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# Modelling and simulation of full vehicle to study its dynamic behavior

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*Abstract*—**Integration of Multibody Systems Analysis with Design of Experiments creates a powerful combination of tools for thorough investigation of a specified design space, identification of the optimal system configuration, and the illustration of the effects on system changes on a given output. Classical Vehicle dynamics uses a mathematical model for evaluation of handling characteristics. This study is to demonstrate the use of modelling and simulation in assessing the performance of the whole vehicle system using Multi body system software and plot the effect of Kinematic and Compliance characteristics using virtual model. Step by step building complete vehicle model in Adams/Car, independently modelling various subsystems such as front suspension, steering, rear suspension, body, Powertrain, brakes and wheels as per vehicles specification. All these subsystems integrated to make full vehicle assembly. After validation of the virtual model, study the effect of these Kinematic and Compliance characteristics on handling performance of the vehicle. The vehicle mass, cornering stiffness of tires, the distance of center of gravity from both axles and vehicle speed are the parameters considered in the vehicle handling analysis. Compare these results with actual measurements done on a physical prototype using Suspension parameter measuring machine. Further testing of the vehicle model as per ISO guidelines and analyzing the impact of selected Kinematic and Compliance variables on the vehicle handling behavior.**

*Index Terms*— **Kinematic and Compliance, Suspension parameter measuring machine, Automatic Dynamic Analysis of Mechanical Systems (ADAMs)**

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## I. INTRODUCTION

Simulations in various mechanical systems using computers is becoming increasing important in many areas of engineering. The power of such programs lies in their ability to accurately simulate real world mechanical systems using computer code and equations. This eliminates design iterations of the prototype, lab testing and model revision. This reduction in hardware constructions saves time and money. Because of this and other benefits afforded by such digital simulation programs, their use is becoming more and more widespread. One of the dominant users of these programs is the automotive industry which is using ADAMs and other similar programs to do many types of studies, such as vehicle dynamics.
Vehicle Dynamics is the study of body motion of complete vehicle. The total vehicle system is subjected to different degrees of free motion. The interaction of these movements, each with its own velocity, acceleration, and frequency, makes a road vehicle one of the most complex systems in the field of dynamics. One objective of this study is to demonstrate the use of modeling and simulation in assessing the performance of the whole vehicle system using Multi body system software. And plot the K&C characteristics using virtual model, compare these results with actual measurements done on a physical prototype using Suspension parameter measuring machine. After validation of the virtual model, study the effect of these K&C characteristics on handling performance of the vehicle. Step by step building the vehicle model in Adams/Car and comparing the suspension K&C plots with those obtained from actual SPMM machine and thus validating the model. Further it continues with the testing of the vehicle model as per ISO guidelines and analyzing the impact of selected K&C variables on the vehicle handling behavior.

## II. LITERATURE REVIEW

1. Reza Kazemi and Kaveh Soltani et al- In this paper, the effects of important design parameters on passenger cars untripped rollover were discussed and sensitivity of vehicle to some of parameters was determined. The prediction and simulation of vehicle rollover is very difficult. It needs additional modeling based on empirical data by taking energy dissipation, nonlinearities and effects of vehicle surrounding parameters like road surface, embankment into consideration. Based on the results of this study, conclusions are drawn that vehicle is very sensitive to the distance from body C.G. to roll axis, and the sensitivity is strongly related to other parameters such as inertia properties, maximum suspension travel, and suspension stiffness and damping. Also adjusting vehicle parameters to make vehicle more stable, needs very careful attention of an expert. Some vehicle design parameters have adverse and nonlinear effects on vehicle responses.
2. Aleksander Hac et al– In this paper the effects of some design parameters of passive independent suspensions on rollover propensity of vehicles with high center of gravity were examined. A model derived from simple physical principles was projected to evaluate vehicle rollover. The model includes the effects of lateral movement of vehicle center of gravity during body roll, the effects of suspension jacking forces, the effects of tire lateral compliance, of gyroscopic forces, and the effects of dynamic overshoot in the roll angle. A simplified formula was derived for the lateral acceleration at the rollover threshold, which includes the effects of suspension

design parameters, such as roll stiffness and damping, stiffness in the heave mode and locations of roll centers. To improve rollover resistance the design parameters and guidelines for suspension were discussed. In particular, an analytical expression for the optimal roll center height from the viewpoint of rollover resistance was developed. The analytical results obtained are supported by the results of simulations, which show that the lateral accelerations at the rollover threshold predicted by the model are in a reasonably good agreement with the results of simulations.

3. Orlandea et al- This paper describes a computer simulation of the front suspension of a Chevrolet using the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) computer program. The model was proposed by the SAE fatigue design and evaluation on committee for evaluating the speed, economy and accuracy of various computer simulations in predicting displacements and loads in a suspension system.

In this paper author concluded that there is a substantial disagreement between experimental and simulated loads. Most of these errors are produced by the following factors like: Linear approximation of forcing effects, neglecting friction, representing the elastic bushing as ideal joints,

This model suggests that displacement behavior of the suspension can be simulated more accurately than reaction force.

