-scale frame prototype. When making the model, I had to keep in mind the bicycle standards that I wanted to adhere to. On my frame, these included mounting for 165mm by 65mm trunnion mount rear shock, a 12mm by 148mm rear axle, a tapered head tube, and a standard 73mm BSA threaded bottom bracket. These are the same standards that are used on the transition patrol which is the bike that I currently own. This means that when I build the prototype, I can test fit parts without having to spend the money to buy them. The modular design of the frame also means that this geometry can very easily be changed if necessary. In order to calculate the angles that needed to be implemented into the tube interfaces, I created a separate *SolidWorks* file where I placed the known point on my frame. I then created a 3D sketch between those points and measure the resulting angle. I used this technique to help make every part that interfaces with the frame tubing. The frame pieces are designed to interface with tubing that has an ID of 22 millimeters at an OD of 27 millimeters. These are the dimensions of a standard ski gate used for collegiate ski racing competitions. Luckily, I had access to a large number of old ski gates that I could cut to the right length and use as frame tubing. The interfaces between suspension links are designed to house bearings in order to decrease friction as the suspension moves through its travel. Now that I had a working model in software, it was now time to start to manufacture components.

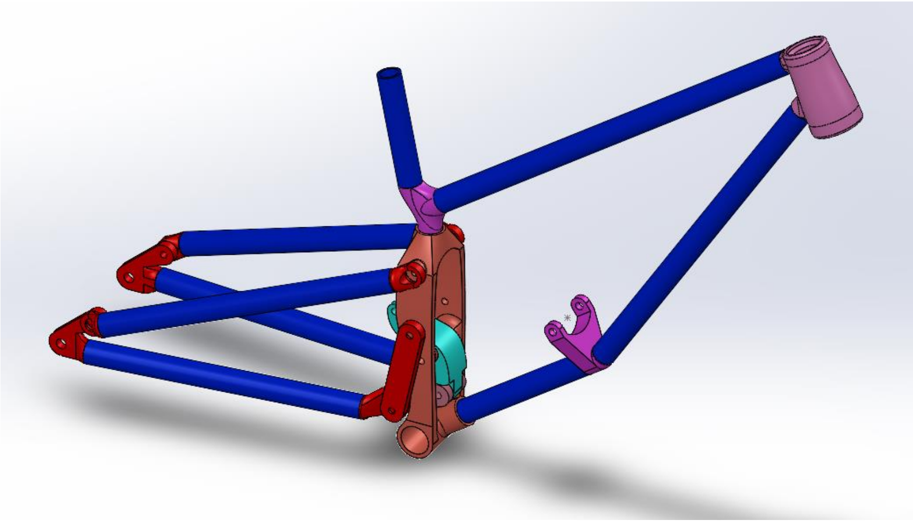


Figure 15: 3D model of final frame assembly

3.6 3D Printed Prototype

I was able to 3D print a full-scale prototype using my FDM 3D printer as shown below (Figure 16). In total I had to design and print 15 separate pieces (Figure 17) to assemble my prototype. As stated before, the frame tubing is made from old ski gates that were cut to a desired length. Each frame piece had a feature that was designed to interface with either the ID or OD of the frame tubing. This made assembly fairly easy. The frame tubing was secured onto the frame pieces using hot glue, and the separate suspension links used 8mm threaded rods cut to various lengths as axles. The prototype allowed me to validate my suspension design and ensure that there was no interference between any of the suspension links that could cause problems.

Figure 16: The fully assembled 3D printed prototype

Figure 17: disassembly of the prototype frame

4 Discussion

The discussion session includes an analysis of my results, as well as addresses any issues that was able to overcome during the project.

4.1 2D Frame Design

The most difficult part of the 2D design process was implementing my conceptual sketch into the linkage X3 design software. Because my suspension design is so unique, I had trouble finding any similar suspension templates that I could start from. After I figured this out, the software itself proved to be a minor inconvenience. The user interface is quite dated and there was no good way to accurately move points around on the model. My final design was the result of looking at the suspension analysis graphs and moving suspension points around until the graphs had the shape that I wanted. However, I was still able to achieve the result that I wanted.

4.3 CAD Model

The difficulty of creating the CAD model stemmed from a few sources. One of these was attempting to shape the suspension links in such a way that they would be able to fit in the limited space available within the frame. To overcome this, I went back to my notebook and sketched various designs in order to help me visualize how the pieces would fit together (Figure 18).

