بسم الله الرحمن الرحيم

STUDY OF AUTOMOTIVE HANDLING AND RIDING CHARACTERISTICS USING ADAMS SOFTWARE

BY

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**A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF ENGINEERING
IN
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SUPERVISED BY

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COLLGE OF ENGINEERING AND TECHNOLOGY

PALESTINE POLYTECHNIC UNIVERSITY

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STUDY OF AUTOMOTIVE HANDLING AND RIDING CHARACTERISTICS USING ADAMS SOFTWARE

The Senior Project Entitled:

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HUSAM SAMI **MAMOUN HROUB**

In accordance with the recommendations of the project supervisor, and the acceptance of all examining committee members, this project has been submitted to the Department of Mechanical Engineering in the College of Engineering and Technology in partial fulfillment of the requirements of Department for the degree of Bachelor of Science in Engineering.

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كلية الهندسة والتكــنولوجيا
دائرة الهندسة الميكانيكية

اسم المشروع

Study of Automotive Handling & Riding Characteristics Using ADAMS Software.

أسماء الطلبة

حسام سيد احمد   مأمون الحروب

بناء على نظام كلية الهندسة والتكنولوجيا وإشراف ومتابعة المشرف المباشر على المشروع وموافقة أعضاء اللجنة الممتحنة تم تقديم هذا المشروع إلى دائرة الهندســـــة الميكانيكية وذلك للوفاء بمتطلبات درجة البكالـــوريوس في الهندســـــة تخصص هندسة السيارات وهندسة الميكاترونكس.

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DEDICATION

To our parents who

spent nights and days doing their Best

to give us the best...

To all students and who

Wish to look for

the future...

To whom who loves the knowledge and

Looking for the new

in this world...

To who carry candle of science

To light his avenue

Of life...

To our Beloved country Palestine...

To all of our friends...

Project Team

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Abstract (English)

The idea of the presented project, is to introduce software for monitoring and development of performance of vehicles on the road. Through the usage of vehicle simulation program **ADAMS**, that enables full simulation of a vehicle to be selected, and compare the actual results with the results of the simulation process on this program, and giving the proposed solutions and development, in some cases, for achieving an engineering product that can be effective and highly efficient.

The project includes several stages, begins with collecting the information required for vehicle to be tested, and then applying ADAMS/Car and trying to apply the theoretical principle, that have been studied through specialization, on a dynamic behavior of the vehicle, whether on straight or cornering maneuvers, to reach developing a system work on control the systems of suspension, steering, and brake systems in advanced stage, with special consideration to the centre of gravity, which will form the basis for work on the God willing.

Abstract (Arabic)

تقوم فكرة المشروع على إدخال برامج الحاسوب في عمليات المراقبة والتطوير لأداء المركبات على الطريق، حيث سيتم استخدام برنامج ADAMS لعمل محاكاة لمركبة يتم اختيارها، ومقارنة النتائج العملية مع نتائج المحاكاة على هذه البرامج، وإعطاء الحلول المقترحة والتطويرية في بعض الأحيان للوصول إلى منتج هندسي يمكن استخدامه بطريقة فعالة وبكفاءة عالية.

المشروع يشتمل على عدة مراحل، تبدأ بجمع المعلومات المطلوبة للمركبة المراد اختبارها، ثم التطبيق على برنامج ADAMS ومحاولة تطبيق المبادئ النظرية التي تم دراستها من خلال التخصص على الناحية الديناميكية للمركبة، سواء القيادة المستقيمة أو القيادة على المنعطفات وغيرها من أنواع وإشكال القيادة، من اجل الوصول لتطوير نظام تحكم خاص بالمركبة ليعمل على ضبط أنظمة التوجيه والقيادة مع أنظمة التعليق.

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List of Symbols

Symbol	Title
ADAMS	Automatic Dynamic Analysis of Mechanical Systems.
COG	Center Of Gravity.
ECU	Electronic Control Unit.
PLC	Product Life Cycle.
DADS	Dynamic Analysis Design System.
F	Front.
R	Rear.
L	Left.
RI	Right.
FL	Front Left.
S	Stiffness.
D	Damping.
SQUARE	Means Increase Damping.
SQRT	Means Decrease Damping.
ALL	All Suspension.

Chapter One

Introduction

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Chapter One

Introduction

1.1 General Outlook

Growing worldwide populations increasingly requires faster, safer and more efficient transportation systems. Most of the world's people and cargo are transported by vehicles that move on rubber tires over various roadways construction and quality. The number of such vehicles, increases continually with a growing positive impact on accessibility and a growing negative impact on interactions among humans and their relationship to the surrounding environment.

In particular, the safety of vehicular traffic depends on a man-vehicle-road system that includes both active and passive security controls, and that must be in high level of search and dealing with, since our life is the most important thing we have.

Today's vehicles rely on a number of electronic control systems. Some of them are self-contained, stand-alone controllers fulfilling a particular function while others are co-ordinated by a higher level supervisory logic. Examples of such vehicle control systems include braking control, traction control, acceleration control, lateral stability control, suspension control and so forth. Such systems aim to enhance ride and handling, safety, driving comfort and driving pleasure.

As said, the overall demands on a vehicle are that it should provide safe and comfortable transportation together with good environmental protection and good fuel economy. This means that there are three main objectives for automotive control systems summarized by the following:

- Safety is of course a key issue.
- Efficiency, which leads to lower fuel consumption.
- Emissions, which means protection of the environment.

Due to high costs when developing new vehicle models, computer simulations of vehicle dynamics become more and more important in the product development process. Vehicle dynamics is today a narrow area on the market, which means that it is uneconomic for most small companies to own required licenses for these software's since they only use them temporary. Software used in structural analysis are much more common in the industry today and simulating vehicle dynamics with this kind of software could result in large economic savings and new possibilities.

This Project work investigate the possibility to perform handling and riding simulations in ADAMS/Car from MSC.Software, chosen because it is one of the most common software on the market today used for vehicle dynamic simulation.

Handling simulations of vehicles mean different types of curved maneuvers during different circumstances. Ride simulations of vehicles imply investigation of influences from roughness in the road causing vibrations in the vehicles, but unfortunately it's impossible to carry each in a separate time, since there is a strong correlation between them.

Also as mechanical engineering students to graduate, we working on automotive project, since we have frequently felt the need for a project that deals with common vehicle dynamics control systems, and the dynamic models used in the development of these control systems. A mechatronics engineer needs models that are both simple enough to use for control system design but at the same time rich enough to capture all the essential features of the dynamics, that we must prepare it.

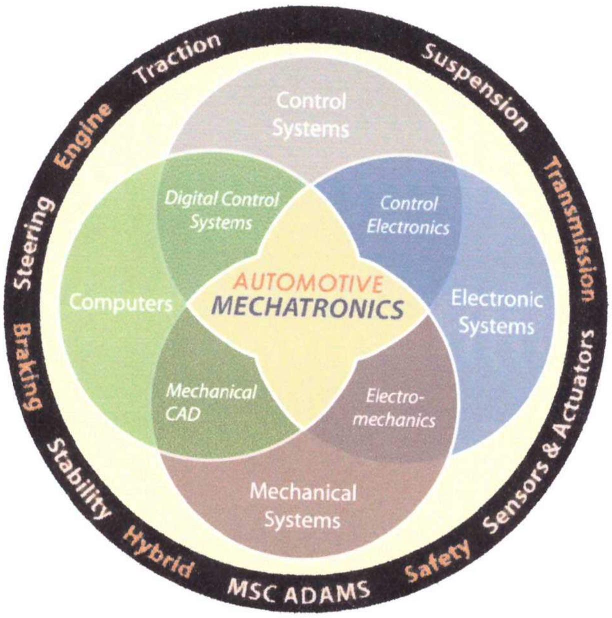

Figure1.1- Integration between many systems that resulted in automotive-mechatronics connection.[8]

1.2 Project Goal

The main purpose of this thesis work is to examine the possibility to perform vehicle dynamics simulations of handling and riding characteristics using ADAMS/Car software, and to use the result in building a control scheme that improving the vehicle stability system, taking into account the systems used and manufactured, and help to improve it.

ADAMS/Car layout is shown in Figure (1.2).

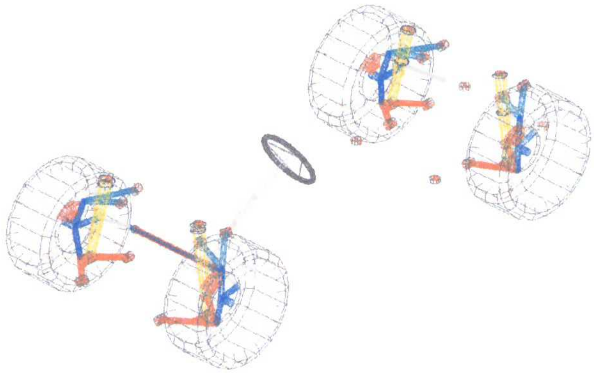

Figure1.2- ADAMS/Car layout.[10]

1.3 Importance of the Project

This project will focus mainly on studying automotive dynamics in contact with ADAMS/Car software, also:

1 Applying theoretical knowledge in automotive application to show the flexibility of the software based design.

2. Study the response of an automotive steering and suspension, using computer, to show the response according to several inputs, and at different time periods.

3. Propose improvement to the efficiency of the vehicle systems studied, to make the design more ideal, using the results taken from the software used.

4. Make a scheme for a developed system and controller, that can interact with the main auto electronic control unit (ECU), to improve the vehicle handling and riding characteristics.

1.4 Literature Review

The study of automobile stability and control is a relatively new field. Although significant quantities of automobiles were being produced in the early 1900, few efforts were made to quantify the handling and riding issues.[6]

Much of the early development was done on a "cut and try" basis. The majority of the effort prior to 1925 was expended in designing suspensions which would keep the tires in contact with the ground as much as possible in order to enable more effective steering control. This preoccupation with controllability is typical of the early work. Progress in the area of automotive stability was not seen until the 1930.[4]

During the 1930, the Cadillac Suspension Group of General Motors, under the direction of Maurice Olley, developed the first independent front suspension used on an American car. It was found that certain steering geometries led to a condition which the group termed oversteer. It was recognized that these geometries led to vehicles which were unsafe at high speeds. Olley's oversteer is recognized today as being roll oversteer.[13]

By the early 1980s, a shift in the vehicle modeling process was taking place. The demand for accurate vehicle dynamics models combined with the difficulty in deriving the equations of motion for large multi-body systems, led to the use of general multi-body simulation [MBS] codes.[2]

A wide range of capabilities are present in modern MBS codes including the ability to handle non-inertial reference frames, to incorporate flexible elements in the model, to utilize generalized coordinates, and to symbolically generate the equations of motion.

R. J. Antoun, discussed a vehicle dynamic handling computer simulation created using the multibody code ADAMS (*Automatic Dynamic Analysis of Mechanical Systems*) in a paper which was published in 1986.[13]

A model of a 1985 Ford Ranger pickup truck was created utilizing a combination of the standard ADAMS model definition language and user written subroutines for non-standard system components such as the tires. A detailed kinematic model of the front I-beam suspension and the rear leaf spring suspension was constructed.[8]

1.5 Project Schedule

Table 1.1- Project Time-Schedule

Process	Week														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Collecting the needed data for the vehicles															
ADAMS/Car templates study and analysis															
ADAMS simulation of the system															
Complete the simulation, data analysis, and conclusion															
Writing Documentation															

Self learning on ADAMS/Car software was the first stage and distributed over the work of the two semester, in order to keep with the program and be able to applying what we aim to do.

Collecting data and literature was the second stage, which started early and passed within six weeks. Here, resources literatures, and researchers were carefully studied, discussed, and analyzed, and the required data were taken into account.

After that, ADAMS/Car built in templates were studied, and making the needed simulation, in order to study the response, and all results were taken into account for the work.

Finally, writing the documentation research was started after finishing the previous steps.

1.6 Report content

This chapter presents the general idea of the project and its importance, in addition the field of application and specialization also, conduction the literature reviews of the previous studies about this project, this chapter also includes the time plan for the project.

Chapter two presents an introduction about ADAMS Software, advantages and usage capability, ADAMS/Car in this projects and its ability under several maneuvers and conditions.

Chapter three presents the main topic of the project, that is handling and riding characteristics of a vehicle. A brief definition and description for new systems used and their correlations.

Chapter four discuss the work on ADAMS/Car, and the results that used in developing a new moderate control scheme for improving stability, that will be discussed briefly according to theoretical science of vehicle dynamics. Also, the complete vehicle characteristics were described in detail, and the files for more data listed in the appendix

Chapter five presents the control scheme that constructed by the project team and its contribution in vehicle stability system.

Chapter six discusses the recommendations and conclusions.

Appendix, as the end stage of this project, contains the complete ADAMS/Car files, for the templates, subsystem, and maneuvers condition. Tire characteristics also shown in its simple form to exit from magic tire formula and its complexity.

Chapter Two

ADAMS

(*Automatic Dynamic Analysis of Mechanical Systems*)

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Chapter Two

ADAMS

(*Automatic Dynamic Analysis of Mechanical Systems*)

2.1 Introduction

The concept of simulation based engineering has been embraced by virtually every research and industry sector, as the engineering and science communities have become increasingly aware that computer simulation is an indispensable tool for resolving a multitude of scientific and technological problems.

Design and analysis engineers, increasingly simulating complex mechanical systems. The Virtual Prototyping approach to the Product Life Cycle (PLC) is adopted in industry due to its economic advantages, that is reduced cost and time to market. It is clearly desirable to gain a reliable perspective on the behavior of a system early in the design stage, long before actually building costly prototypes.

The potential of Virtual Prototyping further increases when the final system is the assembly of components/subsystems contributed by several manufacturers at different geographic locations. These components/subsystems might be in various stages of development, and building the physical prototype is either impractical (due to cost and time constraints) or outright impossible.

The simulation capability integrates the vehicle, tire, and powertrain/driveline into a unified high-fidelity simulation environment that enables study of vehicle performance and ride comfort; suspension design for improved ride, vehicle stability and maneuverability, active control strategies, etc.

2.2 Computational Methods

Whether the equations of motion have been derived by hand or uploaded to a commercial software package, the primary goal when considering vehicle dynamics is to be able to predict the time-domain solution to those equations. Once the equations of motion have been assembled, they are integrated numerically. This is a specialized field in its own right.

