Optimization of Front Suspension and Steering Parameters of an Off-road Car using Adams/Car Simulation

Andrew S.Ansara, Andrew M.William, Maged A.Aziz, Peter N. Shafik
Department of Mechanical Engineering
Alexandria University
Alexandria, Egypt

***Abstract*— The design of an off-road vehicle is very complicated as the car is subjected to very harsh conditions and it can fail easily causing a lot of damage if it isn't designed well. One of the most important parameters affecting the car's performance is the suspension and steering systems design as it affects the vehicle's performance in handling, during breaking and cornering, the tires contact with the ground, the forces acting on the vehicle's chassis and it also affects the driver's comfort during the ride. So given all that we need to pay a lot of attention to designing a set up where all the systems harmoniously work together to give the optimum performance that can allow to vehicle to operate with maximum safety, stability and reliability.**

Keywords*— Adams/car, front-suspension, optimization, double A- arms, camber, caster, kingpin inclination, scrub raduis, wheel travel, steering, toe angle, roll center.

I. INTRODUCTION

An off-road vehicle goes though big bumps and sometimes large obstacles and rocks and the systems primarily responsible for the vehicle being able to cross these harsh conditions are the suspension and steering systems ,*but what are they*.

The suspension system is the system responsible for keeping the wheels of the car in contact with the ground at all times at optimum position and it also minimizes the loss of traction, tire wear and lateral movement. It consists of the mechanical linkages connecting the chassis to the upright, the springs and the dampers of the vehicle which allow the vehicle to absorb and damp the impacts and vibrations caused from going over bumps and obstacles without affecting the driver too much so that the driver can still easily control the vehicle with ease and comfort as much as possible.

The steering system is one of the most important systems in any vehicle as it allows a directional control of the vehicle according to the driver's desire. And that's done by controlling and directing the steering wheel which is placed in front of the driver, which is allowed only to rotate but this rotational motion is converted into a linear motion by the rack and pinion and finally this linear motion is transmitted into the front wheels by some linkages which are the tie roads and steering arms which are connected to the uprights by ball joints that can withstand the off-road hard conditions.

To reach this best possible case, we need to optimize a number of suspension and steering parameters like (camber, caster and toe angles – track width - kingpin inclination angle – scrub radius – roll center height – roll axis inclination – motion ratio). All these parameters can be changed by changing the points and angles of the fixations of the mechanical linkages on the chassis and the uprights.

II. FRONT SUSPENSION

A. *Front suspension geometry:*

Any suspension geometry design must be designed specifically for the type of vehicle and the shape of its chassis as the suspension geometry is also defined as the method of connecting the un-sprung mass to the sprung mass and that method controls the path of relative motion and the forces acting between them. So there is no one perfect design or geometry setup but it differs from one vehicle to the other.

B. *Geometry selection:*

A number of geometry setups were compared based on its (weight – cost – design simplicity – ground clearance – impact protection – cornering characteristics – ease of maneuverability). After studying a variety of systems, we found that the best one for our requirements is independent unequal length, non-parallel double wishbone system; because it is better to use an independent suspension so that when one wheel takes a bump the other one is not affected. The Double wishbone system also gives the best cornering performance, an increased negative camber gain while rolling and provides an optimum compromise between vehicle handling and ride comfort.

C. *Steering System Selection:*

After studying different types of steering system we have finally chosen the rack and pinion system as it has several advantages like Simple construction, Cheap and readily available, High mechanical efficiency and Small space requirement .

D. *Design Goals:*

1. Suspension system must allow for enough travel of the tires so the disturbance is not transmitted directly to the driver when hitting a bump. 7 inches of up travel and 5 inches of droop from the ride height are acceptable.

2. Front track width of 52 inches, rear track width of 50 inches are chosen. Rear track width is smaller than that of front to aid maneuverability and promote stability during cornering.

3. Front Roll center is kept at optimized height (10.63 in.) to reduce the body roll. The front roll center is kept lower than the rear one so that the roll axis is inclined towards the front to promote over steering causing more lateral acceleration in the front of the vehicle.