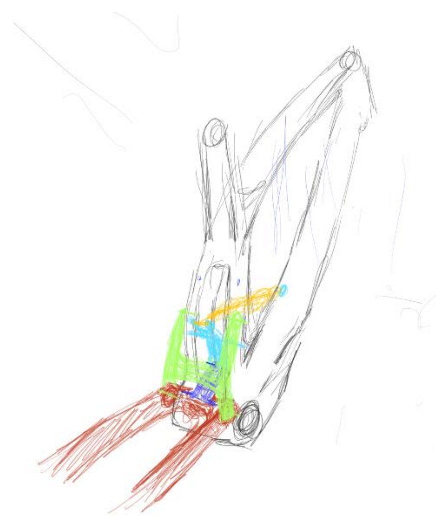


Figure 18: Initial sketch of frame linkage

Once I had come up with a basic concept, I was then able to implement that concept into the CAD model and come up with dimensions. Another difficulty I had while creating the CAD model was spacing the rear dropouts correctly. In order to do this, I had to calculate the angle that the seatstays and chainstays needed to be at in order to go from the 80mm spacing on the central frame piece to the 148mm spacing at the rear dropouts. Again, I used the method I talked about earlier where I created a separate *SolidWorks* document and created a 3D sketch that I could use to calculate the angles. After I had created the final assembly, I then started the process of 3D printing all of the pieces.

4.4 Prototype

The process of 3D printing the components was relatively simple. Luckily, almost all of the pieces printed correctly, and I only needed to reprint one component. That component was the piece that connected the two chainstays, and it needed to be reprinted because there was interference between it and one of the connecting links. After this component was reprinted the final frame was assembled and I verified at the eyelet spacing was indeed 165mm and that I had designed enough clearance into the central frame component so that it would not interfere with the rear shock. The only dimension that I did not get to validate was the length of the chainstays because I did not have access to a rear mountain bike wheel of the correct size.

5 Future Work

This section will describe the steps that I will take in the weeks following my MQP and the work that I hope to complete.

5.1 Testing on Current Model

As stated above, I have not validated all of the dimensions of the prototype model. I still need to verify that the chainstays are long enough and the frame accepts a 650b sized rear mountain bike wheel. I also need to verify that there is adequate clearance for a chainring on the right side of the frame near the bottom bracket. If any of these parts had clearance issues then I need to go back to the CAD model and redesign set pieces with the clearances taken into account. Before I redesign the model for a different method of manufacture, I want to ensure that all of the dimensions are correct and that all of the components will fit onto the finished product.

5.2 Manufacture of Usable Prototype

In the future I hope to create a working model of my prototype by machining the frame components out of aluminum and welding them together using aluminum frame tubing. In order to do this I need to redesign the components said they will be able to be CNC manufactured. I would prefer to simplify the components so that they take less steps to machine. To create a fully functioning mountain bike I also need to add a few features to my design. These include adding a seat tube that has a correctly sized ID so that standard size seat post will fit. I also need to add a derailleur bracket to the rear dropouts so derailleur can be mounted. I also need to add the idler gear that would be placed at the top linkage pivot point on the right side of the frame. When all of these components are added to the model, I will begin creating toolpaths in order to CNC machine the parts. Once all the parts have been machined out of out of aluminum I will then need to cut frame tubing to length and Weld the components together. This should result in a frame that is strong enough to be ridden.

6 Conclusion

I believe that my friend design will accomplish the goals that I set out to achieve. Some of the features that my frame includes are:

- 160 mm of rear suspension travel and 170mm of front suspension travel
- An inverted high-pivot 4-bar suspension with a shock linkage of my own design
- A progressive suspension leverage curve
- A steep seat angle that moves the rider into a more efficient pedaling position
- A slack headtube angle that provides stability at high speeds and on aggressive descents
- short chainstays to maximize responsiveness

7 References

"2017 Evil Insurgent." Geometry Geeks, geometrygeeks.bike/bike/evil-insurgent-2017/.

Kazimer, Mike. "Evil Insurgent - Review." Pinkbike, 16 Nov. 2015, www.pinkbike.com/news/evil-insurgent-review-2015.html.

Linkage Administrator. "Evil the Calling." 23 Jan. 2020.

Linkage Manual, Racooz Software, www.racooz.com/linkagedoc/diagrams.htm.