The equations can be solved in a fairly direct fashion as assembled by the commercial package pre-processor, or they can be subject to further symbolic manipulation before numerical solution. So called 'symbolic' codes offer some tremendous computational efficiency benefits, and are being held by many as the future of multi-body system analysis, since they allow real-time computation of reasonably complex models without excessive computing power. The prospect of a real-time multi-body system of the vehicle solved onboard in order to generate reference signals for the generation after next vehicle control systems seems genuine.

Commercial Computer Packages

General purpose programs, such as MSC.ADAMS, have been developed with a view to commercial gain, and as such are able to address a much larger set of problems across a wide range of engineering industries. In addition to the automotive industry, MSC.ADAMS is an established tool within the aerospace, electro-mechanical, and the general mechanical engineering industries. The general nature of the program means that within any one industry, the class of applications may develop and extend over a broad range.

MSC.ADAMS program, is typical of the range of multi-body vehicle dynamic analysis programs described as numeric, where the usage is concerned with assembling a physical description of the problem, rather than writing equations of motion. Till now, the development of the software has moved on considerably, particularly in the area of graphical pre- and post-processing.

2.3 Motivation

In the university education, students sometimes find that it's difficult to understand the properties of rigid body motion, especially due to the difficulty of visualizing three-dimensional dynamics. Generally, dynamics are learned much better in an interactive way; with the use of a mechanical simulation software.

The choice of ADAMS, based on its utility in industry and its integration in a mechanical engineering. The focusing on ADAMS/Car; a graphical interface used for simulating and animating models, that make vehicle study under tips, or in other words, in house test lab.

2.4 ADAMS/Car Definition

ADAMS is a motion simulation solution for analyzing the complex behavior of mechanical assemblies. It allows to test virtual prototypes and optimize designs for performance, safety, and comfort, without having to build and test numerous physical prototypes.

Several modules that are part of ADAMS can be used to accomplish specialized tasks and achieve better fidelity of results. For example, ADAMS/Flex can be used to examine the impact of flexible parts on the mechanism, and ADAMS/Controls can be used to model control systems such as hydraulics, pneumatics, electronics and more. ADAMS also offers a range of modules tailored to industry specific applications.

ADAMS/Car model hierarchy is comprised of the following components, which are stored in its databases:

1. *Templates*: are ADAMS/Car models built using ADAMS/Car Template Builder by users who have expert privileges. Templates are parameterized and generally are topological representations of vehicle subsystems, which can include front suspensions, brakes, chassis, and so on. It permits the change of many parameter like stiffness, damping, and geometry.[11]

2. *Subsystems*: are based on ADAMS/Car templates and allow standard users to change the parametric data of the template. For example, users can change the location of hard points, modify parameter variables, and so on (Figure 2.1).[11]

Figure 2.1- The steering subsystem from ADAMS/Car software.[9]

3. *Assemblies*: are comprised of subsystems that can be grouped together to form suspension assemblies, full-vehicle assemblies, and so on, then will be

tested/simulated over any track model under some condition of subsystem (Figure 2.2).[11]

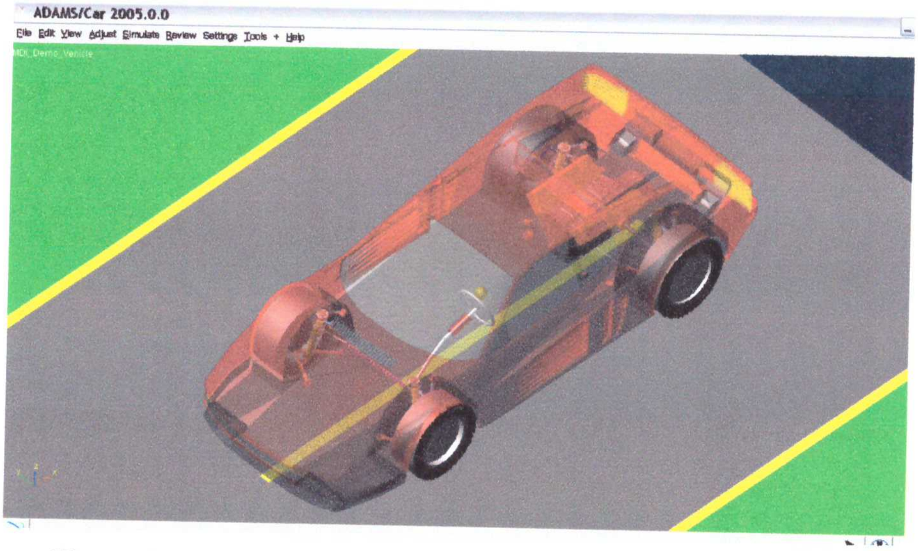

Figure 2.2- The full vehicle template from ADAMS/car Software.

2.5 What Can be done with ADAMS/Car?

MSC-Software has developed ADAMS/Car with the funding and technical support of many of the world's leading automotive manufacturers. Recognizing that to develop a complete vehicle simulation environment would be impractical for just one software vendor and one user organization to tackle alone, a consortium of automakers including *Audi*, *BMW*, *Renault*, and *Volvo* teamed up with MSC-Software to sponsor the software's joint development. From this initial group, the roster of ADAMS/Car users has grown to over 30 companies worldwide.

With ADAMS/Car, engineering teams can quickly build and test functional and virtual prototypes of complete vehicles and vehicle subsystems. This helps cut time, cost, and risk in vehicle development and improve the quality of new vehicle designs.

Working within the ADAMS/Car simulation environment, automotive engineer can exercise their vehicle designs under various road conditions, performing the same tests they normally run in a test lab or on a test track, but in only a fraction of the time.

Virtual prototyping with ADAMS/Car, can be applied to almost any vehicle design, everything from compact passenger cars to heavy trucks. The software lets quickly explore multiple "what-if" design scenarios. Animation of vehicle or subsystem motion on-screen, displaying graphs of important parameters, and producing standardized test reports, also possible. Engineer can then progressively refine and retest their designs until optimizing vehicle performance.

What used to take months or years to physically design and test, can now be done in just days or even hours within the ADAMS/Car simulation environment. Most importantly, the results the software provides are complete and accurate; engineer can be confident their full vehicle and vehicle subsystem designs, will function properly when they actually do build and test hardware prototypes.

When engineers analyze an assembly, ADAMS/Car applies the analysis inputs that they specify. For example, for a suspension analysis they can specify inputs to:

1- Move the wheels through bump-rebound travel and measure the toe, camber, wheel rate, roll rate, and side-view swing arm length.

2- Apply lateral load and aligning torque at the tire contact path and measure the toe change and lateral deflection of the wheel.

3- Rotate the steering wheel from lock to lock and measure the steer angles of the wheels and the amount of Ackerman, that is, the difference between the left and right wheel steer angles.

Based on the analysis results, engineers can quickly alter the suspension geometry or the spring rates and analyze the suspension again to evaluate the effects of the change. For example, a quick change of a rear suspension from a trailing-link to a multi-link topology to see which yields the best handling characteristics for the vehicle.

2.6 How to Benefit from Using ADAMS/Car?

ADAMS/Car enables to work faster and smarter, enabling more time to study and understanding how design changes affect vehicle performance. ADAMS/Car enables:

1. *Exploring* the performance of designs, and refines this designs before building and testing a real physical prototypes.
2. *Analyzing* design changes much faster, and at a lower cost than physical prototype testing would require. For example, changing springs with a few mouse clicks instead of waiting for altering to install new ones in the physical prototype before re-evaluating the design. [11]
3. *Varying* the kinds of analyses faster and more easily than to modify instrumentation, test fixtures, and test procedures.
4. *Working* in a more secure environment without the fear of losing data from instrument failure or losing testing time because of poor weather conditions.
5. *Running* analyses and "what-if" scenarios without the dangerous associated with physical testing.

2.7 ADAMS/Car Capabilities

ADAMS/Car's design tools include Steering, Brakes, Chassis, and both front and rear conceptual suspension models, with suspension characteristics defined by toe, camber, and wheel-rate curves and a compliance matrix. These characteristic curves provide the location and orientation of the wheel center for any given wheel height and loading condition. So can design both compliant and kinematic suspension models, with compliant models including the effects of suspension bushings, and the same for others subsystems, but since suspension is the first contact point -after tires of course- the project will proceed in its explanations.

ADAMS/Car provides on the computer the same test results obtained with a physical one on a test rig. Engineers will create an initial suspension design for example, with the aid of a built in template, modifying parameters, such as hardpoint locations, stiffness and/or damping values, and bushing parameters, then finding the desired characteristics.

Conceptual suspension models, or any other subsystems, can be especially useful in the early stages of vehicle development, as initial design concepts are tested and benchmark activities carried out. This minimizes physical testing. With conceptual suspensions, engineers can find desired vehicle characteristic targets even before the detailed suspension design is known. Also, with conceptual suspensions, engineers can speed simulation times since the number of equations to be solved is significantly reduced.

Once a desired suspension characteristic has been found, the design engineer and the development engineer first match the suspension characteristics, and then further refine vehicle responses. At this stage, virtual prototyping allows the engineering team to change every conceivable design parameter. Whether studying durability, vehicle dynamics, or noise. Engineers can use ADAMS/Car to gain early insight into "what-if" scenarios, with cause and effect closely attributed to changes.

ADAMS/Car can also be used to investigate full vehicle maneuvers. This helps save on costly instrumentation and test track time, and minimizes the problems of repeatability associated with physical vehicle testing.

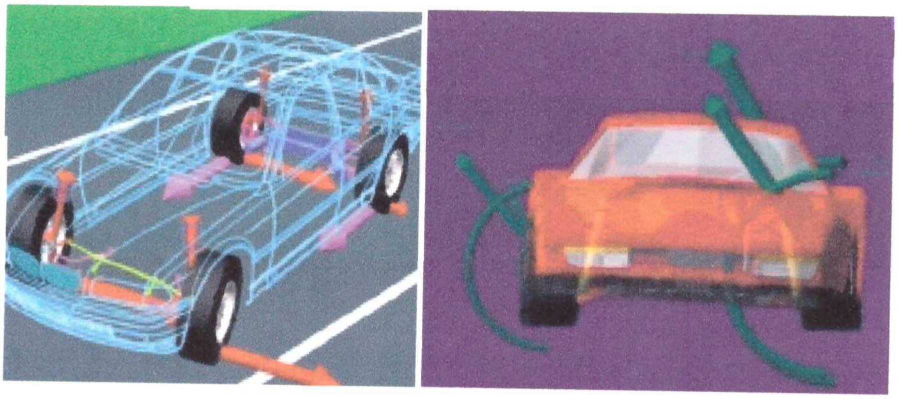

Figure 2.3- Control actions of a vehicle driver such as steering, braking, accelerating, gear shifting, and clutching for a variety of maneuvers can be simulated with ADAMS/Driver that associated with ADAMS/Car.

2.8 ADAMS/Car Limitations

ADAMS/Car permits to simulate a lot of different maneuvers, but presents some limits when has to model the torque transmitted by clutch, synchronizer, brakes, considering operating conditions that require a continuous change of the slipping velocity sign. During transients that determine those changes, oscillations appear due to a discontinuous model of friction transmitted torque. To overcome such limit, extending the ADAMS/Car ability to model the vehicle dynamics also including active systems, the model can be connected to Matlab/Simulink environment.

Chapter Three

Automotive Handling and Riding Characteristics

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Chapter Three

Automotive Handling and Riding Characteristics

3.1 General Outlook

The handling characteristics of a road vehicle refer to its response to steering commands and to environmental Inputs, such as wind and road disturbances, that affect its direction of motion. There are two basic issues in vehicle handling: one is the control of the direction of motion of the vehicle, and the other is its ability to stabilize its direction of motion against external disturbances.

In Riding quality, that is vehicle comfort, concerned with the sensation or feel of the passenger in the environment of a moving vehicle. Ride problems mainly arise from vibrations of the vehicle body, which may be induced by a variety of sources, including surface irregularities, aerodynamic forces, vibrations of engine and driveline, and non-uniformities (imbalances) of the tire/wheel assembly.

Usually, surface irregularities, ranging from potholes to random variations of the surface elevation profile, act as a major source that excites the vibration of the vehicle body through the tire/wheel assembly and the suspension system. Excitations by aerodynamic forces are applied directly to the vehicle body, while those due to engine and driveline vibrations are transmitted through engine/transmission mounts. Excitations resulting from mass imbalances and dimensional and stiffness vibrations of the tire/wheel assembly are transmitted to the vehicle body through the suspension.

Human sensitivity varies according to the nature of disturbances. Consequently a "good ride" depends on the overall design of the vehicle, rather than just the design of the suspension system and also the steering. To produce a comfortable ride, the high frequency vibrations of wind and drive train noise must be minimized and properly isolated, and the suspension must be set in appropriate rubber mountings, or bushing, to isolate high frequency roadway induced vibrations. However, the natural frequency of the suspension system is still considered the cornerstone of a comfortable ride.

So, the riding and handling characteristics of an automobile center on the characteristics of tires, suspension, and steering system design. Tires mainly are the first vehicles reaction point of the roadway, but in this project we will deal only with suspension and steering, since tires is manufactured and available in different design, also their data is not available.

3.2 Suspension

A suspension algorithm is designed to reduce chassis acceleration as well as dynamic tire force. Chassis acceleration is related to ride and comfort, and tire force to road holding and handling.

There are two general types of suspensions: dependent, in which the left and right wheels on an axle are rigidly connected, and independent, in which the left and right wheels are disconnected. Solid axle is the most common dependent suspension, while McPherson, double wishbone, and double A-arm are the most common independent suspensions.

The roads commonly used by motor vehicles are uneven. This unevenness causes vertical movements of the vehicle and the passengers during the driving process.

The vehicle is connected to the road by the tire. Small unevenness in comparison to the tire contact patch size can be compensated by the tire elasticity, whereas larger unevenness entails a vertical acceleration or deflection of the wheels. In order not to transfer these accelerations into the vehicle structure, a length compensating element has to be placed between the wheel and the vehicle structure.

Steel springs are the technologically simplest elements with variable length. Due to this fact it is also the most common length compensating element, whose force is a function of the length variation. It is usually used in the suspensions of motor vehicles. Different parts connected with springs generate oscillating systems. So there has to be added energy absorbing element, the damper.

