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Design of Three and Four Link Suspensions for Off Road Use

By

Benjamin Davis

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Submitted in partial fulfillment
of the requirements for
Honors in the Department of Mechanical Engineering
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Abstract

DAVIS, BENJAMIN Design of three and four link suspensions for off road motorsports.

Department of Mechanical Engineering, Union College

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This thesis outlines the process of designing a three link front, and four link rear suspension system. These systems are commonly found on vehicles used for the sport of rock crawling, or for recreational use on unmaintained roads.

The paper will discuss chassis layout, and then lead into the specific process to be followed in order to establish optimal geometry for the unique functional requirements of the system. Once the geometry has been set up, the paper will discuss how to measure the performance, and adjust or fine tune the setup to optimize properties such as roll axis, antisquat, and rear steer.

The goal of this paper is to provide a step by step guide for the DIY builder creating an off road vehicle based on a stock vehicle platform. It should allow this person to successfully create a suspension system that adequately suits the needs of their recreational activity.

Introduction:

Background

Across the united states, and in other parts of the world such as Australia or South America, recreational and competition off road driving of 4x4 vehicles is a popular activity. Participants range from weekend warriors who tinker with their rigs after work, to full time sponsored teams with \$200,000 vehicles. Any vehicle used in this broad range of motorsports

will have been modified in some way, and the most common area of modification is the suspension.

There are many branches of 4x4 motorsports such as high speed desert racing, hill climbs, sand dune racing, and rock bouncing. This paper will focus on an application known as rock crawling. In this “sport”, the driver is not focused on speed. The goal is to traverse extreme terrain one inch at a time by puzzle piecing the vehicle over the terrain profile, while maintaining a typical enough setup that the vehicle can still travel at a reasonable speed between obstacles, or even around town at low speeds on public roads. Figure 1 - Typical rock crawling obstacle shows a typical rock crawling obstacle. What is different about this activity from most other motorsports is that there is no focus on time to complete a course. There is no dangerous speed, and no tech inspection. This leads to an extreme reduction in cost of safety gear such as harnesses, roll cages, and fire suppression systems. It opens up the activity to recreational users who can't afford such things, and can't justify the expense of beating on and breaking their vehicles every time they go out. This design guide should help this specific group through the design process of a front and rear suspension system which allows them to crawl with the best.



Figure 1 - Typical rock crawling obstacle (Metalcloak)

Functional Requirements

There are a specific set of functional requirements for the suspension on rock crawling vehicles, and this set of requirements is vastly different from other speed based motorsports. First, where most racing cars focus on stiffness and extremely tight control over the wheel alignment, a rock crawling vehicle will focus on a soft ride to soak up the terrain, with little focus on controlling alignment, which does not matter at such low speeds. These systems are also vastly different from high speed off road racing suspensions. Instead of focusing on having high up and down travel of the whole front or rear, which is useful for maintaining contact with the road at high speed or landing jumps, these systems focus on a flexibility and articulation. Articulation can be described as the system's ability to maintain four wheel contact with equal pressure on the ground even as the opposite corners of the vehicle are raised up by obstacles. For example, if the front right, and rear left tires are each on a two foot tall rock, the other tires need to retain reasonable ground pressure in order to maximize stability and traction. The need

for articulation is where the engineering challenge arises, and it is this functional requirement that this paper will focus on.

Alternative Designs

There are a number of popular suspension designs used in this sport. This is largely a result of the diversity of setups that come on original equipment manufacturers, or OEM vehicles. One common and somewhat antiquated system is the leaf sprung beam axle, or Hotchkiss setup shown in Figure 2 - Leaf sprung beam axle. This system uses only the spring (pictured in dark grey) to locate the axle and resist forward, sideways, vertical, and torsional motion. Advantages of this system include limited space requirements, inexpensive parts and modification, and the fact that they are often found in OEM setups. The disadvantages include low wear life, and less flexibility due to binding components and friction within the spring pack (Four-Link Suspensions, 2007). Using the spring to locate the axles also causes unpredictable motion of the axle when it's under a high load, which allows the axle to rotate in the windup direction as a result of drive and brake torques. This increase in driveline angle can potentially cause a bind in the joints which are already under high load in an off-road scenario (Gillespie, 1992). For a person who does not have the skills or resources to make heavy chassis modifications, this is often the best setup due to its simplicity and cost effectiveness. It is often used as an initial stepping stone when people first get into modifying a vehicle for dedicated off-road use. While this paper will not focus on a Hotchkiss setup, it will focus on designing a system around a beam axle, which has higher load carrying capacity than other suspension types.

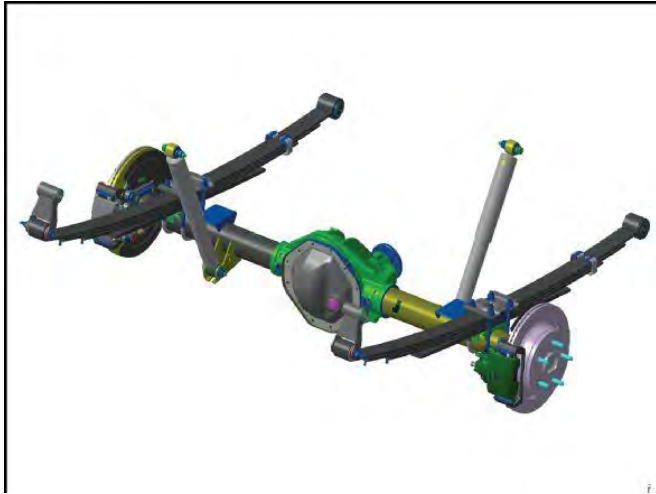


Figure 2 - Leaf sprung beam axle (Leaf-Spring Rethink, 2008)

Another commonly used OEM style system is known as independent suspension. Instead of using a beam axle which directly connects the left and right wheels, an independent suspension uses a double a-arm style linkage system. Figure 3 - Independent front suspension on the 2017 Ford Raptor shows an example of one of these systems on a Ford Raptor, which is marketed towards a high-speed desert type sport called prerunning. In the picture, you can see the lower A arms extending from the wheel to the frame. Many high speed off road and racing car applications use this system because of its superior alignment, roll center, and antisquat control, and the ability to make the system lightweight. The nature of its geometry also makes fitting an engine between the wheels easy, and it eliminates much of the steering wobble and shimmy often seen in beam axle applications (Gillespie, 1992). The main reason for this is that the motion of the left wheel does not in any way affect the right wheel, since the systems are decoupled. In a solid axle application, raising the right wheel causes camber in the left. This design also allows for a very predictable spring and damper behavior model since the motion is so well controlled. The downside to this system, and the primary reason that this system is not used in rock crawling is that wheel travel is limited by the nature of the design, as well as overall brute strength (Frontend Fued - IFS Vs. Solid Axle., 2013). Even with control arms that span the

entire width of the vehicle, there is no way to maintain flexibility and wheel travel comparable to that of other systems, and under shock loading frequently seen in rock crawling applications, the various joints and members frequently bend. Other major flaws include cost, difficulty of manufacturing and designing, and weak axle shafts because it requires an inboard and outboard joint on each side, which contrasts to the single outboard joint of a beam axle.