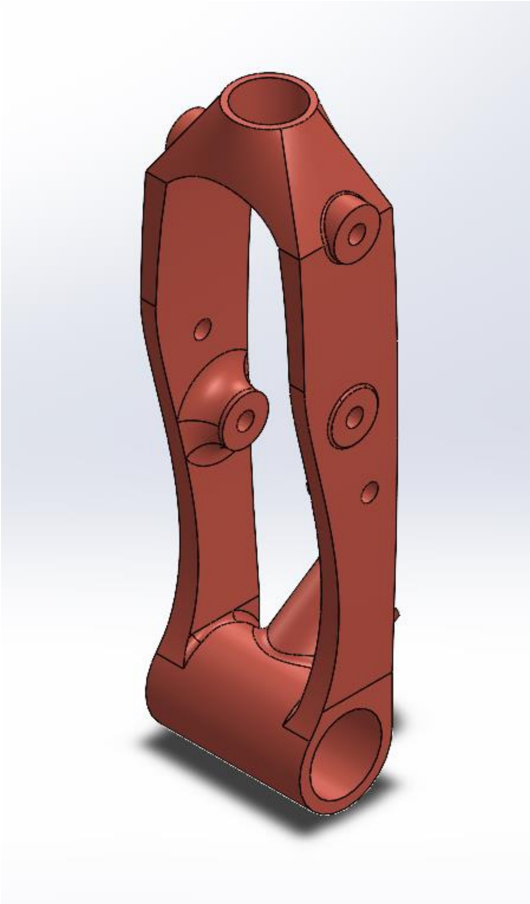
Martin, Christophe, and Minh Nguyen. "Forbidden Druid." 13 Dec. 2020.

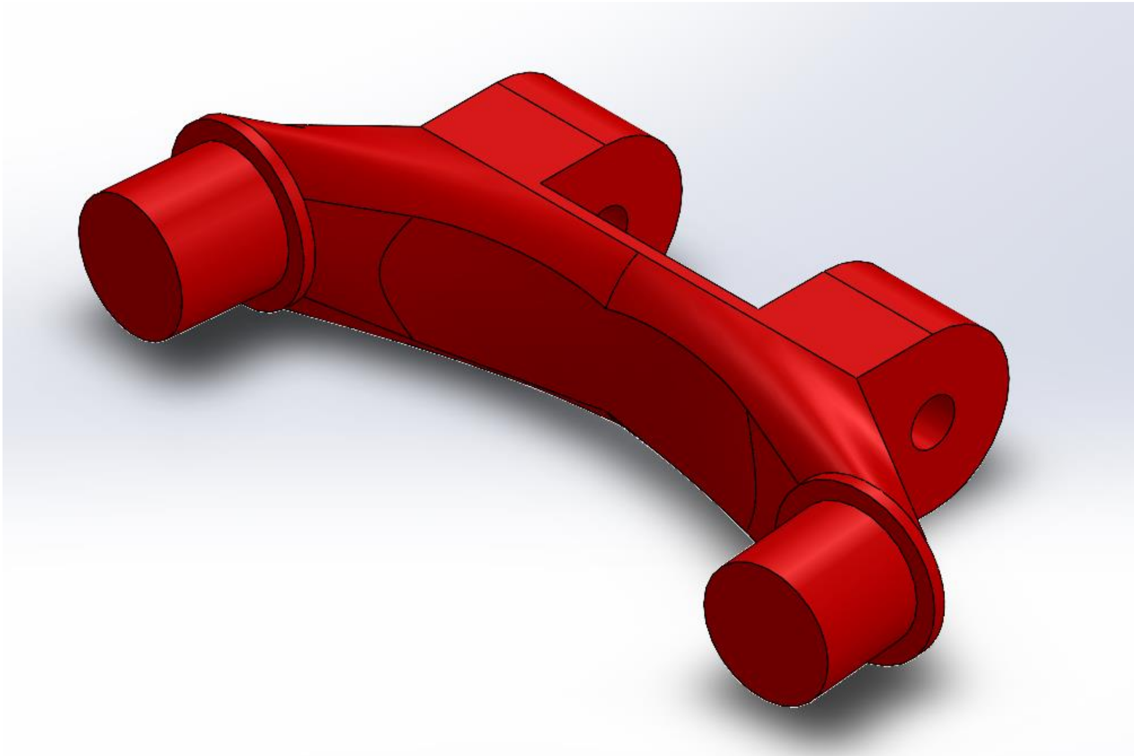
Roberts, Dan. "Enginerding: What Is Anti-Squat & How Does It Actually Affect Mountain Bike Performance?" Pinkbike, 20 Mar. 2020, www.pinkbike.com/news/definitions-what-is-anti-squat.html.