The suspension's job in the motor vehicle is to reduce these vertical movements. The essential criteria specifying the quality of a suspension can be listed as follows:

- Suspension comfort for the passengers (Effective acceleration affecting the passengers).
- Forces affecting the load (Effective value of structure acceleration).
- Wheel load variation (Effective value of the dynamic wheel load), which influences the grip between tires and road (driving safety) and the load application upon the road surface.

The further demands on the suspension in a motor vehicle are various and partially contradicting are shown in figure 3.1.

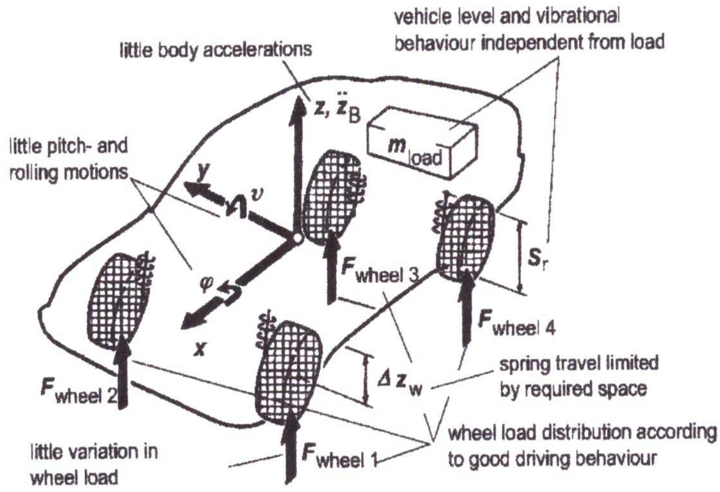

Figure 3.1-Demands on a vehicle suspension.[3]

3.3 The Road as the Source of Excitation

The representation of the road profile is vital for vehicle dynamic simulations because it is the main source of excitation. An accurate road model is as important as a good vehicle model.

The unevenness of the road represents the most intensive source of excitation for the vibratory system of the motor vehicle in the frequency range up to approximately 30 Hz. The road's unevenness causes vertical movements of the vehicle structure, and as a consequence, the road is affected by tire load variation itself.[12]

Generally road unevenness appears as an excitation with different amplitudes and wavelengths at irregular periods of time. This is called a stochastic excitation of the vehicle (Figure 3.2).

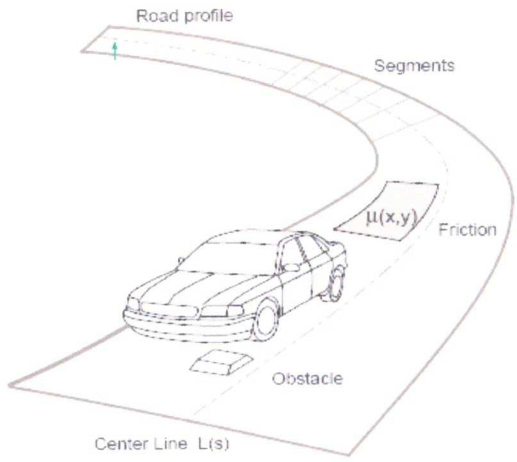

Figure 3.2- Sophisticated road model.[12]

3.4 Steering

To maneuver a vehicle, its need a steering mechanism to turn wheels. Steering dynamics introduces new requirements and challenges, to increase vehicle ability to maneuver more safety and easily.

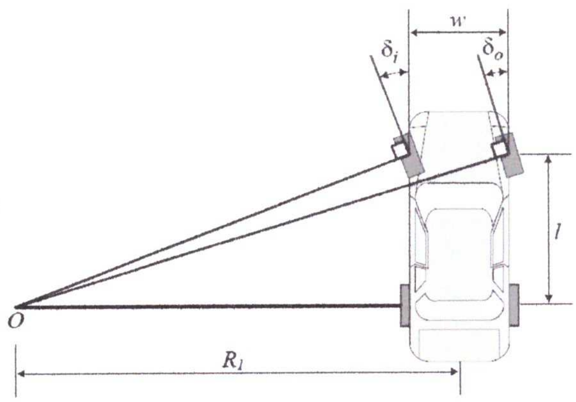

Figure 3.3- A front wheel steering vehicle under the Ackerman condition.[1]

Considering a front wheel steering vehicle, that is turning to the left, as shown in figure 3.3. When the vehicle is moving very slowly, there is a kinematic condition between the inner and outer wheels, that allows them to turn slip-free. The condition is called the Ackerman condition and is expressed by:

$$\cot \delta o - \cot \delta i = w/l$$

The distance between the steer axes of the steerable wheels (here the front) is called the *track*, and is shown by *w*. The distance between the front and rear axles is called the *wheelbase* and is shown by *l*. Track *w* and wheelbase *l* are considered as kinematic width and length of the vehicle.

The Ackerman condition is needed when the speed of the vehicle is too small, and slip angles are zero. There is no lateral force and no centrifugal force to balance each other. The Ackerman steering condition is also called the kinematic steering condition, because it is a static condition at zero (or near zero) velocity.

A steering that passes according to the Ackerman condition is called Ackerman steering, Ackerman mechanism, or Ackerman geometry. Taking into account that there is no four bar linkage steering mechanism that can provide the Ackerman condition perfectly. However, engineer can design a multi-bar linkages to work close to the condition and be exact at a few angles, that is trapezoidal steering which have a semi-perfect characteristics which help in vehicle handling and kept safety during any dangerous high speed maneuvers.

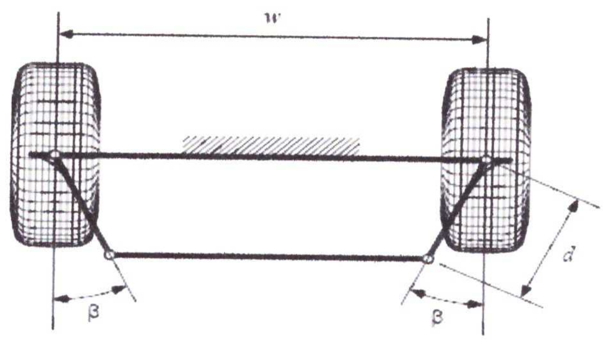

Figure 3.4- A trapezoidal steering mechanism.[1]

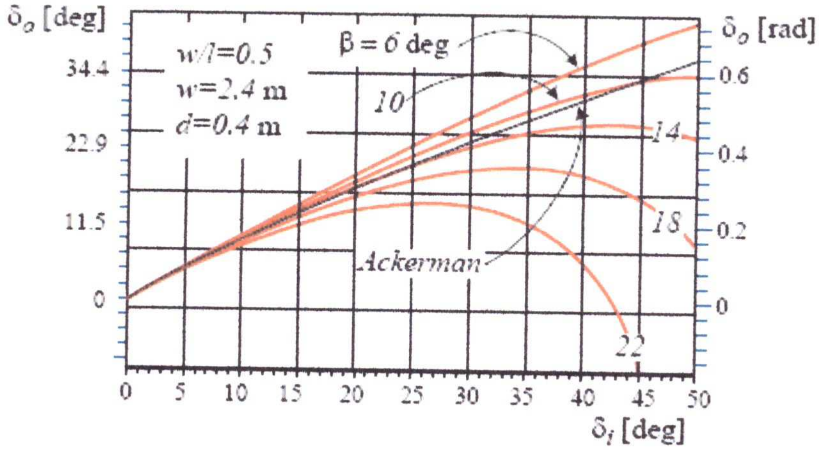

Figure 3.5- Behavior of a trapezoidal steering mechanism, compared to the associated Ackerman mechanism.[1]

In the control loop consisting of the driver and the vehicle, the steering wheel angle forms a control variable, which has to be given by the driver in such a way, that a deviation from the desired course remains small. However, there does not exist any distinct functional relation between the steering wheel turn executed by the driver and the change of direction necessary for a correction of course. The reasons for this are, for example, the elasticity's in the steering system components and the occurring lateral accelerations. The relation between steering actuation and change of driving direction is represented in Figure 3.6:

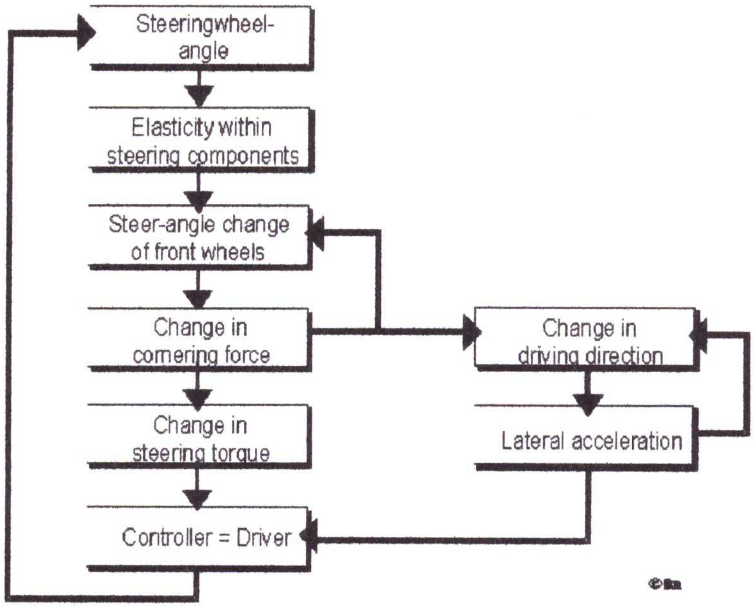

Figure 3.6- Relation between steering actuation and change of driving direction.[12]

In order to drive a vehicle, the driver must constantly analyze the relation between steering wheel turn and change of driving direction. Apart from the optical information (deviation from the desired course), he receives a lot of further information, including for example lateral acceleration transmitted by the seat and steering torque passed on by the steering wheel.

The function of the steering system is not only to transfer the steering wheel angle by a distinct allocation into a wheel steering angle but also to transmit information about the status of the vehicle movement to the driver.

3.5 Specifications of Steering Systems

Since humans are integrated into the overall driver-vehicle system by the steering, the demands on this component are defined by the characteristics of humans and those of the vehicle.

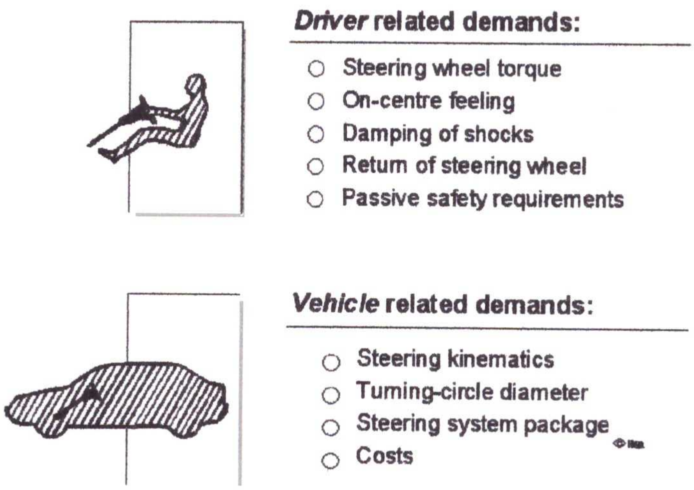

Figure 3.7- Demands on the steering system.

3.6 Center of Gravity Height[16]

The center of gravity height, relative to the track, determines load (or weight) transfer from side to side and causes body lean. Centrifugal force acts at the center of gravity to lean the car toward the outside of the curve, increasing downward force on the outside tires.

The center of gravity height, relative to the wheelbase, determine load transfer between front and rear. The cars momentum acts at its center of gravity to twist the car forward or backward, respectively during braking and acceleration.

Since it is only the downward force that changes and not the location of the center of gravity, the effect on over/under steer is opposite to that of an actual change in the center of gravity. When a car is braking, downward load on the front tires increases and that on rear decreases, with corresponding change in their ability to take sideways load, causing oversteer.

3.7 Compromises

Ride quality and handling have always been a compromise technology, has over time allowed to automakers to combine more of both features in the same vehicle.

High level of comfort are difficult to reconcile with a low center of gravity, body roll resistance, low angular inertia, support for the driver, steering feel and other characteristics that make a car handle well.

For ordinary production cars, manufacturers are towards deliberate understeer as this is safer for inexperienced or inattentive drivers than oversteer. Other compromise involve comfort and utility, such as preference for a softer smother ride or more seating capacity, also engineers, may at some time, neglect the small effect of some parameters when others show good response. Any parameters that is very important against other must taken into account, as when neglecting pitch angle against yaw and roll angles.[7]

Chapter Four

Automotive Dynamics Study using ADAMS/Car

Chapter Contents:

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Automotive Dynamics Study using ADAMS/Car

4.1 Introduction

Vehicle dynamics study and analysis using three-dimensional four-wheel modeling are tedious, and take a huge amount of time for any parameter change. Therefore, adopting complete vehicle models generated by ADAMS/Car will help to save the time and effort. This helps to study and analyze almost all parameters even the less essential ones that affect handling-riding characteristics. Also, it allows designing of a control scheme that improve the vehicle quality.

Any vehicle can be thought as being composed of two main subsystems: the sprung mass (chassis) and the unsprung masses (wheels, axles and linkages), connected via a number of elastic and dissipative elements (suspensions, tyres), and subjected to external inputs coming from the road profile, the steering system and other external disturbances such as wind force.

To produce a vehicle computer-based model, representation of the individual parts of the vehicle is required, which is possible by using templates to create assembly. In ADAMS, each part is characterized by its, geometry, mass, the three coordinates of its center of gravity, and its moment of inertia around the three main inertia axes.

The vehicle on which the project simulation is based, adopted simplifications that do not affect the accuracy, but simplifies the calculations, because of the limited calculating resources available; needs fast workstations with big memory. For example, tire characteristics, component elasticity, and engine-powertrain properties, used in ideal form that available at ADAMS/Car library, to enable the study of handling-riding characteristics of the vehicle.

The motion of the considered vehicle, which is a concept car, prepared by MSC-ADAMS, especially for vehicle systems study and design, has six degrees of freedom (6 DOF), classified as follows:

- Longitudinal translation (forward and backward).
- Lateral translation (side slip).
- Vertical translation (bounce or heave).
- Rotation around the longitudinal axis (roll).
- Rotation around the transverse axis (pitch).
- Rotation around the vertical axis (yaw).

The main parameters in the vehicle under study were chosen to build the ideal model, in order to show there effect with different road conditions, regardless of the other important parameters. The main parameters of the vehicle under study are shown in the following table:

Table 4.1- Vehicle under-study Parameters.