4. Tatsuya Fukushima et al– Vehicle was modeled using finite element to represent tires and kinematics of the front and rear suspension systems. This vehicle model was used to simulate dynamic behavior of the vehicle like cornering and braking situation, including extreme conditions. The tires and suspension systems are fully modelled using finite elements and connected to a rigid body that represents the whole vehicle body. The model is used to perform cornering and braking behavior simulations and the results were compared with experimental data. In cornering behavior simulation; lateral acceleration and yaw rate calculated at vehicle CG where as in braking behavior simulation; longitudinal acceleration calculated shows good experimental results.

## III. PROBLEM STATEMENT

Transient behavior describes vehicle handling characteristics in response to transition from straight-line motion into a turn or to a sudden course change. With a large time lag between steering input and rise in yaw rate, the vehicle feel sluggish and unwilling to corner. To improve transient behavior of the vehicle it is very important to identify the parameters which are largely determine the driver assessment of the vehicle. To identify these critical parameters and their governing design variables; work will be the analysis of the suspension characteristics & improve handling properties by varying values of its governing design variables. Transient handling analysis of full vehicle system using ADAMs and experimental results.

## IV. OBJECTIVE

The main factors have considered completing the research paper as follows:

1. Prediction of Kinematic & Compliance characteristics of vehicle suspension, steering systems using Adams/Car software
2. Measurement of Kinematic & Compliance characteristics of vehicle suspension using Suspension parameter measuring machine (SPMM).
3. Comparison of results obtained using Adams/Car and Suspension parameter measuring machine.
4. Identify the critical suspension parameters for better vehicle handling performance.

## V. METHODOLOGY

1. Study of literature survey & fundaments of vehicle dynamics - Collection and study of research papers and books relative to the objective
2. Learn ADAMS software & develop full vehicle model. Modelling of different vehicle sub-systems in Adams/Car (steering, suspension (front & rear), body, tire, brakes and powertrain). Assembling these sub-systems to make a full vehicle model
3. Simulating Kinematic and compliance analysis & measuring its characteristics - Setting up complete suspension assembly & Perform wheel travel analysis (parallel & opposite) using kinematic and compliance characteristics in Adams/Postprocessor
4. Comparison of results and model validation. Compare kinematic and compliance analysis results obtained from Adams/Car with those obtained from physical prototype on SPMM.
5. Simulating handling test iterations; conduct maneuvers/tests of geometrical suspension parameters (toe angle, track width, caster angle, scrub radius, camber angle). Use Adams/Postprocessor to plot & analyze results. Identify critical suspension parameters for better handling performance.

*2. Modelling of different vehicle sub-systems in Adams/Car:*

ADAMs is an interactive motion simulation software for analyzing the complex behavior of mechanical assemblies. ADAMs allows virtual testing of prototypes and optimize
designs for performance, safety, and comfort, without building the physical prototypes. Building a solid model of the mechanical system from major CAD systems. Apply joints and constraints while creating articulated mechanisms of virtual prototypes.

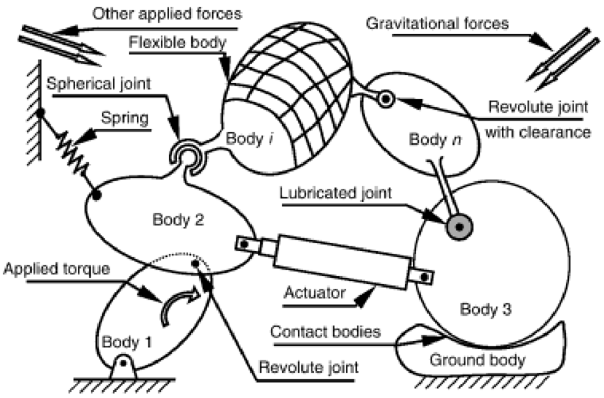



Fig. 1 Schematic representation of Multi body system.

Various vehicle modules prepared in ADAMS system are:

*a) Front Suspension System:*

Modeling of vehicle consists following subsystems; body, front suspension, steering, rear suspension, tire, powertrain and brakes. The vehicle used for this study is having double wishbone with coil spring type front suspension. Modelling of suspension system is begun with plotting hard points.