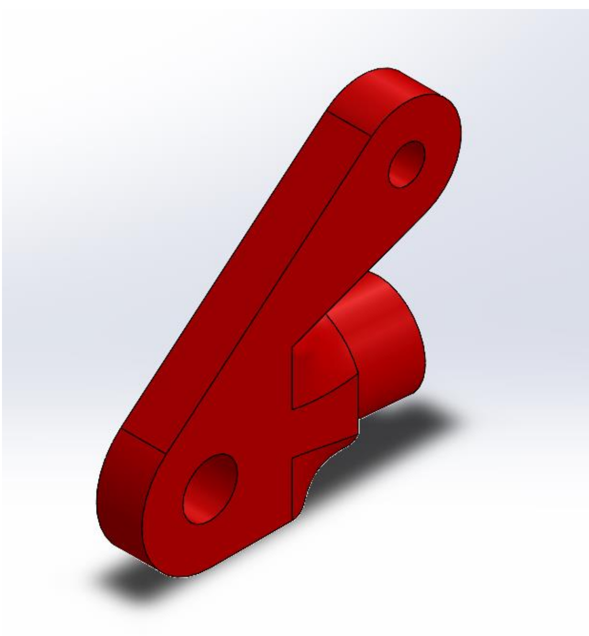
"Transition Bikes." Transition Bikes - It's Time To GiddyUp, Transition Bicycle Company, 2021, www.transitionbikes.com/Bikes_Patrol.cfm.

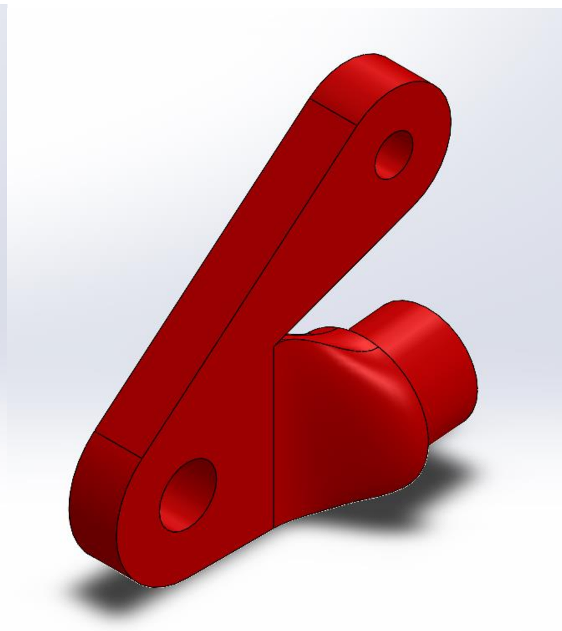
8 Appendix A

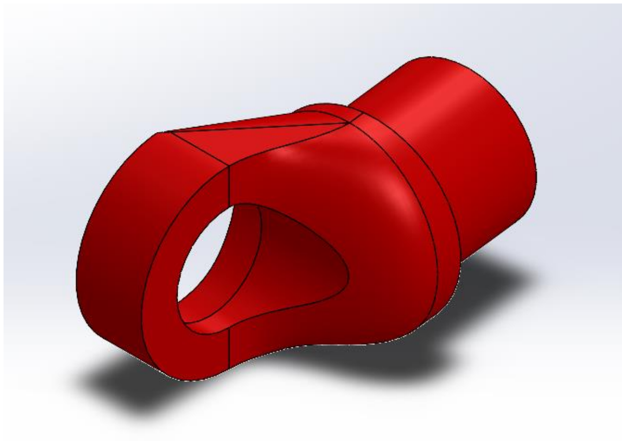
Appendix a shows pictures of every piece of the finished CAD assembly.