Vehicle Attribute	Type/Value
Front/Rear Suspension	Double-Wishbone.
Steering	Rack and Pinion.
Max rack- Displacement/Force	100 mm/1.0E+004
Steering Angle/Torque	720°/6.0E+004
Steering Ratio	27.6
Rack Ratio	174.5
Sprung Mass	1200 Kg
CG height	300 mm

Wheelbase	2000 mm
Camber angle (Front/Rear)	-0.5^{o}
Toe angle (Front/Rear)	0.0

The double-wishbone suspension system was used since of its simplicity as McPherson suspension, and its widely usage in passenger cars, despite the modern change in its structure.

The steering system was chosen in its simplest form; that is rack and pinion, that is also the most widely available. Also, the moderate improvement used the steering by wire system that give variable steered wheel angles, that improving handling of the vehicle. The other values of angles and dimensions are the MSC-ADAMS vehicle model, beside the full vehicle and its subsystems ADAMS files, shown in the appendix at the end of the thesis.

The main parameters changed based on spring stiffness and damping value, to show the response at different values, and build the scheme based on this results to improve vehicle stability and comfort.

Vehicle ride is essentially concerned with car vertical dynamics (bounce, pitch, and roll) whereas handling is concerned with lateral dynamics (side slip, yaw, and roll). Figure 4.1 shows the vehicle three-axes motion.

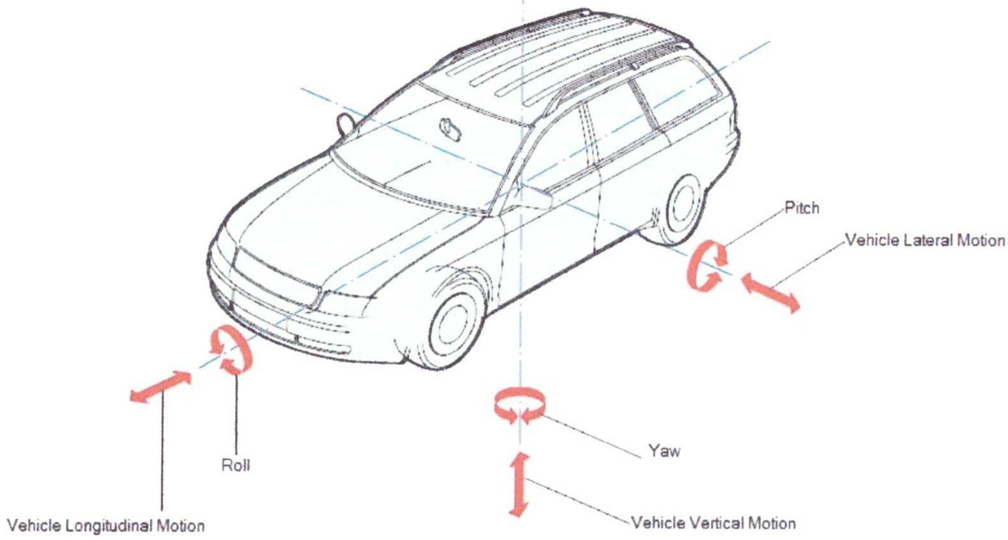

Figure 4.1- Vehicle three Axles of Motion.

The work for this project is divided into four road-driving standard maneuvers that include:

1- Straight-line Longitudinal acceleration with bump at a predetermined time.
2- Launching and Braking over longitudinal path.
3- ISO-Lane change.
4- Different road conditions for vehicle wheels.

Much of the driver's input to the vehicle has already been mentioned in the steering, brake, and powertrain subsystems. The driver mass and inertias are lumped together with the chassis part. The driver inputs to the vehicle are: throttle, clutch, brake, transmission gear, and steering wheel. All the inputs using the driving machine to perform the orders.

4.2 Maneuvers

ADAMS/Car permits a large choice of handling and comfort maneuvers. Each maneuver gives a direct indicator about the response of the vehicle, that shows a different change on each part and accordingly, a change (improve or not) in the parameters under study.

Most interesting results of this work will be presented briefly in the following sections.

4.2.1 Straight-line Longitudinal acceleration with bump at predetermined time

It's the most of common maneuvers, that includes a change in the vehicle velocity launched from zero to reach a predetermined value. Then at a known time, the vehicle will facing a bump that causes a vertical motion of the vehicle sprung and unsprung masses. After the bump, the vehicle will stop, but the velocity remains constant.

In this simulation, the results of full vehicle model executing such maneuver, which is similar to what occurs in races, will be presented. ADAMS/Car controls the throttle position, transmission gear, and steering inputs. The straight-line acceleration event was simulated with the inputs shown in Figure 4.2.

Output prefix is a character string added to the beginning of each ADAMS/Car file produced by the simulation with "_accel" as the rest of the filename. *End time* refers to the total time for the simulation and is sufficient to allow the full vehicle model to reach the required velocity and/or acceleration. *Number of steps* determines the rate at which the ADAMS/Car solution marches to the given *end time*. The time between each simulation step is kept to 0.01s, that is 100 steps for 1.0s, which maintained a good balance of simulation accuracy and solver efficiency.

Initial velocity is the vehicle's initial speed at t = 0s and ADAMS/Car maintains this speed up until t = *start time*. At t = *start time*, ADAMS/Car steps the driver's throttle control to *final throttle* at the specified transition time called *duration of step*. *Gear position* is the initial transmission gear for the simulation and the *shift gears* toggle is turned off to prevent ADAMS/Car from changing gears throughout the event. *Steering input* is set to "straight line" which tells ADAMS/Car to control steering wheel input as required to maintain the vehicle's straight line heading.

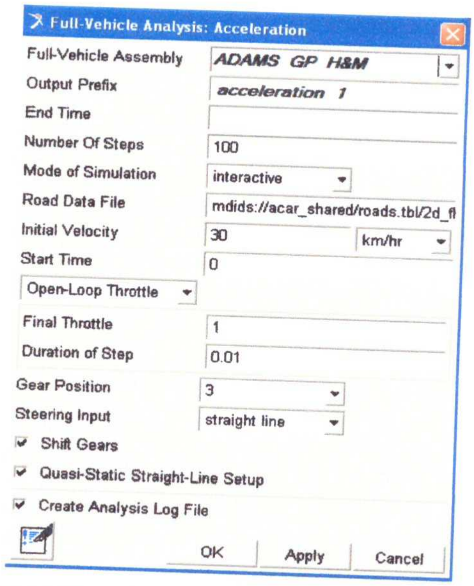

Figure 4.2- ADAMS order table for "Full_Vehicle_acceleration".

In such maneuvers, the most important thing is the study of the vehicle launching, entrance and exit of the bump. In the bump region, all things change, since there is a moment change in tire road reaction, and the vehicle suspension must reacts accordingly to cause no change to occupants.

The used road contains a regular crown bump that faces the two front/rear wheels at the same time. The complete data for the road and the bump are shown in the appendix.

Bump Entrance and Exit:

The main purpose of active/semi active suspension systems, is to control the vehicle height within predetermined range of vertical motion, especially when there is a bump, obstacle, and holes on the road, or any irregularities; to minimize the effect on vehicle occupants, and improving ride comfort (Figure 4.3).

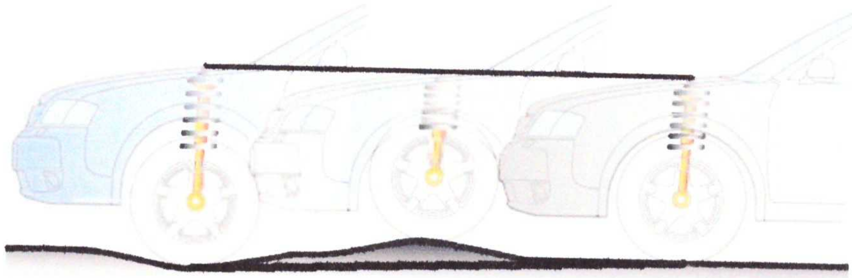

Figure 4.3- The vehicle height must remains constants to increase occupants comfort.

The work in this case is focusing on the study of pitch angle and the sprung mass displacement. Yaw and Roll angles will not affect; because the bump is symmetry and parallel to front and rear wheels. Figure 4.4 shows a vehicle during the entrance of a bump.

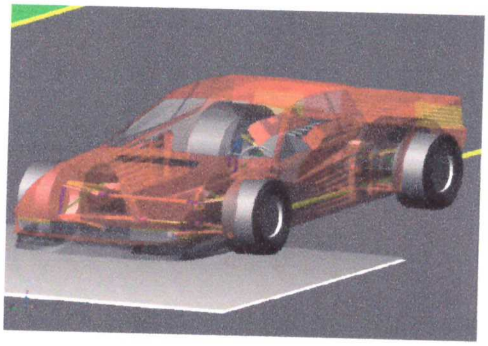

Figure 4.4- Bump entrance in ADAMS/Car environment.

The height of the obstacle was 100 mm and the width was more than the vehicle width. The same tire was used as the model in the running simulations. There is a slight bevel edge on either side of the bump to avoid heavy impact of the vehicle onto it. Different vehicle parameters include inertia, mass, location, and shape of various vehicle components, as well as damping and stiffness coefficients of the suspension.

Bump Entrance:

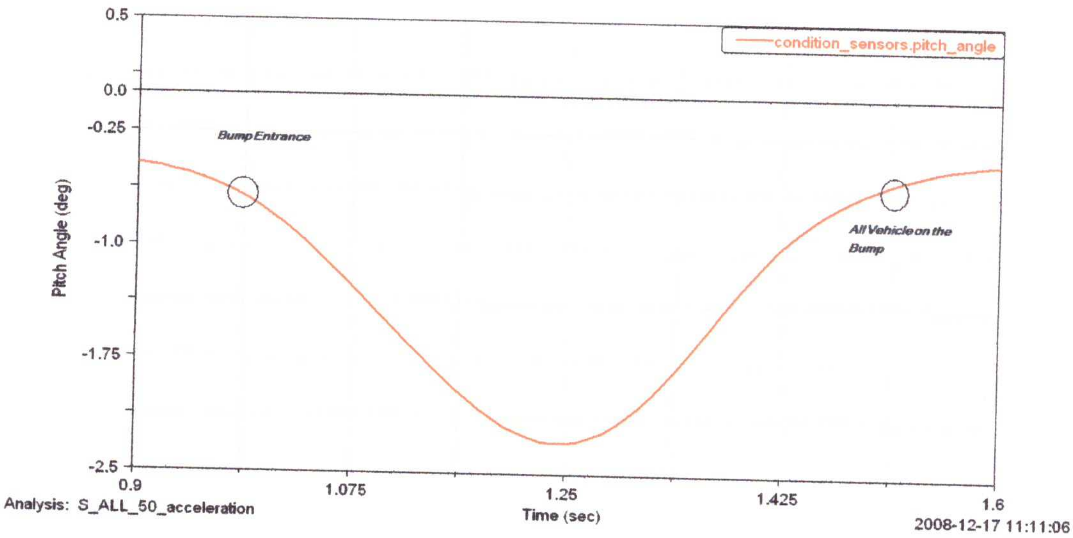

Figure 4.5- Pitch angle of the vehicle entering a bump during acceleration.

As shown in the figure 4.5, the vehicle undergoes a regular crown bump at t=1s, that cause a pitch angle increasing (the lowering of the curve in the minus region is a result of sign convention in ADAMS/Car routines, that the pitch increasing-upward- is negative and its decreasing-downward- is positive), but suspension control system must try to make this condition reach to zero or around.

The solution of this phenomenon is the suspension (spring and damper) altering, to continuously adapt the road condition, so the change must be in the stiffness and/or damping to resist the pitch changing.

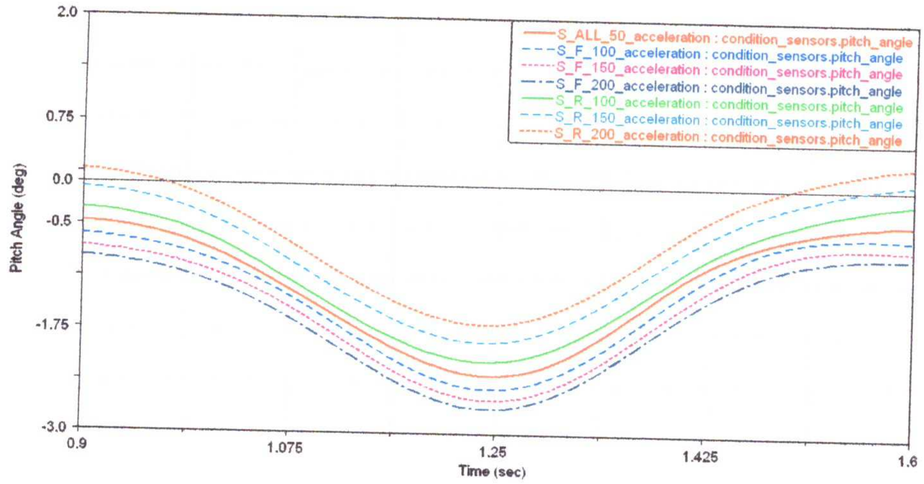

Figure 4.6- Pitch angle of the vehicle entering a bump during acceleration/stiffness increasing.

Figure 4.6, shows a time period of entering the bump, and an increasing in the stiffness at different locations occurs. The increasing of stiffness in rear suspension; cause an improvement in pitch angle (close to zero). But, on contrast, the increasing of stiffness in front, cause an opposite result, that made the pitch angle increases.

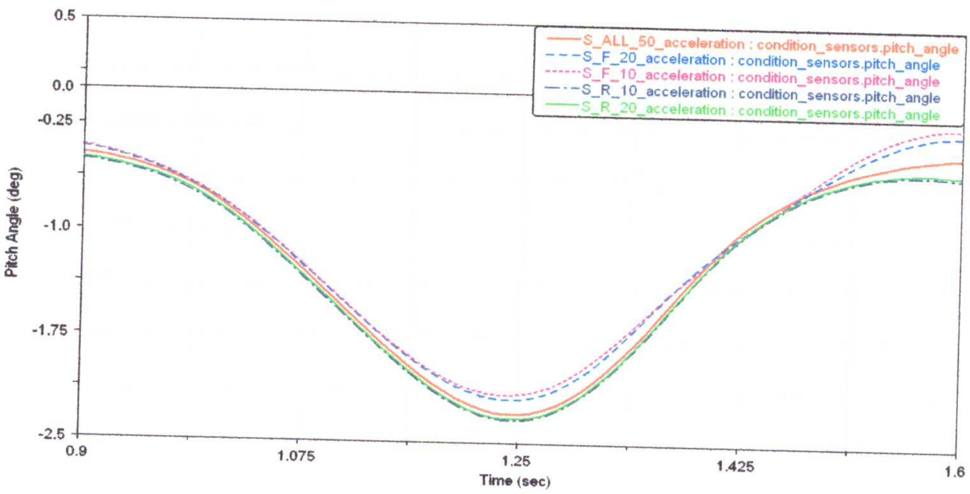

Figure 4.7- Pitch angle in vehicle entering a bump during acceleration/Stiffness decreasing.