Figure 3 - Independent front suspension on the 2017 Ford Raptor (Frontend Fued - IFS Vs. Solid Axle., 2013)

Fundamentals of Three and Four Link Systems

The last option, and most commonly used, is a link controlled beam axle suspension design such as the one shown in Figure 1 - Typical rock crawling obstacle . This system is used for its superior ability to articulate without having components bind, and its relative ease of design and manufacture. When built correctly, the geometry is more predictable than leaf springs, allowing the designer to plan precise roll centers, roll steer, and antisquat. These designs are also far more rigid than a Hotchkiss setup since the primary structural components do not have to bend to provide vertical freedom (Gillespie, 1992). It also allows for a broad range of applications, from high speed racing to this particular motorsport. While there are a

whole subset of types of link suspensions such as radius arm and leaf spring and traction bar, this paper will focus on the design and implementation of a three link plus pan-hard bar front, and four link rear system due to its proven long term popularity among off road enthusiasts. Figure 4 - Three link front (left) and four link rear (right) shows a three link and four link system.



Figure 4 - Three link front (left) and four link rear (right)

(Four-Link Suspensions, 2007)

The three link suspension in Figure 4 - Three link front (left) and four link rear (right) uses three primary links shown in blue. These allow vertical motion while resisting forward and aft motion. The vertical separation of the top and bottom links, mounted at the top of the differential housing, and centerline of the axle tube, respectively, resists torsion from drive and braking torque. The fourth link shown in grey is called a pan-hard bar, or track bar. This resists sideways motion of the axle caused by steering and horizontal loads from obstacles. This is considered a secondary link, and is subjected to much lower forces. The most common reason this system is used in the front of a vehicle is space restriction. Some people manage to fit a four-link system in the front, however with most OEM based vehicles, this would require an awkward amount of height gain in order to clear steering and engine components. The model in figure 4 looks clean and uncluttered, however when this system is implemented, there are drive shafts, an engine oil pan, steering gear, and radiators and coolers all within six inches of the axle. These make a marginally more predictable four link system impossible to implement.

The four link rear suspension shown in Figure 4 - Three link front (left) and four link rear (right) uses four primary links and no secondary links. Like the front system, the vertical separation of the links resists the drive and braking torsion. The triangular layout of the top links resists sideways motion, and the lower links resist thrust. This is only possible with the top links pointed in towards the axle, and the bottom links pointed straight back or outwards. The higher the upper link separation angle, the less force is transmitted through the links due to side loading of the axle (Gillespie, 1992).

Alternative Methods of Improving Link Suspensions

The method discussed in this paper involves removing nearly every part of the factory suspension from the vehicle, and deconstructing down to a bare frame as a starting point. Many times, implementation of this design requires building frame cross-members, or removing sections of existing frame. For many people, the best path is not to design the chassis around the suspension design as this paper will, but rather to design the suspension around the existing chassis and available pre-fabricated kits. For example, many jeeps already have provisions for link suspension, and just need longer links to make them more capable and optimized for the unique application. In this case, many people purchase pre-fabricated, bolt on cross members and mounts, and even pre-fabricated links. This allows the manufacturer to take care of the detailed design which this paper will discuss. It also eliminates hundreds of hours of cutting and constructing custom links, brackets, frame members, and more. For a non-technical person, or a person who does not want to purchase all of the fabrication equipment to create a custom system, this is a fitting path.

Detailed Design: Rear Four Link

Chassis Layout – Frame and Axle Location

The chassis layout consists of critical but difficult to change parameters such as wheelbase, frame dimensions, and wheel well location on the vehicles body. Depending on the vehicle, this may be something the designer can change. For the purposes of this guide, we will use the arbitrary frame shown below, roughly follows the layout of a 1973-1991 Chevy Blazer. Most vehicle frames will follow this layout with raised portions above the axles, and a narrower front end. Often it is beneficial to stretch the wheelbase of the vehicle by a few inches, and this is easy since the axle mounting linkages are being redesigned. The most common limitations to stretching wheelbase are having the tires contact the vehicle body, and causing steering gear geometry to bind. For the purpose of this paper's example, there will be no wheelbase stretch, and tire size will be set at 42 inches in diameter. This scenario would apply to a designer who knows they will need the smallest possible turning radius, and as a result needs the shortest possible wheelbase.

