8

3 Link – Live Axle
Rear Suspension Kinematics
(*It's just not this simple!)*

Important Note: Many of the examples in this chapter, for the sake of clarity, are shown in single plane format which may not always represent the realities of three dimensional co-ordinate analysis. Points that intersect on a single plane do not **necessarily** intersect in three dimensional space. That is why the use of a three dimensional kinematics program such as WinGeo3 is so important.

As with an independent suspension system, in order to make the live axle work, one must first understand how the axle housing is affected by the various kinematic motions i.e. axle motion not chassis motion.

The rear beam axle is/can be controlled in three linear and three rotational modes - Figures 8-1 & 8-2 - (Looking *at just the beam or housing while not considering the hub, rim and tire*). This is accomplished with the use of four control arms - two lower control arms, one upper control arm and a track/panhard bar.

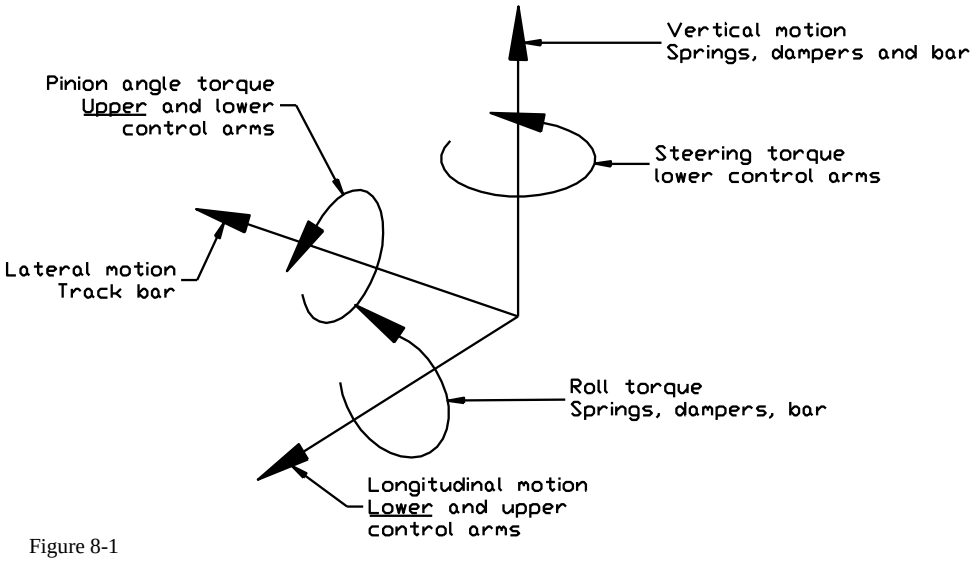


Figure 8-1

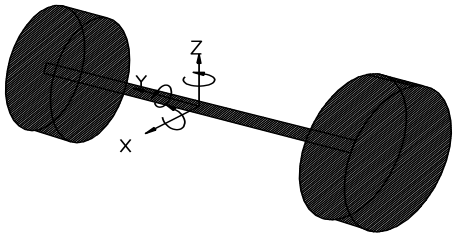


Figure 8-2

Primary and Secondary Live Axle Kinematic Control:

- Lower Control Arms
    - Live axle steering motion – Primary
    - Live axle longitudinal, fore/aft, motion - Primary
    - Pinion angle/axle tube rotation - Secondary
    - Acceleration and braking load/force transfer from the tires to the chassis (action forces) and from the chassis to the tires (reaction forces) - Primary
    - If the lower control arms do not run parallel with each other, they will tend to exhibit some amount of lateral control on chassis motion - the greater the angle, the higher the amount of lateral control - Secondary
- Upper Control Arm
    - Pinion angle/axle tube rotation - Primary
    - Offset or amplify axle torque effect - Primary
    - Acceleration and braking load/force transfer from the tires to the chassis (action forces) and from the chassis to the tires (reaction forces) - Secondary
- Track Bar
    - Lateral control - scrub of live axle and/or chassis - Primary
    - Lateral load/force transfer from the tires to the chassis (action forces) and from the chassis to the tires (reaction forces). These forces are referred to as jacking forces – Primary

Figure 8-3 shows a model of a three link system with its two lower control arms, upper control arm and panhard/track bar. In this case, all the control arm and track bar frame mounts are tacked to the table. This allows the user to study the kinematics of the axle housing independently of chassis motion.

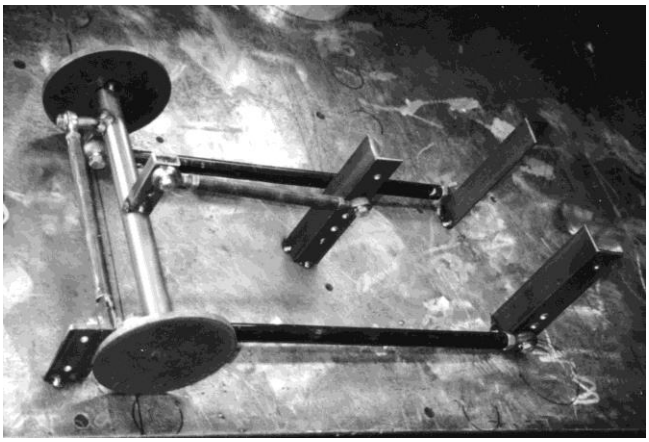


Figure 8-3

Side View Instant Centers (Single Plane)- The side view instant center of a three link system is found by extending lines drawn through the upper and lower control arms to their point of intersection in the side view plane. Where the lines intersect is the side view instant center - Figure 8-4. As always, remember that the instant center co-ordinates will change each time there is any amount of suspension or chassis motion. If the upper and lower control arms run parallel with each other, the instant center point is at infinity.

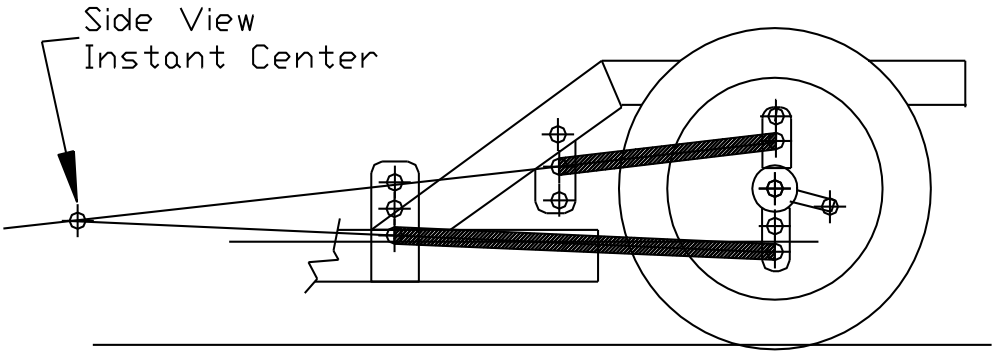


Figure 8-4

The height of the upper and lower control arm mounts on the axle housing can have a considerable effect on the percentage of load transfer that passes through the various links - Chapters 15 & 16. Additionally, if the left and right lower control arms are not the same length and/or not at equal angles, the left and right instant center co-ordinates will end up positioned at different lengths from the axle center line and/or at different heights from the track surface - Figure 8-5. Asymmetric side view instant centers tend to produce asymmetric loads at the tire contact patches - Chapter 16. An asymmetric side view instant center also produces roll and bump rear axle steer as discussed later in this chapter.

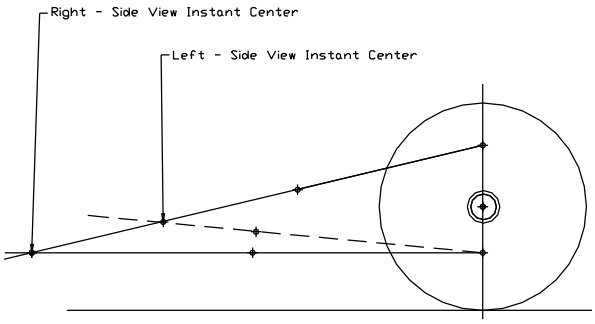


Figure 8-5

SOMETHING TO THINK ABOUT

Milliken and Milliken state, “The third link or upper link is often mounted in the center of the axle. Another option is to mount it off to the right-hand side of the center. It can be shown that if the offset distance is in the correct proportion to the axle ratio being used, the load on the tires will remain equal under acceleration and the sprung mass will not roll. Under braking there would be a slight tendency to roll to the right, however.”[1]

According to Steve Smith, “ The upper third link should be mounted to the chassis at the center of the weight mass of the car. The center of the weight mass is found by multiplying the rear track width by the car’s left side weight percentage. If the car has a 60 inch rear track width, and a 58 percent left weight percentage, the calculation is: 60 x .58 = 34.8. So, the center of the weight mass at the rear is located 34.8 inches to the left of the center of the right rear tire. If the link is not mounted at the center of the weight mass of the car, under acceleration the loading of the rear tires will not be equal. It will add more force to the side of the car that the link is closest to.

[1] W. F. Milliken and D. L. Milliken. Race Car Vehicle Dynamics. USA; SAE International, 1995. pg. 653

For example, if the link is mounted 10 inches to the right of the weight center, under acceleration it would add more loading to the right tire and unload the left rear tire by an equal amount."[2]

Can both of the above quotes possibly be right? The short answer is yes - - well mostly.

The two quotes illustrate difficulties the race engineer faces when trying to optimize a suspension system. GT type cars (Trans-Am, GTS, etc.) often have the third link offset a few inches to the right of center as indicated in the first quote, while short track, asymmetric stock cars often have their third link offset a few inches to the left of center as indicated in the second quote.

Attaching the third link to the right of center is done to help offset the effects of axle torque, torque roll and torque wedge. One effect of live axle torque is that it can wedge the right front and left rear under acceleration as the drive shaft and axle housing rolls counterclockwise and/or the frame rolls clockwise viewed from the rear. If the right front spring and bar have a higher roll resistance than the right rear spring and bar, the wedging effect will increase. If the right rear has a higher percentage of the roll resistance, the wedge effect is decreased. Much of this has to do with the fact that the pinion gear wants to climb up the ring gear, but, because the pinion gear is mounted in the rear end housing, the housing feels and reacts to these resultant drive forces.

Figure 8-6 illustrates a jig that was originally used to look at the effects of moment arm length between the axle centerline and the contact patch. While applying 180 lb. ft. of torque at the pinion gear, four tack welds let go on the right side axle mount, lifting the axle in the process. This turned out to be a great lesson in the forces involved in axle torque. As you can imagine, "*It's not that simple".*

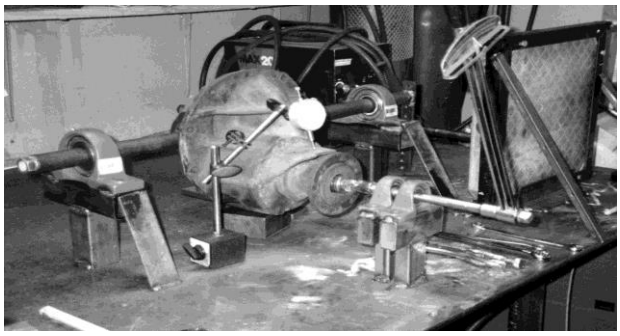


Figure 8-6

The effects of axle torque on the chassis can be offset in a number of ways including running a stiffer RR spring (oval track car), a stiffer rear roll bar or one of many possible kinematic compromises. Each method used to offset the effects of axle torque will result in different amounts of loading seen at the outside and inside contact patches. Offsetting the third link to the right on a road course car is used to lessen the effects of axle torque\torque wedge. Chassis longitudinal load transfer directed through the upper or third link can help counteract the upward force at the right side axle housing. This upper link force is very sensitive to the upper link angle. As the front downward angle of the upper link increases, the angle of the resultant forces decreases, thereby lessening resultant axle torque vertical force. If the upper link is angled down too much, it can actually increase the effect of axle torque. Figure 8-7 shows the upper link of a GT car offset some distance to the right of the axle centerline.

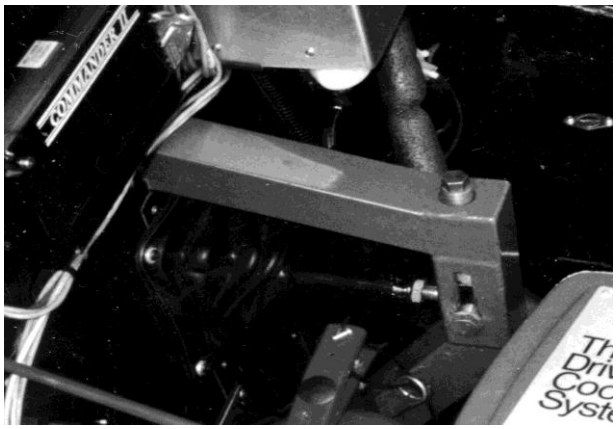


Figure 8-7

[2] Steve Smith. Paved Track Stock Car Technology. USA; Steve Smith Autosports, 1997. pg. 56

Unlike a road course car which must be able to turn both left and right, a stock car only has to turn left. This allows the race engineer to maximize left turn performance. The engineer can play with suspension kinematics in order to maximize left to right wheel balance during left turn power on exit - offsetting the upper link to the left amplifies the effects of torque wedge, thereby increasing the load seen by the left side tire and decreasing the load seen by the right side tire. The upper or third link effect on axle torque is primarily a result of longitudinal load transfer, and, unless the chassis is a wet noodle, the lateral positioning of the center of gravity has no bearing on the resultant forces the upper link generates. As with the right hand offset, the angle of the upper link is quite critical i.e. it can increase or decrease the effects of axle torque. Figure 8-8 illustrates an upper link slightly offset to the left. This leftward offset increases RF/LR wedge under acceleration which can help tighten the car at turn exit. Offsetting the third link to the left of center is sometimes a better compromise than staggering the lower control arm angles, but, as always, *it is far from that simple*.

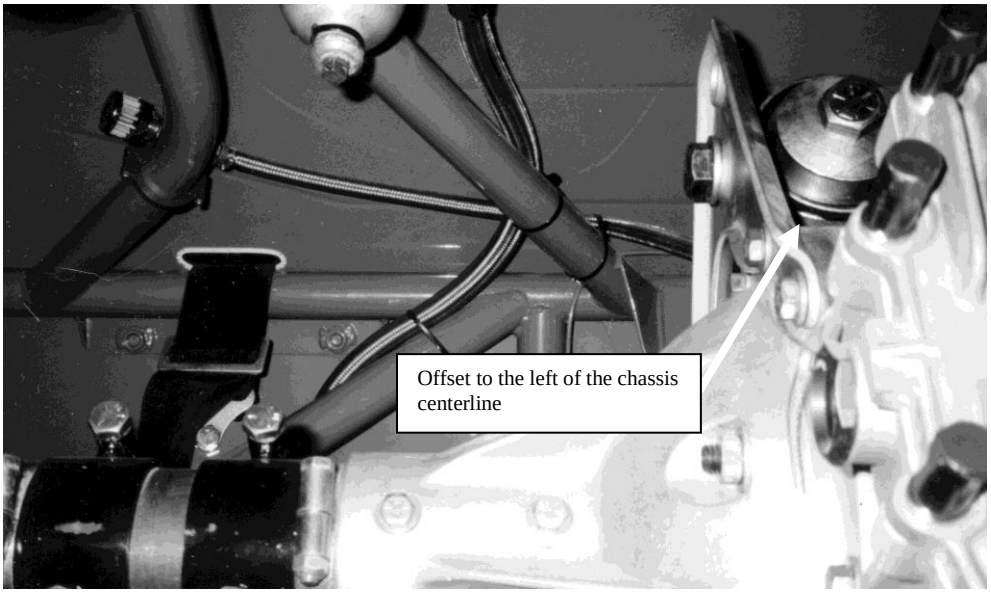


Figure 8-8

Rear View Instant Centers - Unlike an independent suspension system, the beam or live axle does not have easily defined rear view instant centers. Therefore, the motions of the rear live axle are normally discussed in terms of pivot points rather than roll axis. At this point, we are simply looking at axle motion, independent of chassis motion - our model has its suspension points welded to the test table.

Rear View Axle Motion:

- Right wheel up in bump - Figure 8-9
    - Axle pivots about opposite tire - in the case of our model's narrow steel tires, it pivots about the outside edge
    - Track bar pivot is primarily about the axle mount if the chassis does not move
    - The angular difference between the track bar and axle increases with the amount of right wheel bump
- Left wheel up in bump - Figure 8-10
    - Axle pivots about opposite tire - in the case of our model's narrow steel tires, it pivots about the outside edge
    - Track bar pivot is primarily about the frame mount if the chassis does not move

- The angular difference between the track bar and axle remains more or less constant with left wheel bump

- If both wheels move but with differing amounts of bump, the axle pivot point will be located somewhere between the two track bar mounting points

- These pivot points are fundamental to the understanding of live axle kinematics

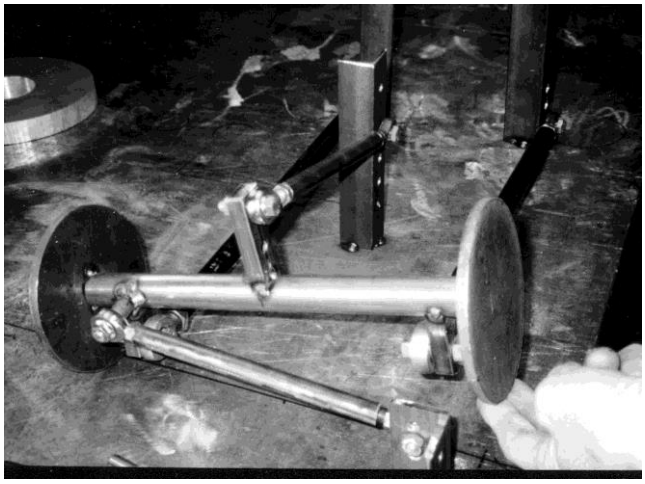


Figure 8-9

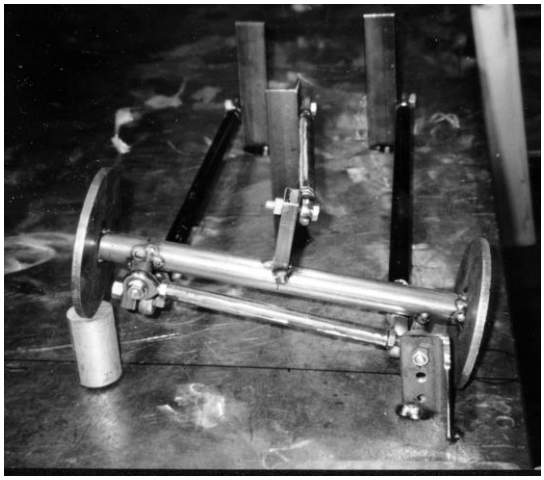


Figure 8-10

One of the primary problems I come across when working with three link systems is binding at the rod ends due to insufficient axial motion either from improperly aligned rod ends or poorly designed mounts. One must always run both the frame and the axle through all possible kinematic iterations to make sure there are no kinematic binds. Teams, even mega buck teams, far too often overlook this problem,. Building a model like the one illustrated in the proceeding pictures is an excellent way to see how easy it is to end up with kinematic binding. The rod ends don't need to be misaligned very much before they begin to bind during various kinematic iterations. No load kinematic binding is considerably simpler to find compared to dynamically loaded binding. One of the best things teams can do is always make sure the various rod ends and pick up points have substantially more rotational freedom than is needed for just kinematic motion. Locating dynamic binding points often entails some serious detective work. A considerable degree of dynamic or kinematic binding normally shows itself as a snap change in handling i.e. the chassis is neutral at 1 degree of roll but at 1.1 degrees of roll it goes snap loose. Data acquisition helps a great deal when looking for this type of problem.