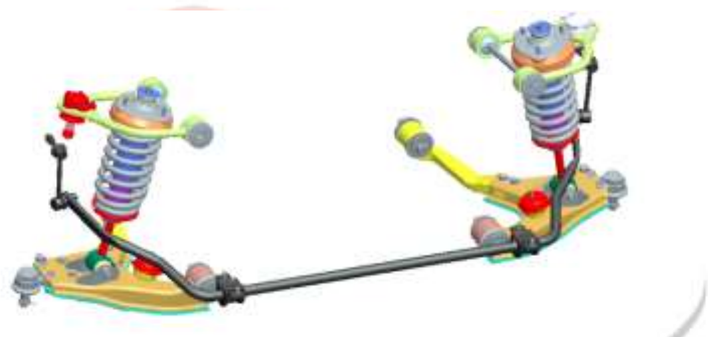


Fig. 2 Different Parts of Front Suspension

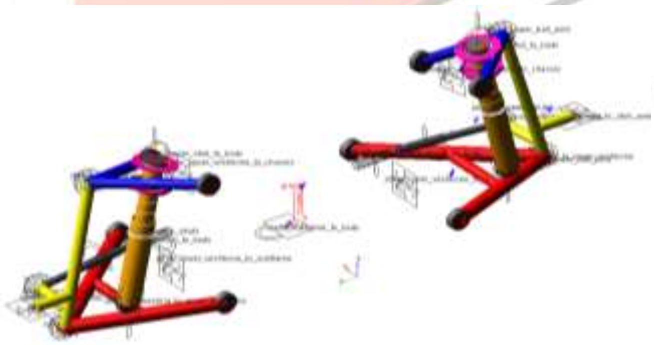


Fig. 3 Front Suspension Model in Adams/Car

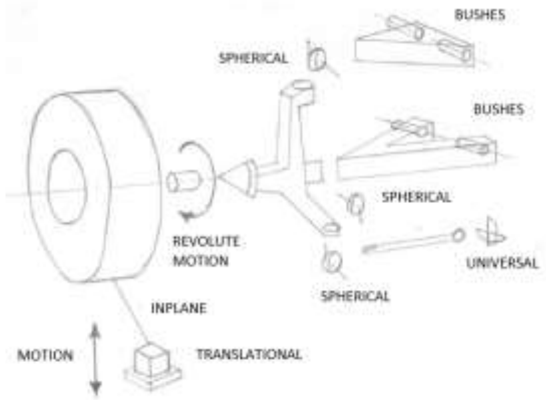



Fig. 4. Double Wishbone Suspension Modelled With Bushes

The hard point coordinates for front suspension are as per table 1, these points belongs to right hand side of the suspension. As the suspension is symmetrical about the vertical center plane of the vehicle, the left hand side hard points are found out by putting negative valve for the y-coordinate.

Table I. Hard point Coordinates for Front Suspension

| Location | | X (mm) | Y (mm) | Z (mm) |
|---|---|---|---|---|
| Wheel center | | 0 | 790 | -78 |
| Track center | | 0 | 790 | -410 |
| Lower wishbone | Ball joint | -6 | 708 | -173 |
| | Front Pivot | -155 | 345 | -156 |
| | Rear Pivot | 277 | 345 | -156 |
| Upper wishbone | Ball joint | 21 | 611 | 240 |
| | Front Pivot | -173 | 402 | 254 |
| | Rear Pivot | 67 | 402 | 254 |
| Rack & Pinion | On Rack | 164 | 400 | -121 |
| | On stub axle | 130 | 682 | -124 |
| Damper | On Chassis | -60 | 476 | 294 |
| | On lower W/B | -60 | 560 | -121 |

Table II. Mass and MI Properties for Front Suspension Parts

| Part Name | Mass | Ixx | Iyy | Izz |
|---|---|---|---|---|
| Upper control arm | 3.54 | $2.3 \times 10^4$ | $4.1 \times 10^4$ | $6.3 \times 10^4$ |
| Lower control arm | 11.6 | $1.2 \times 10^4$ | $2.1 \times 10^4$ | $3.2 \times 10^4$ |
| Steering Knuckle | 8.2 | $2.2 \times 10^4$ | $1.1 \times 10^4$ | $1.2 \times 10^4$ |
| Tie rod | 0.86 | $2.2 \times 10^4$ | $1.02 \times 10^4$ | $1.03 \times 10^4$ |

*b) Steering System:*

The steering inputs required to vehicle are applied as motion or torque inputs at this joint. The steering rack part is connected to the vehicle body by a translational joint and connected to the tie rod by a universal joint. The translation of the rack is related to the rotation of the steering column by a coupler statement that defines the ratio.

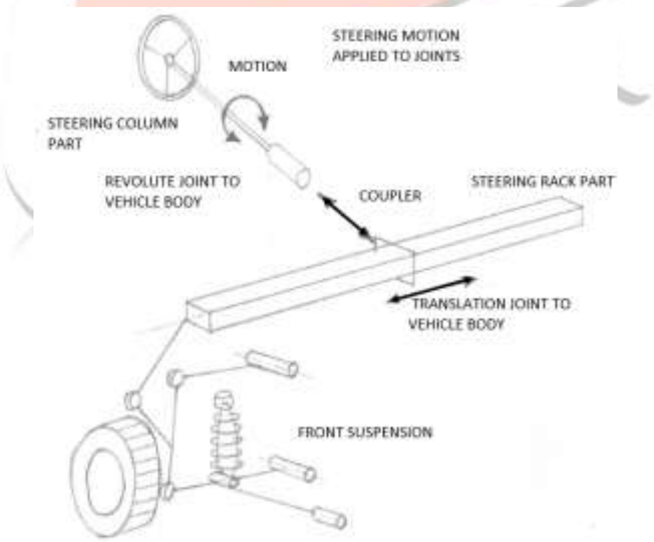



Fig 5. Parts and Joints Involved in Steering System

In order to implement the ratios used in the coupler, linking the rotation of the steering column with the steer change at the road wheels it is necessary to know the steering ratio. Hard points of steering system modeling shown in table III.