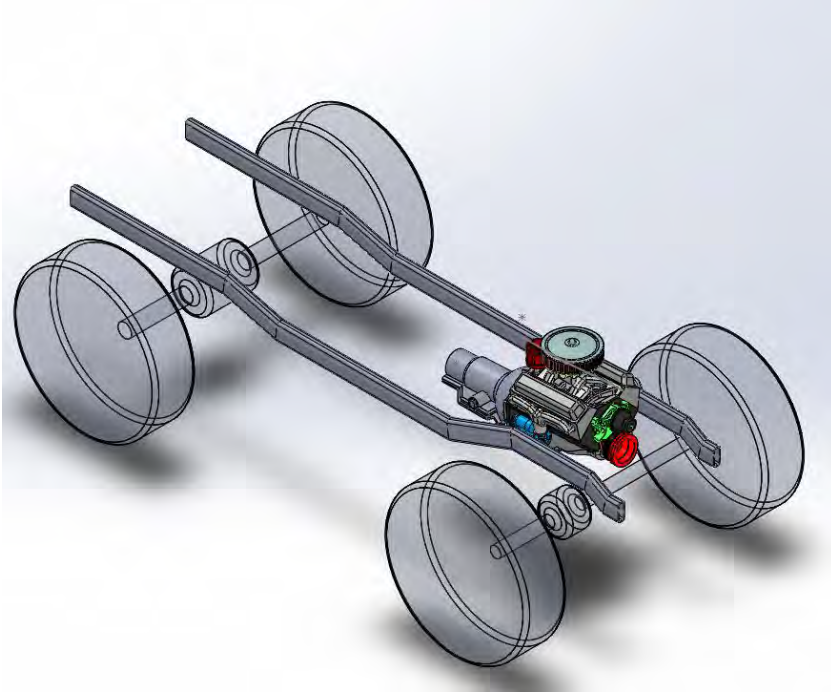


Figure 5 - Example Chassis

Another consideration which should go into the chassis layout is the height of the frame above the axles. This should be determined by measuring the distance in stock form, and adding the height of lift desired. The lift should be as small as possible to lower the center of gravity. Often there is a minimum lift required to eliminate tire contact with the frame or body of the vehicle. A common method of determining lift height is looking at internet pictures of other similar vehicles which have a known lift height and tire diameter.

It is helpful to enter as much known information about fixed points on the chassis. For example, in Figure 5 - Example Chassis the engine and transmission have been added. Obviously there can be no mounting points inside of the space taken up by these components, so visualizing them early ensures that the design is possible to manufacture.

Axle Link Mounts

To establish the rear link layout, first we will examine a side view of the chassis. On the axle side of the links, nothing should hang below the axle tube, as it could be impacted and torn off by protruding rocks. This limits the lower link mount to the centerline of the axle tube as seen in Figure 6 - Rear Axle Link Mount Locations. The vertical separation of the mounts determines the compressive and tensile forces exerted on the links from axle torsion, and a good rule of thumb is to set them apart at 25% of the tire diameter, which yields 10.5 inches for this example. Limitations and considerations for this location include whether this point is so high that it impacts the floor of the vehicles body upon suspension compression, or whether it is so low that the links would have to be mounted inside of the differential housing of the rear axle. It is also important to keep the upper links mounted as close together as possible near the center of the axle, because the angle between them must be close to 45 degrees to provide adequate lateral stability. The lower links are mounted as close to the inner wheel surface as possible. In this paper's example, the mounts are 6" in from the wheel to account for brake components. Upper and lower link mounts in this paper's example can be seen in Figure 7 - Rear Axle Link Mount Locations (Horizontal) (Four-Link Suspensions, 2007).

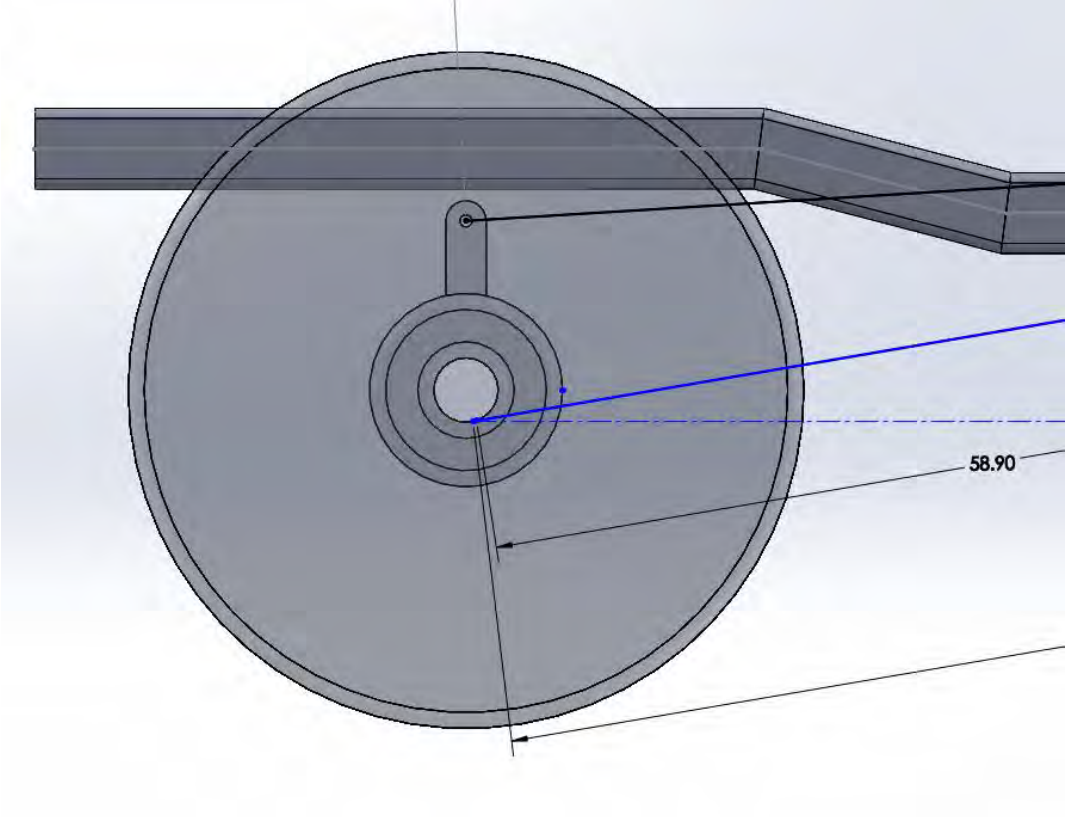


Figure 6 - Rear Axle Link Mount Locations (Vertical)