A very quick change in chassis performance is usually either the result of inappropriate driver input or suspension bind. Unfortunately, small amounts of suspension binding are many times more difficult to locate than when the suspension completely stops moving. Suspension binding can have you chasing your tail for a good long time so time spent in the shop making sure you have more than adequate axial motion pays big dividends at the track. One other problem is that smaller amounts of suspension bind can often have a similar effect to running the wrong spring, bar and damper rate combinations and/or the wrong kinematic co-ordinates. It can become very confusing. God, I love racing.

Kinematic Chassis Motion in Roll About a Live Axle - Though illustrated here to help simplify a concept, a chassis **seldom** pivots about only **one** axle or frame track bar mount; however, it is possible. Examples in this section are at 5 degrees of roll.

During a left turn, if the chassis **only** rolls about the track bar **frame mount**, the right side of the chassis would move down a comparatively small amount while the left side would move up a much larger amount as it rotates about the track bar frame's rotation/pivot point - Figure 8-11. If the chassis only rolls about the track bar frame mount, neither the frame nor axle track bar mounts would move vertically. The track bar angle would remain constant.

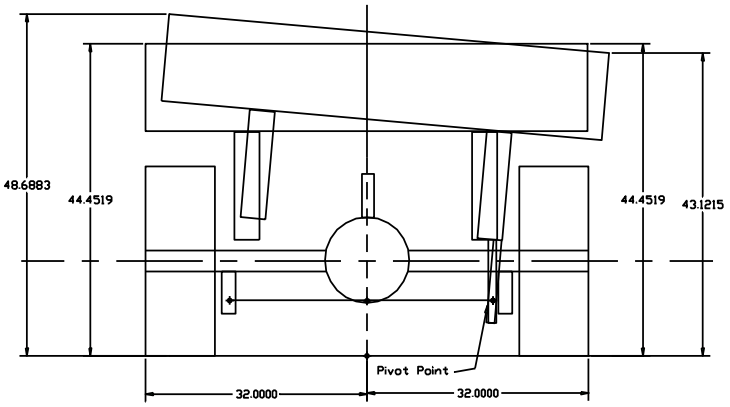


Figure 8-11

During a left turn, if the chassis **only** rolls about the track bar **axle mount**, the right side would move down proportionally more than the left side would move up - Figure 8-12. If the chassis only rolls about the track bar axle mount, the frame mounted pivot point would move down and the track bar angle would change proportionally.

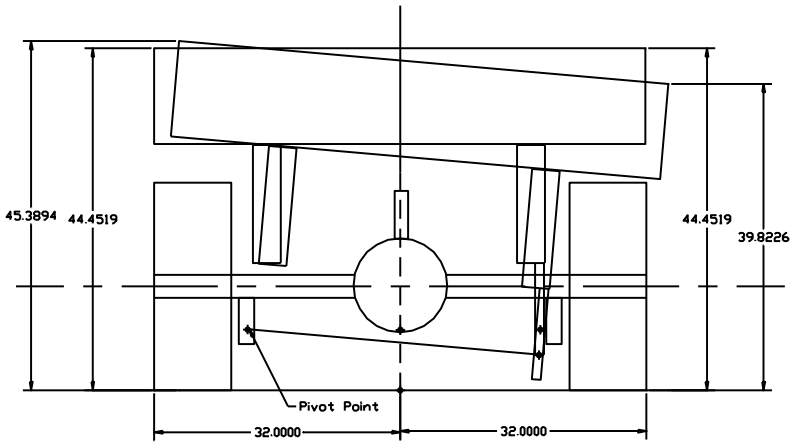


Figure 8-12

The **horizontal pivot point** for a chassis rolling about a live axle is most often somewhere between the two track bar mounting points. This is the result of the chassis pivoting about the track bar frame mount and the track bar pivoting about the axle mount. If, during a left turn, the track bar's angle is changed relative to the ground, the chassis will have pivoted about the axle mount. If during left turn roll the chassis right side moves down a different amount than the left side moves up, the chassis will have pivoted about the track bar frame mount. Roll is almost always a combination of these two motions and pivots.

Kinematic geometry programs such as WinGeo3 often use a point where the track/panhard bar passes through the horizontal center line of the live axle as a reference point to calculate the kinematic roll center. **This may not be the Datum or actual roll center**.

If the chassis rolls/pivots about a point at the vertical and horizontal centerline of the axle, the right and left sides of the chassis will move up and down a proportional amount. However, if the pivot point/ kinematic roll center is at the center line of the track bar, as shown in Figure 8-13, the left and right side vertical motion will not be equal because, as the track bar moves down, the roll center co-ordinates will also change i.e. instant pivot point.

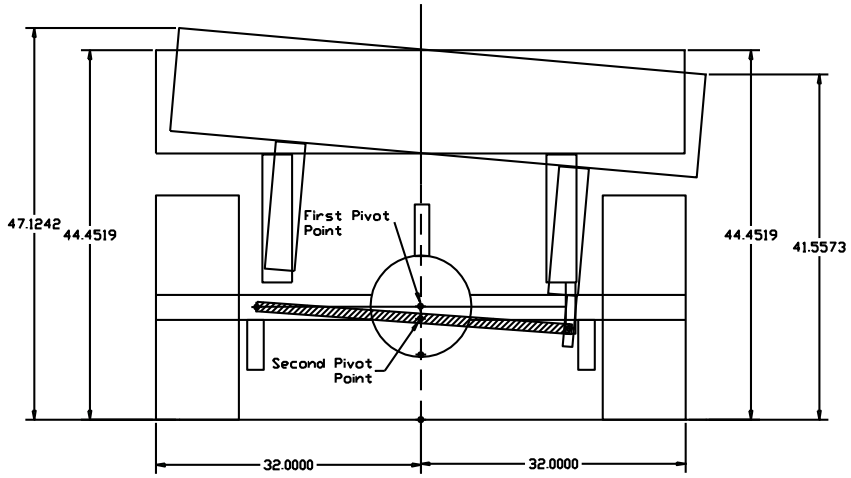


Figure 8-13

Using the center point of the track bar to illustrate a pivot point, it is easy to see how the repositioning of the track/panhard bar up or down affects the amount of vertical motion at the right and left sides of the chassis. Figure 8-14 shows the chassis pivoting about the center of the track bar at a point several inches below the differential housing. The chassis is rolled at 5 degrees. The distance from just outside the right frame rail to the top of the axle housing is now 15.3043" while the distance from outside of the left frame rail to the top of the axle housing is 18.4759". The right side of the frame has moved down to 41.6681" and the left side has moved up to 47.2375".

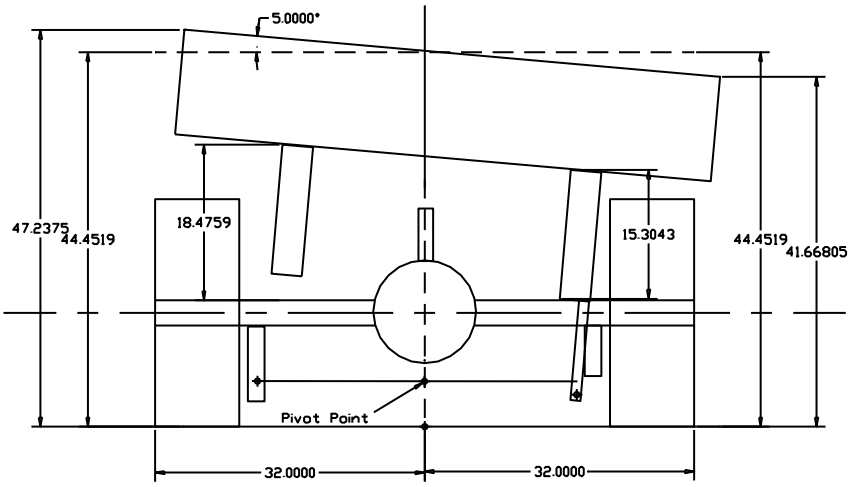


Figure 8-14

Figure 8-15 shows the chassis pivoting about the center of the track bar at the vertical center of the differential housing. The chassis is rolled at 5 degrees. The distance from just outside the right frame rail to the top of the axle housing is now 15.1968" while the distance from outside of the left frame rail to the top of the axle housing is 18.5067". The right side of the frame has moved down to 41.5645" and the left side has moved up to 47.1313".

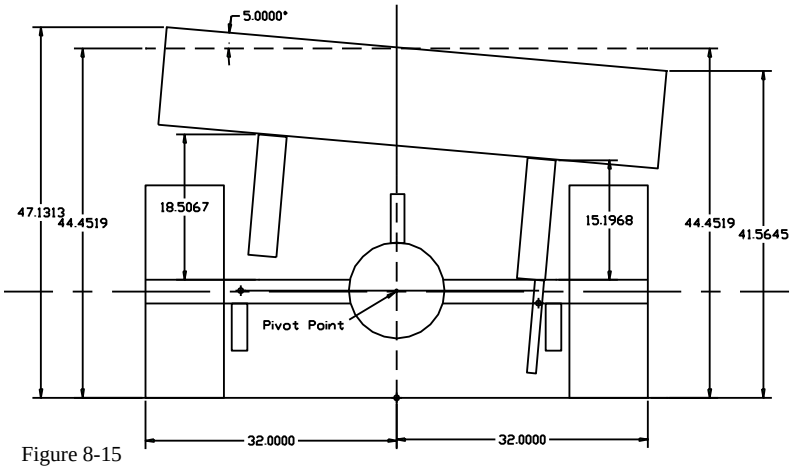


Figure 8-15

The previous two examples show a number of kinematic differences as the result of raising or lowering the track bar but they are quite subtle. As will be discussed shortly, this is not the primary **kinematic** reason for moving the track/panhard bar up or down. It, instead, has more to do with scrub motion and moment arm length from the roll center to the center of mass. Notice that in the previous two examples, the track bar was not shown as moving with the track bar frame mount. If it had followed the change in frame mount pivot point co-ordinates, as it would have, the instant roll center would have been lowered, thereby, once again, changing the calculation. As we will discover shortly, changing the track bar angle would also result in the axle and/or chassis being scrubbed i.e. horizontally repositioned.

Note: Remember this section of the book is primarily dealing with **kinematic motion** only. The dynamics section of the book deals with the suspension **jacking** and **anti forces**.

During actual dynamic movement, virtually all chassis motion is the result of different amounts of left and right wheel bump and offset roll. As a result, the kinematic roll center is seldom positioned precisely at the horizontal center line of the axle. Unlike an independent suspension system, locating the rear view kinematic roll center and left and right instant centers for a live axle suspension system is extremely difficult. Understanding the track bar pivot points is paramount to understanding live axle kinematics, and, hence, the importance of playing with small models.

Combined Chassis and Axle Motion - Once again, experimenting with a free body type of model can greatly simplify the understanding of how a chassis moves about a live axle and how a live axle moves about a chassis. Virtually all on track movement is a combination of axle and chassis motion. Though experimenting with full size race cars and good three dimensional computer programs are also extremely important and necessary, a model that the race engineer can hold in his/her hands adds a dimension of understanding that the previous two cannot. The model shown in Figure 8-16 takes only minutes to build, doesn't look very sophisticated (it isn't), but is totally indispensable. The engineer can move the chassis about the axle, move the axle about the chassis or do a combination of both. A model of this type **never** fails to teach even the most seasoned race engineer.

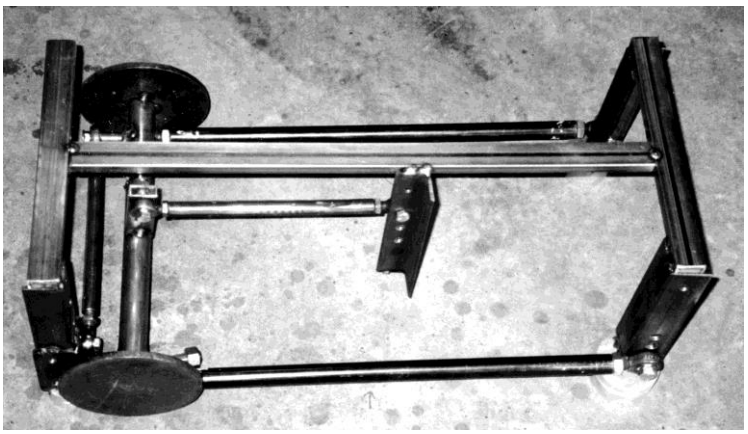


Figure 8-16

Datum Live Axle Roll Center - As in the case of an independent suspension system, the actual instant roll center is the result of kinematics, jacking forces and spring, bar and damper wheel rates. This instant roll center is referred to as the live axle datum roll center.

Remember:

- Kinematic pivot points and jacking points must be combined with the various rear spring, bar and damper wheel rates in order to locate the actual dynamic point of rotation
- Front kinematics, jacking forces and spring, bar and damper wheel rates also affect the rear datum roll center, even if the chassis is torsionally weak
- Conversely, rear kinematics, jacking forces and spring, anti roll bar and damper wheel rates can also affect the front datum roll center
- Never forget that all roll centers are only instant centers during dynamic conditions

- It is always important that the front and rear kinematics, jacking forces and springing forces work in consort with each other. One end of the car never works independently of the other end.

- Opposing dynamic forces are just as real as kinematic binding forces but they are often more difficult to isolate.

Track Bar Scrub Kinematics - Because the track bar laterally locates the rear end to the chassis, the length, mounting point and angle of the track bar will influence resultant bump and roll scrub. Remember the effects of bump and roll often have different scrub kinematics just as in the case of an independent suspension system. As in the case of an independent suspension system, scrub can be seen as wheel motion or chassis motion. Unlike an independent suspension system, when using a live axle, the left and right wheels are not laterally independent one from the other. When one wheel scrubs, they both scrub.

The static track bar angle influences the amount and direction of scrub seen during dynamic iterations - (all examples are left turn if not otherwise stated). If the track bar is set statically parallel with the ground, then, as the chassis rolls down to the right, the horizontal distance between the bar ends is reduced, but, because the length of the track bar does not change, either the tires will be laterally moved to the right or the frame laterally moved to the left, or, in most cases, some combination of the two - Figures 8-17 & 8-18. As can be seen, moving the bar's static position up or down does not change this relationship.

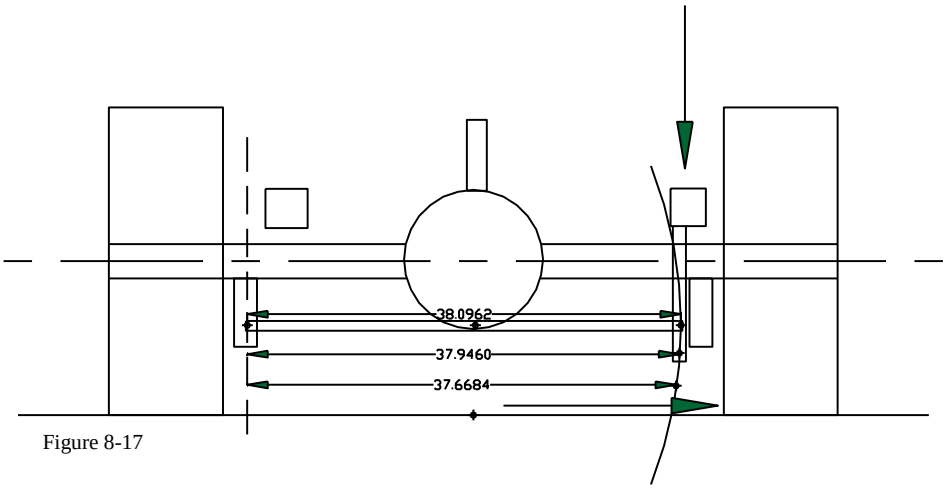


Figure 8-17

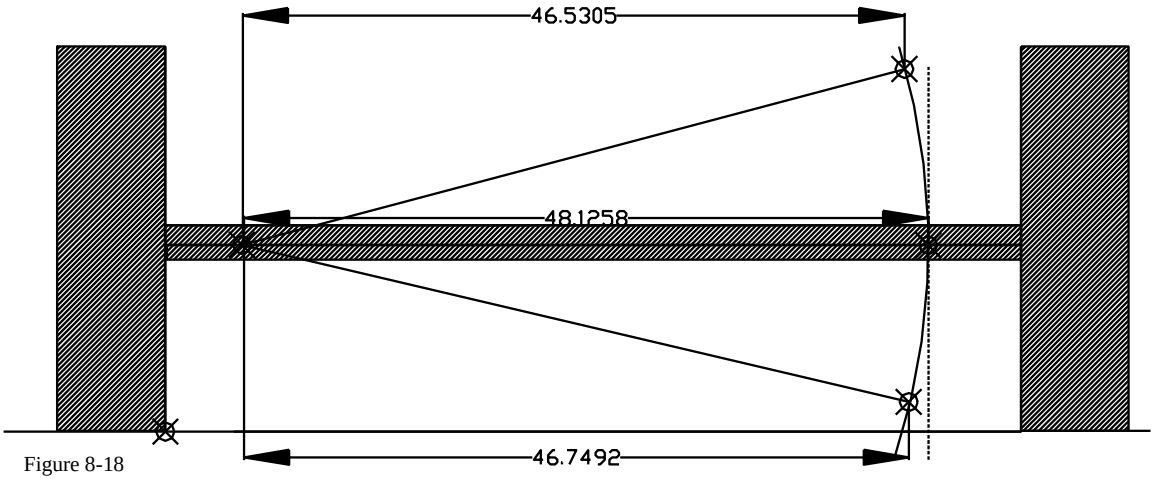


Figure 8-18

Shortening the track bar will exaggerate the arc length changes for the same amount of roll. A model such as shown in Figure 8-19 illustrates this quite graphically.