4. Maximizing obstacle avoidance and accounting for varying terrains ,so that ground clearance can be designed to be 11 inches from the lowest member on the chassis and a-arms to the ground.

5. Making the steering as fast as possible for the driver with the lowest effort and this mainly depends on the steering ratio which is the ratio between the number of degrees of rotation of steering wheel to the number of degrees of rotation of the front wheels depending on that of steering wheel. The steering ratio mainly depends on the radius of the steering wheel and radius of turning of the front wheels. For normal cars the steering ratio is relatively larger than that of racing cars for example most of passengers cars have a steering ratio from 12:1 to 20:1. But on the other hand, the racing cars have much smaller steering ratio, in fact it will be better if it is as small as possible i.e. closer to 1:1.

III. VEHICLE KINEMATICS

The front suspension geometry previously selected has a great effects on the kinematics of the system. The kinematics is how the system behaves when the wheel travels up and down over an obstacle or a droop and goes round a turn. Many suspension parameters affect the vehicle kinematics like : camber, cater and toe angles ,scrub radius ,kingpin inclination angle. These parameters affect the orientation of the wheel with respect to the ground and the performance of the vehicle while acceleration and cornering.

In order to optimize suspension parameters to analyze the vehicle kinematics , Adams/Car software is used which allow the user to input suspension hard points for various geometries. Simulation is then can be performed , and it displays visual animation and graphs which indicate how the suspension would move when hitting a bump or a droop. In order to find the best available design ,many iterations would be done to optimize the parameters and the results. As a first step , 2D sketch is drawn with initial parameters assumptions on AutoCad, then these hard points were imported into Adams/Car to begin the iteration process.

We can judge on our design by observing the generated graphs after simulation which indicate the change of a selected parameter with wheel travel.

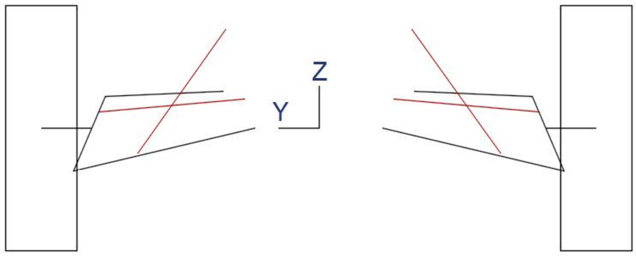

Fig. 1. CAD model on AutoCad (Front view).

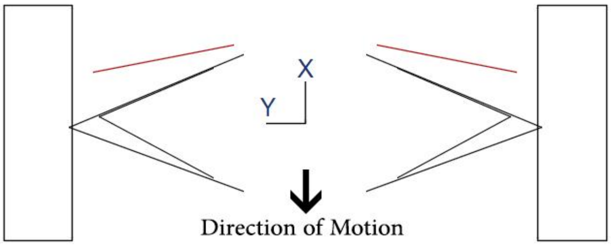

Fig. 2. CAD model on AutoCad (Plan view).

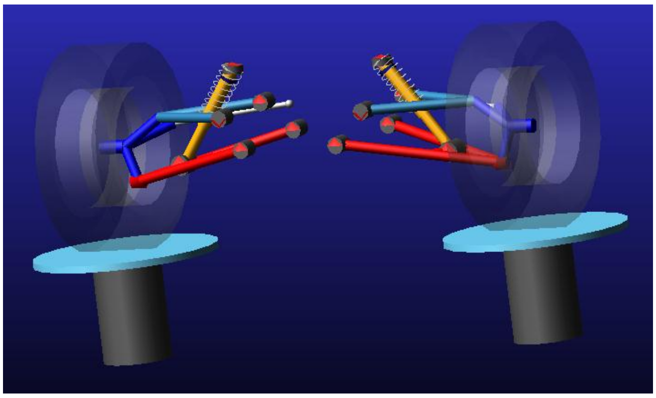

Fig. 3. Kinematic model of front suspension on Adams/Car.