Table III. Hard point Co-ordinates for Steering System

| Location | X (mm) | Y (mm) | Z (mm) |
|---|---|---|---|
| Rack house mount | 164 | 375 | -121 |
| Tie Rod inner | 164 | 400 | -121 |
| Intermediate shaft forward | 400 | 300 | 500 |

| Location | X (mm) | Y (mm) | Z (mm) |
|---|---|---|---|
| Rack house mount | 164 | 375 | -121 |
| Intermediate shaft rearward | 550 | 300 | 600 |
| Pinion pivot | 164 | 300 | 121 |
| Steering wheel center | 900 | 300 | 700 |

*c) Rear Suspension System:*

Four-link type rear suspension is modeled in similar way as explained in front suspension. The springs are modeled as per the L-D characteristics.

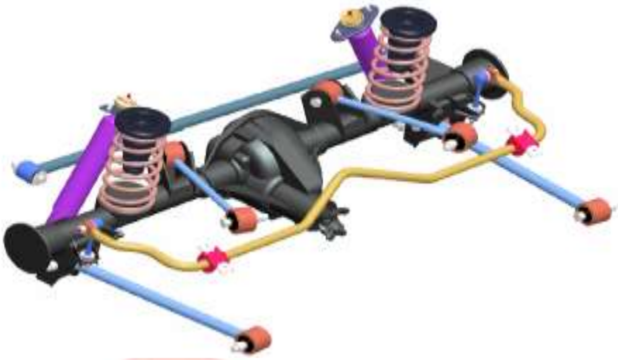


Fig. 6 Rear Four Link Suspension

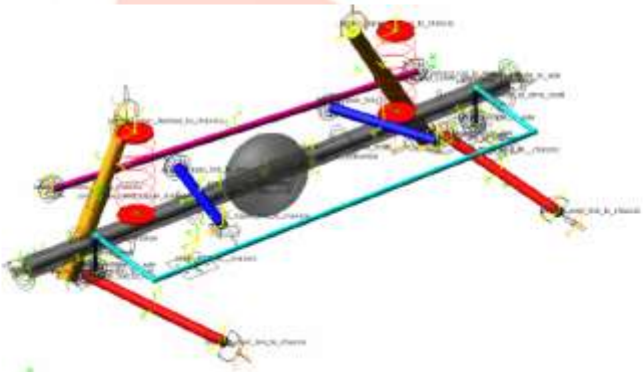


Fig.7 Rear Suspension Model in Adams/Car

*3. Simulating Kinematic and compliance analysis & measuring its characteristics:*

*a) Using ADAMS/CAR:*

A steering sub-system and a front suspension sub-system, plus a suspension test rig, form the basis of a suspension assembly that is analyzed for kinematic behavior. Several parameters about the vehicle which include vehicle's wheel base and sprung mass, un-sprung mass, wheel drive, braking ratio, loading conditions. For this analysis, front-wheel drive a brake ratio of 70% front and 30% rear are assigned.

*Parallel & opposite/crossed wheel travel:*

For this analysis, ADAMS/Car software generates a load case file based on specified inputs road load data. The test rig applies forces or displacements, or both to the assembly. During parallel wheel travel analysis both wheel centers move from -75 mm to +105 mm relative to their input position, while holding the steering fixed. Whereas during opposite travel

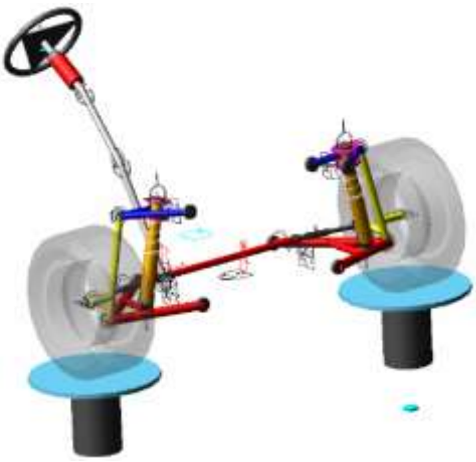


Fig. 8 Adams/Car MDI Suspension Test Rig

analysis, when one wheel goes in bump the other wheel simultaneously goes in rebound. This analysis is performed to simulate roll behavior of the vehicle. During the wheel motion, various suspension & steering characteristics, such as camber and toe angle, wheel rate, and roll center height are calculated.