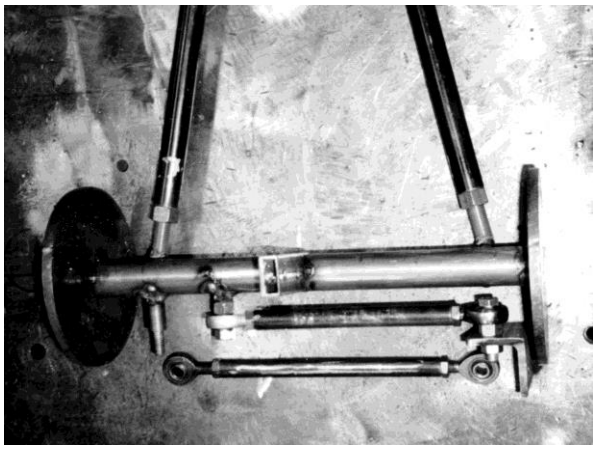


Figure 8-19

Scrub as the Result of Roll - Figures 8-20 & 8-21 illustrate axle lateral motion as the result of chassis roll. In the following examples, as the chassis moves down in roll, it follows a straight line vertical path (frame line of motion). What this means is that as the track bar arc lengthens or shortens the horizontal distance between the track bar mounting points, the axle will be forced to move laterally i.e. scrubbed. As stated previously, this is seldom, if ever, the case, but, in fact, scrub or lateral motion is normally a combination of both axle and chassis motion. These examples are used to illustrate a point; they are not intended to exactly mirror actual on track kinematics. Figure 8-20 shows a track bar at its static setting. The axle mount is at the horizontal centerline of the axle. The bar is angled up at 11.1609 degrees. The distance between the vertical line representing the chassis motion (frame line of motion) and the right side wheel is 6.7091".

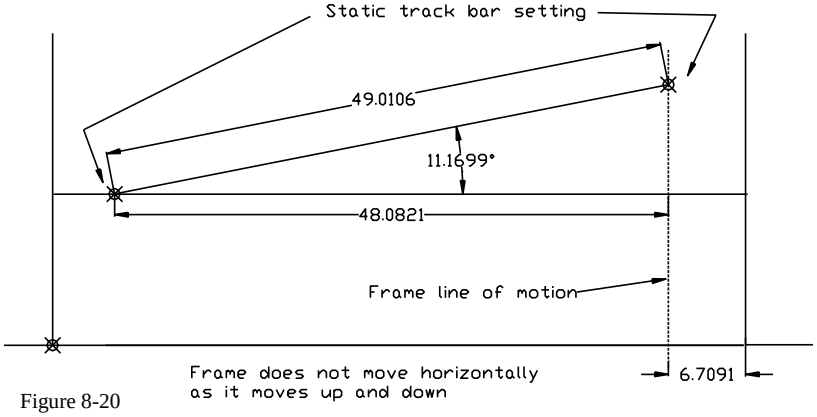


Figure 8-20

Figure 8-21 illustrates the same set up as in Figure 8-20 but the chassis has rolled down so the track bar angle is now only 2.49 degrees. Notice that because the track bar length has not changed, it results in the axle being laterally shifted to the left because the horizontal distance between the track bar mounting points has increased as the frame mounted end of the bar moves closer to the center of the arc. The distance between the frame line of motion and the right wheel has been reduced to 6.5105".

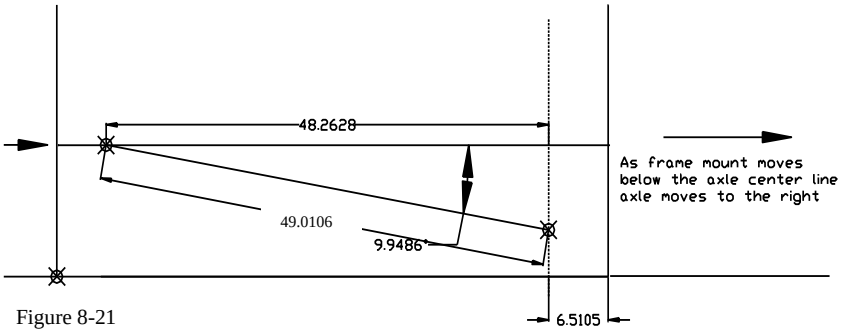


Figure 8-21

Figure 8-22 shows various axle and frame mounting points on our live axle model.

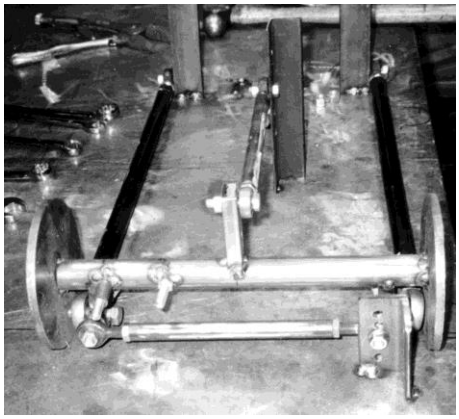


Figure 8-22

Scrub as the Result of One Wheel Bump - Figure 8-23 shows a basic live axle. For this set of examples we will assume that the tires are constructed from a hard, inflexible material and that the rotation point is at the bottom outside of the tire. The letter A represents the track bar axle mount while letter C represents the track bar frame mount. The track bar length is 26.31". This single plane example assumes that the upper and lower control arms are of appropriate length, parallel with the ground and each other and that all rod ends have sufficient axle rotation. These aforementioned conditions reduce the amount of roll and bump steer, which, to a lesser degree, can also affect scrub.

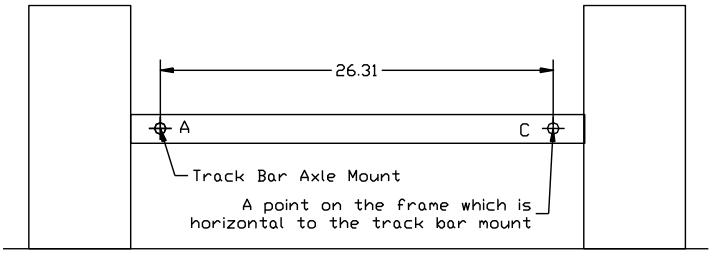


Figure 8-23

Figure 8-24 shows the right wheel going over a bump. The letter A1 represents the track bar axle mount position after bump while A is the track bar axle mount before bump. Notice that the track bar axle mount moves up and to the left and that the horizontal distance between A1 and C is greater than between A and C. Therefore, if the track bar length is not changed, C will be scrubbed horizontally towards A1. The amount of scrub would decrease if C also moved vertically as the result of upward spring, bar and damper forces caused by the right wheel moving over the bump. This later motion is referred to as bump roll (to be discussed shortly) where the attitude of the chassis is changed as the result of spring, damper and /or bar forces and motion.

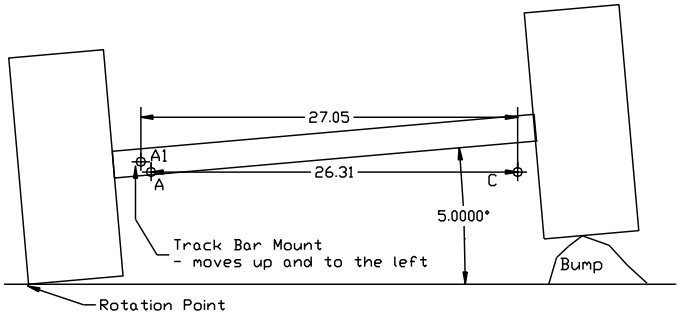


Figure 8-24

Figure 8-25 shows the same axle as in the previous example but the track bar is mounted lower.

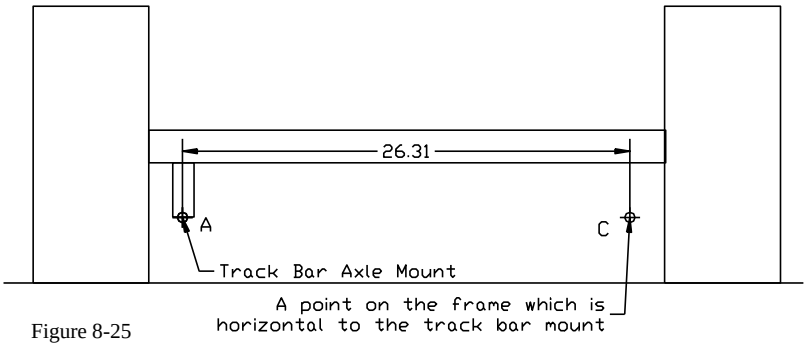


Figure 8-25

Figure 8-26 shows the right wheel moving over the same bump as in the previous example, but, because of the lower A and C track bar mounting points, the resultant axle mount A1 moves horizontally less than when the axle mount was higher. Remember, A is the axle mount position before right wheel bump and A1 is the changed track bar axle mount position after right wheel bump. Lowering the track bar mounts, all other things being equal, reduces the amount of scrub.

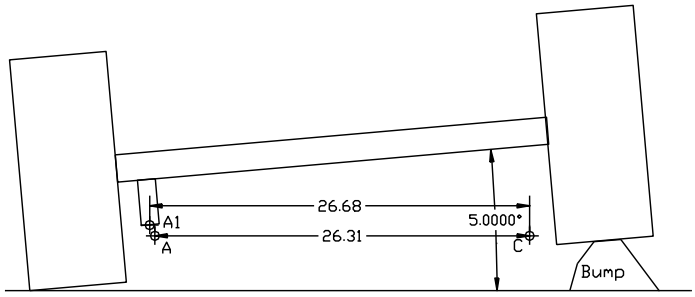


Figure 8-26

The reason that lowering the track bar mounting position results in less scrub is simply a matter of geometry as seen in Figures 8-27 & 8-28. Figure 8-27 shows two axle track bar mounting positions before right wheel bump. It can be seen in Figure 8-28 that for the same amount of right wheel bump, the higher mount moves laterally 1.48” and vertically 0.49" while the lower mount moves laterally 0.22" and vertically 0.59". The higher mounting point moves laterally considerably more than the lower mount while the lower mounting point moves vertically slightly more than the upper mount. Of course, if the springs were infinitely stiff in the previous examples, there would be no scrub at all because the chassis would have moved in consort with the axle.

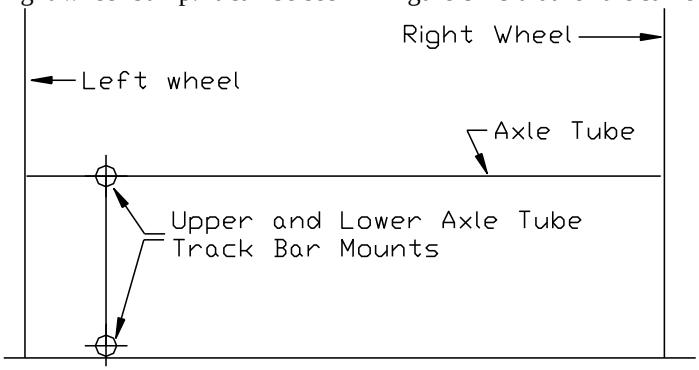


Figure 8-27

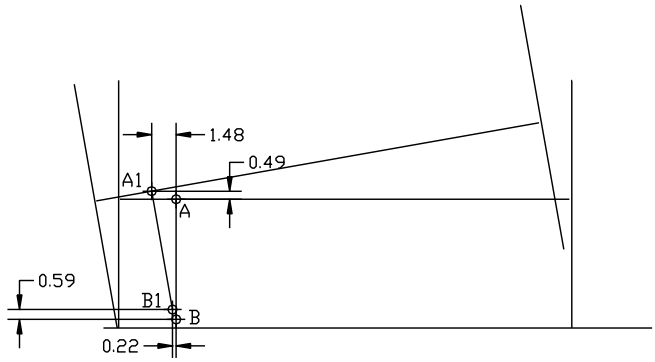


Figure 8-28

Scrub Due to Track Bar Geometry - The amount and direction of resultant live axle scrub is the combined result of track bar geometry/kinematics, suspension motion and chassis motion.

Track Bar Geometry/Kinematic Factors:

- Length of track bar
- Static angle of track bar
- Horizontal positioning of track bar

Track Bar Mounting Systems - Figure 8-29 shows the track bar axle mount of a NASCAR® Cup Car. Figures 8-30 & 8-31 illustrate adjustable track bar frame mounts.

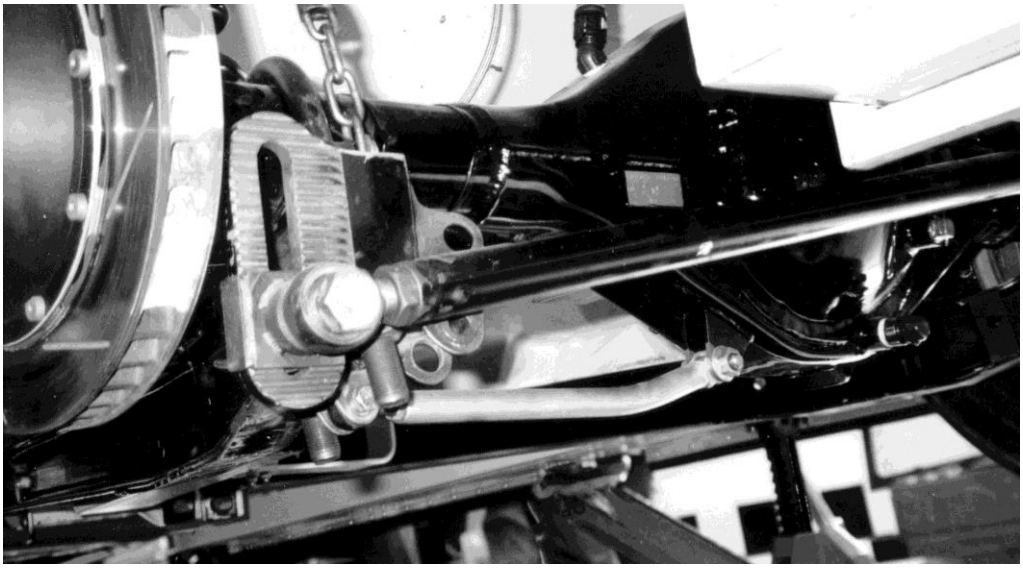


Figure 8-29



Figure 8-30

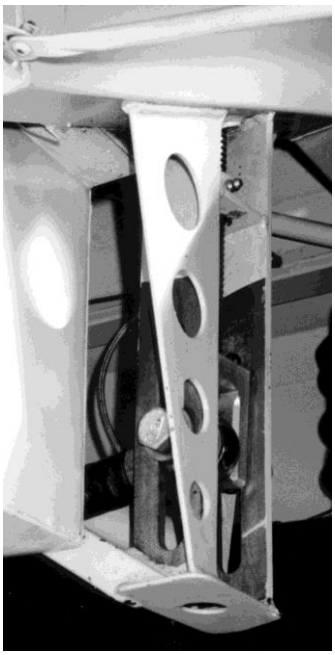


Figure 8-31

Figure 8-32 shows a gear motor which can be used by the driver to adjust the track bar frame mounting position (only where legal of course). Figure 8-33 illustrates a Howe adjustable track bar frame mount.



Figure 8-32

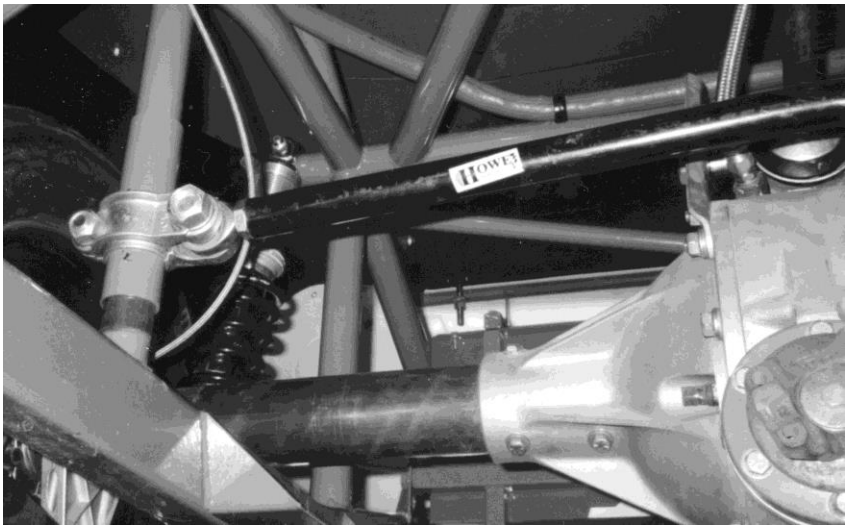


Figure 8-33

Live Axle Ride, Bump and Roll Kinematics:

Ride:

- Both wheels travel in the same direction and have the same amount of travel

One Wheel Bump/Droop:

- One wheel moves up or down
  - Axle pivots about the opposite wheel
  - Bumped wheel sees negative camber increase while the opposite or pivoted wheel sees positive camber increase
  - Normally results in a chassis attitude change (roll)

Two Wheel Bump:

- Outside and inside wheels travel different amounts
  - They can travel in either the same direction or in different directions

  The wheel with the greatest upward motion sees an increase in negative camber while the wheel with less upward motion sees an increase in positive camber
  - The axle pivots about the wheel with the least amount of motion - either negative or positive motion
  - Normally results in a chassis attitude change (roll)

Pure Roll:

- Outside frame moves down the same amount as the inside frame moves up - this is theoretically possible but seldom, if ever, happens during dynamic conditions

    - Chassis/frame pivots about the horizontal centerline of the axle

Offset Roll:

- The outside and inside of the frame move different amounts

    - Both sides can move in the same or opposite directions

    - The chassis/frame pivot point is not at the horizontal centerline of the axle

Roll Forces - The primary differences between overturning roll and bump roll are in how the forces are reacted i.e. overturning roll is the result of an overturning moment while bump roll is the result of spring compression or extension and/or springing forces.

It is no doubt already painfully obvious to the reader that live axle kinematics is not particularly straightforward. For example:

- Pure right wheel bump has its track bar pivot point about the axle mount

- Offset right side chassis roll has its track bar pivot point about the frame mount

- Right rear bump affects scrub more than left rear bump when the track bar is angled down towards the frame side.

- If the lower control arms are angled in towards each other, body roll will have less effect on axle housing motion

The fact that bump and roll may have different force effects doesn't particularly make comprehending all of this that much easier.

The tables beginning on page 21 illustrate resultant changes in scrub for a typical three link live axle suspension system due to motion iterations and static track bar settings. Remember that changing the track bar mounting points also affects the amount of jacking forces and contributes to the overall datum roll center to CG moment arm length.

When I am studying any one suspension system, I normally run tests that look at 10 different effects, scrub, steer, etc., in combination with 100 suspension motion iterations including ride, roll, bump and pitch. Including pitch within your motion study is very important. Remember the chassis has two ends - the front and rear. Unless the chassis has little torsional rigidity, one end affects the kinematics, loads and forces at the other end.

Watts Link Lateral Control - The Watt's Link is a somewhat more complex device used for controlling lateral movement between the chassis and live axle. The main advantage is that, it, in theory, does not allow any lateral movement of the rear end Figure 8-34. I used the term, "in theory," because I have often seen the pivot arm and/or links designed too short for the amount and type of wheel and chassis motion generated by both stock cars and GT chassis. Once the pivot arm runs out of motion and binds, the Watts link becomes a really ugly track bar. This can happen, for example, on turn in when soft front springs and comparatively stiff rear springs are used which result in the chassis pivoting about the rear outside corner i.e. the outside rear corner remains fairly level, the outside front corner drops dramatically and the inside rear corner lifts even more dramatically. Watts link bind can also happen under heavy braking resulting in live axle hop. Figure 8-35 shows an old TransAm Watts link that did not work well for a number of reasons including pivot mount flex and pivot bind. On the other hand, if designed and used properly, the Watts link is an indispensable live axle road course lateral locating suspension link.