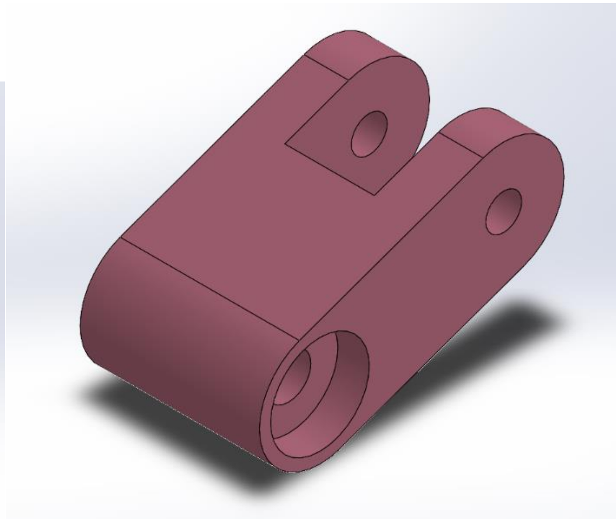


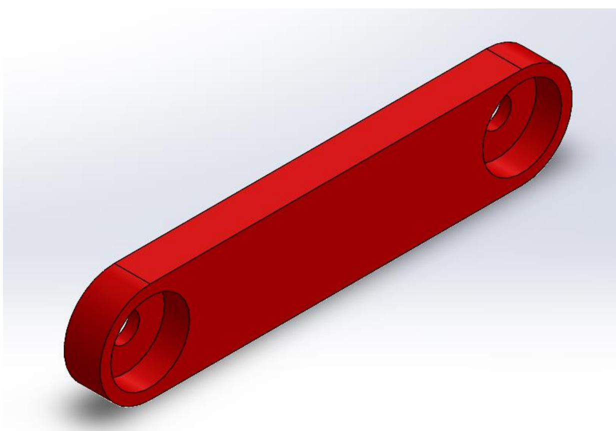


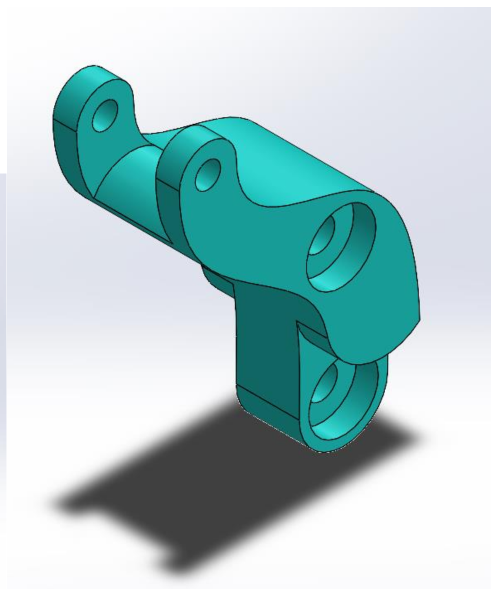


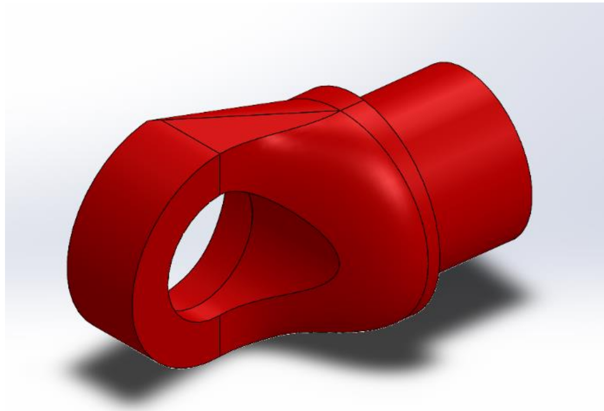


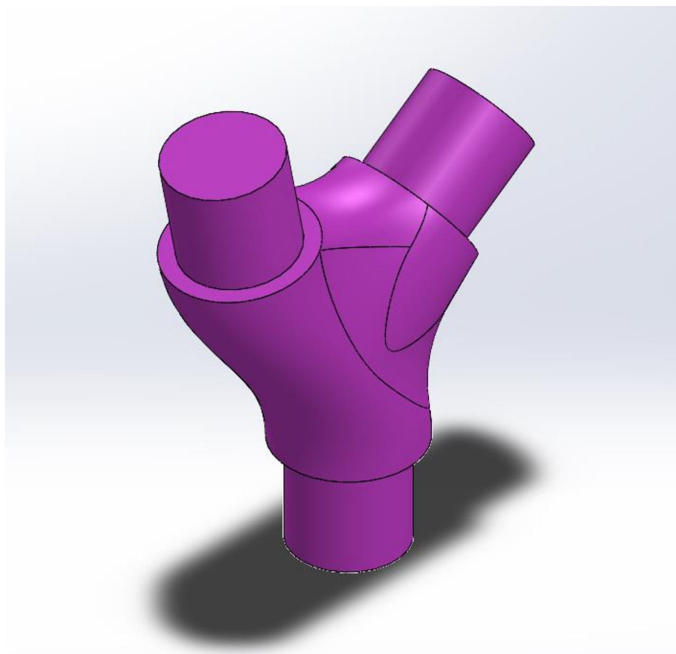






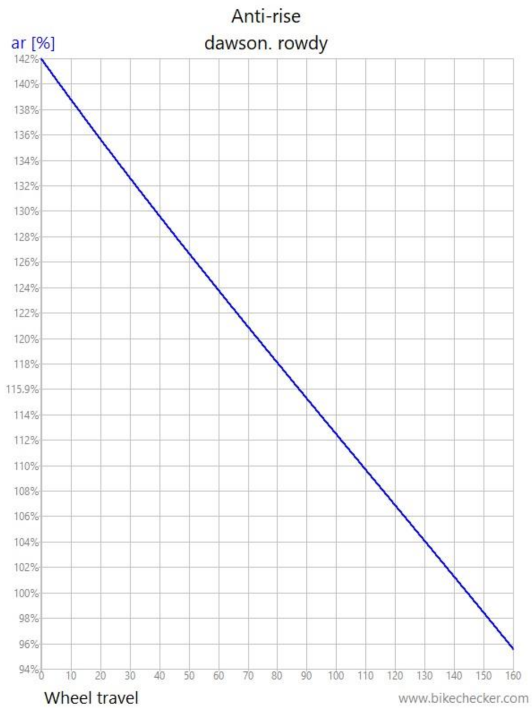


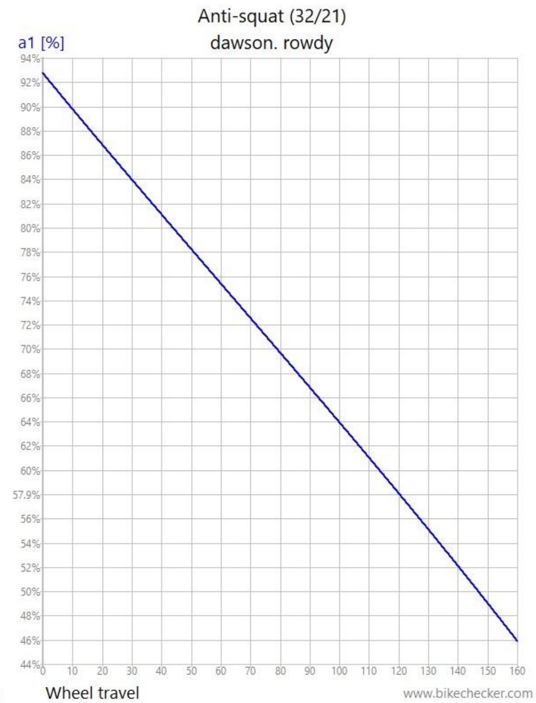