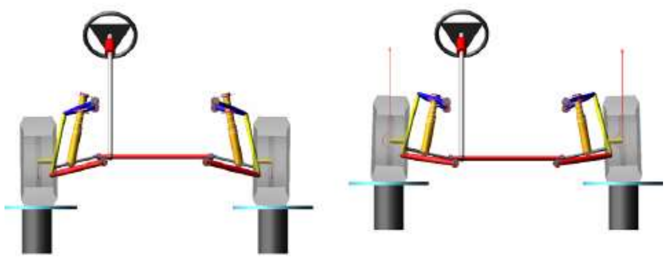


Fig. 9 Parallel Wheel Travel Analysis Using MDI Test Rig

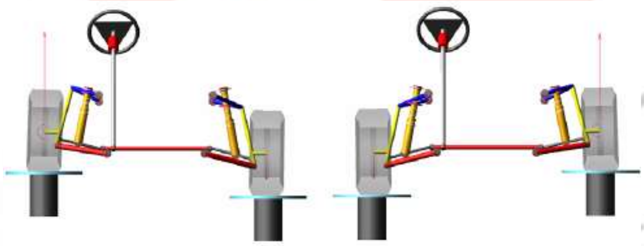


Fig. 10 Opposite Wheel Travel Analysis Using MDI Test Rig

*b) Suspension analysis using K & C test rig:*

Standard Suspension Parameter Measuring Machine (SPMM) is designed to measure the quasi-static suspension characteristics. Also it qualifies tests performed at higher frequencies to characterized dynamic properties which are important for vehicle's ride and handling.

Fig. 11 Suspension parameter measuring machine (SPMM) test rig.

The machine can impart a wide variety of displacements, forces and moments to quantify a wide range of suspension characteristics; like suspension stiffness, bump-steer, roll-steer, roll stiffness distribution, longitudinal & lateral compliance. Various measurements are made at the wheel center & most commonly calculated outputs are as listed below:

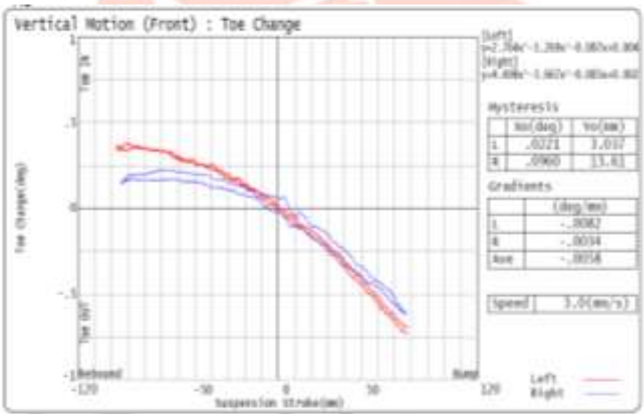
| | |
|---|---|
| Bump movement | Caster angle |
| Half-track change | Camber angle |
| Steer Toe angle | Steering inclination |
| Roll center height | Wheel rate. |

*4. Comparison of results and model validation.*

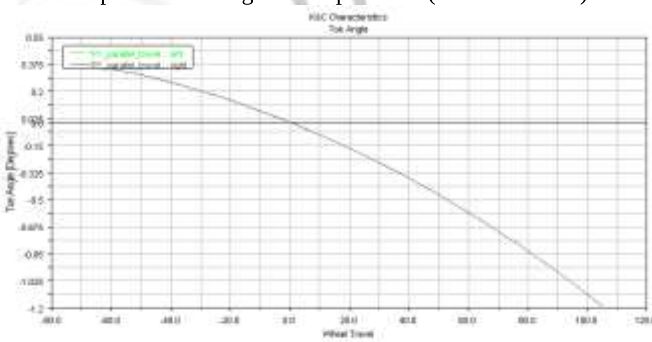
An actual prototype under development is mounted on SPMM. The wheels are subjected to vertical displacement and roll displacement. An exercise conducted on the suspension test rig with the use of ADAMS virtual test, where front suspension with steering system is mounted on the test rig. Parallel & opposite wheel travel analysis are performed and results are plotted in ADAMS/ post-processor. The plots are evaluated based on the three criteria, viz. nature of curve, values obtained and gradients of the curve.

1. *Simulating Kinematic and Parallel wheel travel*

*1.1 Measured Parameter: Toe angle*

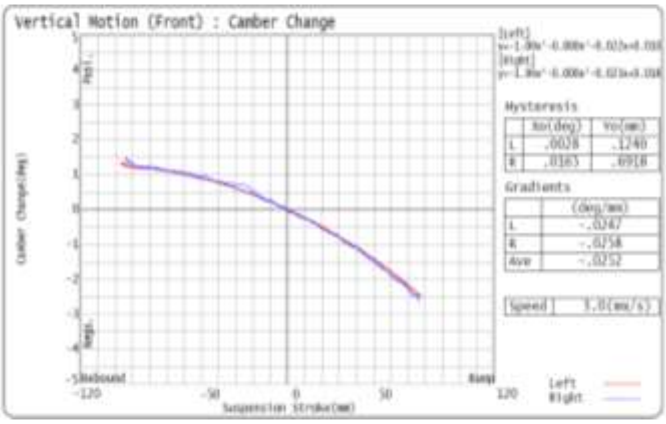



Graph 1. Toe change Vs Susp. Stroke (SPMM Results)