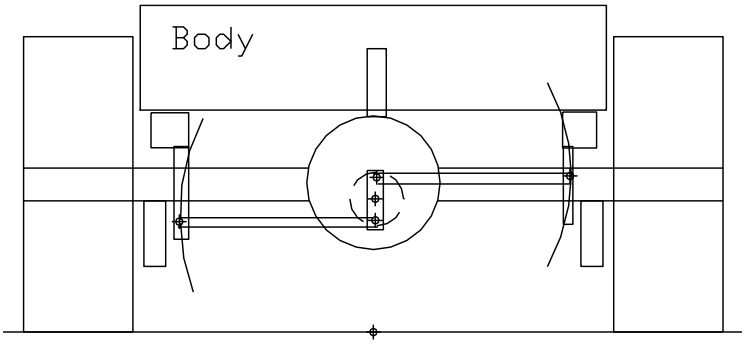


Figure 8-34


Figure 8-35

For a stock car, because the Watts link pivot point is also the kinematic pivot point, it makes changing the roll center height more difficult. It also makes offsetting the lateral portion of the roll center extremely difficult. For these reasons, it is normally only used for road racing. If a mounting bracket is affixed to the rear of a Ford 9" rear end housing, great care needs to be taken to make sure the bracket is strong enough and that it does not flex. There are some serious kinematic considerations that need to be addressed if the linking arms are not close to level within the suspensions mean working range and/or if the arms do not move in parallel motion with each other. Placing track bar types of adjusters at both outer link mounts does allow for a slight change in roll center height but the kinematic consequences often out weigh the change in roll center height. The outer link mounting positions should only be adjusted to realign the links after a ride height change. As a general rule, once the Watts link pivot and links have been properly aligned for ride height, they should not be used for changing loose/tight chassis performance.

The use of a Watts link in lighter GT types of live axle cars is indispensable. In this case, the Watts link is normally mounted under the rear end housing to get the kinematic pivot points and center of gravity as low as possible - Figure 8-36. Figures 8-37 & 8-38 show two road course Watts link systems that worked extremely well. As in the case of the Watts link stock car suspension, this type of system is not used to change the front to rear performance characteristics at the track. Changing the characteristics of a Watts link involves a whole new design. Figure 8-39 illustrates two outside Watts link adjusters used on a traditional rear mounted system.

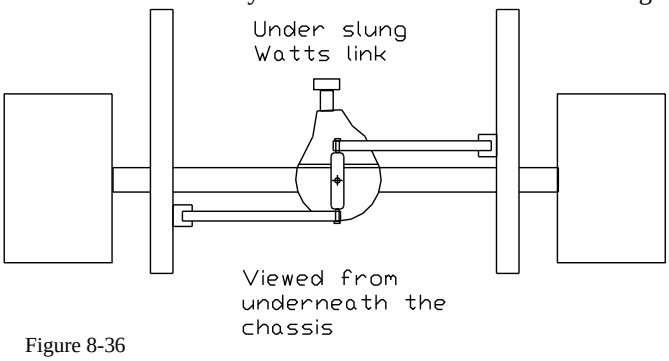


Figure 8-36

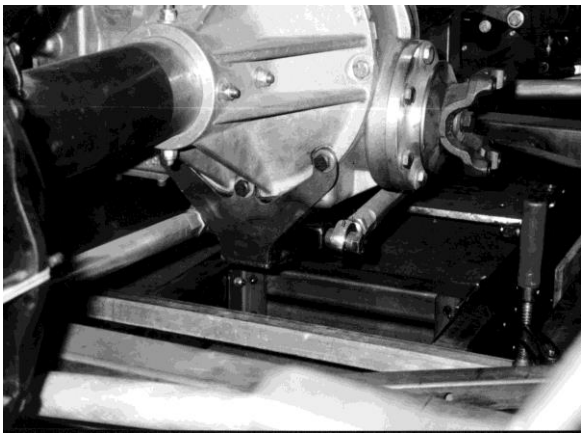


Figure 8-37

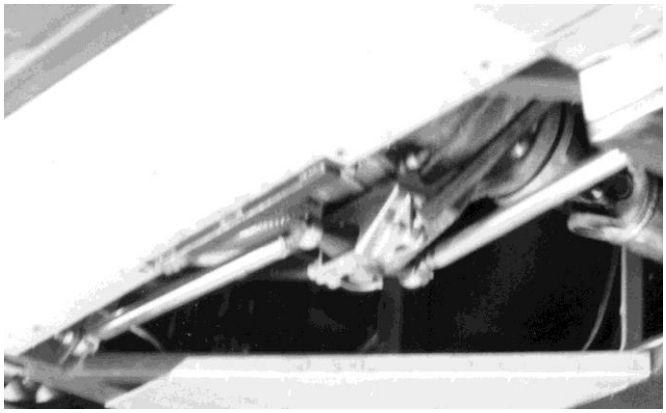


Figure 8-38

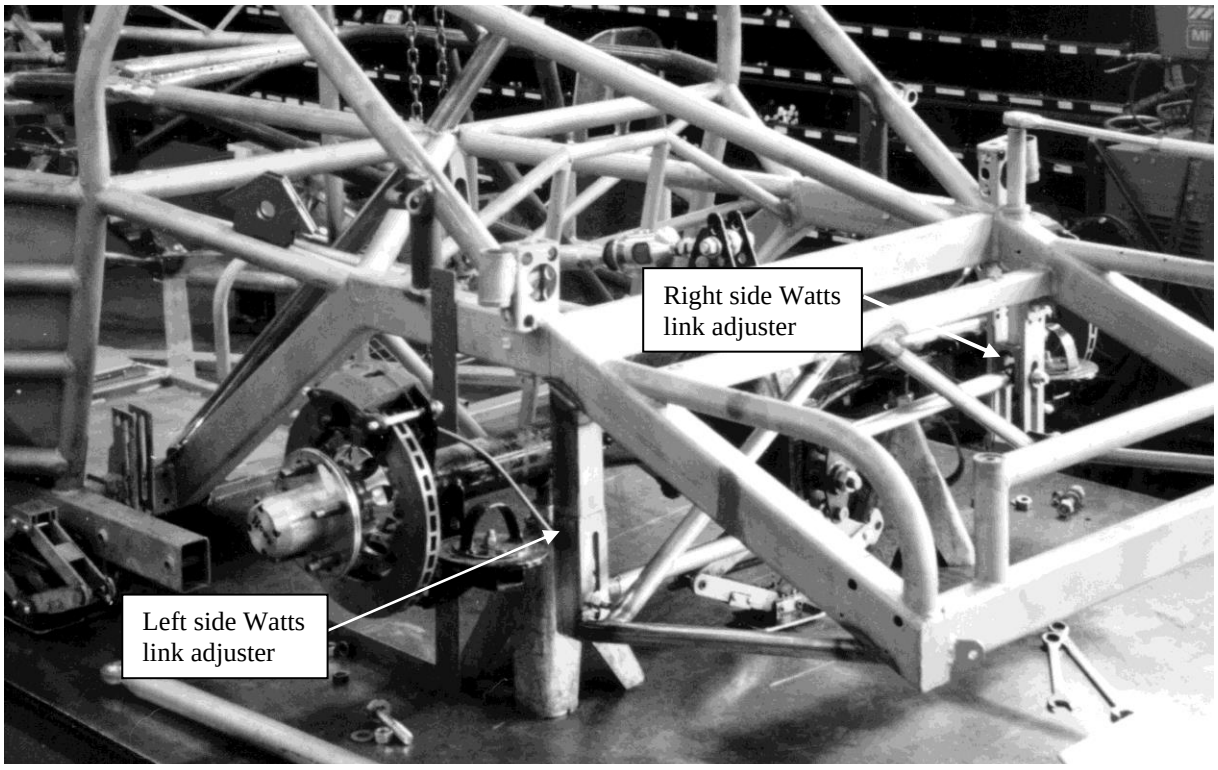


Figure 8-39

Rear Live Axle Roll and Bump Steer - Roll and bump steer are a result of the rear axle steering the car. This happens primarily because the two lower control arms are following different arcs, which, in turn, offsets the axle from being perpendicular with the longitudinal center line of the chassis. If the right tire moves forward in relation to the left tire, the car will understeer - Figure 8-40. If the right side tire moves back in relation to the left tire during body roll or bump, the car will oversteer - Figure 8-40. If both sides follow equal arcs, the car will have neutral rear steer, all other things being equal. A model, as shown in Figures 8-41 & 8-43, helps clarify any confusion about which way a car steers with left or right side offset.

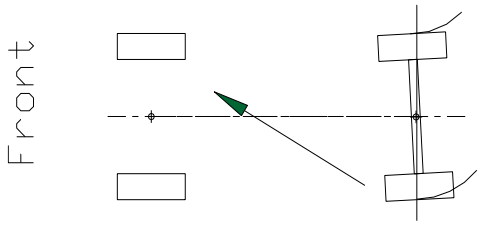


Figure 8-40

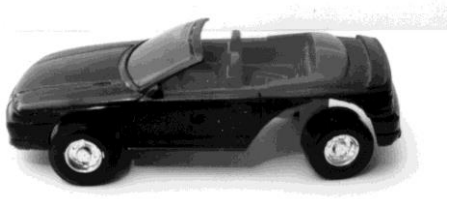


Figure 8-41

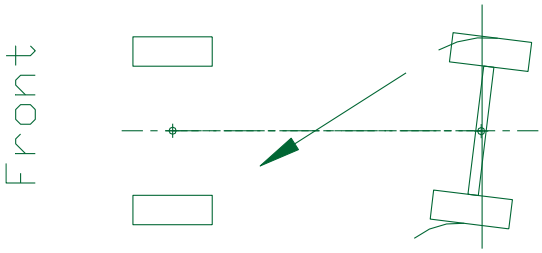


Figure 8-42

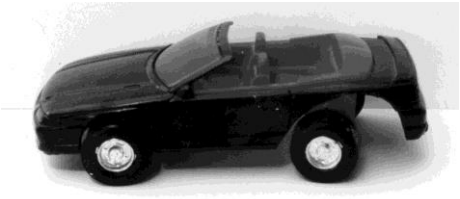


Figure 8-43

SOMETHING TO THINK ABOUT

> **"**Roll understeer should be avoided. It is difficult to balance the chassis with it present."[3]
>
> "The preferred design characteristics are very little roll steer, and if there is any, it should be in the understeer direction."[4]

Can both of the above quotes possibly be right? The short answer is no - - well, not likely. Though it is theoretically possible that a team would need to design a small amount of oversteer into the rear axle kinematics, certainly the preponderance of rear steer kinematic settings are towards a small amount of understeer if anything at all. Rear live axle understeer is used to help reduce power on oversteer. Any rear live axle steer settings should be used in considerable moderation. Most rear steer kinematics are the result of the team not knowing that it exists at all. This often leads to considerable handling problems that the team has no idea it has caused when trying to achieve some unrelated effect such as anti squat. This is a major problem.

[3] Steve Smith. Paved Track Stock Car Technology. USA; Steve Smith Autosports, 1997. pg. 53

[4] Herb Adams. Chassis Engineering. USA: HP Books, 1993. pg.63

The following (single plane) kinematic examples are used to show the basics of live axle steer as the result of lower control arm motion - all examples are for either a change in ride or left turn rightward roll. Ride has both wheels moving the same amount in the same direction. Roll is pure roll where the right side moves down the same amount as the left side moves up. All track bar effects are ignored.

- Both lower control arms parallel to the plane of the chassis at set up height - Figure 8-44. No change in steer angle will result from a kinematic change in ride (squat/anti squat) or pure roll. As the frame mounts of the lower control arms move up/down during ride or pure roll, the wheel base length will change.

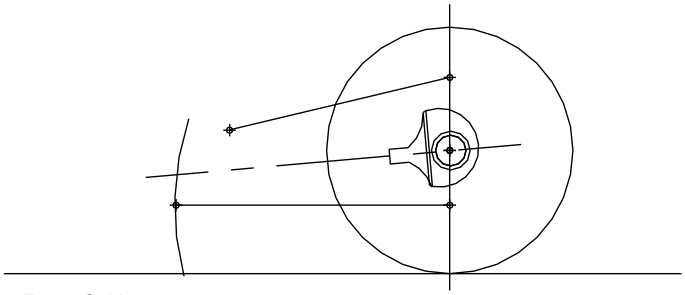


Figure 8-44

- Right lower control arm angled up at set up height - Figure 8-45. **Ride** - if wheels move up (chassis down) the right side lower control arm arc will lengthen while the left side arc shortens. The axle will be offset to the right, and, as a result, the car will oversteer. If the wheels move down in ride (chassis up), the right side arc will shorten more than the left side. The axle will be offset to the left, and, as a result, the car will understeer. **Roll** - as the body rolls to the right (left turn), the right side lower control arm arc will lengthen while the left side arc shortens. The axle will be offset to the right, and, as a result, the car will oversteer.

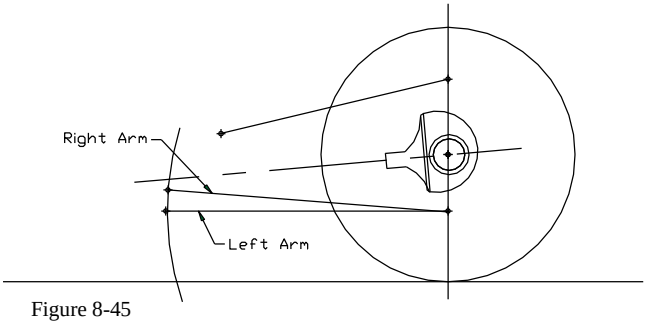


Figure 8-45

- Both arms angled up at set up height - Figure 8-46. **Ride** - if wheels move up (chassis down) or down (chassis up), the wheelbase will shorten but there will be no resultant steer effect. **Roll** - as the body rolls to the right (left turn), the right side control arm arc will lengthen while the left side arc will shorten more than in the previous example. The axle will be steered to the right a greater amount, and, as a result, the car will have an increased oversteer condition.

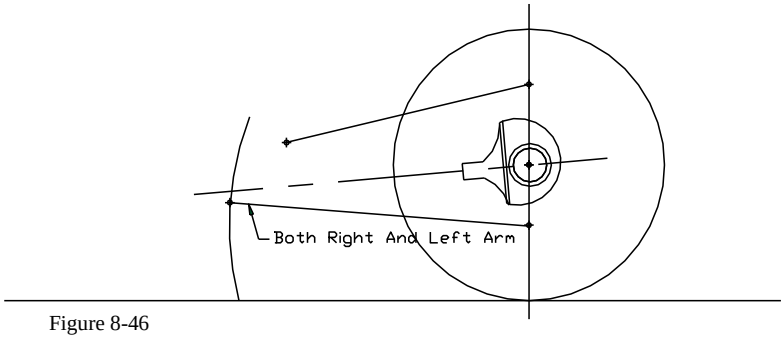


Figure 8-46

- Left arm angled down at set up height - Figure 8-47. **Ride** - if wheels move up (chassis down), the right side lower control arm arc will shorten while the left side arc will shorten even more. The axle will be steered to the right, and, as a result, the car will oversteer. If the wheels move down in ride (chassis up), the right side arc will shorten while the left side arc length will increase. The axle will be steered to the left, and, as a result, the car will understeer. **Roll** - as the body rolls to the right (left turn), the right side lower control arm arc will shorten while the left side arc lengthens. The axle will be steered to the left, and, as a result, the car will understeer.

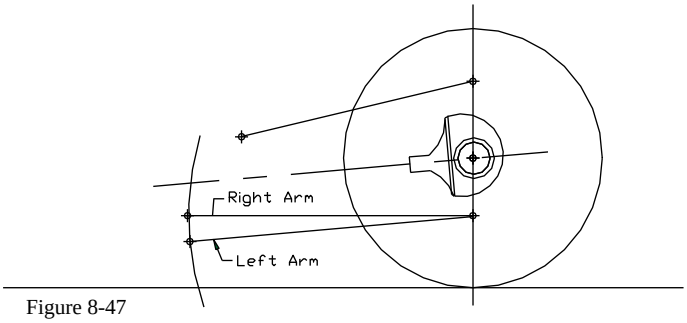


Figure 8-47

- Both arms angled down - Figure 8-48. **Ride** - if wheels move up (chassis down) or down (chassis up), the wheel base will shorten but there will be no resultant steer effect. **Roll** - as the body rolls to the right (left turn), the right side control arm arc will shorten while the left side arc will lengthen. The axle will be offset to the left, and, as a result, the car will understeer.

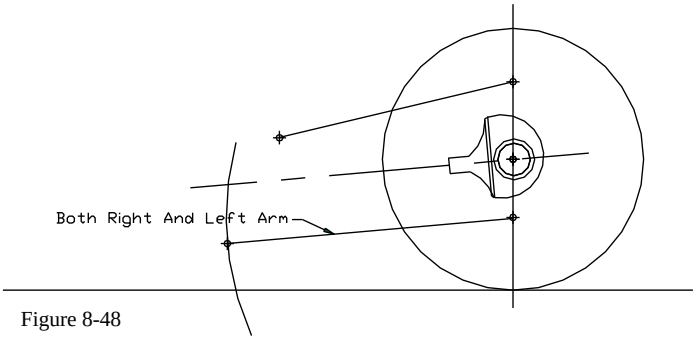


Figure 8-48

Spring Loaded Control Arms - An alternative to skewing the axle in the static state or through suspension kinematics in the dynamic state is the use of a spring loaded control arm. For example, if the car has power oversteer, the use of a compressible control arm on the right side will, under acceleration, compress the arm, thereby skewing the axle into understeer geometry. When the wheel torque is removed, the arm will spring back to its original length. This sort of thing is, more often than not, simply a crutch for a chassis or set up problem unless used in very subtle amounts.

Pinion Angle Change – For convenience pinion angle is normally measured as the angular difference between a line drawn through the pinion and a line drawn parallel with the ground from the center of the universal joint - Figures 8-49 & 8-50. However, as discussed later in this chapter, what we are primarily concerned about is the angle between the pinion and the drive shaft. Negative pinion angle has the line drawn from the pinion pointed down towards the ground. The amount of pinion angle change is determined by the rear suspension kinematics and torque. If the pinion angle runs at too much of a positive angle relative to the **drive shaft**, there is a possibility that the drive shaft yokes will bind; therefore, the static pinion angle is normally set at a negative angle. The amount of force needed to torque the rear housing x degrees is dependent on the suspension kinematics. Racers tend to think pinion angle always moves up during acceleration but this is quite often not the case. Pinion angle motion is dependent on suspension kinematics, torque at the axle and the tire's coefficient of friction.