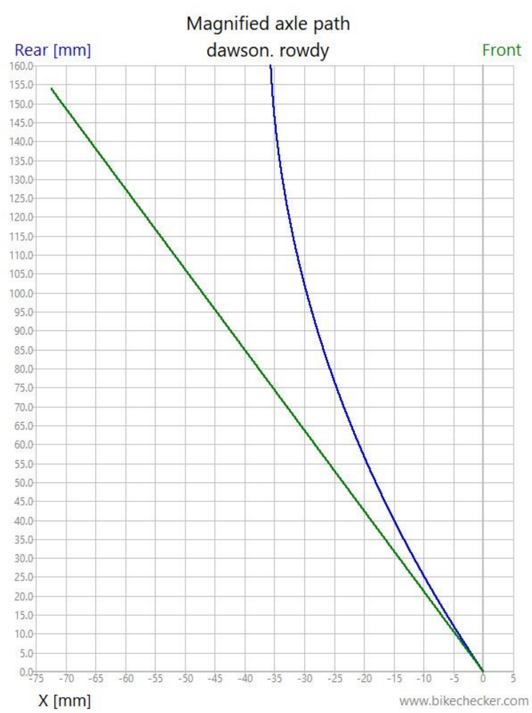


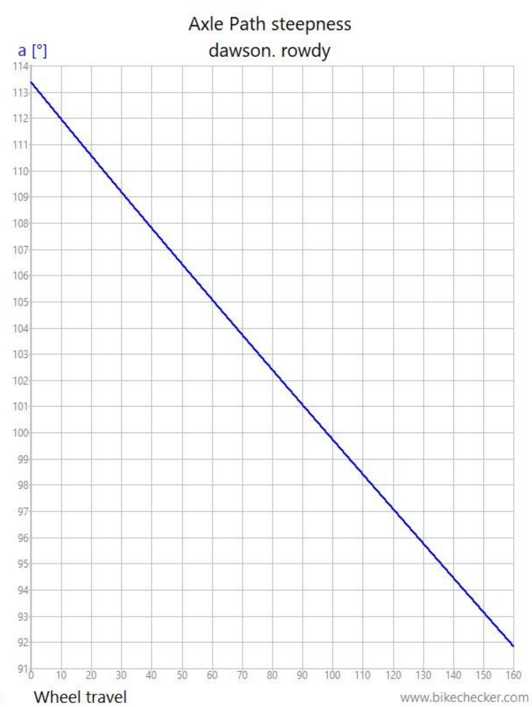
9 Appendix B

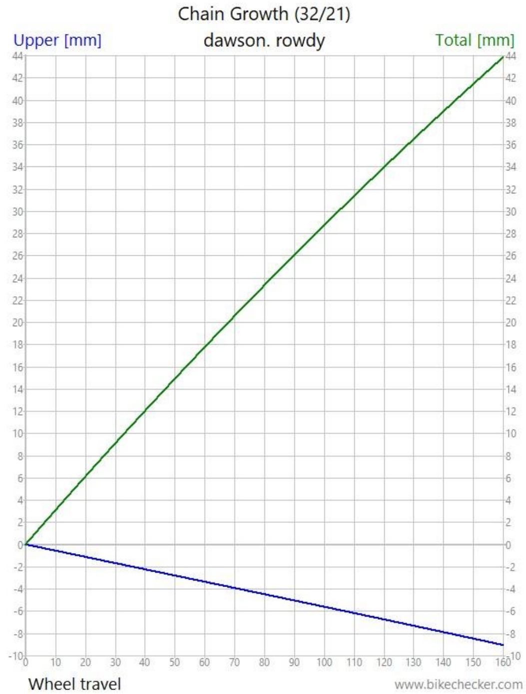
Appendix B shows every graph that linkage X3 was able to generate. These graphs were used to analyze my design and compare them with other existing frames.