Figure 4.7 shows the criteria of decreasing the stiffness in different locations. In the front, with decreasing stiffness, the system will show a good response that the sprung mass will be in reliable of vertical motion. When the rear stiffness decreases, it shows a bad response on the system that makes extra addition to the pitch angle.

Bump Exit:

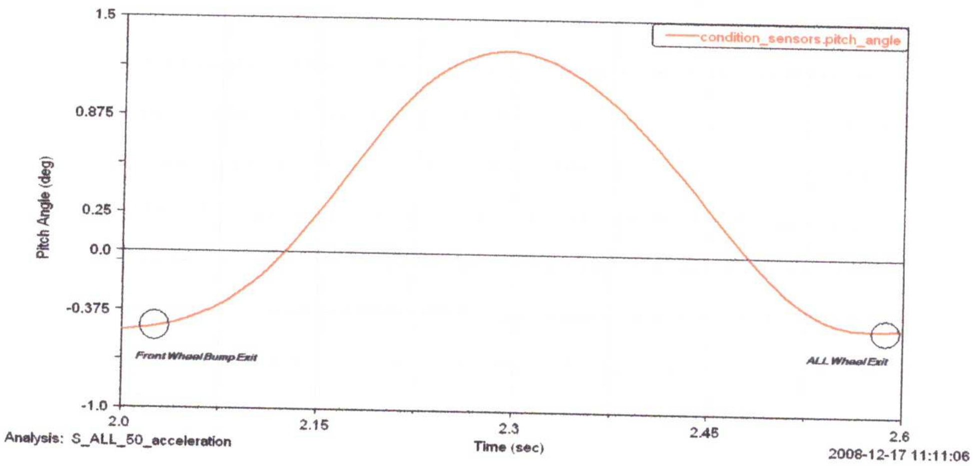

Figure 4.8- Pitch angle in vehicle exit a bump during acceleration.

As shown in the figure 4.8, the vehicle undergoes a regular bump, that cause a pitch angle increasing, the engineering system must try to make this condition reach to zero or around also.

The solution of this phenomenon is the suspension parameters altering, to continuously adapt the road condition, so the change must be in the stiffness and/or damping to resist the pitch changing.

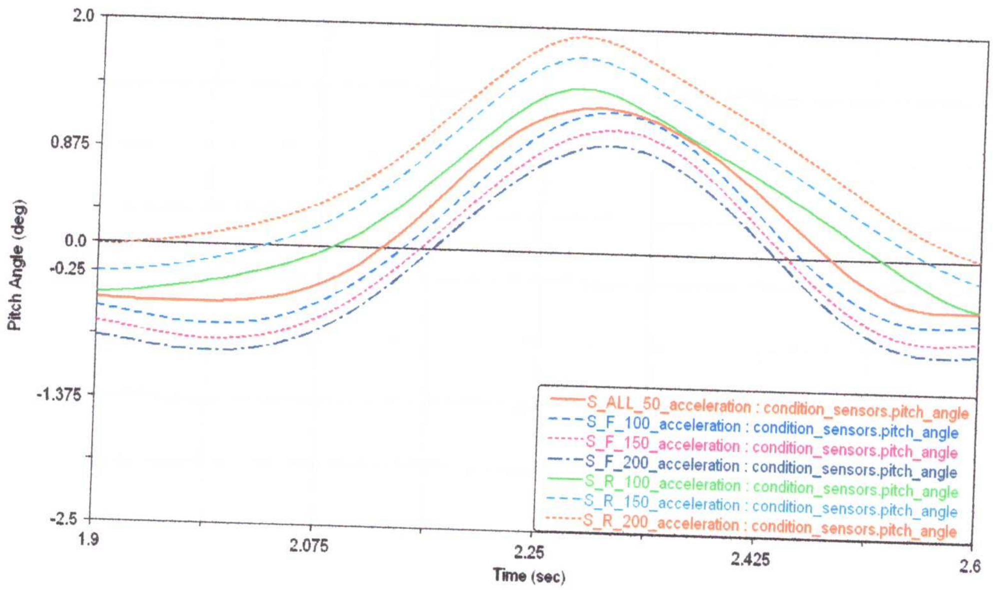

Figure 4.9- Pitch angle in vehicle exist a bump during acceleration/Stiffness increasing.

Figure 4.9, shows a time period of exit with an increasing in the stiffness at different locations. The increasing of stiffness in front suspension causes an improvement in pitch angle (close to zero). But, on contrast, the increasing of stiffness in rear, cause an opposite result, which lead to pitch angle increases.

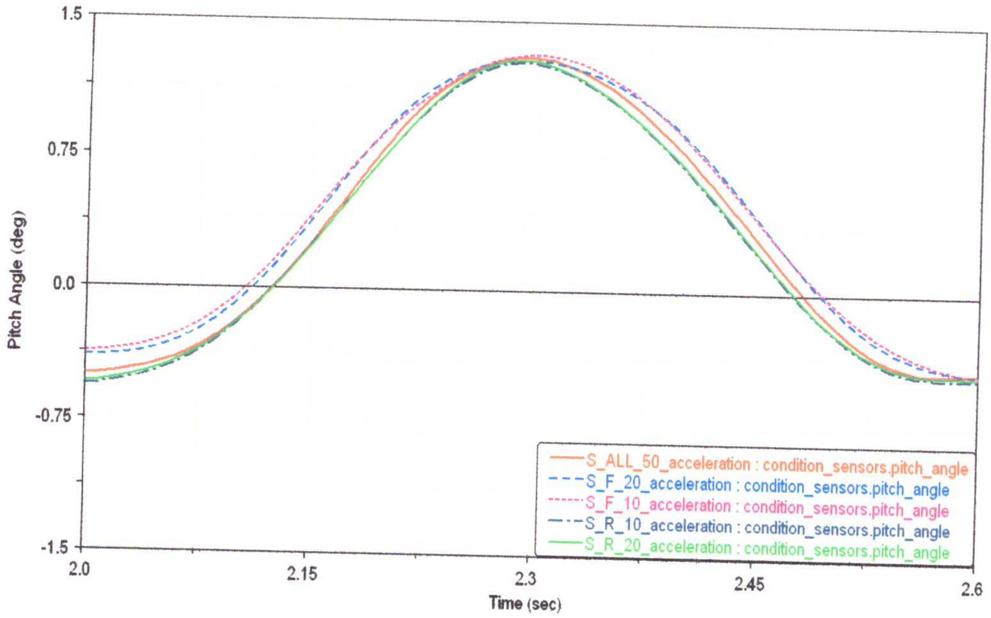

Figure 4.10- Pitch angle in vehicle exist a bump during acceleration/Stiffness decreasing.

Figure 4.10, shows the criteria of decreasing the stiffness in different locations. In the rear suspension, with decreasing stiffness, the system will show a good response. The front suspension stiffness decreasing, shows a bad response on the system that makes increase in the pitch angle.

The rest of the study on bump entrance, based on the other important angles that are changed with lower rate (that may be neglected), that is yaw, roll, and side slip angles.

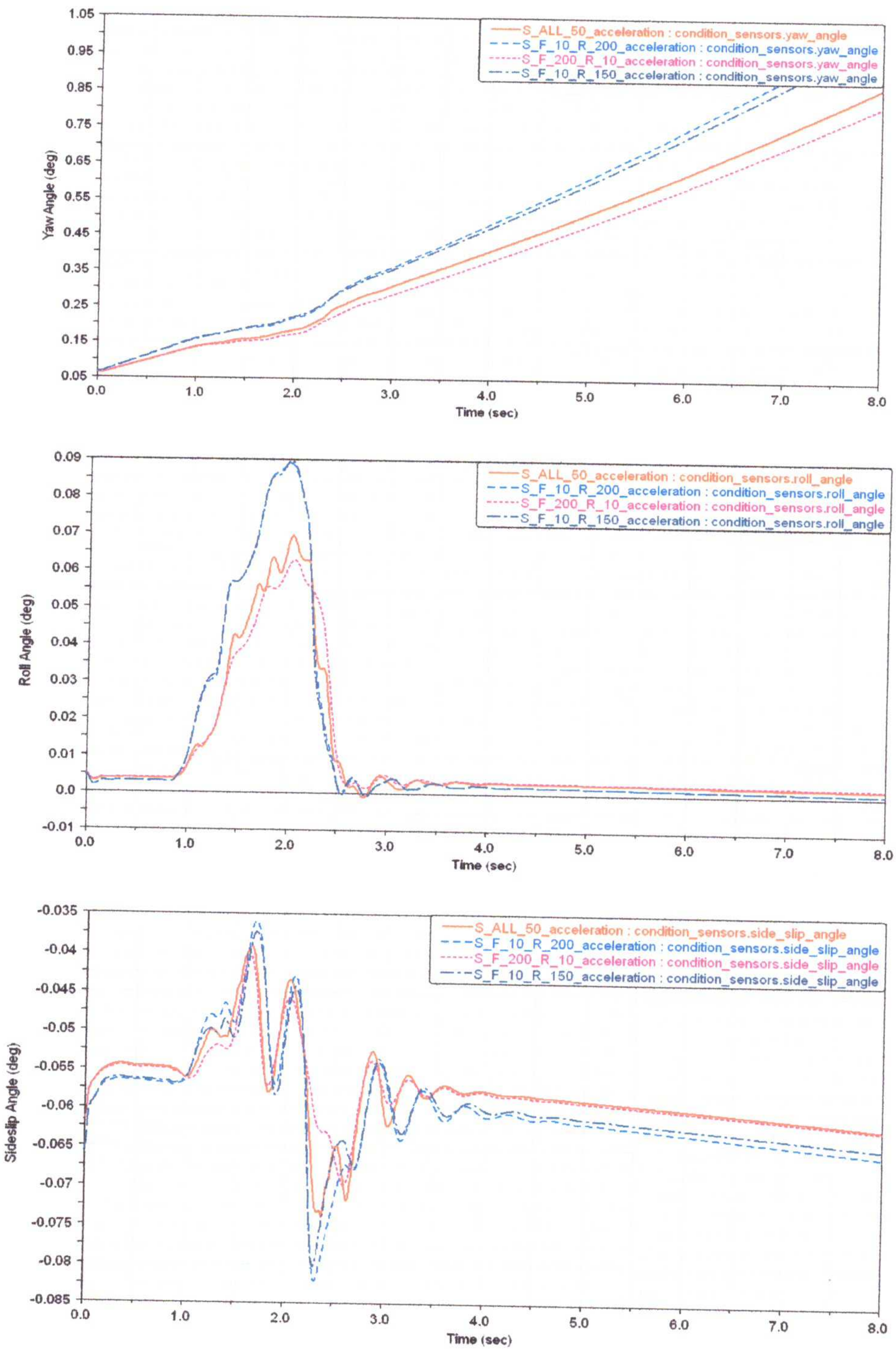

Figure 4.11- Yaw/Roll/Side slip angles of bump entrance simulation(Stiffness change).

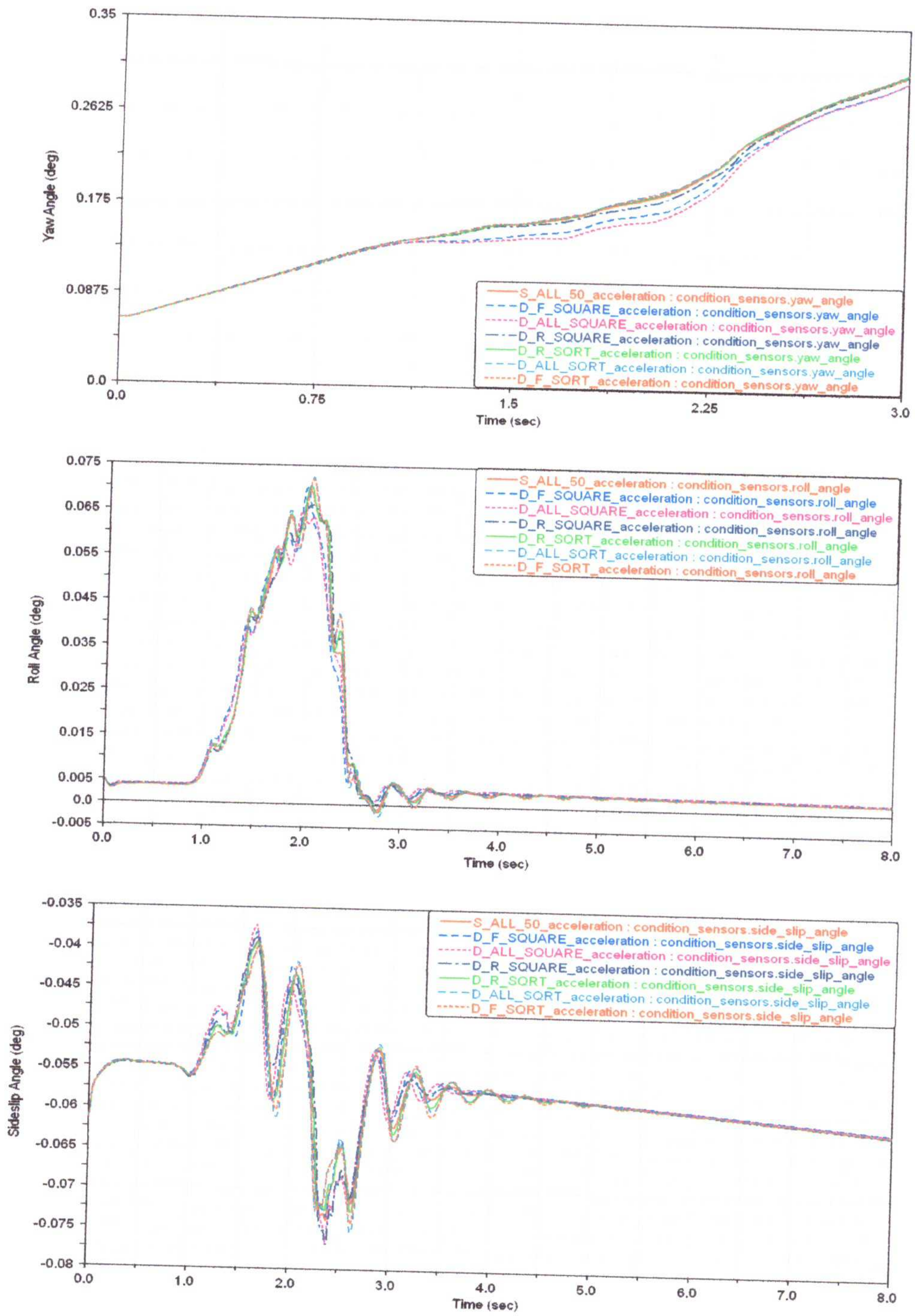

Figure 4.12- Yaw/Roll/Side slip angles of bump entrance simulation(Damping change).