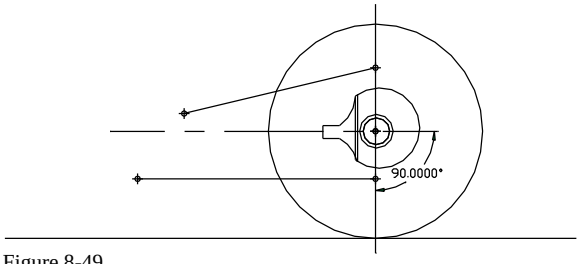


Figure 8-49

0 Degree Pinion Angle

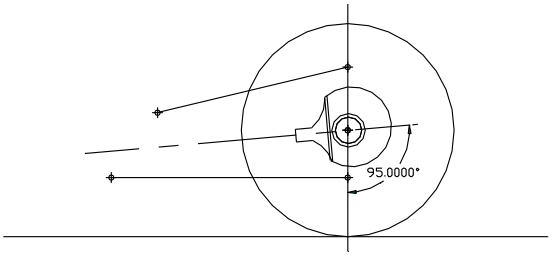


Figure 8-50

5 Degrees Pinion Angle

Table 8-1 illustrates a number of bump iterations and the related changes in pinion angle. Table 8-2 uses the same bump iterations but with a variety of lower control arm settings.

Table 8-1

Live Axle Three Link Suspension											
Y Rotation Point = 10.00			Z Rotation Point = 1.00			Y Rotation Point = 10.00			Z Rotation Point = 1.00		
Left wheel	Right wheel	Roll	L Lower Fr/Ax	R Lower Fr/Ax	Pinion change	Left wheel	Right wheel	Roll	L Lower Fr/Ax	R Lower Fr/Ax	Pinion change
-1.0	-1.0	0.0	10/10	10/10	-0.982	-1.0	-1.0	0.0	8/10	14/10	-1.172
-2.0	-2.0	0.0	10/10	10/10	-2.020	-2.0	-2.0	0.0	8/10	14/10	-2.398
1.0	1.0	0.0	10/10	10/10	0.929	1.0	1.0	0.0	8/10	14/10	1.121
2.0	2.0	0.0	10/10	10/10	1.808	2.0	2.0	0.0	8/10	14/10	2.195
1.0	-1.0	1.8	10/10	10/10	0.048	1.0	-1.0	1.8	8/10	14/10	-0.396
1.0	-2.0	2.8	10/10	10/10	-0.377	1.0	-2.0	2.8	8/10	14/10	-1.137
2.0	-0.5	2.3	10/10	10/10	0.778	2.0	-0.5	2.3	8/10	14/10	0.363

Cambered Live Axle Rear End Housings - If the sanctioning body does not allow purpose designed cambered axle snouts, hubs and drive plates, the rear housing can be heated and bent to get between 0.5 and 1.0 degrees of negative camber on the right side and 0.5 to 1.0 degrees positive on the left side - Figure 8-51.

Note: There is always the very real danger of bending the axle housing too much, causing the axle to have an undue amount of stress to the point that it will shear. Cambering the rear housing definitely helps on track performance. However, if great care isn't taken, there are often more negatives resulting from this procedure than positives. Using a crowned axle will help reduce bind between the axle splines and the drive flange, but it is still pretty dicey. If allowed, always use a purpose designed cambered axle snout, hub and drive plate.

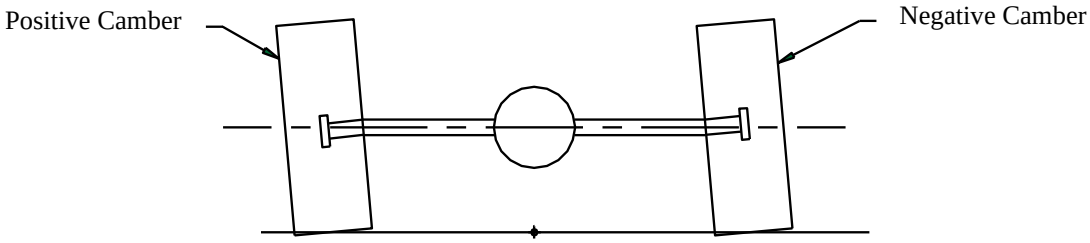


Figure 8-51

Teams also bend both ends of the housing forward to create a small amount of toe in, or, if it were allowed, use the previously mentioned offset axle snouts, hubs and drive plates to achieve housing toe-in. This is done to prevent the housing from bending into a toe out condition under the weight of the chassis and during drive torque. Always make sure that both ends are toed the same amount. Asymmetric toe will result in a form of rear steer called hunting.

Bump Camber - One wheel bump will produce a small change in camber. The amount of change can be calculated by dividing the amount of bump travel by the track * tan θ - 2" of right rear bump divided by a 64" track equals a 1.8 degree change in camber at both wheels - - negative at the bumped wheel and positive at the pivoted wheel.

Stagger Camber - Running stagger will also provide a small amount of camber - Figure 8-52.

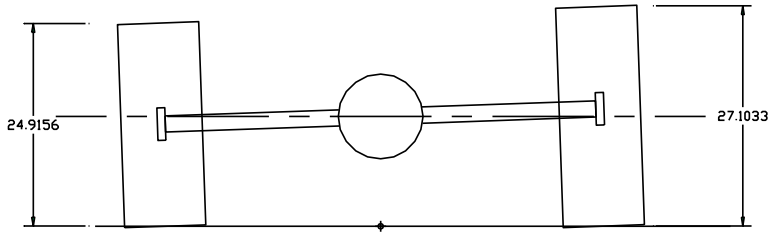


Figure 8-52

Toe Camber - Care needs to be taken when determining the range of dynamic pinion angle change in relation to the toe and camber settings. As the axle rotates, toe can produce a change in camber - toe becomes camber or conversely camber becomes toe. Figure 8-53 illustrates a top view of a live rear axle housing which has an exaggerated amount of rear toe in (3 degrees). If the axle was rotated down 90 degrees from this point rather than having toe in, it would now have 3 degrees of positive camber at each wheel - Figure 8-54. This, of course, is an extremely exaggerated example used only to illustrate a point. However, smaller changes between toe and camber over the pinion angle dynamic range are quite real and can result in a performance change - either negative or positive depending on the design. Designing and fabricating a cambered and toed rear live axle is far from simple - Book Two. The shorter the side view swing arm is, the more the axle will rotate during kinematic motion.

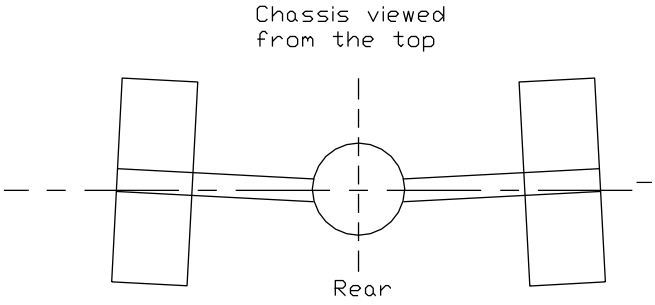


Figure 8-53

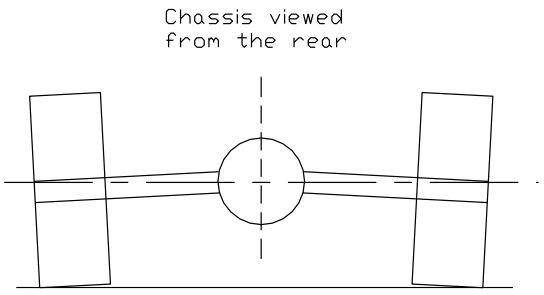


Figure 8-54

The following six tables offer a small glimpse into the type of research needed to understand three link live axle kinematics. You cannot fully develop any suspension system without the use of a highly accurate three dimensional software program such as WinGeo3.

Table 8-3 illustrates six different datum roll center positions:

- Position #1 (y = 0, z = 0) - at ground level and at the lateral center line of the chassis
- Position #2 (y = 20, z = 0) - at ground level and 20" to the left of the chassis lateral centerline
- Position #3 (y = -20, z = 0) - at ground level and 20" to the right of the chassis lateral centerline
- Position #4 (y = 0, z = 14) - 14" above ground level and at the lateral center line of the chassis
- Position #5 (y = 20, z = 14) - at 14" above ground level and 20" to the left of the chassis lateral centerline
- Position #6 (y = -20, z = 14) - at 14" above ground level and 20" to the right of the chassis lateral centerline

The chassis has 0.50" of left wheel droop (chassis up) and -1.00" of bump (chassis down) on the right side. The clearance point is measured at 30" from the axle centerline and 5" above ground. Y and Z change.

Notice that for the given amount of bump input:

- Ride = -0.250 upward motion of the axle and/or downward motion of the chassis
- Roll = 1.386 degrees to the right
- At y/z = 20/0 (third column), both the left and right side clearance is higher than y/z = 0/0 (first column) - more load is removed from the left spring and less load is added to the right spring - y change is 0.003" to the right while the x change is -0.349 less than at the y/z = 0/0 roll center - the CG will be raised and the overturning moment is increased
- At y/z = -20/0 (fourth column), both the left and right side clearance is less than y/z = 0/0 (first column) - 86.2 lb. of load is added to the left spring while 429.3 lb. of load is added to the right spring - y change is -0.003" to the left while the x change is 0.349 more than at the y/z = 0/0 roll center - the CG will be lowered and the overturning moment will decrease
- y/z = 0/0 sees a small amount of steer to the left - y/z = 20/0 sees a small amount of steer to the right while y/z = -20/0 sees a larger amount of steer to the left than y/z = 0/0 - steer is not affected by a change in roll center vertical height
- Scrub is 0.296 (axle right) at y/z =0/0 - changing the lateral position of the roll center has little effect on scrub
- Changing the roll center height dramatically changes scrub - scrub at y/z = 0/14 is -0.043 (axle left)
- Changing roll center height has little effect on loads seen at the springs

Table 8-3

Live Axle Three Link Suspension											
Bump L = 0.50			Ride = -0.250			L Base Clearance = 5.00					
Bump R = -1.00			Roll = 1.386			R Base Clearance = 5.00					
Y Rotation	Z Rotation	L Clear.	R Clear.	L spring	R Spring	Scrub	Steer	L Load	R Load	Y Change	Z Change
0.00	0.00	5.474	4.023	0.258	-0.802	0.296	0.012	-83.714	259.762	0.000	0.000
20.00	0.00	5.958	4.507	0.780	-0.279	0.299	-0.011	-251.839	90.353	0.003	-0.349
-20.00	0.00	4.990	3.539	-0.265	-1.324	0.301	0.034	86.191	429.347	-0.003	0.349
0.00	14.00	5.478	4.027	0.263	-0.797	-0.043	0.012	-85.146	258.326	0.224	0.002
20.00	14.00	5.962	4.511	0.784	-0.275	-0.040	-0.011	-253.256	88.920	0.247	-0.347
-20.00	14.00	4.995	3.543	-0.261	-1.320	-0.038	0.034	84.744	427.911	0.241	0.351

Table 8-4 shows pure chassis roll of 3 degrees. The datum roll center is10" to the right of the axle lateral center line and 1" above ground level - all subsequent tables have the same datum roll center. In this table, the lower control arm axle and frame vertical mounting positions are changed - (Fr = frame - Ax = axle). Clearance is in the same position as Table 8-1. The Y and Z change is the change from roll center at 0/0 (ground level at the axle centerline).

Notice that as shown in Table 8-4:

- Changing the lower control arm angles does not affect clearance if the chassis sees 3 degrees of roll
- Changing the lower control arm angles can dramatically affect both spring travel and spring load - spring travel and spring load are interconnected in all the table examples - if the spring compresses, the load will increase while if the spring extends, the spring load will decrease
- Column One and Four show a similar amount of scrub - also notice the small difference between Column Two and Four scrub
- All examples show rightward steer but at very different amounts

Table 8-4

Live Axle Three Link Suspension											
Bump L = 0.00		Ride = -0.00		L Base Clearance = 5.00			Y Rotation Point = 10.00				
Bump R = -0.00		Roll = 3		R Base Clearance = 5.00			Z Rotation Point = 1.00				
L Lower Fr/Ax	R Lower Fr/Ax	L Clear.	R Clear.	L spring	R Spring	Scrub	Steer	L Load	R Load	Y Change	Z Change
10/10	10/10	7.088	3.948	1.703	-0.588	0.586	-0.051	-548.254	190.361	-0.039	0.525
14/10	14/10	7.088	3.948	1.735	-1.552	0.651	-0.452	-593.993	189.566	-0.039	0.525
14/10	8/10	7.088	3.948	1.774	-0.516	0.621	-0.272	-579.649	169.718	-0.039	0.525
8/10	14/10	7.088	3.948	1.650	-0.642	0.585	-0.030	-540.571	210.692	-0.039	0.525

Table 8-5, as in Table 8-3, has its datum roll center at 10" to the right of center and 1" above ground. Left bump = 1.00" while right bump = 2.00". Table #5 also has the same lower control arm vertical changes as Table #4. As expected, we see no change in clearance when the control arm angles are changed.

Notice:

- The change in clearance, spring motion, spring load, scrub and steer from Table 8-4
- The Y and Z changes are almost a reverse of Table 8-4

Table 8-5

Live Axle Three Link Suspension											
Bump L = 1.00		Ride = -0.500		L Base Clearance = 5.00			Y Rotation Point = 10.00				
Bump R = -2.00		Roll = 2.773		R Base Clearance = 5.00			Z Rotation Point = 1.00				
L Lower	R Lower	L Clear.	R Clear.	L spring	R Spring	Scrub	Steer	L Load	R Load	Y Change	Z Change
Fr/Ax	Fr/Ax										
10/10	10/10	6.431	3.528	1.038	-1.083	0.544	0.003	-335.337	351.229	0.041	-0.348
14/10	14/10	6.431	3.528	1.033	-1.083	0.605	-0.367	-355.010	372.474	0.041	-0.348
14/10	8/10	6.431	3.528	1.095	-1.025	0.556	-0.082	-358.883	337.524	0.041	-0.348
8/10	14/10	6.431	3.528	0.978	-1.140	0.564	-0.097	-321.947	374.927	0.041	-0.348

Table 8-6 illustrates differences as the result of various ride and roll iterations and lower control arm calculations. As many of the changes are quite dramatic, the reader needs to spend a considerable amount of time thinking about the handling ramifications as a result of the various iteration combinations.

Table 8-6

Live Axle Three Link Suspension											
					L Base Clearance = 5.00			Y Rotation Point = 10.00			
		L Lower	R Lower		R Base Clearance = 5.00			Z Rotation Point = 1.00			
Ride	Roll	Fr/Ax	Fr/Ax	L Clear.	R Clear.	L spring	R Spring	Scrub	Steer	L Load	R Load
-2.00	0.00	10/10	10/10	3.000	3.000	-2.173	-2.157	0.069	0.000	713.020	696.531
-2.00	0.00	10/10	14/10	3.000	3.000	-2.243	-2.221	0.129	-0.318	759.899	738.476
-2.00	0.00	14/10	10/10	3.000	3.000	-2.238	-2.226	0.022	0.318	757.964	741.486
0.00	3.00	10/10	10/10	7.088	3.948	1.703	-0.588	0.586	-0.051	-548.254	190.361
0.00	3.00	10/10	14/10	7.088	3.948	1.677	-0.612	0.606	-0.170	-557.420	203.954
0.00	3.00	14/10	10/10	7.088	3.948	1.761	-0.528	0.631	-0.332	-584.567	176.357
-2.00	3.00	10/10	10/10	5.088	1.948	-0.459	-2.751	0.646	0.150	150.026	892.474
-2.00	3.00	10/10	14/10	5.088	1.948	-0.556	-2.840	0.731	-0.288	188.114	950.778
-2.00	3.00	14/10	10/10	5.088	1.948	-0.467	-2.759	0.640	0.188	157.161	923.276

Tables 8-7 and 8-8 represent changes as the result of changing the track bar axle and frame mounting positions. Table 8-7 has a roll base of 3 degrees while Table 8-8 has a ride base of -2.00".

Table 8-7

Live Axle Three Link Suspension											
					L Base Clearance = 5.00			Y Rotation Point = 10.00			
		L Lower	R Lower		R Base Clearance = 5.00			Z Rotation Point = 1.00			
Roll	Bar Ax/Fr	Fr/Ax	Fr/Ax	L Clear.	R Clear.	L spring	R Spring	Scrub	Steer	L Load	R Load
3.00	12/12	10/10	10/10	7.088	3.948	1.705	-0.588	0.573	-0.051	-548.695	190.576
3.00	12/12	10/10	14/10	7.088	3.948	1.679	-0.612	0.593	-0.170	-577.889	204.176
3.00	12/12	14/10	10/10	7.088	3.948	1.763	-0.529	0.618	-0.332	-585.011	176.574
3.00	12/8	10/10	10/10	7.088	3.948	1.726	-0.595	0.406	-0.051	-562.601	192.178
3.00	12/8	10/10	14/10	7.088	3.948	1.700	-0.619	0.431	-0.169	-572.355	205.742
3.00	12/8	14/10	10/10	7.088	3.948	1.785	-0.535	0.440	-0.334	-600.163	178.374
3.00	8/12	10/10	10/10	7.088	3.948	1.710	-0.590	0.530	-0.051	-542.768	192.137
3.00	8/12	10/10	14/10	7.088	3.948	1.685	-0.614	0.545	-0.170	-551.847	205.892
3.00	8/12	14/10	10/10	7.088	3.948	1.767	-0.530	0.586	-0.332	-578.118	177.939

Table 8-8

Live Axle Three Link Suspension											
					L Base Clearance = 5.00			Y Rotation Point = 10.00			
		L Lower	R Lower		R Base Clearance = 5.00			Z Rotation Point = 1.00			
Ride	Bar Ax/Fr	Fr/Ax	Fr/Ax	L Clear.	R Clear.	L spring	R Spring	Scrub	Steer	L Load	R Load
-2.00	12/12	10/10	10/10	3.000	3.000	-2.173	-2.157	0.069	0.000	713.017	696.534
-2.00	12/12	10/10	14/10	3.000	3.000	-2.243	-2.221	0.129	-0.318	759.903	738.471
-2.00	12/12	14/10	10/10	3.000	3.000	-2.238	-2.226	0.022	-0.318	757.961	741.491
-2.00	12/8	10/10	10/10	3.000	3.000	-2.195	-2.126	0.304	0.000	727.023	671.805
-2.00	12/8	10/10	14/10	3.000	3.000	-2.265	-2.187	0.377	-0.318	774.131	710.277
-2.00	12/8	14/10	10/10	3.000	3.000	-2.262	-2.193	0.271	-0.318	773.667	714.521
-2.00	8/12	10/10	10/10	3.000	3.000	-2.145	-2.182	0.166	0.000	692.951	715.196
-2.00	8/12	10/10	14/10	3.000	3.000	-2.214	-2.248	0.117	-0.318	738.751	759.641
-2.00	8/12	14/10	10/10	3.000	3.000	-2.209	-2.252	0.225	-0.318	735.326	761.413

The Front and Rear Datum Roll Centers and the resulting Roll Axis - The roll axis is a line drawn through the front and rear datum roll centers. The front and rear datum roll centers determine the height, angle and offset of the chassis roll axis. The roll axis, as the name implies, is the axis about which the chassis rolls - Figure 8-55.