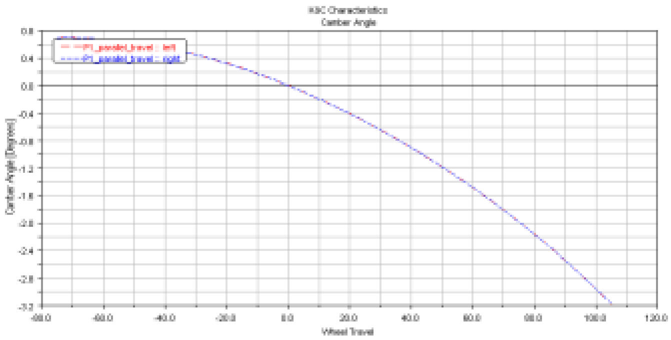



Graph 2. Toe change Vs wheel travel (Adams/Car Results)

*1.2 Measured Parameter: Camber angle*

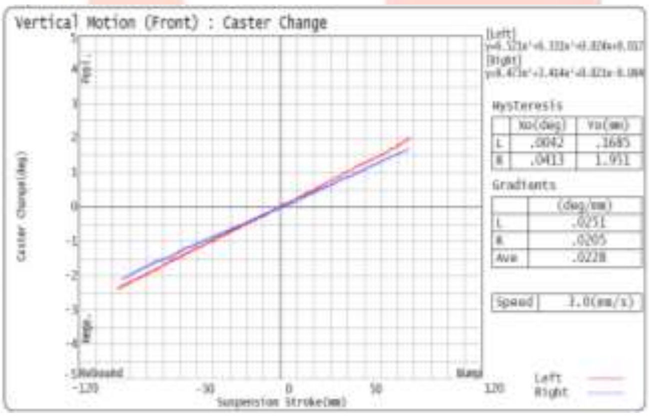



Graph 3. Camber change Vs Susp. Stroke (SPMM Results)

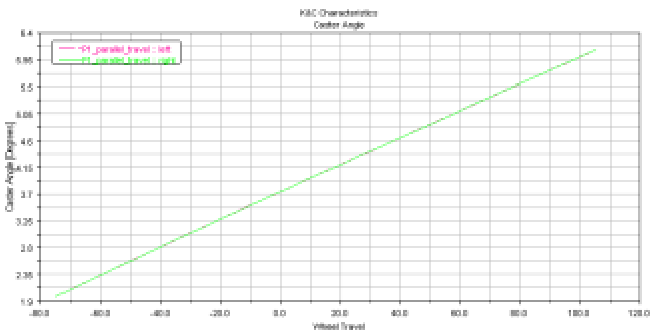



Graph 4. Camber angle Vs wheel travel (Adams/Car Results)

*1.3 Measured Parameter: Caster Angle*

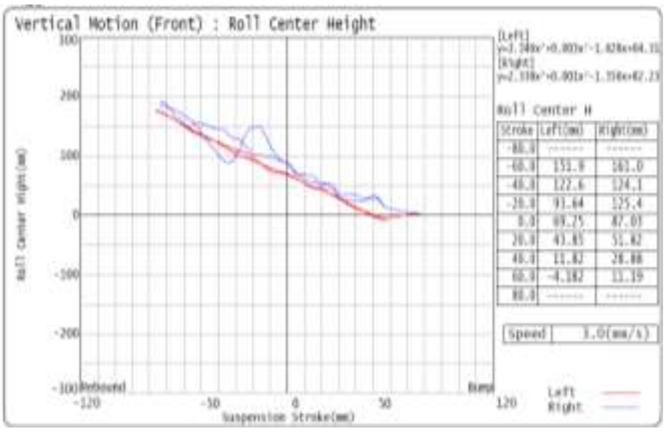



Graph 5. Caster change Vs Susp. Stroke (SPMM Results)

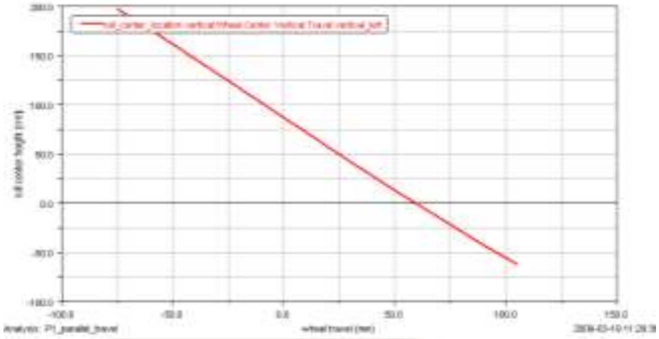



Graph 6. Caster angle Vs wheel travel (Adams/Car Results)