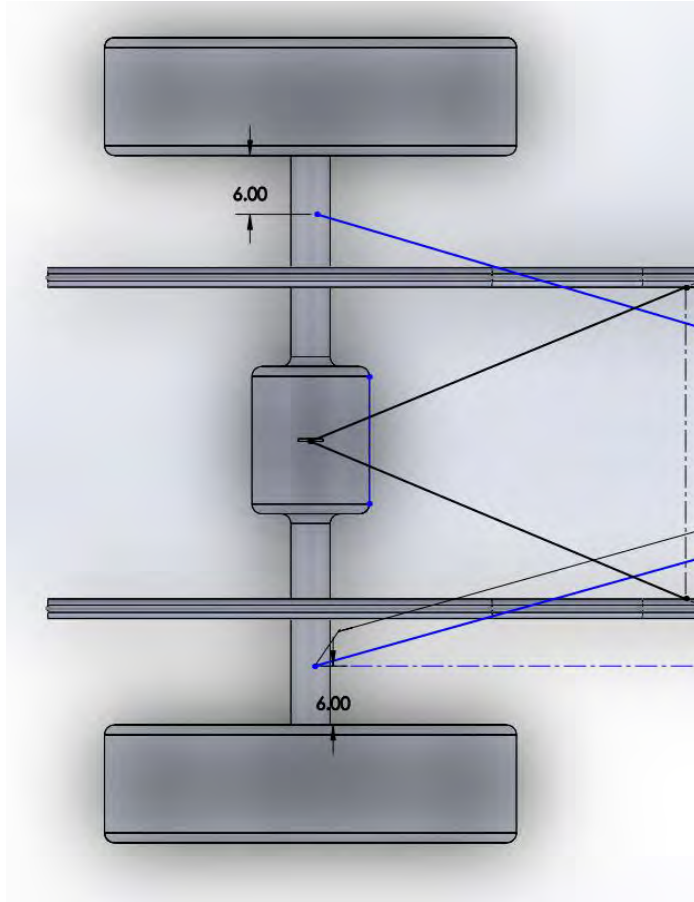


Figure 7 - Rear Axle Link Mount Locations (Horizontal)

Frame Link Mounts

It is generally accepted that the lower links should be at a 5 to 10 degree angle upwards from a level line, and the vertical link separation on the frame side should be half of the axle side's separation (Four-Link Suspensions, 2007), which is 5.25" for our example. The upper link should be around 70% of the lower link's length, and the angle between the upper links should be close to 45 degrees. With this in mind, our example first sets the upper links at a 45 degree angle from each other. The links end where they intersect the frame, and the height of these

frame mounts is set at the top of the frame rail. This way the 5.25" lower sits near the bottom of the frame rail and nothing protrudes down to be caught on rocks. The horizontal distance between the upper link frame mounts should be near 60% of the axle sides horizontal width. Figure 8 - Lateral Constraint Points shows a top view of this paper's example with all the above rules applied.

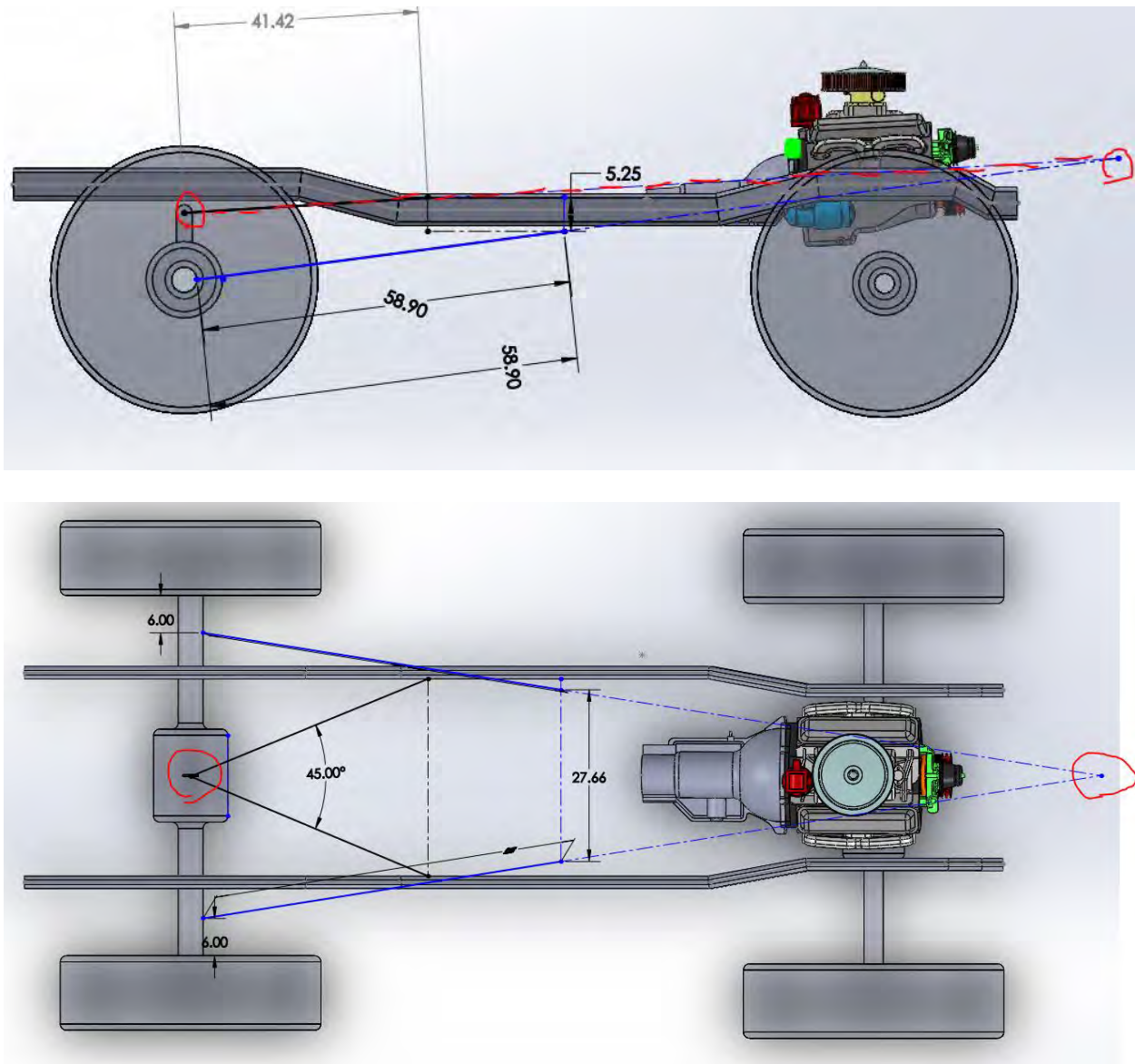


Figure 8 - Lateral Constraint Points

Reducing Rear Steer, and Roll Axis

Rear steer is a common undesirable characteristic of four link suspensions. Rear steer occurs when the axle articulates, meaning one side is near maximum height, and the other is nearly fully drooped out. When poorly designed, this situation can result in the raised tire moving significantly forward, and the drooped tire moving backwards. This causes the rear axle to steer the vehicle off whatever line of approach a driver is attempting.