IV. EFFECT OF THE SUSPENSION PARAMETERS

1. Camber Angle:

Camber is the angle between the inclination of the wheel plan with respect to the vertical axis of the car when looked from the front view. Camber angle affects the lateral force development and road holding of a car. The wheel is connected to the chassis through the suspension system which rotate to allow wheel travel. As a result ,the wheel is subjected to camber changes as it moves up and down. So, the more the wheel travel is , the more difficult it is to maintain an ideal camber angle.

We can adjust the camber to be positive or negative depending on the application of the vehicle. A Positive camber angle : a) reduces contact patch of the tire, b) maximizes the amount of forces acting on the tire during cornering, c) results in an desirable tire wear patterns. Therefore ,off-roading cars should have negative camber angle in the front to a) allow for better cornering performance, b) reduce lateral load through linkages.

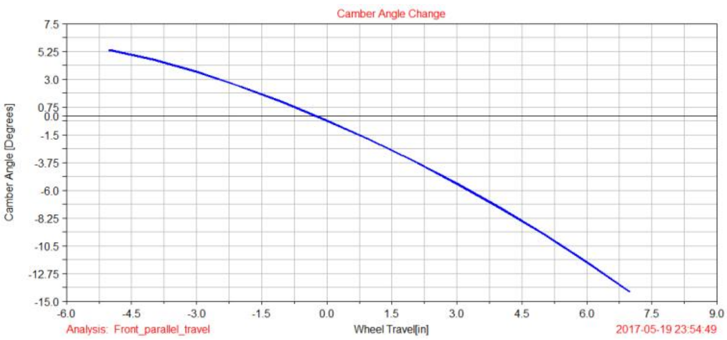

Fig. 4. Camber angle VS Wheel travel.

It is more desirable for the wheel to gain negative camber angle while traveling. The more negative camber angle, the more stable is the vehicle. The suspension geometry is designed to reduce positive camber gain and this could be done by designing the control arms points such that a-arms are unequal in length. For our design, zero static camber angle is used. Camber angles varies from (-14.5 degree) for maximum bump travel to (+5.25 degree) for maximum rebound travel.

2. Caster Angle:

Caster angle is the angle to which the steering axis is tilted forward or rearward from vertical viewed from the side of the vehicle. Steering axis is the line about which the wheel will turn when steered and it connects the upper and lower ball joints of the a-arms. Caster angle has great effect on vehicle handling. Positive caster angle centers the steering wheel after a turn and makes the tires straight again. Most street cars are made with (+4 degree) to (+6 degree) caster angle to enhance straight line stability. In case of an off-road vehicle with no power steering system installed, we keep caster angle limited between (+5 degree) and (+10 degree) because large angle makes the steering heavier and less responsive. For our design ,(+8.25 degree) static caster angle is used. Caster angles varies from (+8.1 degree) for maximum rebound travel to (+9.5 degree) for maximum bump travel.

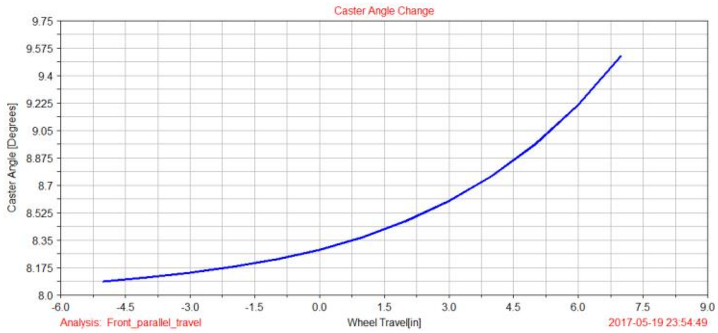

Fig. 5. Caster angle VS Wheel travel.