*1.4 Measured Parameter: Roll Centre Height*



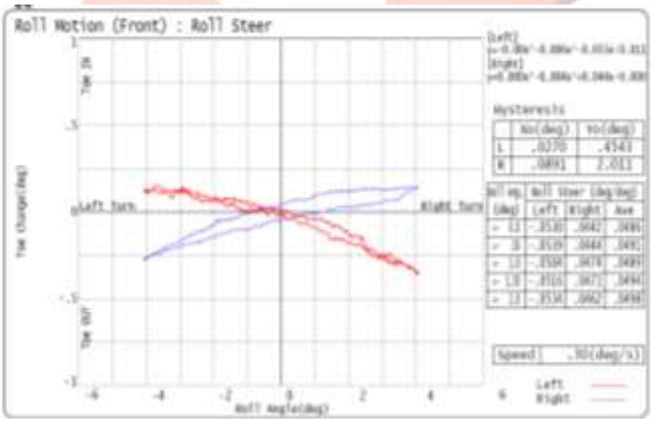

Graph 7. Roll center ht. Vs Susp. Stroke (SPMM Results)



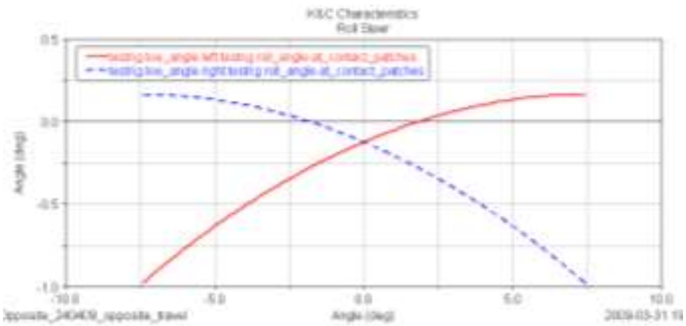
Graph 8. Roll center ht. Vs wheel travel (Adams/Car Results)

*2. Roll Motion Analysis: opposite wheel travel*

*2.1 Measured Parameter: Roll Steer*

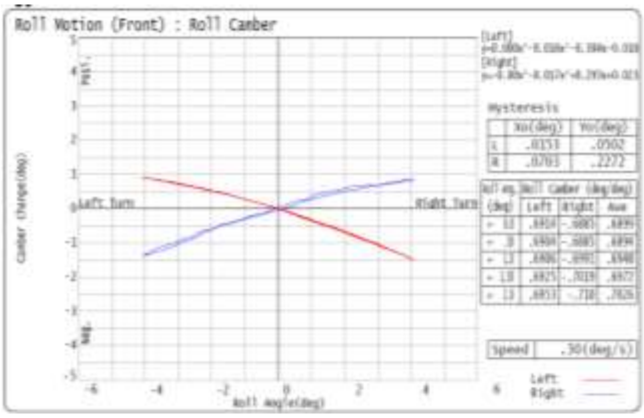



Graph 9. Toe change. Vs Roll angle (SPMM Results)

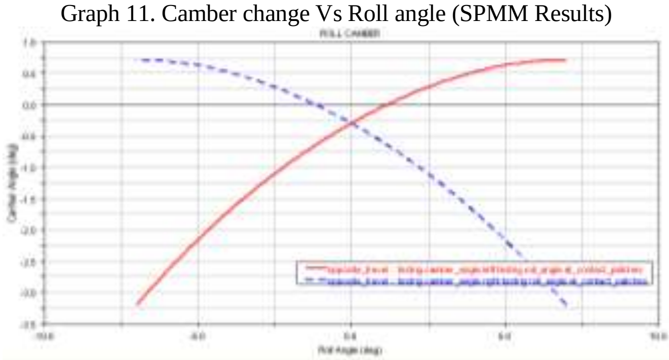



Graph 10. Toe angle Vs Roll angle (Adams/Car Results)

*2.2 Measured Parameter: Roll Camber*

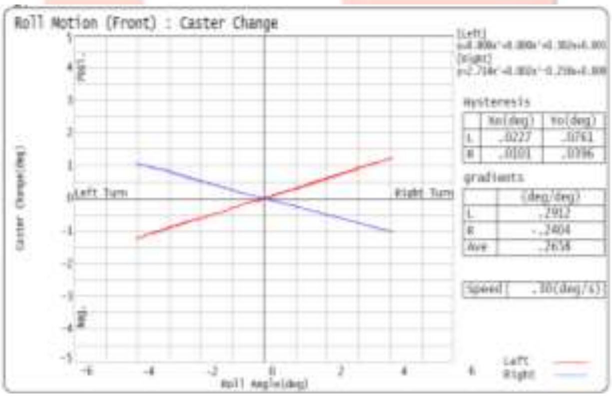



Graph 11. Camber change Vs Roll angle (SPMM Results)