As is the case of the datum roll centers, the roll axis is always seen as an instant axis under dynamic chassis conditions - it is in a constant state of flux.

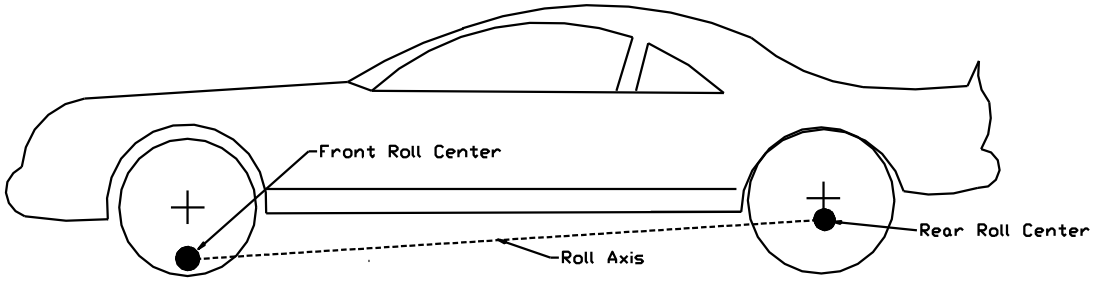


Figure 8-55

If one or both of the front and rear Datum roll centers are offset, the chassis roll axis would also be offset from the center line of the car. This has considerable ramifications in regards to the car's ultimate handling characteristics i.e. overturning moments, moment arm length, etc. Figure 8-56 illustrates a chassis with both its front and rear datum roll centers and the roll axis offset to the right. Figure 8-57 shows the front datum roll center offset to the left and the rear offset to the right while Figure 8-58 shows the opposite roll center offset. Where the roll axis crosses the centerline of the chassis is determined by the amount of front and rear datum roll center offset. **Remember**, the datum roll centers and roll axis are a "result" not a "cause". The datum roll centers are determined by the geometric (jacking/anti) forces and dynamic (springing) forces, not the other way around.

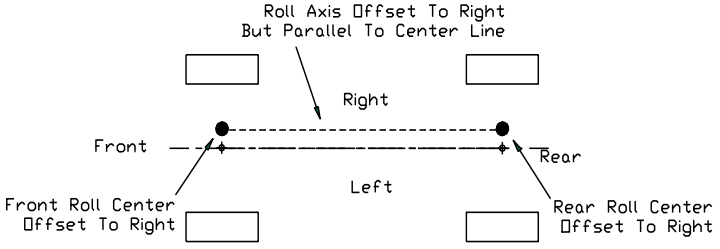


Figure 8-56

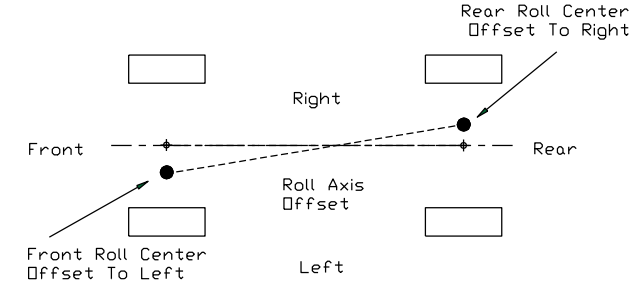


Figure 8-57

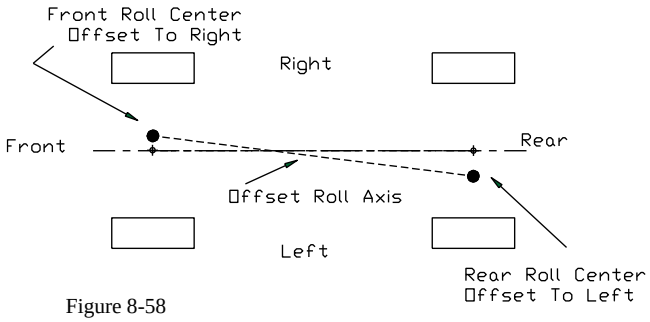


Figure 8-58

Anti Squat Kinematics - This is a very basic introduction to anti squat kinematics. Anti squat and its effects are discussed in some considerable detail in Chapters 15 & 16. The bottom line **– Anti squat geometry does not increase rear tire loading under acceleration**. An increase of load seen by the rear tires is directly proportional to the amount of longitudinal load transfer. Even though anti squat does not increase the total load on the rear tires, it can be used to dictate the percentage of load presented at the left and right rear tires as well as the percentage of load transfer that is directed through the links as opposed to the loads directed though the springs. The most basic concept of anti squat in regards to how the axle torque is applied to the suspension links is quite straight forward but its application is extremely complex (see Chapter 15 for an mathematical analysis of the anti and jacking forces). The **action** and **reaction** component of anti squat forces are applied to the chassis at the side view instant center or centers. Whether the instant center is ahead or behind and above or below the center of gravity is of considerable importance in determining how the loads are presented at the tire contact patches i.e. angle of resultant forces etc. - Figure 8-59. Anti squat **action** forces, as the result of torque seen at the axle, primarily affect the suspension kinematics. Anti squat **reaction** forces develop because of longitudinal acceleration reaction forces being transmitted though the chassis into the lower and upper links. The type, vertical or longitudinal, and percentage of anti squat is primarily determined by the placement of the instant center.

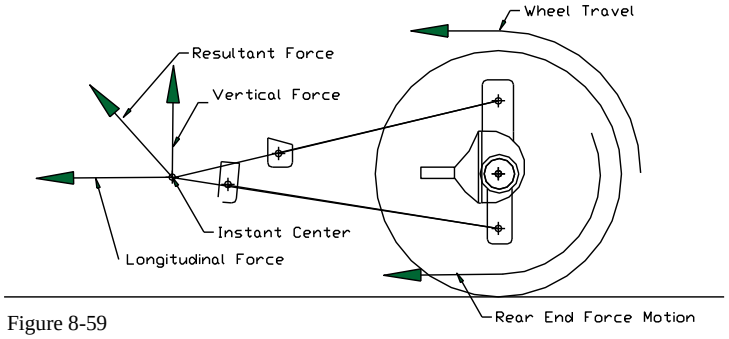


Figure 8-59

If the lower control arms are mounted at different angles, each will have its own instant center, and, therefore, produce asymmetric jacking forces. Also remember the instant center is not a stationary point, but, instead, continuously moves with axle torque in conjunction with lateral, longitudinal and vertical chassis movement. A great many of the decisions regarding kinematic settings need to be made in consort with data acquisition combined with various force calculations.

If no anti squat is present, all rearward longitudinal load transfer will be through the springs. In this case, during the first few milli-seconds of load transfer, a percentage of the increased vertical load will be absorbed through spring compression rather than being applied directly to the tire contact patch.

If 30 percent anti squat is present, this means 30 percent of the chassis' reactive forces are reacted through the suspension links. At 100 percent anti squat, all of the longitudinal load transfer is carried by the upper and lower control arms and none of the additional loads are carried by the springs. Though the formulas for calculating anti squat are discussed in Chapter 15, a simple and quasi accurate method of determining anti squat percentage is by calculating the height of the intersection point of a line extended from the center of the rear contact patch through the side view instant center which intersects a vertical line drawn up through the center of the front tire. If the height of this intersection point is at the same height of the center of gravity, the suspension is said to have 100 percent anti squat.

Figure 8-60 illustrates a rear suspension with 100% anti squat.

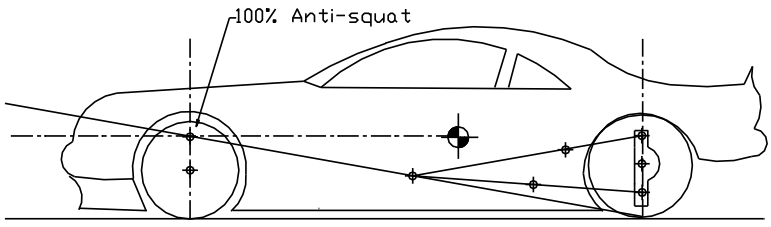


Figure 8-60

Figure 8-61 shows a chassis with its instant center well ahead of the CG. Moving the instant center (anti-squat pivot point) forward increases the resultant suspension motion but decreases the resultant forces. It works the same as any first class lever. Moving the instant center up increases the resultant vertical component while moving it down decreases the resultant vertical component. Anti squat jacking forces apply even if the instant center co-ordinates are in front of the chassis.

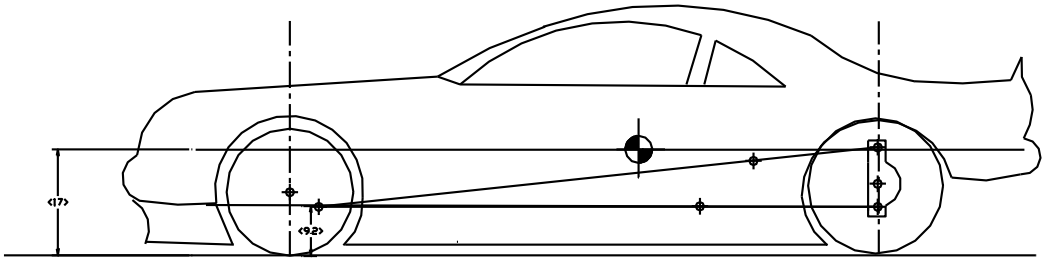


Figure 8-61

In theory, it is possible for the rear kinematics to produce more than 100 percent anti-squat. When this happens, the forces are reacted through a lever/moment arm, thereby multiplying said forces. Under acceleration, anti squat forces can actually jack the front or rear of the chassis up or down from their static ride height settings but jacking forces can not increase the load seen at the rear tires beyond their static load plus the additional longitudinal load transfer. If the rear rises under acceleration, the anti squat geometry is extending the rear springs from their static set up position i.e. the suspension arms are seeing a higher percentage of the static load plus all of the longitudinal load transfer while the springs are seeing none of the longitudinal load transfer and seeing a smaller percentage of the static load.

The amount of jacking force seen at any given **instant center** is largely the result of the upper and lower control arm axle mounting position in relation to the vertical center line of the axle i.e. moment arm lengths. Vertically repositioning upper and/or lower control arm axle mounting co-ordinates can have a considerable effect on the jacking forces - Chapter 16. Figure 8-62 illustrates a lower control arm mounting bracket that allows the racer to position the lower control arm in one of two holes. Also notice the two damper mounts which allow the team to change the damper and spring motion ratio.

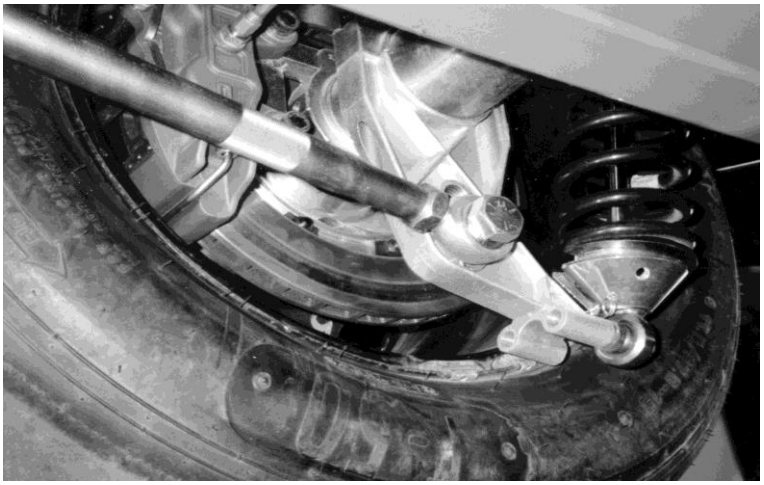


Figure 8-62

Figures 8-63 & 8-64 illustrate the difference in the vertical **reaction** force component of the upper/third link between two mounting positions. If the upper mount was offset to the right of the axle, the higher mounting position would counteract axle torque to a greater extent than the lower mount (a longer moment arm results in higher **reaction** force).

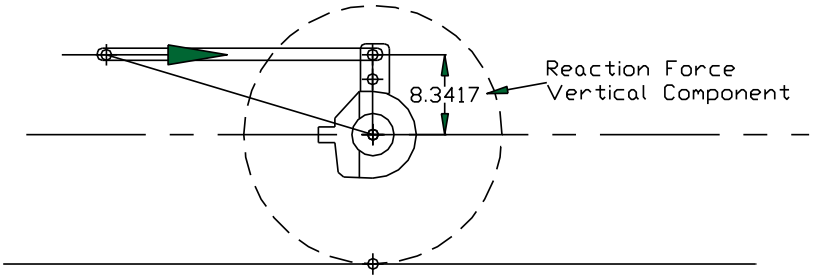


Figure 8-63

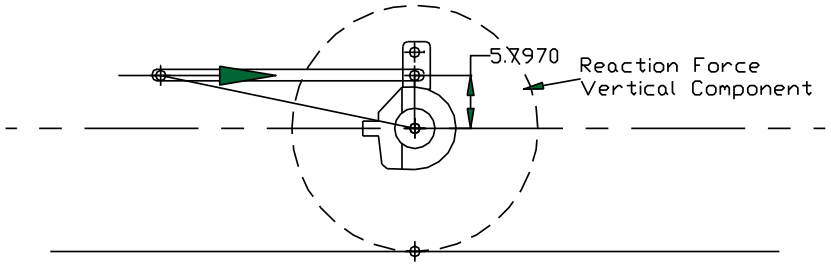


Figure 8-64

Figures 8-65 & 8-66 show the vertical **action** force component of two lower control arm mounting positions. The higher mounting position, with its shorter moment arm, will produce greater action forces as the result of axle torque (a shorter moment arm results in higher **action** forces).

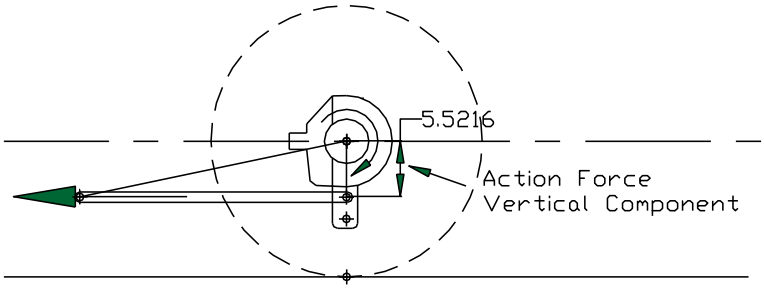


Figure 8-65

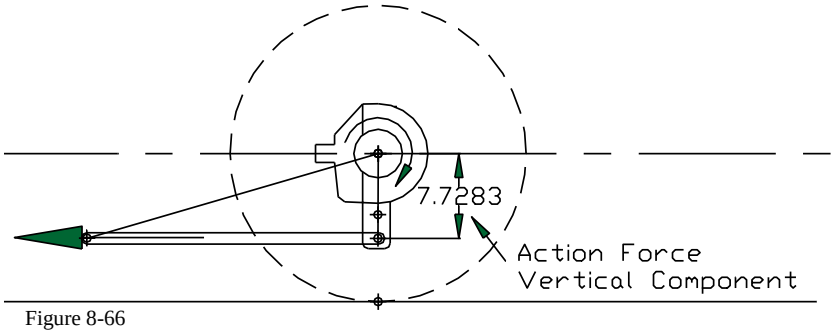


Figure 8-66

Action anti squat forces while changing the chassis pitch attitude can raise or lower the CG, which, in turn, will increase or decrease the amount of longitudinal load transfer.

Decoupled Torque Arm and Telescoping Third Link - An alternative to the traditional third link would be to use a fairly long decoupled torque arm in consort with a telescoping third link. The torque arm would transfer the wheel torque into the chassis and would, in turn, vertically load the rear tires as a result of the chassis reactive forces - Figure 8-67. The telescoping third link would be used to control braking forces. Figures 8-68 show one of many systems developed to decouple the third link.

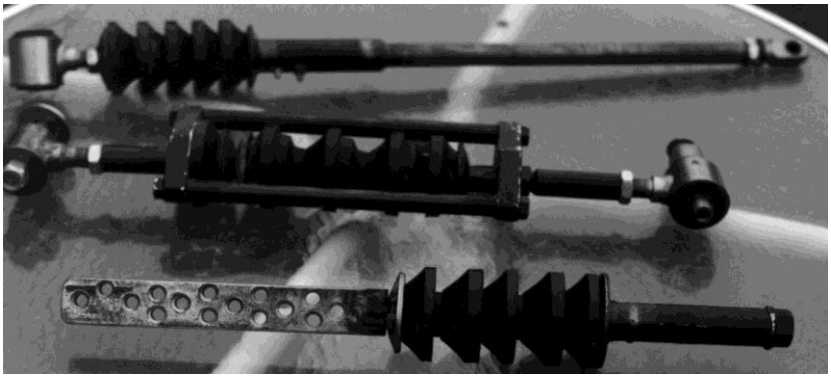


Figure 8-67

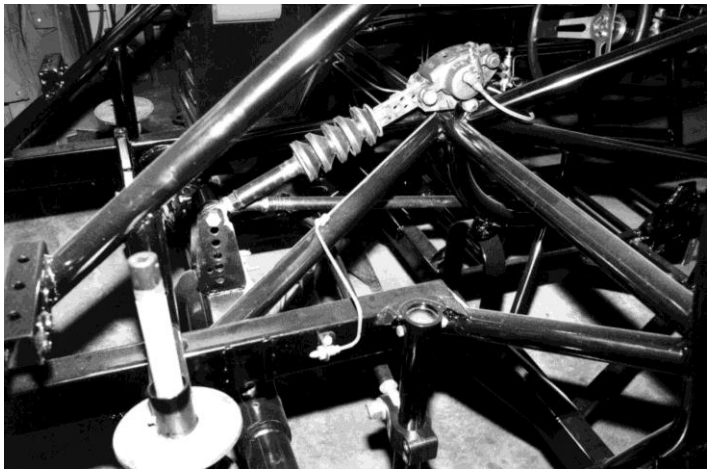


Figure 8-68

Wheel and Axle Housing Lateral Offset - Laterally offsetting the axle housing or individual wheels through the use of spacers or rim offset does not affect inline steer under coast conditions - Figures 8-69 & 8-70. However, as we will discover in Chapters 14 /21, offsetting either the wheel or the axle housing does affect the front to rear balance due to both static lateral load percentage changes and dynamic load changes i.e. changing how the wheel loads are distributed during longitudinal and lateral load transfer.



Figure 8-69

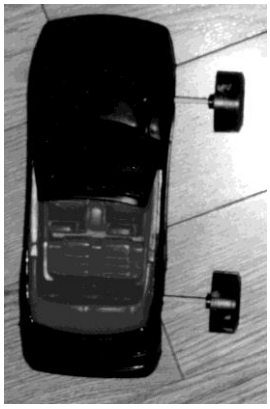


Figure 8-70

** Begin WinGeo3 Example(s)**

Edit: Rear Axle – As was the case with an independent suspension system, the initial measured or design data is entered using the *Edit* menu. The Edit menu is **not** used to modify the original suspension data.