4.2.2 Launching and Braking over Longitudinal Path

In these maneuvers, challenges to engineering activity continuously appear, that must help in improving the two phenomena appearing here, anti-squat and anti-dive.

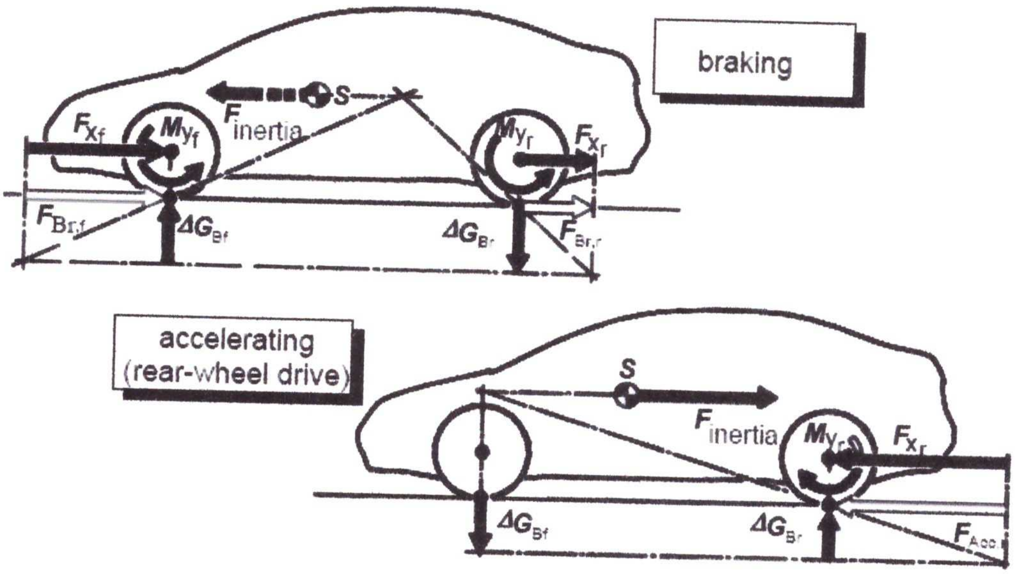

Figure 4.13- Forces acting on the wheel carrier during Braking and/or Accelerating (*F: Force/G: Reaction/S: Center of Gravity*).

Braking torque compensation reduces pitching motion of the body during braking and thus has a positive effect on suspension comfort. Starting torque compensation can be realized in a similar way as braking torque compensation.

The two phenomena described here, represent the cornerstone of any suspension design, that the dive and squat responses are the major problems that are difficult to solve, since they are related to physical situation where there is mass transfer as a result of inertia changing (Figure 4.13).

Vehicle Launching:

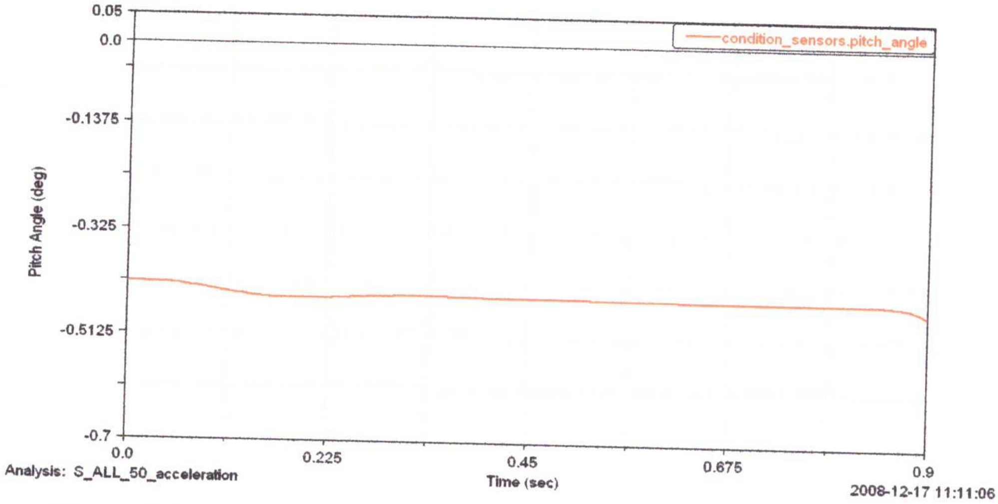

Figure 4.14- Pitch angle under Vehicle Launching over longitudinal path.

The launch of the vehicle will produce a time limited increasing of the pitch angle, which will decrease continuously during constant velocity to value around zero. This value cannot be zero during launching, because a permanent constant (or non constant at variable accelerations) weight transfer will occur.

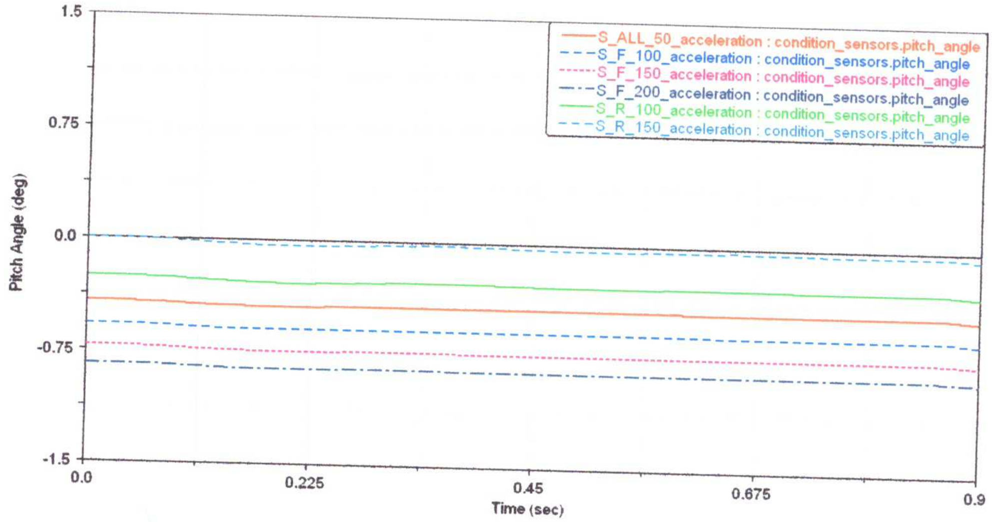

Figure 4.15- Launching over longitudinal path/Stiffness increasing.

Figure 4.15, shows different simulation trials, that an increasing in the stiffness in the rear; produce an approximate ideal pitch angle (that is zero), but the front increasing will make the opposite.

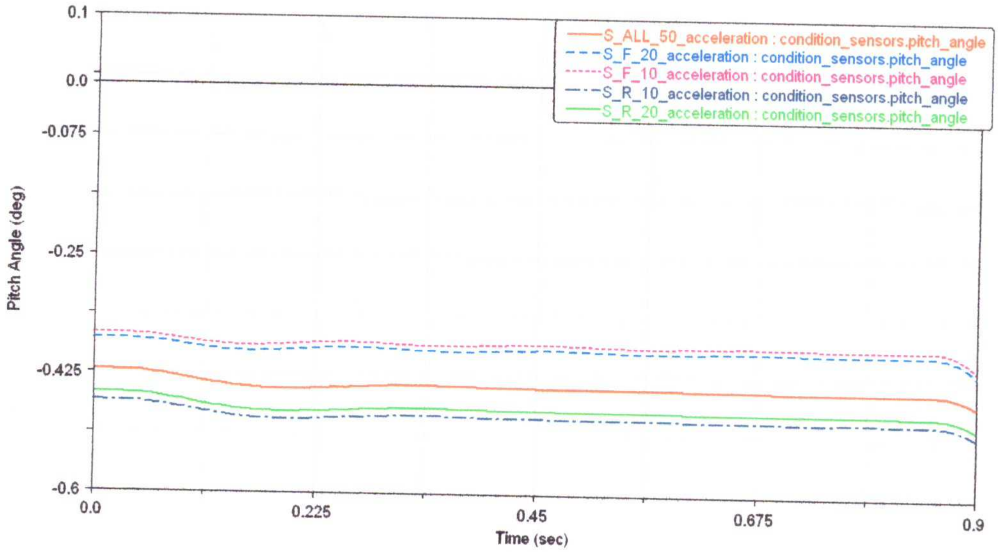

Figure 4.16- Launching over longitudinal path/Stiffness decreasing.

In Figure 4.16, the response for decreasing the stiffness, the improvement rotate around the ideal spring used by ADAMS/Car, that no visible improvement in decreasing the stiffness.

To show the complete effect of suspension parameters, the damper change must be consider as the following figures appear:

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Palestine Polytechnic University (PPU)
The Library المكتبة
Acc. 23.666 الرقم المتسلسل
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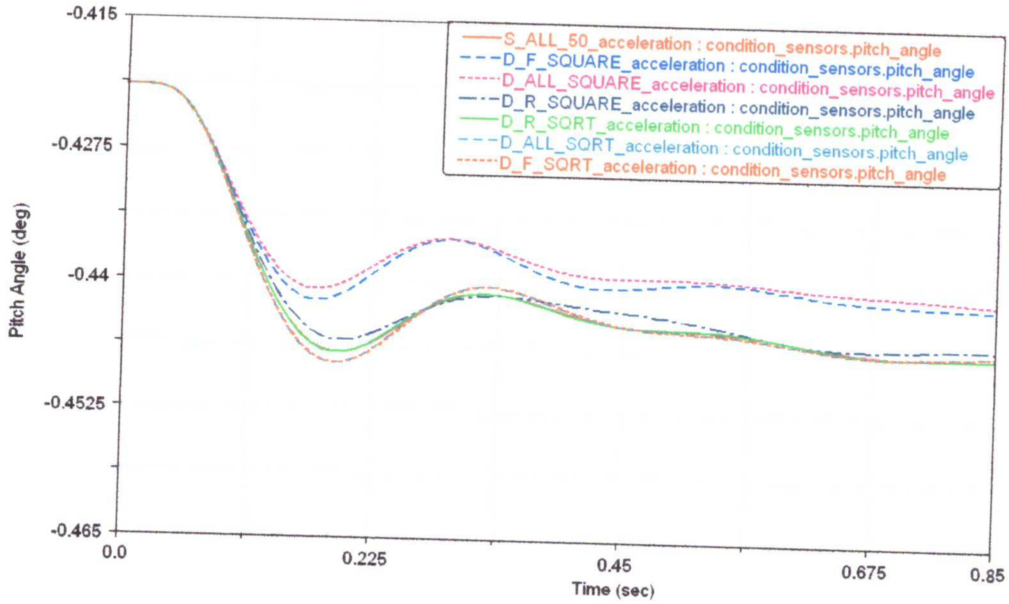


Figure 4.17- Launching over longitudinal path/ Damping change

In Figure 4.17, a solution of the vehicle suspension engineering problem is obtainable, that relates to the same effect for changing of damper and/or stiffness, so an increase of front or all suspension damping will decrease the pitch angle produced during launching of the vehicle, and also, minimizing the overshoot appear in other situation.

The effect on the other important parameters can be seen in figures 4.11 and 4.12 for stiffness and damping respectively.

Vehicle Braking:

In braking period the vehicle must be studied under three braking conditions:

- Fully front brake (100% front).
- Fully rear brake (100% rear).
- Front and rear braking (50% for each).

ADAMS/Car having this property, but no difference occur during this simulations, so the good choice to use the value of 55% front brake bias, that will produce 55% of braking torque at the front wheels, whereas the remaining for the rear wheels, that is 45%.

Dive phenomena appear here strongly, that is the weight transfer from rear to front become larger as front braking force increasing. The study for pitch and other critical parameters will be discussed in the following section.

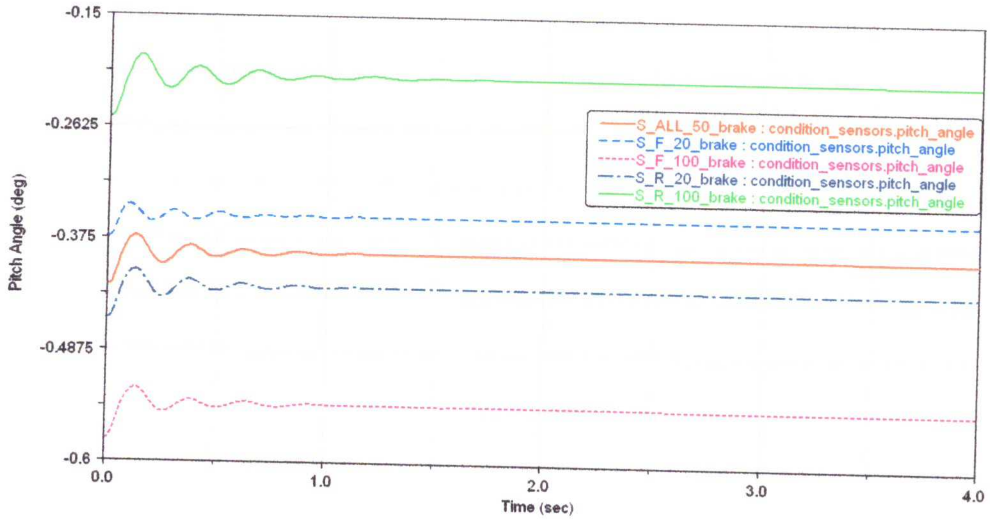


Figure 4.18- Pitch angle during Braking/Stiffness.