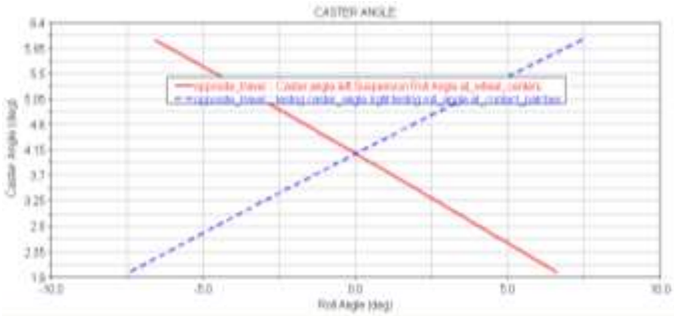



Graph 12. Camber angle Vs Roll angle (Adams/Car Results)

*2.3 Measured Parameter: Caster Change*

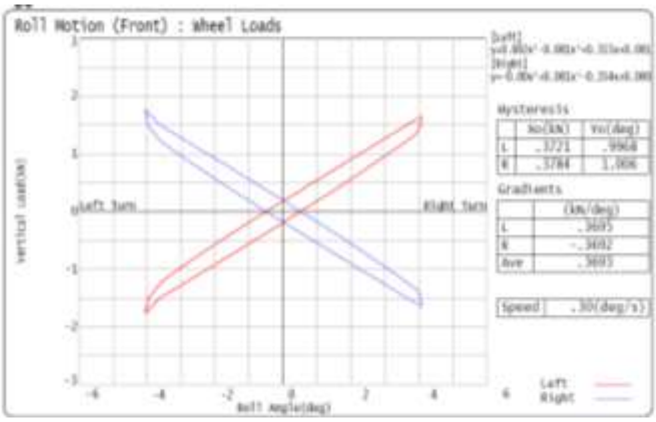



Graph 13. Caster change Vs Roll angle (SPMM Results)

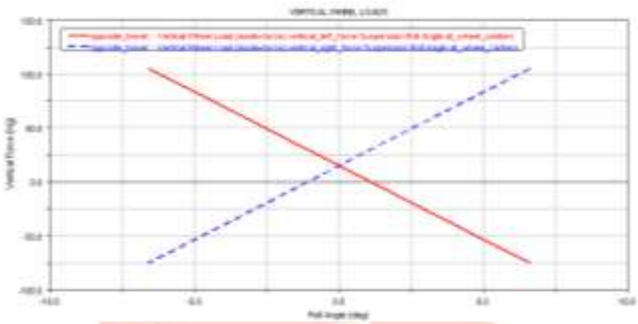



Graph 14. Caster change Vs Roll angle (Adams/Car Results)

*2.4 Measured Parameter: Vertical Wheel Loads*




Graph 14. Wheel loads Vs Roll angle (SPMM Results)



Graph 16. Wheel loads Vs Roll angle (Adams/Car Results)

## VI. RESULTS AND VALIDATION

An exercise is undertaken to correlate the results obtained from ADAMS/Car with those obtained from the SPMM. The co-relation of values is summarized as following:

Table IV. Comparison of vertical motion analysis

| **Parameters** | **Results** | | **Co-relation of values in %** |
|---|---|---|---|
| | **(SPMM)** | **(ADAMS)** | |
| Toe angle | 0.0058 | 0.006 | 90 |
| Camber angle | 0.025 | 0.020 | 78 |
| Caster angle | 0.0228 | 0.0230 | 84 |
| Roll center height | 1.25 | 1.50 | 76 |

Table V. Comparison of Roll motion analysis

| **Parameters** | **Results** | | **Co-relation of values in %** |
|---|---|---|---|
| | **(SPMM)** | **(ADAMS)** | |
| Roll Steer | 0.078 | 0.085 | 80 |
| Roll Camber | 0.220 | 0.277 | 78 |
| Caster angle | 0.265 | 0.293 | 88 |
| Wheel loads | 0.369 | 0.320 | 76 |

## VII. CONCLUSION

The following are the some major conclusions drawn from this dissertation work:

1. The kinematic and compliance characteristics are predicted using Adams/car and the results obtained are shown in the form of graphs.
2. Also these kinematic and compliance characteristics are measured on suspension parameter measuring machine and the results obtained are shown in the form of graphs.
3. By following the comparison made between Adams/Car and SPMM results, conclusion can be drawn that Adams/Car results match very well with the corresponding SPMM results. On an average the co-relation obtained in the values is 83%.
4. By randomly choosing five geometrical suspension parameters, handling test iterations are carried out in Adams/Car by assigning different values to these parameters.
5. After comparing the obtained results, conclusion can be drawn that, out of the chosen five parameters, toe angle and caster angle had profound impact on the vehicle's overall handling behavior. Even a slightest change in the value of toe and caster angle was inducing large change in the vehicle's understeer gradient.
6. Also it is seen that, on the other hand, the remaining parameter viz. camber angle, track width, scrub radius did not had any appreciable influence on the vehicle cornering ability as well as transient roll over stability.
7. Using this knowledge, automobile designer will be able to focus only on these critical parameters to achieve good handling performance.
8. Using the method of virtual prototyping, reduction in development time and cost can be achieved.

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