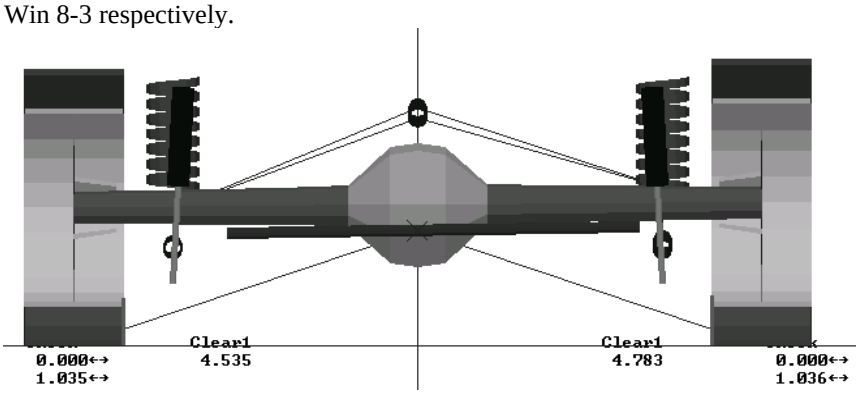
For a three link live axle suspension, the upper/third link co-ordinates are entered in both the left and right sides. The Twist Axle – Type False box should not have a check mark in it. This option is for a four link suspension. As is the case with an independent suspension system, the wheelbase is only entered with the right side co-ordinates. The tire diameter is calculated as **loaded** radius * 2. Tire roll out is the same as tire circumference. Using the *Utility / Edit Option*, the user can choose either *Check Sums or Incline Angle*, though, in most cases, both options are already shown. A positive incline number indicates the forward frame mount is higher than the axle mount.

Edit: Lateral – The *Lateral* menu is used for entering the *Panhard*/Track Bar co-ordinates. A positive incline number indicates the right side front mount is higher than the axle mount.

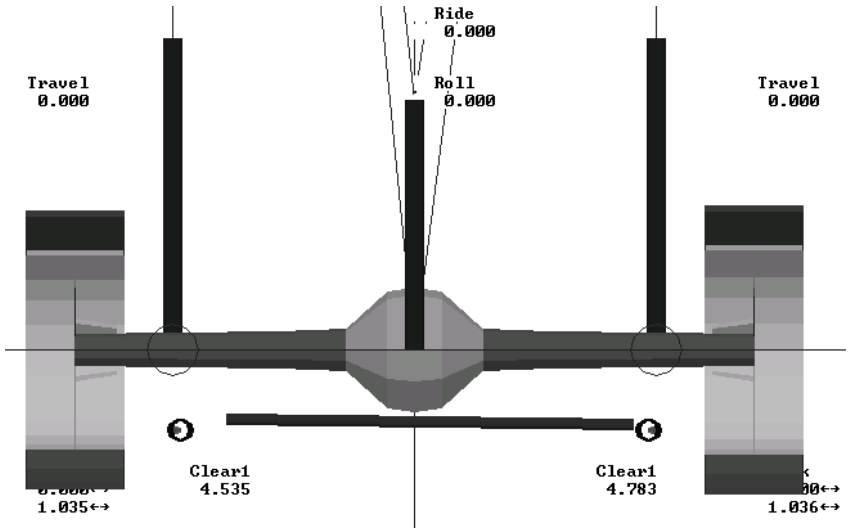
The *Auxiliary*, *Swaybar* and *Clearance* menus work the same as described in Chapter 6.

Viewing the Chassis – The chassis view can be changed by using the toggle buttons found at the bottom left of the main graphics screen or by using the *Edit / Screen Layout* menu. The size of the main screen can be increased by using the *Edit / Show or Hide 3-D panel* option and hiding the 3-D panel.

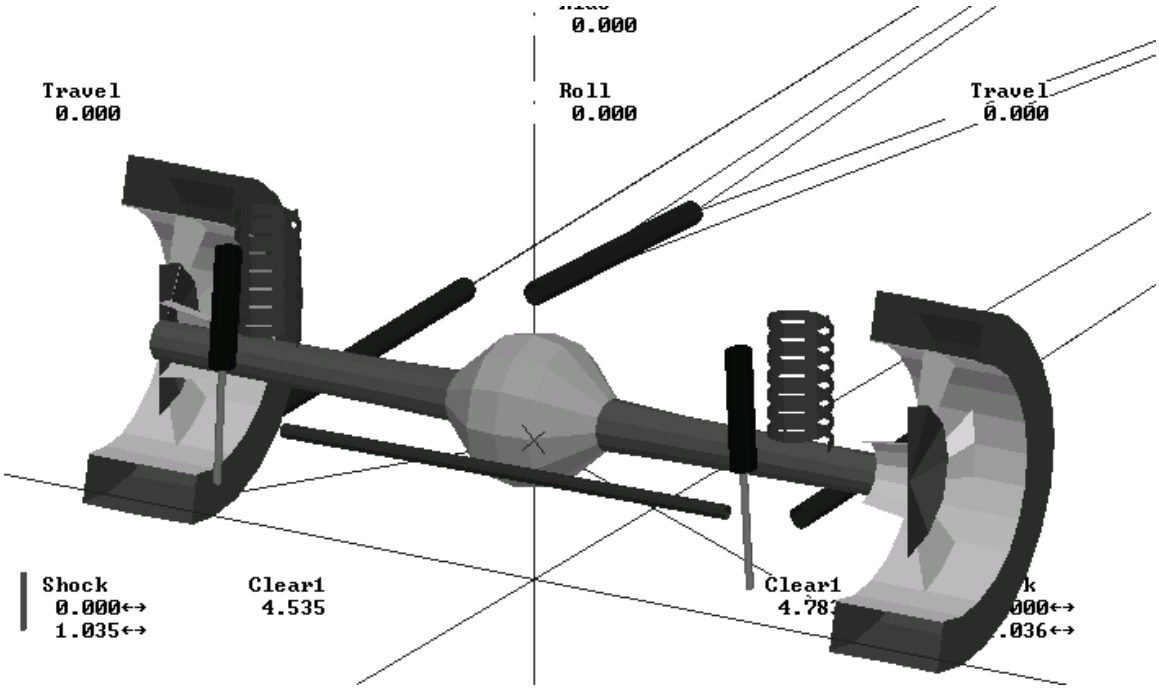
Being able to manipulate the chassis' view is a very useful tool when looking at the various suspension points. The third link suspension is shown in Rear View, Plan View and Offset View in Win 8-1 through Win 8-3 respectively.



Win 8-1 Rear View

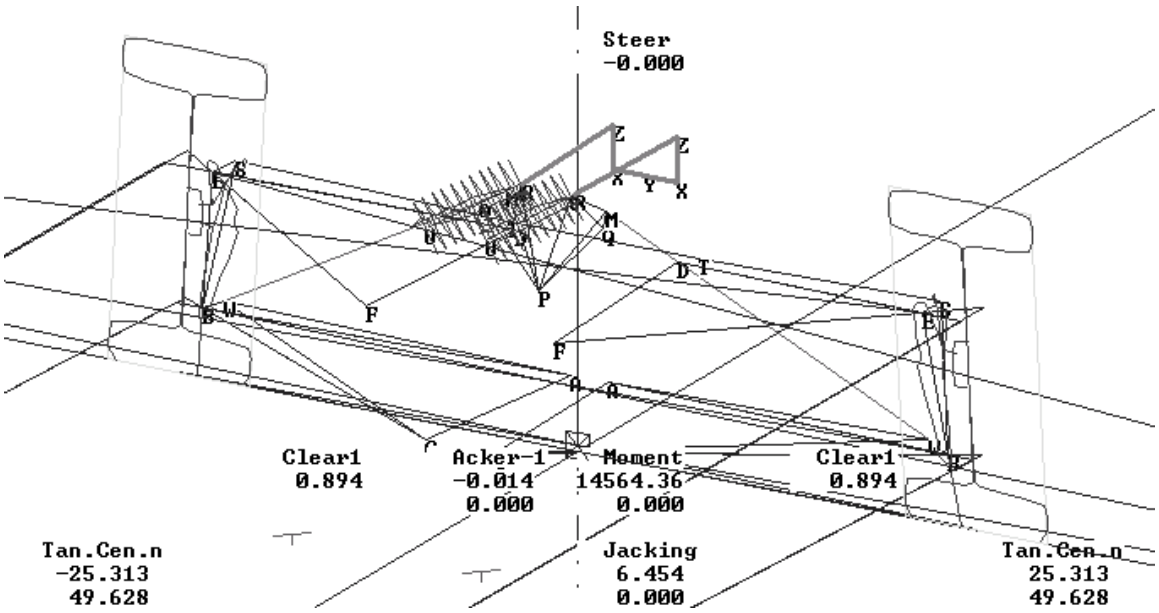


Win 8-2 Plan View

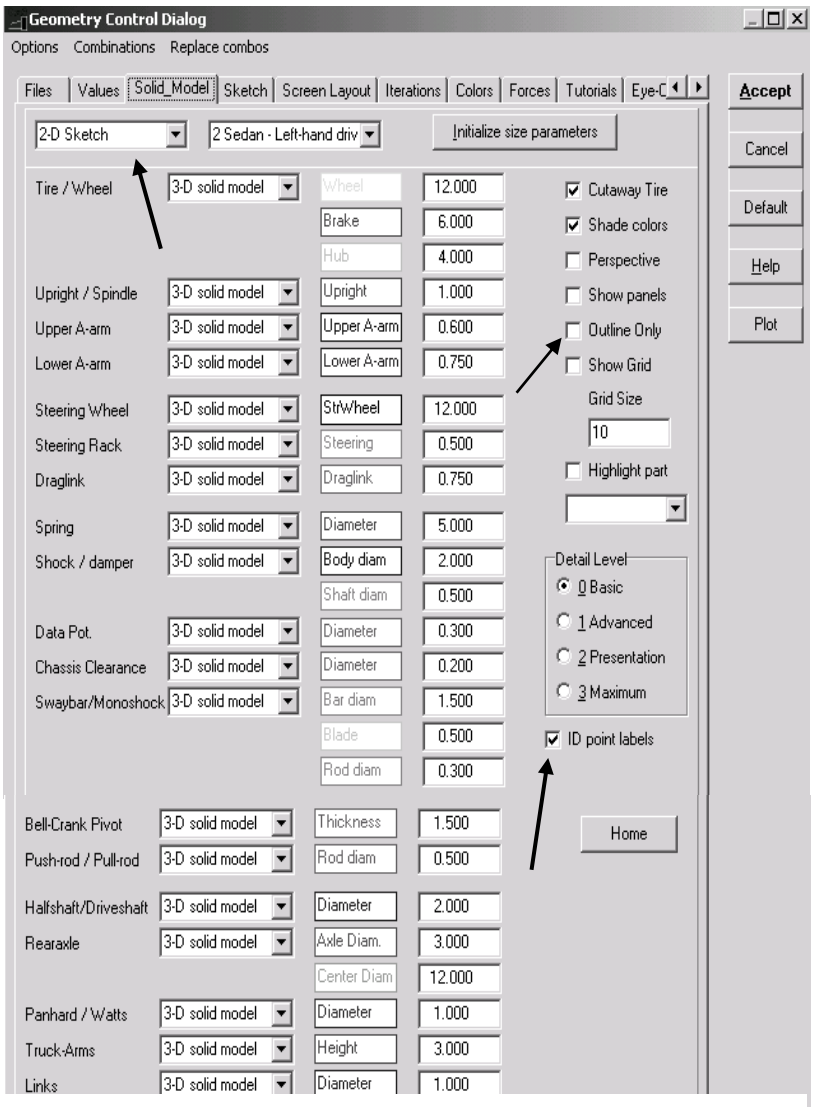


Win 8-3 Offset View

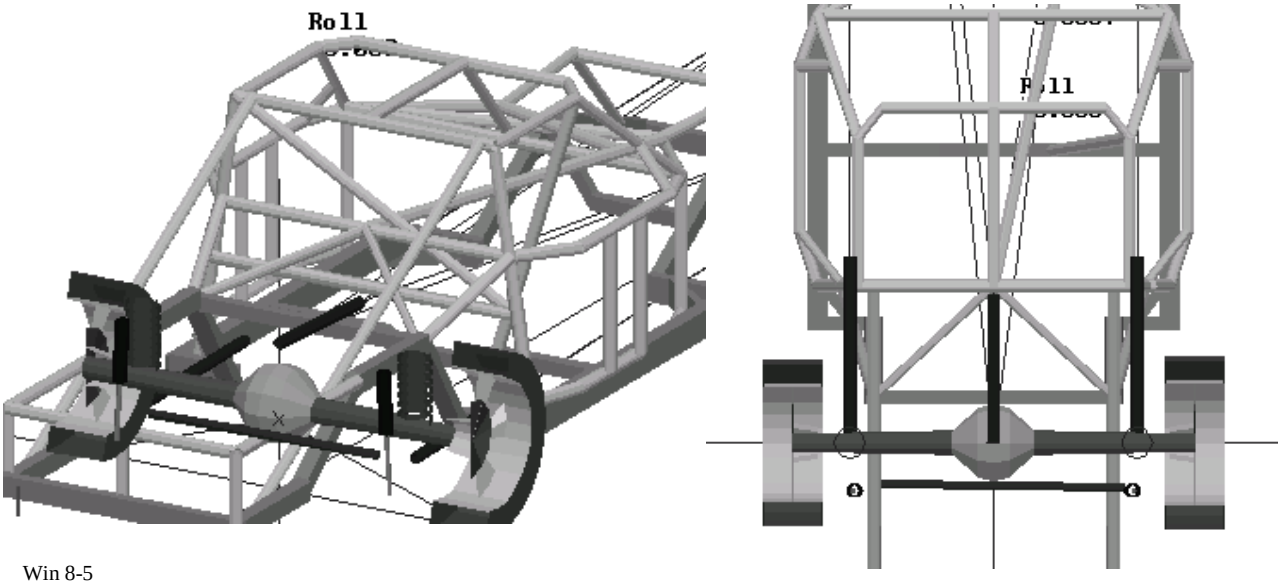
Geometry Control Dialog -To view the chassis in single line configuration as shown in the Win 8-4 open wheel graphic, go to the *Geometry Control Dialog* menu (right mouse click), select the *Solid Model* menu and select *Lines Only* from the upper left options box (see arrow - Win 8-5). The **suspension ID points** can be added by putting a check mark in the *ID point labels* box found about halfway down on the right hand side of the *Solid Model* menu (see arrow – Win 8-5). The ID points option is used with the single line graphics **only**. Using the *Geometry Control Dialog* / *Eye-Candy* menu, the user can add a frame to the suspension – Win 8-5.



Win 8-4

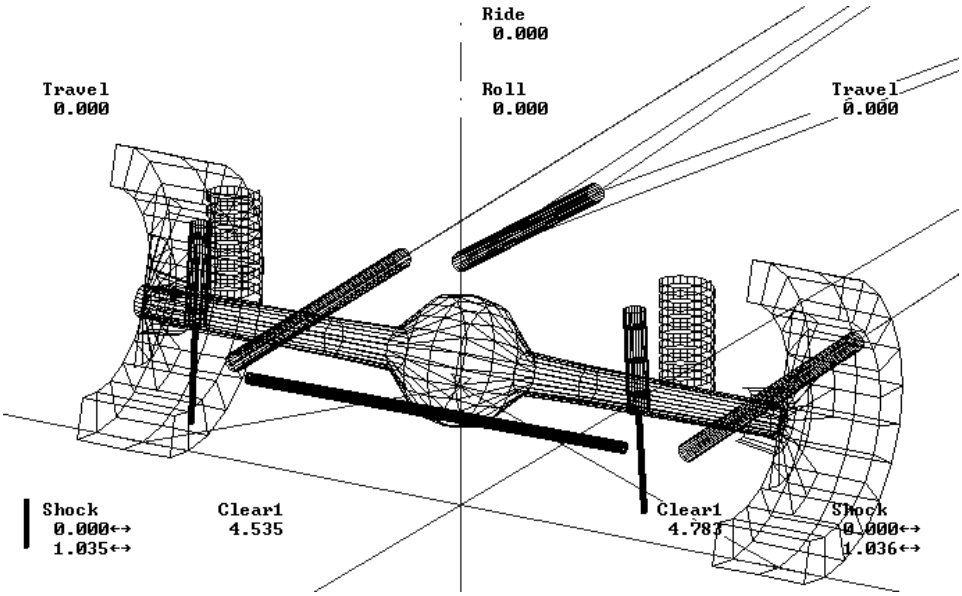

Geometry Control Dialog
Options Combinations Replace combos
Files Values Solid_Model Sketch Screen Layout Iterations Colors Forces Tutorials
Accept
Cancel
Default
Help
Plot
2-D Sketch
2 Sedan - Left-hand driv
Initialize size parameters
Tire / Wheel 3-D solid model Wheel 12.000
Brake 6.000
Hub 4.000
Upright / Spindle 3-D solid model Upright 1.000
Upper A-arm 3-D solid model Upper A-arm 0.600
Lower A-arm 3-D solid model Lower A-arm 0.750
Steering Wheel 3-D solid model StrWheel 12.000
Steering Rack 3-D solid model Steering 0.500
Draglink 3-D solid model Draglink 0.750
Spring 3-D solid model Diameter 5.000
Shock / damper 3-D solid model Body diam 2.000
Shaft diam 0.500
Data Pot. 3-D solid model Diameter 0.300
Chassis Clearance 3-D solid model Diameter 0.200
Swaybar/Monoshock 3-D solid model Bar diam 1.500
Blade 0.500
Rod diam 0.300
Bell-Crank Pivot 3-D solid model Thickness 1.500
Push-rod / Pull-rod 3-D solid model Rod diam 0.500
Halfshaft/Driveshaft 3-D solid model Diameter 2.000
Rearaxle 3-D solid model Axle Diam. 3.000
Center Diam 12.000
Panhard / Watts 3-D solid model Diameter 1.000
Truck-Arms 3-D solid model Height 3.000
Links 3-D solid model Diameter 1.000
Cutaway Tire
Shade colors
Perspective
Show panels
Outline Only
Show Grid
Grid Size
10
Highlight part
Detail Level
0 Basic
1 Advanced
2 Presentation
3 Maximum
ID point labels
Home

Win 8-4


Roll
Roll

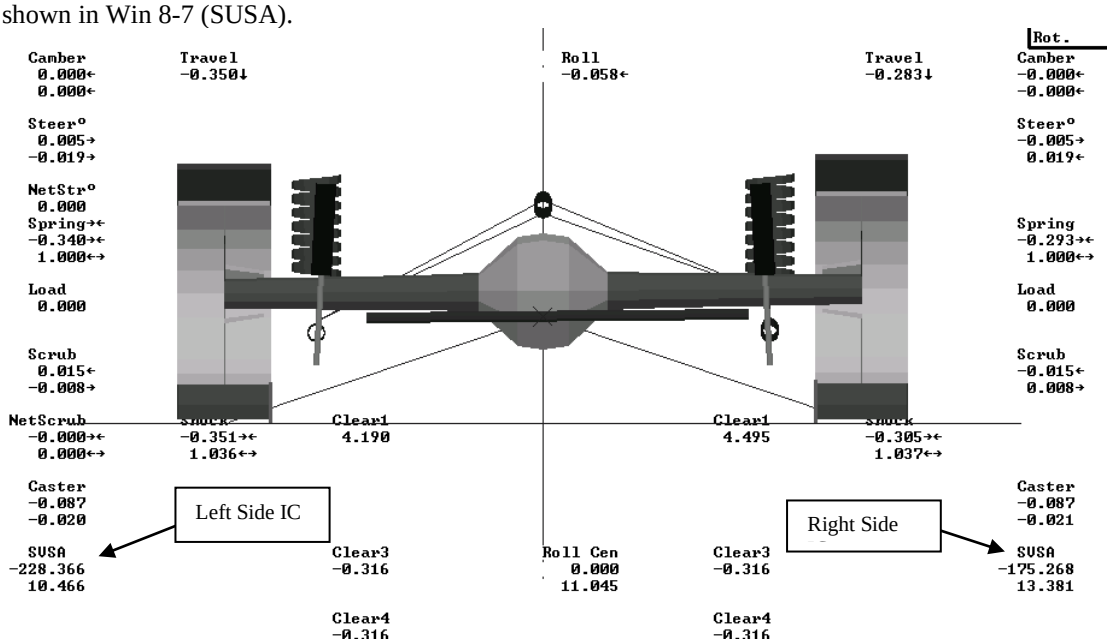
Win 8-5

Geometry Control Dialog – The chassis can also be viewed in a wire frame mode by clicking on the *Outline Only* box located on the upper left side of the *Geometry Control Dialog / Solid Model* menu (see arrow) – Win 8-6.