As shown in figure 4.18, to decrease the vehicle rotation around its lateral axis (that is pitch motion), the rear wheels spring must become more stiff and the front become less stiff (or soft enough), so low weight transfer occurring during the braking, but the ripple will be more (the *green* line show three shots that have a higher amplitude than the other ones), since the change occurs during approximately rigid links at rear wheels.

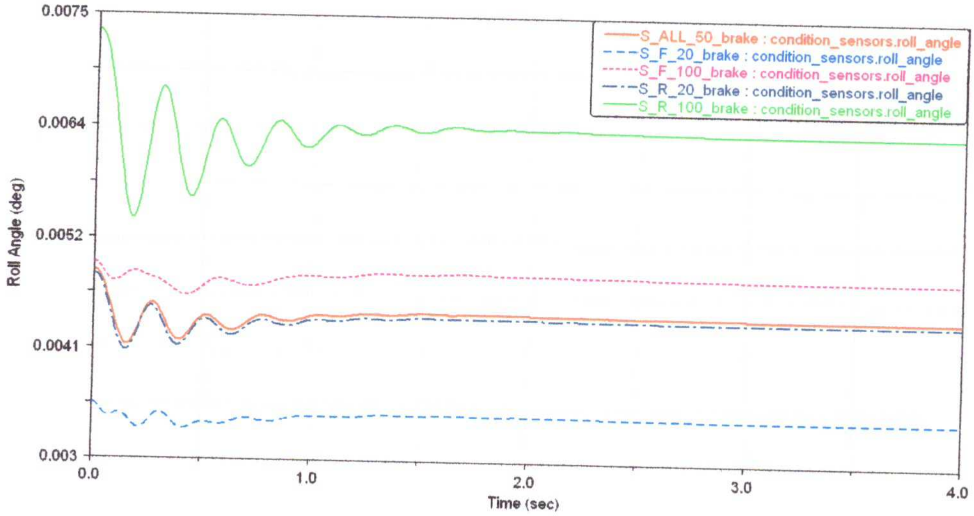


Figure 4.19- Roll angle during Braking/Stiffness.

Roll angle increases as rear and also front stiffness increases, that makes the weight transfer move the vehicle body. But the change here can be neglected, since the change is very small (partition of 10000 degrees). Also, a compromise model of system controlling must change what is most important and improve handling and comfort. In the sideslip case, the angle monitoring is similar to the response in pitch angle as shown in next figure.

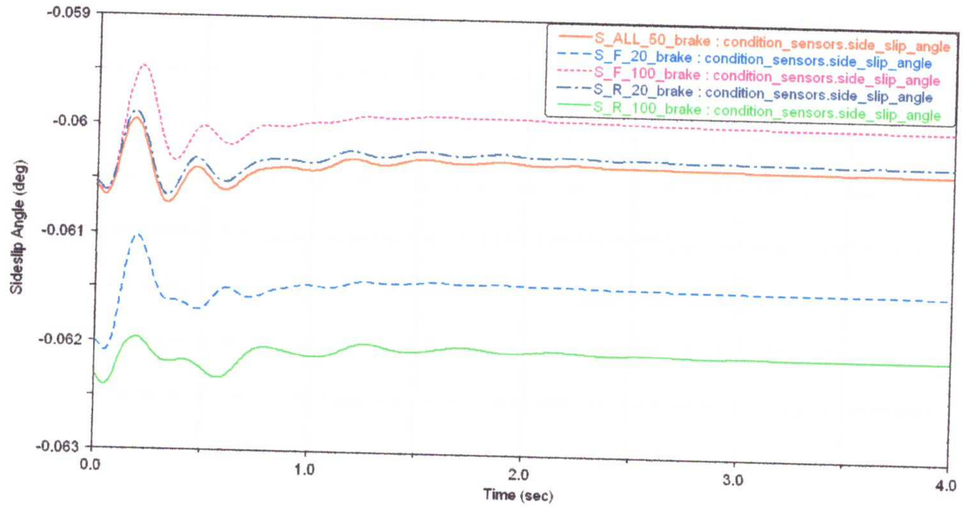


Figure 4.20- Sideslip angle during Braking/Stiffness.

To show the complete effect on the suspension response, the damper change must be considered here also, as the following figures appear:

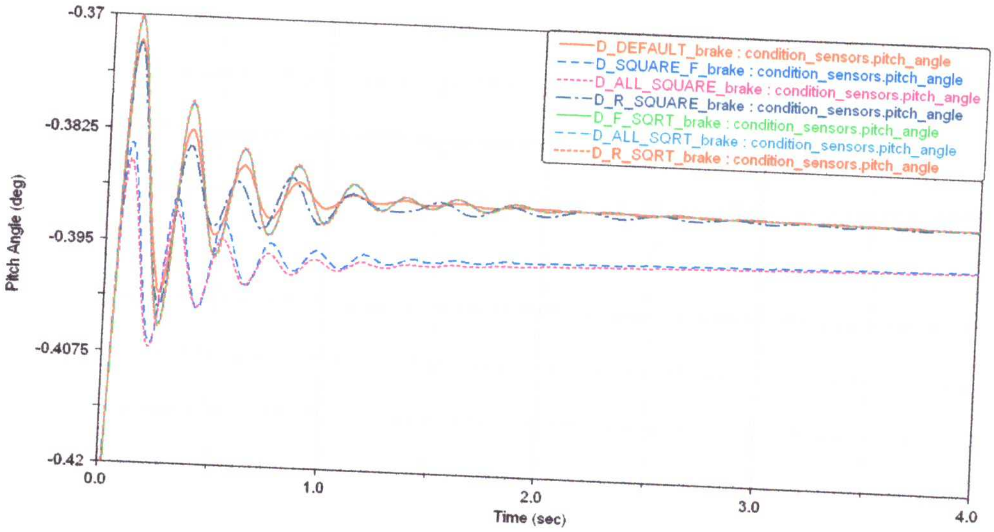


Figure 4.21- Pitch angle during Braking/Damping.

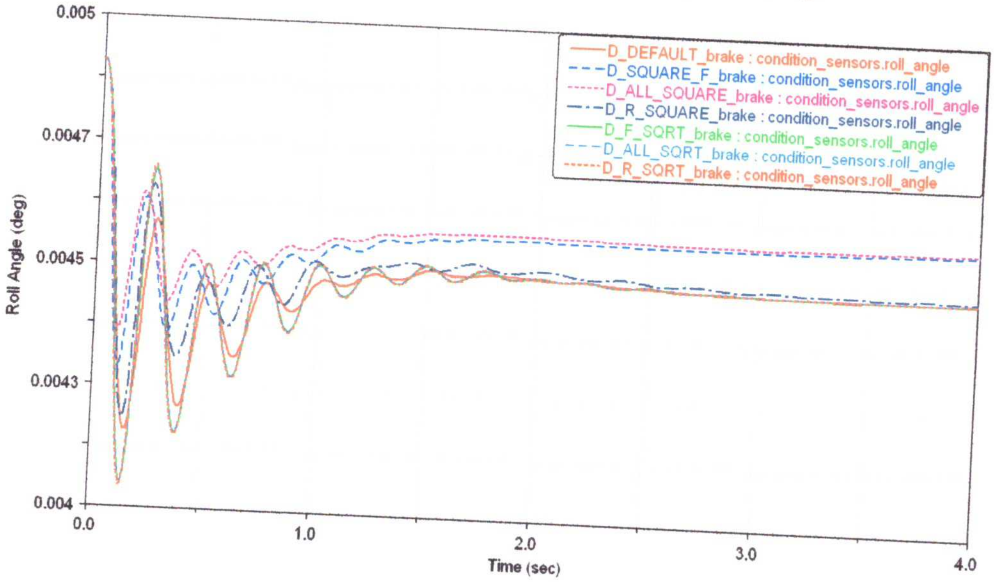


Figure 4.22- Roll angle during Braking/Damping.

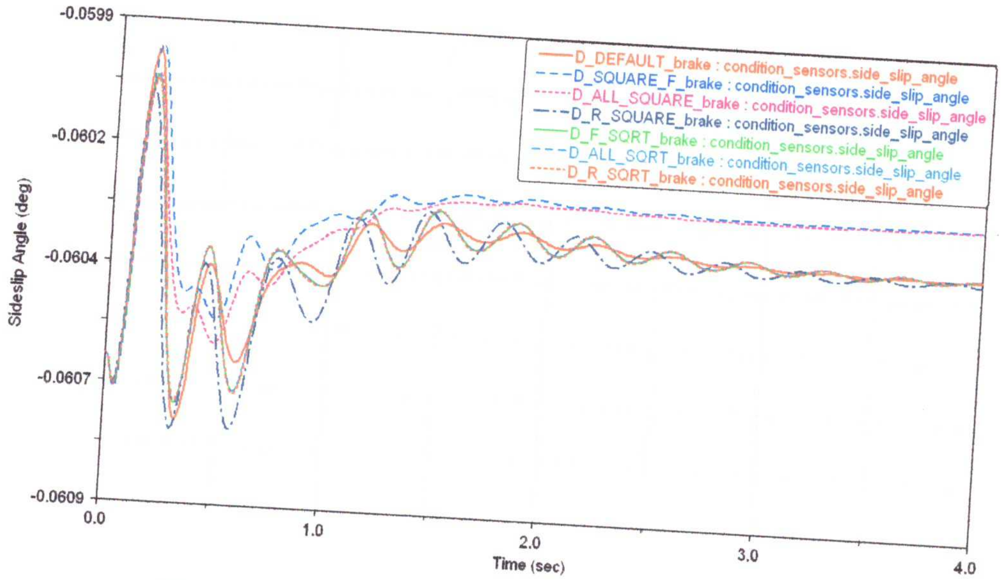


Figure 4.23- Sideslip angle during Braking/Damping.

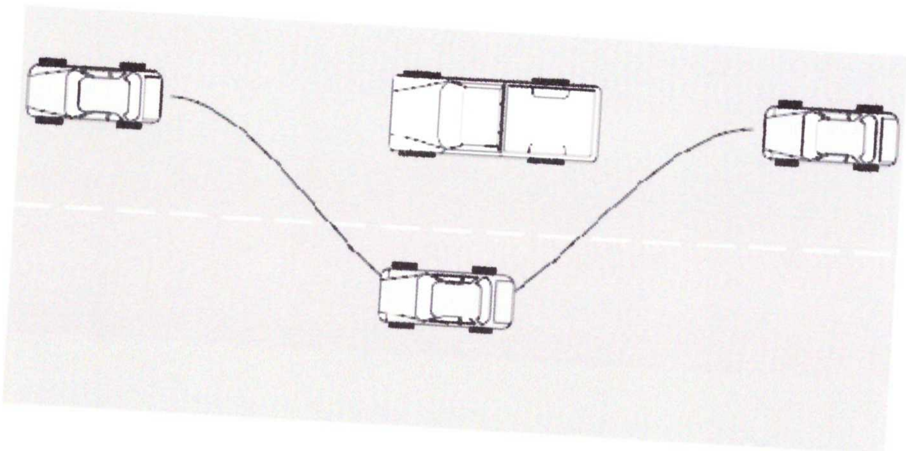
The results produced from the damper simulations produce a good engineering reference, that enable the controller to neglect the small effect of changing the damping constant, in order to improve other properties. So the small change in this results give a better case that deadens the ripple appears in vehicle body, to make the ride more comfort.

4.2.3 ISO-Lane change

It's a one sinusoidal wave steering input. During a single lane-change analysis, the steering input goes through a complete sinusoidal cycle over the specified length of time. The steering input can be:

- Length: which is a motion applied to the rack of the steering subsystem.
- Angle: which is angular displacements applied to the steering wheel.
- Force applied to the rack.
- Torque applied to the steering wheel.

It simulates for example, the driver on avoiding an obstacle as seen in figure 4.24. This maneuver points out the vehicle ability on recovering side slip angle in critical handling conditions, beside the anti-roll improvement.



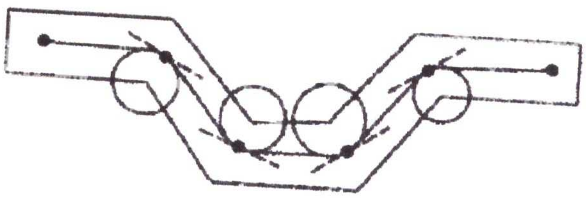


Figure 4.24- Vehicle under ISO-Lane change conditions.

In such maneuver, a lot of parameters change needed; since here the steering will be one of the most important parameter causing this motion. The focusing will be on roll and pitch angles, and side slip angle.

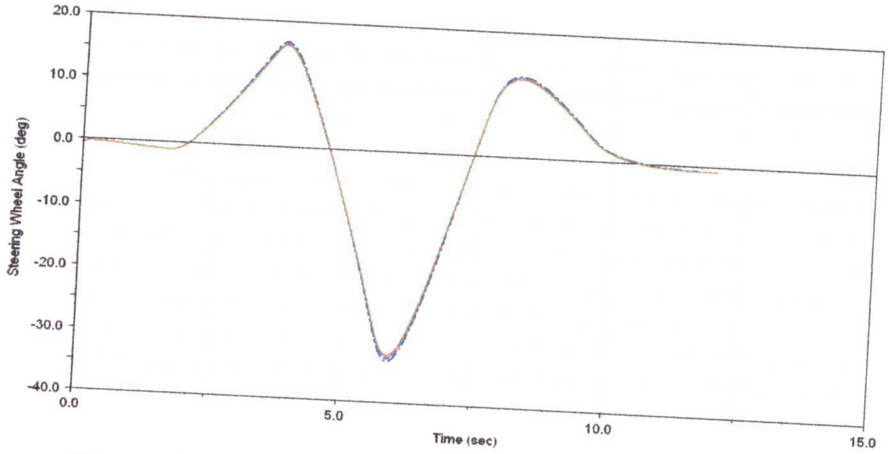


Figure 4.25- Steering wheel angle during ISO-Lane change.

Since the vehicle undergoes two cornering (start and end of maneuvers), the best study is the changing of the stiffness/damping on right and left side, as the centrifugal force and weight transfer acts primarily on the outer side of cornering.