Also due to the geometry of positive caster, negative camber gain will increase when turning giving more stability to the vehicle. Mechanical or caster trail is related to the amount of caster angle and it affects the self-aligning moment that straightens the steering wheel when turning. The more is the mechanical trail, the less time needed by the wheel to return to static condition, the more effort required by the driver to turn the wheel. So, optimization is important to keep the mechanical trail and caster angle within preferred limit.

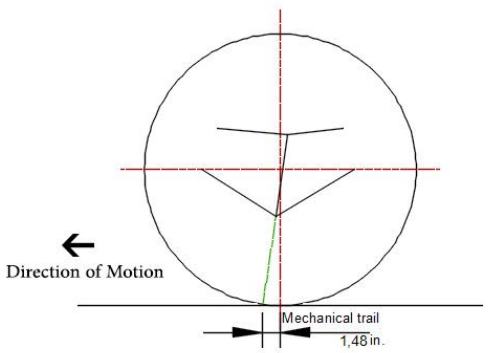

Fig. 6. Mechanical or caster trail (Side view).

3. Toe Angle:

When the leading edges of a pair of wheels are pointed toward each other, the wheel pair is said to have toe in. When pointed away from each other, the pair is said to have toe out. Toe angle has a great effect on straight line stability, steering and acceleration. It is very crucial to minimize toe angle change during wheel travel to avoid bump steer.

What is bump steer ?

Bump steer is when the wheel steers itself without input from the steering wheel and this happens due to the change in toe angle as the wheels travel. It is always important to minimize bump steer in front suspension to avoid undesirable wheel steering. The undesirable steering is caused by bumps in the track interacting with improper length or angles of suspension and steering linkages. In fact, this phenomenon happens because we are dealing with three dimension geometry, where the upper and lower ball joints are not on the same plan with the fixation point of the tie rod with the upright. So, the length of the tie rod is the controller in this case. By optimizing the tie rod hard points coordinates, we can minimize the bump steer as much as possible.

How to minimize or eliminate bump steer ?

Actually, we can not eliminate bump steer in rack and pinion steering system but our goal is to keep it miminum as possible. By changing the tie rod hard points coordinates to be as following:

a) Tie rod outer hardpoint should fall on the imaginary line that connects the upper and lower ball joints.

b) The line coonnecting the inner and outer tie rod hard points has to intersect the instantanoius center of the wheel which represents the center of rotation of the wheel as it bumps or rebounds.

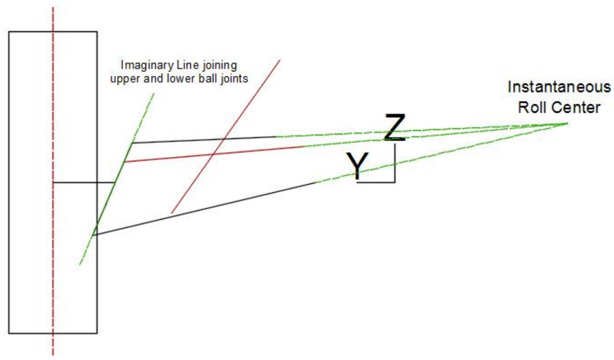

Fig. 7. Suspension and steering geometry to minimize bump steer.

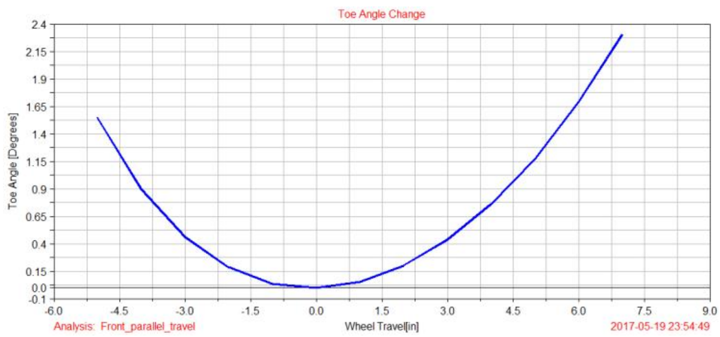

Fig. 8. Toe angle VS Wheel travel.