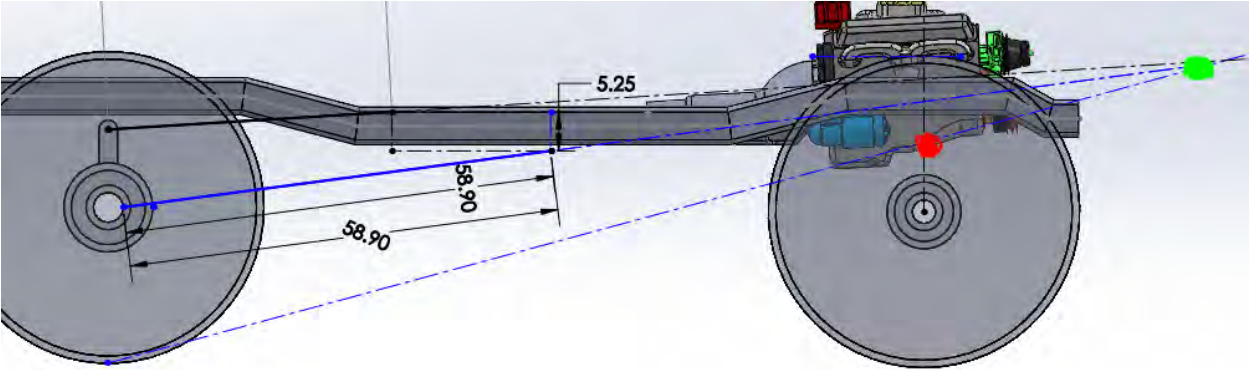
Lateral constraint points, or LCP's are used to eliminate this behavior (also called roll centers). These are the points circled in red in Figure 8 - Lateral Constraint Points. They are defined by the point where the links would meet if extended. To minimize rear steer, the front LCP needs to be at least in front of the transmission (Four-Link Suspensions, 2007). The example design has the front nearly a foot in front of the front bumper because it has followed the general rule for lower link mount widths.

The roll axis is the line about which the frame and body will roll while cornering (Gillespie, 1992). In Figure 8 - Lateral Constraint Points, the roll axis is a dotted red line. Keeping the roll axis close to level or forward slanted also helps to minimize rear steer. One sacrifice made in this design is the height of the roll center, and its relationship with the center of mass. At nearly 40 inches, the roll axis is much higher than a passenger vehicle's would be. Having the center of gravity above this roll axis means that the vehicle's sprung mass will lean as it corners (Gillespie, 1992). In this example, the center of mass is estimated to be at the top and front of the transmission, marked in lime green in Figure 8 - Lateral Constraint Points. In order to maintain the optimal axle flexibility achieved by following the guidelines in the link mount sections of this paper, this poor cornering performance will be accepted as a performance tradeoff. As mentioned in this papers introduction, these vehicles are not intended for long term high speed use, and this is one of the several reasons for it.

Antisquat

When these vehicles are running trails, there are frequently scenarios where a high torque is applied to the axles by gear reduction to get the vehicle moving up an obstacle. The sharp acceleration that results transfers weight to the rear axle. To fight the resulting suspension compression, antisquat is designed into the system. It uses the forces acting on the linkages to lift the frame from the axle (Gillespie, 1992). Various levels of antisquat can be designed into the system, and this example will plan for a slight squat upon acceleration since drastic antisquat can cause the rear axle to walk under the vehicle under high torque.

To determine the antisquat in the example design, lines are drawn from the upper and lower links in a side view, and a third line is drawn to the intersecting point from the rear tires contact patch. Finally a vertical line is drawn up from the center of the front axle. The contact patch line intersects the vertical line at 73% of the height of the center of mass. This means there is a 73% antisquat ratio, which indicates slight squat, but nothing excessive under acceleration.



At this point the system should be ready for building. It is not uncommon to find that there are issues with fitting parts where the design planned, and changes will likely be necessary. This process should reliably get the systems basic geometry down.

Detailed Design: Front Three Link

Chassis considerations

Much like with the rear suspension, the full redesign of the front allows the opportunity to lengthen the wheelbase, and build in some amount of lift from the stock height. The height in this example has been set from the four link section. This example will not modify the wheelbase because it is designed to fit under a Chevy Blazer body, and extending the front end forward like some builders would causes the tire to hit the front of the fenders.

When designing the three link, it is important to know where the steering gear must sit on the frame and axle. Its also important to know exactly where the engine is, since some links will come very close to contacting the bottom of the engine, most notably the pan-hard bar. This example has inserted the engine, transmission, and transfer case into the model in the factory location to design around it.

Axle Side Link Mounts

The lower links are easy to determine an axle side mounting location for. They should be at the centerline of the axle so that they don't hang down and get destroyed by protruding rocks. They should be as wide as possible horizontally, but it is important to consider the limiting factor to how wide they can get, tire clearance. At the maximum steering angle, the rear of the tire

grows extremely close to the lower link. The inward angle of the lower links can create slightly more tire clearance, so this horizontal mounting distance will likely need to be tweaked once the frame side mounts are determined.

The upper link resists all the torsion caused by drive and braking forces on the tire, and as such requires vertical separation from the lower links. Generally, 8" to 12" of vertical separation at the axle is optimal (Kopycinski, 2009). More specifically, vertical separation should be roughly 25% of tire diameter (Barnes, 2015). For the 42 inch tires in this example, that means 10.25" of separation. Because of oil pan considerations, and because taller link mounts will withstand greater stresses, this example compromised for an 8" separation. This allows the bracket to which the link bolts to be only 2" high off of the axles center housing. The link is attached on the passenger side of the axle because that is where the center housing of the axle is, and the cast iron housing is typically stronger than the 8" to 12" tall bracket required to attach the link at the other side of the axle.

The pan-Hard bar will also attach at the axles center housing to be as high as possible with the shortest bracket possible. Ideally, the pan-hard bar will be level with gravity, but if there is angular separation between the steering linkage and pan-hard bar, bump steer will result. This means that as the axle travels up on the road, the steering will be forced to turn, making the vehicle difficult to handle on the road. The example places the axle side pan-hard bar mount in a position between the steering box and axle side steering linkage mount. Once the frame side is established, the pan-hard bar will be parallel with the steering linkage, eliminating bump steer. Figure 9 - Front Axle Link Mounting Locations shows a top and side view of the link locations.