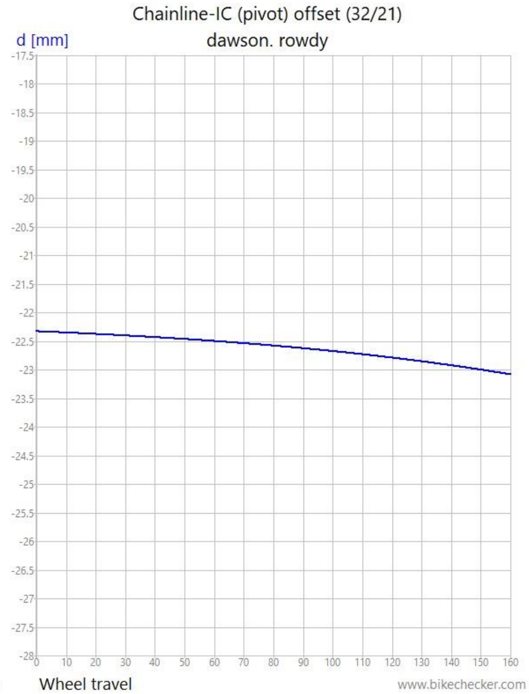


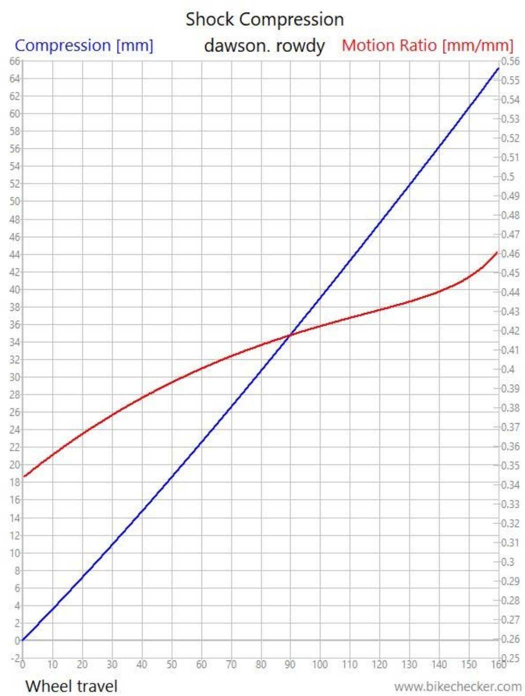


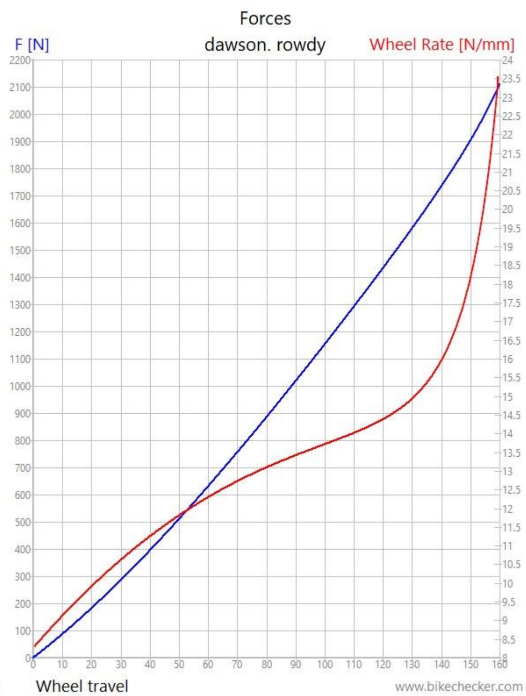


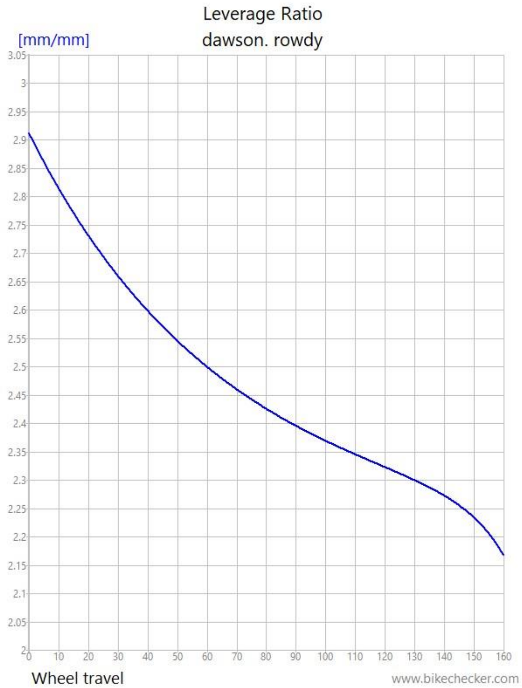


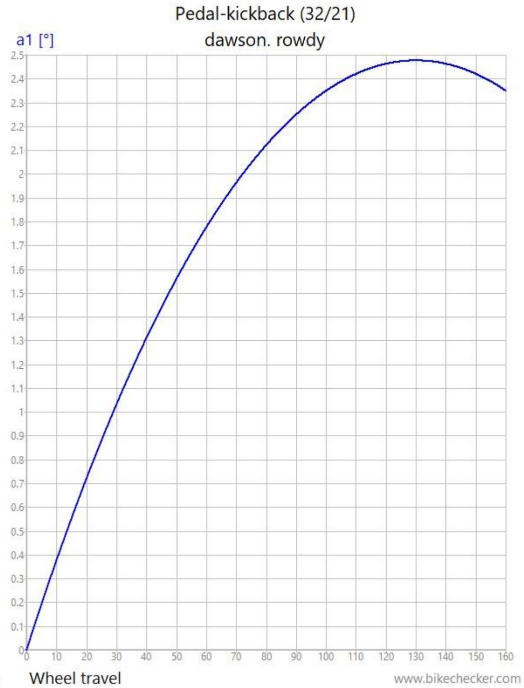

Chain Growth (32/21)
dawson. rowdy
Upper [mm]
Total [mm]
Wheel travel
www.bikechecker.com

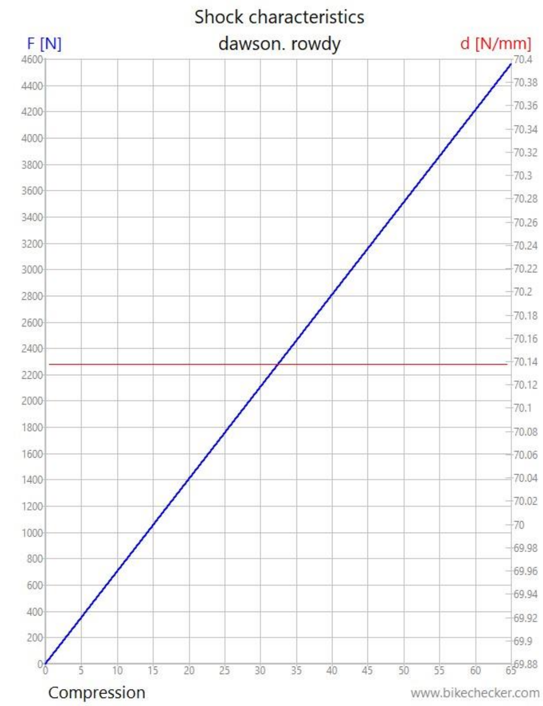

Chainline-IC (pivot) offset (32/21)
dawson. rowdy
d [mm]
Wheel travel
www.bikechecker.com


Shock Compression
dawson. rowdy
Compression [mm]
Motion Ratio [mm/mm]
Wheel travel
www.bikechecker.com


Forces
dawson. rowdy
F [N]
Wheel Rate [N/mm]
Wheel travel
www.bikechecker.com


Leverage Ratio
dawson. rowdy
[mm/mm]
Wheel travel
www.bikechecker.com


Pedal-kickback (32/21)
dawson. rowdy
a1 [°]
Wheel travel
www.bikechecker.com


Shock characteristics
dawson. rowdy
F [N]
d [N/mm]
Compression
www.bikechecker.com