For our design, Static toe angle is zero. The toe change in full bump is (+ 2.3 degree) and in full droop the toe is (+1.5 degree). This is also the bump steer for the front suspension of the vehicle. It is minimal and can not be even seen by naked eye. It is advised to have little toe in static angle for the wheel to accommodate for the toe out effect caused by vehicle accerleration and to minimize tire wear.

4. Roll Center:

Instant roll center come from the study of kinematics of the front suspension geometry in a plan. When drawing imaginary lines joining the inner and outer ball joints of upper and lower a-arms, they will usually intersect at a point called the wheel instantaneous roll center. As the linkages is moved, the instant roll center moves. So proper geometric design is needed to establish all the centers in their optimum position and controls how fast and in what direction they move when the wheel travels. Roll center of the front suspension is the center of rotation of the body with respect to the ground and it can be found by drawing a line from the center of the contact patch of the left tire to its instant center then repeating these steps for the right tire, the roll center is located where these two lines cross.

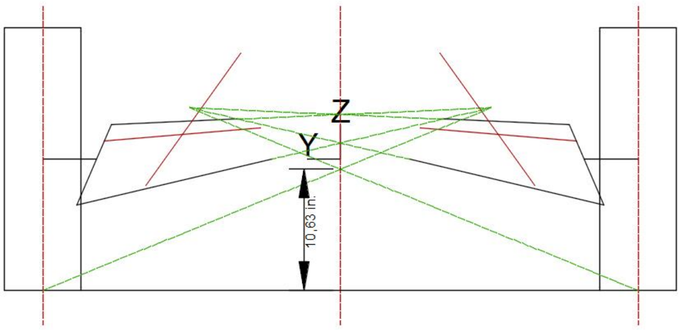

Fig. 9. Roll Center of the Front Suspension (Front view).

Optimization should be done to determine the best location of the roll center because it should be placed near the center of gravity of the vehicle to reduce roll moment and vertical roll center height should be above the ground all the time while the wheel travels.

Fig. 10. Vertical Roll Center Height from the ground VS Wheel travel.

5. Scrub Radius and kingpin inclination angle:

Kingpin inclination angle is the angle between the symmetric axis of the wheel and the imaginary line connecting the outer upper and lower ball joints when viewed from the front. Scrub radius is the distance between the center of the contact patch of the tire and the kingpin axis.

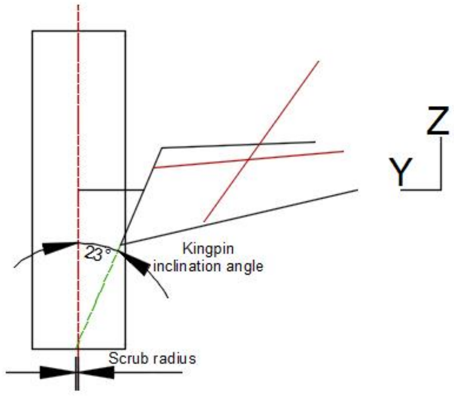

Fig. 11. Kingpin axis and Scrub radius.

Kingpin inclination angle and scrub radius have a significant effects on steering performance and packaging. The more is the kingpin angle, the more the car is lifted when steering. Also, camber gain while steering is affected by the amount of kinpin inclination angle. For off-road vehicles, positive kingpin angle is prefered with negative srucb radius to reduce steering efforts at low speeds and minimize tire wear.

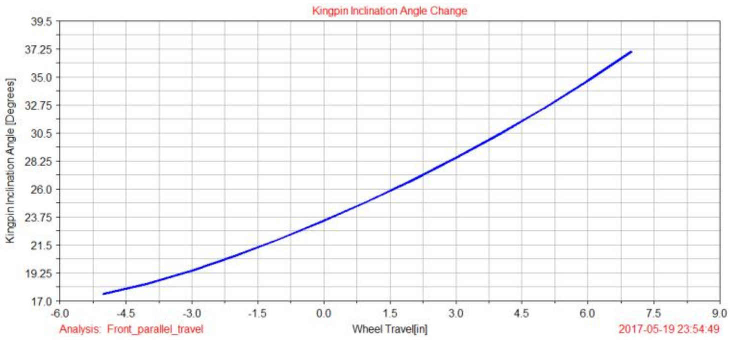

Fig. 12. Kingpin Inclination angle VS Wheel travel.