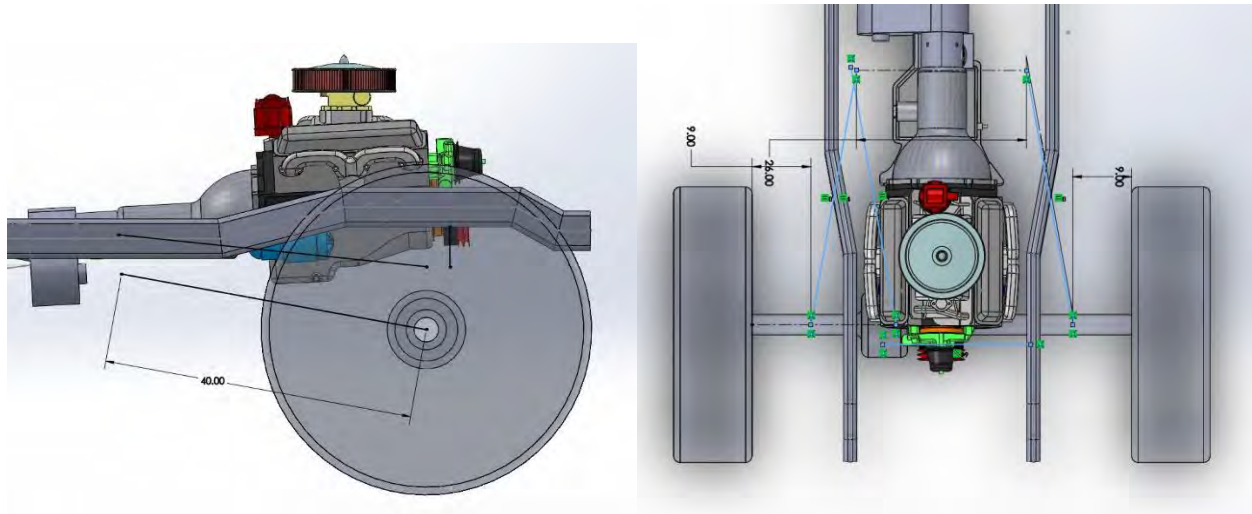


Figure 9 - Front Axle Link Mounting Locations

Frame Side Link Mounts

The lower link mounts on the frame side are located based on two factors; anti dive and tire clearance. As discussed previously moving the frame sides of the links closer together allows more tire clearance, so in this example they are mounted to the inside surface of the frame. Having the links close together on the frame side also helps in lateral stability, since it increases the angular separation between upper and lower links. Figure 9 - Front Axle Link Mounting Locations shows the wide angular separation used in this example. The link length should be close to twice the wheel travel distance desired (Barnes, 2015). For this example, that means 40". This length also allows the links to be mounted to a frame cross member which also can act as the transmission mount, since it is directly in line as seen in Figure 9 - Front Axle Link Mounting Locations.

The upper link length can follow one of two thought processes. The older, classic thought process is to make the upper link 75% of the length of the lowers to maintain the ideal suspension geometry through travel at high speed. The newer thought process used in this example is to make the links equal length to make sure that the axle pinion does not point

downward as the axle droops out (Barnes, 2015). When the pinion, or input shaft of the axle points down under high drive load, the driveshaft is forced to transmit torque through high angle universal joints. This causes premature failure of joints from wear, and even instantaneous stress related failure under heavy use.

Having established the upper link length at 40", the horizontal mounting location is the next consideration. As previously stated, lateral stability is increased with higher angular separation between upper and lower links when viewed from the top. The upper link has been mounted as close as possible to the passenger side frame rail in an effort to increase this stability.

Now that the rough locations exist for axle and frame mounting locations, anti-dive should be considered. This is similar to antisquat in the rear suspension. Under heavy braking, the nose of the vehicle tends to sink down, and anti-dive resists this. With a three link suspension that has some inherent bump steer, braking dive will result in steering angle change, making the vehicle unpredictable in an emergency stopping scenario. Because of this, the example will aim for just over 100% anti-dive. This percentage can be measured with a similar process to the rear. First, a line is drawn from the front tire contact patch on the ground, to the intersection of the rear axle center line and center of gravity line as shown by the dotted blue line in Figure 10 - Anti-dive Analysis. If the instant center, circled in red, sits on this line as shown, there is exactly 100% anti-dive (Kopycinski, 2009). Sitting above this line indicates more than 100% anti-dive, and sitting below this line indicates less than 100% anti-dive. To fine tune this, the frame side vertical link separation is changed. In this case, around 4 inches of vertical separation leads to 100% anti-dive.

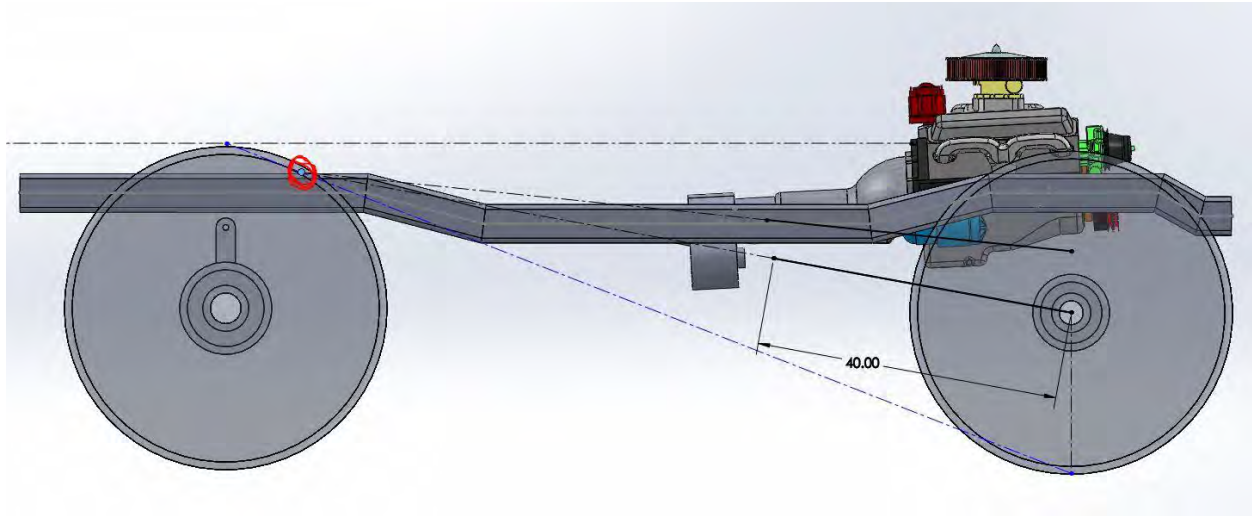


Figure 10 - Anti-dive Analysis

As discussed earlier, the pan-hard bar frame mount is located such that the link will be parallel as possible to the steering link in order to minimize bump steer. The center of this linkage, at 21.5" of height, indicates the roll center for the front suspension. This is the point about which the body will roll in a corner. This example's roll center is about 7" below the center of gravity, which means that the weight can easily roll over the roll center. This is a tradeoff made in the name of flexibility.