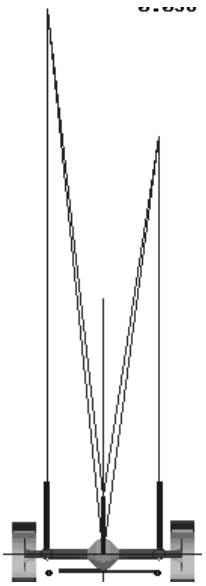
Win 8-6

Dynamic, Live Axle, Side View Instant Centers – As in the case of independent suspension systems the IC length and height co-ordinates can be viewed at the bottom left and right of the main graphics screen as shown in Win 8-7 (SUSA).

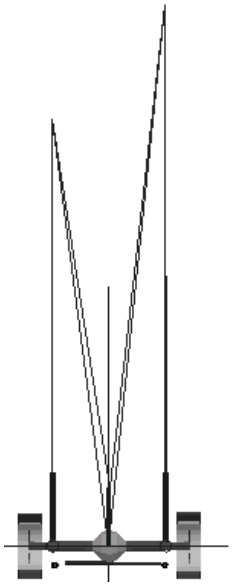


Win 8-7

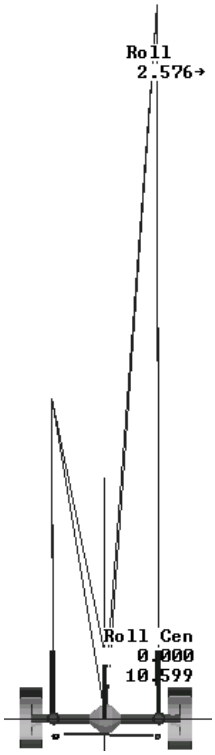
To observe the changes in side view IC positioning while running a *Path file*, the main graphics screen can be reduced in size as shown in Win 8-8 / Win 8-11. The chassis can be relocated on the screen by using the x, y and z buttons found at the lower left of the screen.



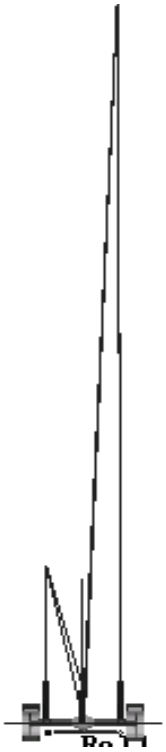
Win 8-8 Phase 1



Win 8-9 Phase 2



Win 8-10 Phase 3



Win 8-11 Phase 5

Instant Center Co-ordinates - As previously discussed, The IC co-ordinates are used to calculate the anti/jacking forces as required by dynamic simulation software such as the Win31 models used in the later dynamic chapters. The IC lengths and heights for a given set of *Path files* can be transferred from the WinGeo3 *Tables* to an *Excel* file where they are used to drive the simulation programs – Win 8-12. The Premier version of WinGeo3 allows the user to download track data into Excel files.

Win 8-12

Table #6	Ride	Roll	Steer	ICIng L	Hub Y L	R.C. lat	R.C. high	R.C. high	ICIng R	Hub Y R
B=1.00g T=0.00g 1	-0.316	-0.058	0	-99	-32.765	0	11.045	6.642	-99	32.735
B=1.25g T=0.50g 2	-0.342	1.223	0	-99	-32.512	0	10.816	6.773	-99	32.988
B=0.60g T=1.00g 3	-0.318	2.576	0	-99	-32.249	0	10.599	6.929	-99	33.251
B=0.15g T=1.25g 4	-0.301	3.255	0	-99	-32.119	0	10.492	7.006	-99	33.381
B=0.05g T=1.53g 5	-0.3	3.993	0	-99	-31.979	0	10.37	7.076	-99	33.521
A=0.00g T=1.37g 6	-0.296	3.577	0	-99	-32.058	0	10.441	7.04	-99	33.442
A=0.30g T=1.00g 7	-0.278	2.628	0	-99	-32.239	0	10.607	6.957	-99	33.261
A=0.40g T=0.70g 8	-0.27	1.85	0	-99	-32.389	0	10.742	6.882	-99	33.111
A=0.65g T=0.50g 9	-0.255	1.342	0	-99	-32.488	0	10.834	6.836	-99	33.012
A=0.85g T=0.00g 10	-0.236	0.049	0	-99	-32.743	0	11.062	6.699	-99	32.757
B=0.00g T=0.00g 0	-0.273	0	0	-99	-32.753	0	11.054	6.673	-99	32.747

Dynamic, Live Axle, Track Bar Angle – The angle of the track bar used to calculate front/rear view IC jacking forces can be found for any particular kinematic iteration by going to the *Analysis / Solid Rear Axle* menu as shown in Win 8-13.

```
Rearaxle analysis for D:\Program Files\Mitchell\WinGeo3\Book\Short Track Rear.GEM
Panhard rod length     39.135
Rod Inclination        -0.007%      -0.414 degrees
Vertical Instant Center is at -55493.924 fore-aft.
                       and at    -94.477 width.
dSteer per lateral shift is      0.001 degrees.
LateralRodDelta is      0.000
Steer shift is      0.000
```

Track Bar Angle
A negative number indicates the bar is angled down at the right side frame mount.

Win 8-13

Ride/Roll: Upper and Lower Control Arms – During kinematic motion, both live axle scrub and rear axle cock will tend to steer the rear of the chassis. The **static angles** of the upper and lower links/trailing arms play a considerable role in how much the rear axle angle changes during dynamic kinematic iterations. Win 8-14 shows a rear axle iteration table from the short track ten phase – rear *Path file* iterations. A positive steer angle indicates the axle is turned to the right (oversteer/loose condition) while a negative steer angle indicates the axle is turned/cocked to the left (understeer/push condition). A negative hub x co-ordinate indicates the hub has moved forward while a positive number indicates the hub has moved rearward.

Win 8-14

Hub Center Motion - Base Set Up									
	Ride	Roll	Steer°	Hub X L	Hub Y L	Hub Z L	Hub X R	Hub Y R	Hub Z R
B=1.00g T=0.00g 1	0.615	-0.058	-0.014	-0.003	-32.746	13.36	-0.017	32.754	13.855
B=1.25g T=0.50g 2	0.745	1.231	0.048	-0.043	-32.494	13.36	0.014	33.006	13.855
B=0.60g T=1.00g 3	0.329	2.585	0.087	-0.062	-32.246	13.36	0.038	33.254	13.855
B=0.15g T=1.25g 4	0.038	3.255	0.084	-0.064	-32.121	13.36	0.032	33.379	13.855
B=0.05g T=1.53g 5	-0.034	3.993	0.094	-0.079	-31.982	13.36	0.028	33.517	13.855
A=0.00g T=1.37g 6	-0.059	3.577	0.082	-0.066	-32.06	13.36	0.028	33.44	13.855
A=0.30g T=1.00g 7	-0.229	2.628	0.049	-0.036	-32.239	13.36	0.019	33.261	13.855
A=0.40g T=0.70g 8	-0.279	1.85	0.034	-0.022	-32.389	13.36	0.016	33.111	13.855
A=0.65g T=0.50g 9	-0.423	1.342	0.022	-0.014	-32.488	13.36	0.01	33.012	13.855
A=0.85g T=0.00g 10	-0.523	0.049	0.01	-0.007	-32.745	13.36	0.003	32.755	13.855

Win 8-15 shows the same chassis *Path file* iterations as in the previous example but with the left lower trailing arm frame mount moved up 2".

Win 8-15

Hub Center Motion - Left Frame Mount Up 2"									
	Ride	Roll	Steer°	Hub X L	Hub Y L	Hub Z L	Hub X R	Hub Y R	Hub Z R
B=1.00g T=0.00g 1	0.615	-0.058	0.036	-0.046	-32.74	13.36	-0.003	32.76	13.855
B=1.25g T=0.50g 2	0.745	1.231	0.152	-0.132	-32.48	13.36	0.045	33.02	13.855
B=0.60g T=1.00g 3	0.329	2.585	0.201	-0.16	-32.231	13.36	0.072	33.268	13.855
B=0.15g T=1.25g 4	0.038	3.255	0.196	-0.16	-32.107	13.36	0.066	33.393	13.855
B=0.05g T=1.53g 5	-0.034	3.993	0.224	-0.191	-31.966	13.36	0.067	33.533	13.855
A=0.00g T=1.37g 6	-0.059	3.577	0.196	-0.165	-32.046	13.36	0.062	33.454	13.855
A=0.30g T=1.00g 7	-0.229	2.628	0.118	-0.096	-32.231	13.36	0.04	33.269	13.855
A=0.40g T=0.70g 8	-0.279	1.85	0.073	-0.056	-32.384	13.36	0.028	33.116	13.855
A=0.65g T=0.50g 9	-0.423	1.342	0.032	-0.022	-32.487	13.36	0.013	33.013	13.855
A=0.85g T=0.00g 10	-0.523	0.049	-0.032	0.029	-32.75	13.36	-0.01	32.75	13.855

Ride/Roll: Track /Panhard Bar – In **kinematic** terms, the track bar length and dynamic angle primarily control the amount of scrub. Win 8-16 shows the amount of scrub for the base set up. A positive scrub number indicates the axle is being scrubbed to the right.

Win 8-16

Rear Axle Scrub				
	Ride	Roll	Steer°	Scrub R
B=1.00g T=0.00g 1	0.615	-0.058	0.014	0.004
B=1.25g T=0.50g 2	0.745	1.231	-0.048	0.256
B=0.60g T=1.00g 3	0.329	2.585	-0.087	0.504
B=0.15g T=1.25g 4	0.038	3.255	-0.084	0.629
B=0.05g T=1.53g 5	-0.034	3.993	-0.094	0.767
A=0.00g T=1.37g 6	-0.059	3.577	-0.082	0.69
A=0.30g T=1.00g 7	-0.229	2.628	-0.049	0.511
A=0.40g T=0.70g 8	-0.279	1.85	-0.034	0.361
A=0.65g T=0.50g 9	-0.423	1.342	-0.022	0.262
A=0.85g T=0.00g 10	-0.523	0.049	-0.01	0.005

Win 8-17 shows the same set of iterations but with the track bar frame mount static setting moved **up** 2".

Win 8-17

Rear Axle Scrub - Frame Mount Up 2"				
Table #1	Ride	Roll	Steer°	Scrub R
B=1.00g T=0.00g 1	0.615	-0.058	0.014	0.035
B=1.25g T=0.50g 2	0.745	1.231	-0.048	0.315
B=0.60g T=1.00g 3	0.329	2.585	-0.087	0.562
B=0.15g T=1.25g 4	0.038	3.255	-0.084	0.683
B=0.05g T=1.53g 5	-0.034	3.993	-0.094	0.829
A=0.00g T=1.37g 6	-0.059	3.577	-0.082	0.743
A=0.30g T=1.00g 7	-0.229	2.628	-0.049	0.54
A=0.40g T=0.70g 8	-0.279	1.85	-0.034	0.376
A=0.65g T=0.50g 9	-0.423	1.342	-0.022	0.261
A=0.85g T=0.00g 10	-0.523	0.049	-0.01	-0.022

Win 8-17 shows the same set of iterations but with the track bar frame mount static setting moved **down** 2".

Win 8-17

Rear Axle Scrub - Frame Mount Down 2"				
	Ride	Roll	Steer R	Scrub R
B=1.00g T=0.00g 1	0.615	-0.058	0.014	-0.028
B=1.25g T=0.50g 2	0.745	1.231	-0.048	0.197
B=0.60g T=1.00g 3	0.329	2.585	-0.087	0.445
B=0.15g T=1.25g 4	0.038	3.255	-0.084	0.575
B=0.05g T=1.53g 5	-0.034	3.993	-0.094	0.706
A=0.00g T=1.37g 6	-0.059	3.577	-0.082	0.636
A=0.30g T=1.00g 7	-0.229	2.628	-0.049	0.481
A=0.40g T=0.70g 8	-0.279	1.85	-0.034	0.346
A=0.65g T=0.50g 9	-0.423	1.342	-0.022	0.263
A=0.85g T=0.00g 10	-0.523	0.049	-0.01	0.032

Pinion Angle Change – Pinion angle change due to dynamic kinematic changes can be calculated from the change in *Caster Angle*. A negative caster number indicates the pinion has rotated down towards the ground. If the original pinion angle was set at –2.00º and the dynamic caster angle is –0.138º, the total pinion angle will be –2.138º down.

Driveshaft Inclination – There are no drive shaft co-ordinates entered in the WinGeo3 demo version so before working with the driveshaft options, the user needs to enter the driveshaft co-ordinates under th*e Edit / Driveshaft* menu. Generic co-ordinates for the short track chassis are shown in Win 8-18.

Right side		X fore-aft	Y width	Z vertical	Check sums	
Drive-shaft chassis	I	-64.000	0.000	14.500	I to J=	56.056
Drive-shaft rear axle	J	-8.000	0.000	12.000	Incline	90.000

Win 8-18

Analysis: Halfshaft/Driveshaft Analysis - Win 8-19 shows a driveshaft **static** inclination angle of -2.045º. A negative driveshaft angle indicates the driveshaft is angled up towards the front. Win 8-20 shows the same set up but under dynamic conditions. Win 8-20 shows the driveshaft angled down 1.382º.

```
Driveshaft Angle Analysis of D:\Program
Files\Mitchell\WinGeo3\Geometry\TruckArmDemo.gem

Chassis Pitch angle is       0.000

      Driveshaft car   I:    -64.000        0.000       14.000
      Driveshaft axle  J:     -8.000       -0.000       12.000
      Inclination angle       -2.045

      Right Caster is          0.000        0.000
      Left Caster is           0.000        0.000

      Drive-shaft length      56.036       56.036        0.000

      Right Locked Wheel       0.000       -0.000
```

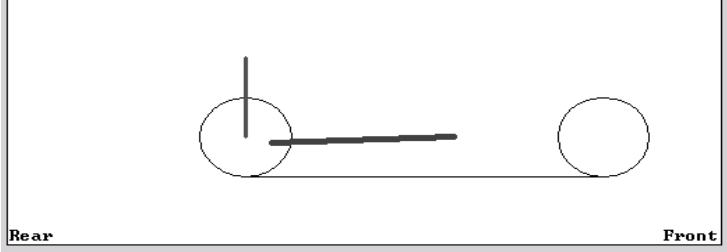


Figure 8-19

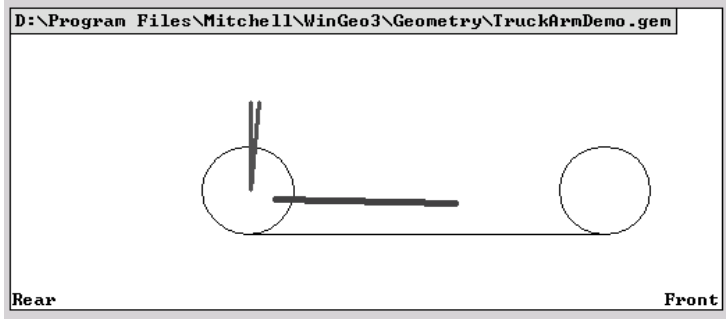
```
Chassis Pitch angle is       0.000

      Driveshaft car   I:    -64.000        0.000       10.000
      Driveshaft axle  J:     -8.630        0.155       11.336
      Inclination angle        1.382

      Right Caster is          -4.814       -1.175
      Left Caster is           -4.812       -1.185

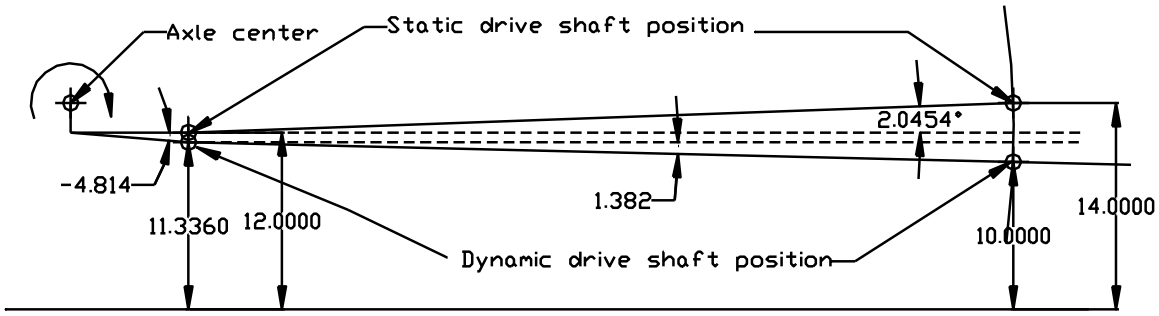
      Drive-shaft length      56.036       55.386       -0.649

      Right Locked Wheel       0.242        0.049
      Right Hub Center        -0.933       14.000
```



Win 8-20

Calculating Driveshaft Inclinations - When calculating the driveshaft inclination angle one needs to consider both the change in **pinion angle** and **chassis high** at the front of the driveshaft as shown in Win 8-21.



Win 8-21

** End WinGeo3 Example(s)**

I have learned so much from so many. Most certainly, my great friend and machining mentor, Gerhard Bergstein, ranks right up there as one of my most loved teachers. Gerhard is an absolutely superb Tool and Die Maker who is always happy to share his skills with others. The steam engine shown in the picture was a gift from Gerhard. One of my most prized positions, it is an exact scale working replica of a Case steam engine. It is completely hand crafted right down to the tiny working valves. Even the nuts and bolts were hand crafted.