Scrub radius determines how the tire contact patch interacts with the road during cornering, braking and acceleration. Negative scrub radius makes the steering less sensitive to braking and compensates for brake system failure. It is preferable to have little scrub radius change with wheel travel to minimize tire wear and increase stability.

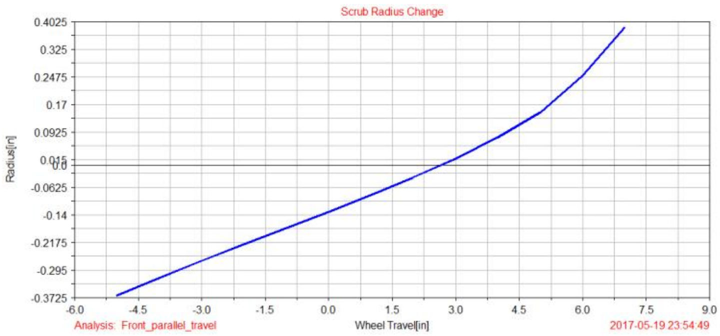

Fig. 13. Scrub Radius VS Wheel travel.

V. FINAL DESIGN SPECIFICATIONS

After hundreds of iterations using Adams/Car, here is the final design of the double wishbone suspension system.

TABLE I. OPTIMIZED SUSPENSION AND STEERING SPECIFICATIONS

Static Camber angle	Zero degree
Camber change when wheel travels	-14.5 to +5.25 degree
Static Caster angle	+8.25 degree
Caster change when wheel travels	+8.1 to +9.5 degree
Static Toe angle	Zero degree
Toe change when wheel travels	+ 2.3 to +1.5 degree
Static Roll Center Height from ground	10.63 inches
Static kingpin inclination angle	23 degree
Static Scrub radius	-0.14 inches

CONCLUSION

A comprehensive optimization of front suspension and steering systems of an off-road car was carried out using ADAMS software which generates graphs indicating vehicle performance. It is clear that changing one parameter usually affects other parameters, so the designer should optimize suspension hard points coordinates to achieve best possible performance. Design would be acceptable only if the value obtained are within limits.

REFERENCES

[1] Milliken, William F.,Milliken, Douglas L. (1995) Race Car Vehicle Dynamics.

[2] Ryan W. Timura. The university of Akron 2015 SAE Zips Baja off-Road racing Team 2015 Suspension system Design(2015).

[3] Reza N.Jazar.Vehcile Dynamics ; theory and application, 2nd edition.

[4] I.P. Dhurai. Optimization and effects of suspension parameter on front suspension of SAE Baja vehicle using Adams (2016). International Journal of Engineering Research & Technology, Vol. 5 Issue 09, September-2016.

[5] Avinash Singh. Off-Road suspension Design ; Ride and Handeling of BAJA buggies.

[6] Adams Manual and Software Package.

[7] Madhu Kodati, Sandipan Bandyopadhyay. Kinematic Analysis of the double Wishbone Suspension System.

[8] Udhav U. Gawandalkar, Ranjith M., Anshej Habin, Design, Analysis and optimization of suspension System for an off-road car. International Journal of Engineering Research & Technology, Vol. 3 Issue 9, September- 2014.

[9] Shpetim LAJQI, Stanislav PEHAN. Design of Independent suspension mechanism for a terrain vehicle with four wheels drive and four wheels steering.International journal of Engineering.

[10] Asst. Prof. N.Vivekanandan, Abhilash Gunaki, Chinmaya Acharya. International Journal of Mechanical Engineering, Volume 2, Issue 6, June,2014.

[11] Thomas D. Gillespie. Fundamentals of Vehicle Dynamics.