Bracket, Joints, Material, and Cost

Now that the geometry is more or less determined, the system must actually be implemented on the vehicle using a set of brackets, joints, and linkage material. The design and material selection of these components is just as critical, if not more important than the specific geometry. Should even one linkage, joint, or mount fail, the vehicle will be disabled wherever it sits, even if it is miles into a trail where no tow truck can go, and even if the driver is alone with no ride home.

Mounting points generally should be made from plate steel of 3/16" or 1/4" steel plate, depending on the size and weight of the vehicle. A full size truck based vehicle like the example in this paper would certainly use 1/4" plate. The material should be 4130 chromoly steel, which has a higher carbon content, and therefore resists deformation longer. Other mild steels will sustain far more plastic deformation before failure, and start to deform at a lower stress, which allows not only easier damage, but damage which throws off the vehicles alignment. Some people prefer the deformation warning signs before catastrophic failure, however most will agree that more strength is better, even at the cost of less warning signs before failure. Figure 11 - Example of axle and frame link mounts shows an example of the plate steel construction used on both the axle and frame side link mounts. Note that all mounts are fully boxed when possible to add strength for unexpected shock loading in unexpected directions. The sport for which this system will be used subjects vehicles to shock loading that is very difficult to mathematically calculate and design for, so the general focus is on oversizing as much as possible whenever weight gain is not excessive.



Figure 11 - Example of axle and frame link mounts (Link Suspension Kits - 4 Link)

Link material is also important, as they are the primary structural member holding axles under the vehicle. Nearly all designers use Drawn Over Mandrel, or DOM tubing. This material is much like other types of tube in its initial manufacturing processes, where SAE 1026 steel is cold formed and flash welded along the seam. What makes DOM tubing superior is that it is cold rolled over a mandrel to reach its final dimensions. This work hardens the material and increase its mechanical strength, as well as its weld strength. Typically, 1/4" wall tubing is used for linkages, and an outside diameter of 2" to 2.5" is most common (Ansell, Suspension Link Construction). It is both cost and strength effective to increase outer diameter of these links rather than go to 4130 steel for these links. To attach joints to the end of these links, a threaded insert is butt-welded to the ends of the link. One side uses a left-handed thread, and the other a right-handed thread. This allows fine tuning of the design by turning the tube to extend or shorten the links length.

Joints are one of the more expensive components in the link suspension system, and there are enough of them to add a significant expense by the end of the project. Typically, heim joints are used for their superior angular deflection and lack of bind through their range of motion. Typically, 3/4" joints are used on vehicles such as jeeps and small trucks (Ansell, Suspension Link Construction). A pair of two joints, their spacers, jam nut, and welded bung will typically run between \$70 and \$100. At the end of a three and four link design, there will be at least 16 of these joints, and even more if they are used for steering components. While the cost adds up fast due to the machining processes required to manufacture these components, the designer should still select quality parts. Foreign made parts are often cheaper, but do not include a Teflon liner to reduce ball wear, or a grease fitting to allow serviceability. Figure 12 - Heim joint with spacers, jam nut, and bung shows a typical joint with spacers in the ball, a jam nut, and a threaded weld-in bung.



Figure 12 - Heim joint with spacers, jam nut, and bung (Ansell, Suspension Link Construction)

Coilovers, Bump and Droop Stops

Bump and droop stops

Link suspensions are used for these vehicles because they allow a large range of motion without bind, however there is a limit to every design's ability to flex. The limiting factor could be joint bind, where the joint meets its maximum angular deflection, or perhaps the shock absorber travel is maxed out. Either way, allowing the joints or shocks to limit the motion of a 500lb axle and tire combination will immediately cause failure. Instead, limiting straps are used to stop downward travel, and bump stops such as the one in Figure 13 – Hydraulic bump stops are used to limit upward travel. For vehicles which will be used at speed, hydraulic bump stops are common. These act like small shock absorbers with under 3" of stroke that only contact the axle

when it is near its maximum up travel. These allow a soft and controlled stop compared to the cheaper, low speed application bump stops which are nothing more than a rubber snubber.



Figure 13 – Hydraulic bump stops (Ansell, Suspension Link Construction)

Spring and damper selection

This paper will only briefly touch on the complex topic of spring and shock selection. There are entire books dedicated to the subject, and this paper is intended only to provide a basic general direction for selection. The process described will enable the selection of a coil-over-shock that enables the suspension to flex to its limiting points, and sit at a desired ride height. The process described does not address suspension frequency, which is extremely important as the speed of the application goes up. This process also will not touch on dual or triple rate springs, which can be extremely valuable depending on the application. Because the

four coilovers on these vehicles are often the most expensive set of components on the entire vehicle, it is advisable to do as much research as is in the designers skill levels before purchasing parts. For a more in depth analysis of spring and damper selection, refer to the references in this section.

The most crucial factors in this selection process are sprung weight, installation ratio, and compressed and extended lengths of the coil-over. Selecting these components is usually done at the very end of the design process. This way, the full vehicle can be weighed at each corner after being built. Everything from wheels and tires to spare equipment and coolers that the end user expects to have in the vehicle should be in the vehicle before measuring corner weights (Shock Measurements).

The first step is to support the frame of the vehicle high enough above the ground that the suspension can be flexed to its limits without hitting the ground. When the axle is as high as it can go on one side, and as low as it can droop on the other, measure the length between frame and axle side shock mounts on each side of the vehicle. These are the maximum and minimum lengths of the shock that will be ordered. Always order the closest size coil-over without going smaller than the required lengths (Ansell, The Coilover Bible). It is often necessary to adjust the locations of the upper and lower coil-over mounts to allow for an overall coil-over length that can support the desired minimum and maximum lengths. While the vehicle is in this flexed position, it is also useful to measure for the locations of bump and droop stopping features.

The shock size selected is largely dependent on type of vehicle, and it's application. Table 1 - Shock and bump stop selection table provides a guide for various applications. This paper's example would fall under the full size truck category, and would be listed under "mild trails". The shock selection process can be as simple as following this table, however the ideal selection process for both size and type is to determine the desired ride frequency, and use that as the driving factor to compute the resulting spring and damper rates. This too would have to

be tweaked to fit within maximum and minimum lengths under articulation (Ansell, The Coilover Bible).

Table 1 - Shock and bump stop selection table (Shock Measurements)

Vehicle Example	Vehicle Use	Recommended Shocks
Mild Jeep on 35-37" Tires	Street	2.0 Emulsion Shocks
Mild Jeep on 35-37" Tires	Mild Offroad	2.0 Shocks with Reservoirs + 2.0 Hydraulic Bump Stops
Mild Jeep on 35-37" Tires	Expedition	2.5 Shocks with Reservoirs + 2.0 Hydraulic Bump Stops
Buggy on 1 Ton Axles and 40-42" Tires	Mild Trails	2.0 Coilovers with Reservoirs
Buggy on 1 Ton Axles and 40-42" Tires	Rock Crawling	2.0 Coilovers with Reservoirs + 2.0 Hydraulic Bump Stops
Buggy on 1 Ton Axles and 40-42" Tires	Rocks & Desert	2.5 Coilovers with Reservoirs + 2.0 Hydraulic Bump Stops
Buggy on 1 Ton Axles and 40-42" Tires	Ultra4 Racing	2.0 Coilovers + 2.5 Bypasses + 2.0 Hydraulic Bump Stops
Full Size Truck with 40-44" Tires	Mild Trails	2.5 Coilovers with Reservoirs
Full Size Truck with 40-44" Tires	Hill-N-Hole	2.5 Coilovers with Reservoirs + 2.5 Hydraulic Bump Stops
Ultra Light Tube Buggy with A-Arms	Recreational	2.0 Coilovers with Reservoirs
Ultra Light Tube Buggy with A-Arms	Aggressive Use	2.5 Coilovers with Reservoirs + 2.0 Hydraulic Bump Stops
Desert Truck with A-Arms/Trailing Arms	Recreational	2.5 Coilovers with Reservoirs + 2.5 Hydraulic Bump Stops
Desert Truck with A-Arms/Trailing Arms	Mild Racing	2.5 Coilovers + 2.5 Bypasses + 2.5 Hydraulic Bump Stops
Desert Truck with A-Arms/Trailing Arms	Hard Racing	2.5 Coilovers + 4.5 Bypasses + 2.5 Hydraulic Bump Stops

The simple method for spring rate selection is to assume the spring preload is set in the middle of its adjustment range, and determine the amount of spring compression desired at ride height. Then calculate the spring rate based on supporting the sprung weight under that desired amount of compression. As a rule of thumb for rock crawlers, ride height should be set such that the shock has 35% up travel remaining, and 65% down travel remaining before the limiting features stop motion (Kopycinski, 2009).

This spring and shock selection process should be repeated independently for the front and rear of the vehicle, since there will be different corner weights and travel restrictions due to mounting options. Following these guidelines will yield a suspension that can use its full range of motion, however there are no guarantees that the system will handle well at high speed or on

the road. This is a result of using the quick method, rather than allowing the suspensions natural frequency to dictate the design (Ansell, The Coilover Bible).

Conclusion

The in-depth design process described in this paper will yield a far superior front and rear suspension on any vehicle when compared to the OEM design, or even an off the shelf lift for an OEM design. Despite tradeoffs made to get the system to fit under the frame of a specific vehicle, there will be a significant functional and cost advantage over any off-the-shelf lift system one can purchase. This is because the system replaces bushing joints used in OEM applications with heim joints, and because the linkage lengths are far longer than any OEM design. The disadvantage with this process is the intensive labor requirement, and skill level required to follow this process in one's own garage. If somebody had to purchase all the tools such as welders, tube notchers, and more, it may also not be cost effective.

Hopefully this paper has provided an in-depth design process for people to follow at home, regardless of technical education. While each section can be improved with further research, the process as described should yield a system worth the envy of fellow off road enthusiasts. Now its time to get the pencil and paper out, and start taking measurements of your own vehicle!

Bibliography

- Ansell, B. (n.d.). *Suspension Link Construction*. Retrieved from Billavista.com:
<https://www.metalsupermarkets.com/difference-between-erw-dom-and-seamless-tube/>
- Ansell, B. (n.d.). *The Coilover Bible*. Retrieved from Billavista:
http://www.billavista.com/tech/Articles/Coilover_Bible_Part_1/index.html#TheBasisForSelectingPreliminarySpringRates
- Barnes, B. (2015). *Installation Tips for Adding a Three Link Suspension*. Barnes 4WD.
- Four-Link Suspensions*. (2007). Four Wheeler Magazine. Retrieved 2017
- Frontend Fued - IFS Vs. Solid Axle*. (2013). Four Wheeler Network. Retrieved 2017
- Gillespie, T. D. (1992). *Fundamentals of Vehicle Dynamics*. Warrendale, PA: Society of Automotive Engineers.
- Kopycinski, J. (2009). *Front Suspension Technology - Link Basics Part 2*. Dirtsports and Offroad.
- Leaf-Spring Rethink*. (2008). Off Road Magazine. Retrieved 2017
- Link Suspension Kits - 4 Link*. (n.d.). Retrieved from Chassisunlimited.com:
<http://www.chassisunlimited.com/product/link-suspension-kits/4-link-suspension-kit-b.html>
- Metalcloak. (n.d.). *Jeep Bumpers, Jeep Tube Fenders, Jeep Suspensions, Jeep Rockers, Jeep Corner Guards and Jeep Accessories for CJ/YJ/TJ/LJ/JK*. Retrieved April 17, 2017.
- Shock Measurements*. (n.d.). Retrieved from CrawlPedia:
http://www.crawlpedia.com/shock_measurements.htm