Left corner:

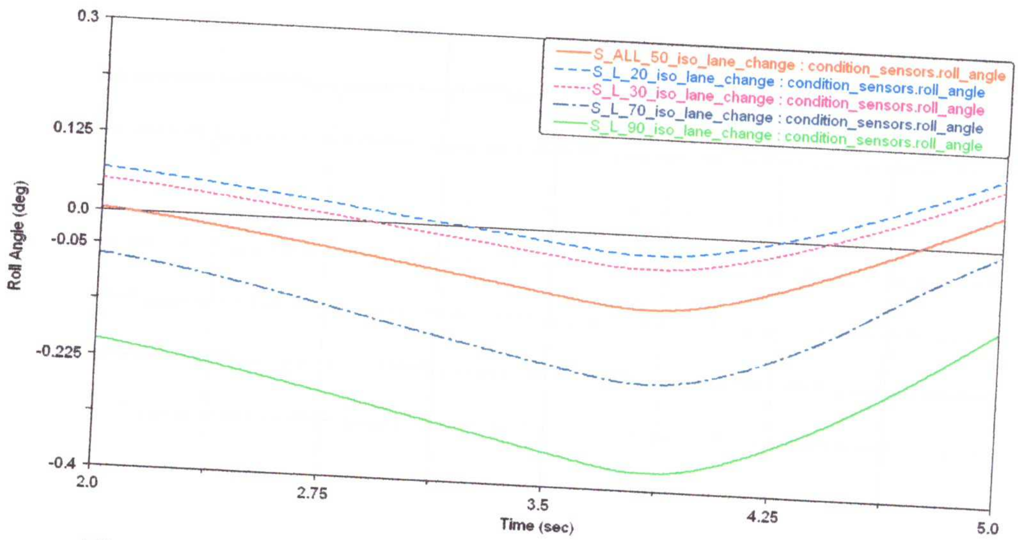


Figure 4.26- "Left-Stiffness change" cornering entrance roll angle.

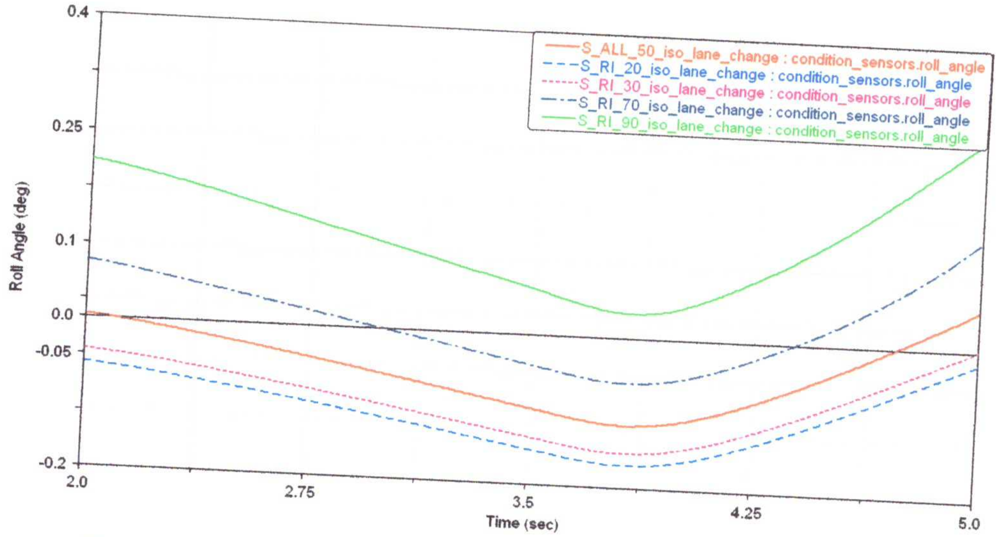


Figure 4.27- "Right-Stiffness change" cornering entrance roll angle.

As shown in figures 4.26 and 4.27, the entrance of the vehicle to the first left corner causing the roll angle increasing (the sign convention for roll angle-from this figures-negative for left-CW and positive for right-CCW). The lowering of left side stiffness will increase the roll on the vehicle, as the centrifugal force acts on the vehicle CG tries to push it outward.

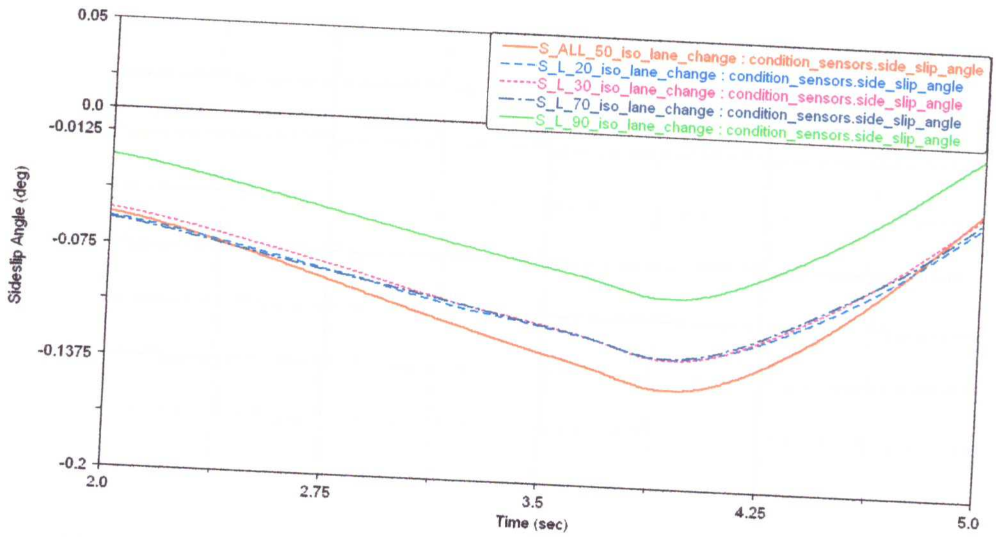


Figure 4.28- "Left-Stiffness change" cornering entrance Sideslip angle.

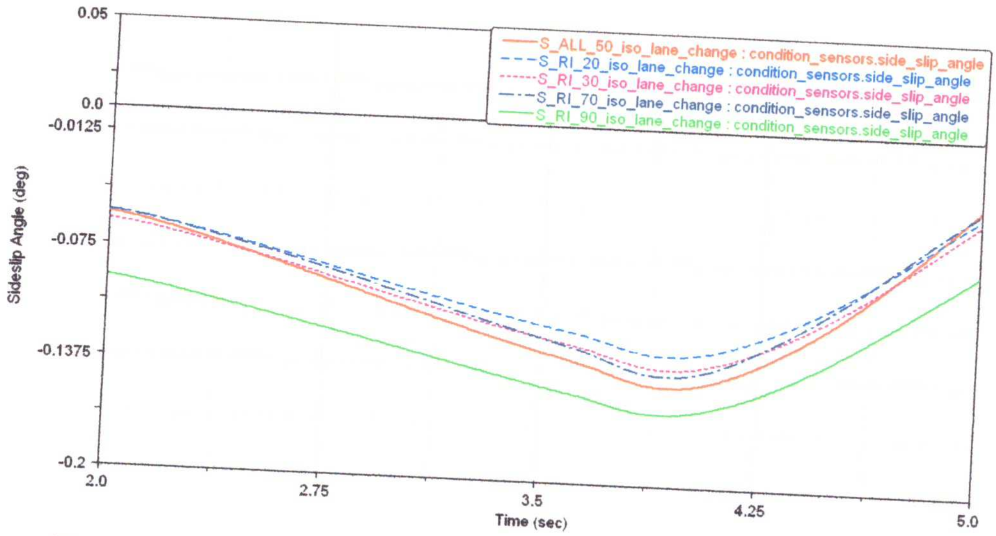


Figure 4.29- "Right-Stiffness change" cornering entrance Sideslip angle.

The results of sideslip angle show the opposite. The increasing of left side stiffness will decrease the sideslip angle on the vehicle, as the centrifugal force acts on the vehicle will transmit completely through the rigid spring to act on the wheel/tyres assembly that mean good response. Right side stiffness change give opposite to left side. But, always in mind, the range of angle change in sideslip can be neglected to improve roll angle.

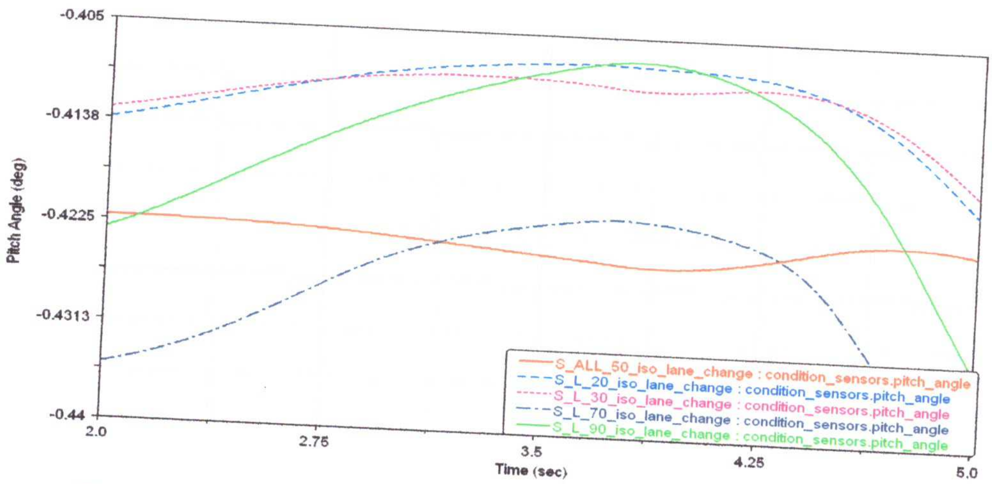


Figure 4.30- "Left-Stiffness change" cornering entrance Pitch angle.

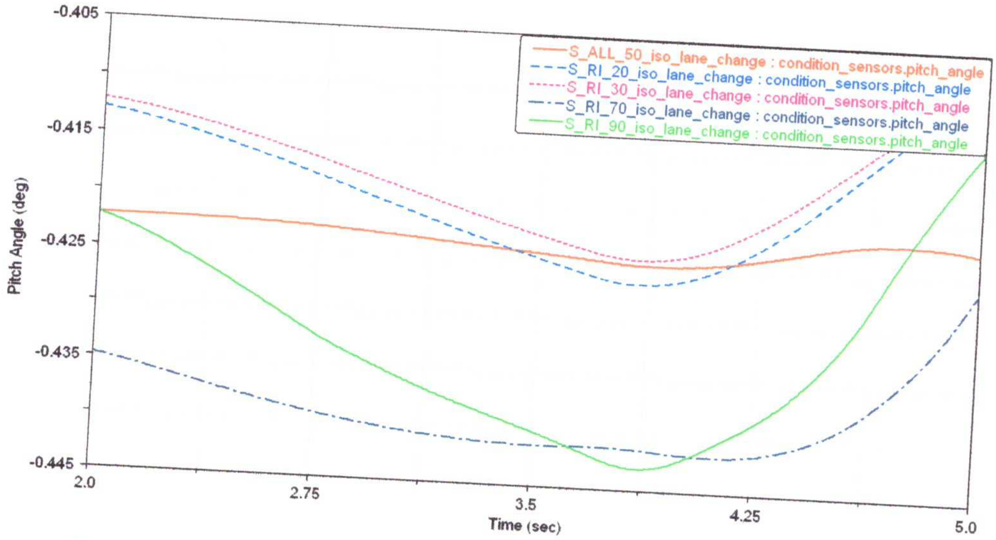


Figure 4.31- "Right-Stiffness change" cornering entrance Pitch angle.

Pitch angle here taken into account, despite that the good response here, appear as an opposite effect in roll angle. Also, the value of changing between the different trials showed, means important contribution of this parameter in control system.

On other side the result in right corner is opposites in left corner ,in chapter five show the difference.

4.2.4 Different road conditions for vehicle wheels

When one of the wheels undergoes different road conditions, such as obstacle, bump, or pothole, the main change in focus will be primarily on the wheel that in action. Despite that, additional enhancement can be added from other wheels, the result response depend on load transfer.

Here, the vehicle under study, facing at the left wheel a crown obstacle (the same for the acceleration with a bump), and its response recorded to be study. Not only pitch and side slip angles change, but also yaw and roll angles may be altering, that decrease vehicle stability that yield in some cases to vehicle failure.

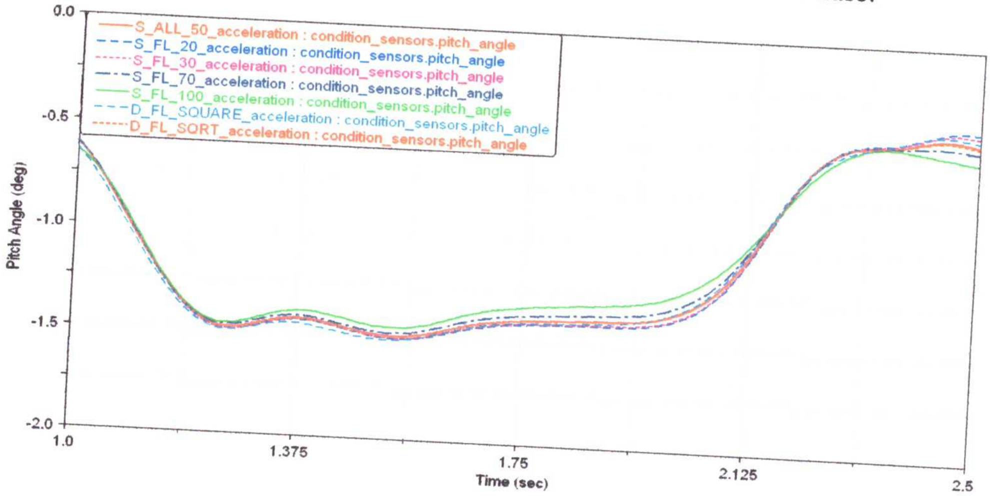


Figure 4.32- Pitch angle during front-left wheel bump.

Pitch angle, that is continuously an important factor in suspension design, is taken here also. Its negative value related to its upward vertical direction during the entering of the bump. The sensor that measure this angle doesn't measure pitch angle for this wheel only but it measures the whole vehicle CG pitch angle, as it located there.

The increasing of stiffness and/or damping at this wheel will improve the pitch angle and the sprung mass displacement.

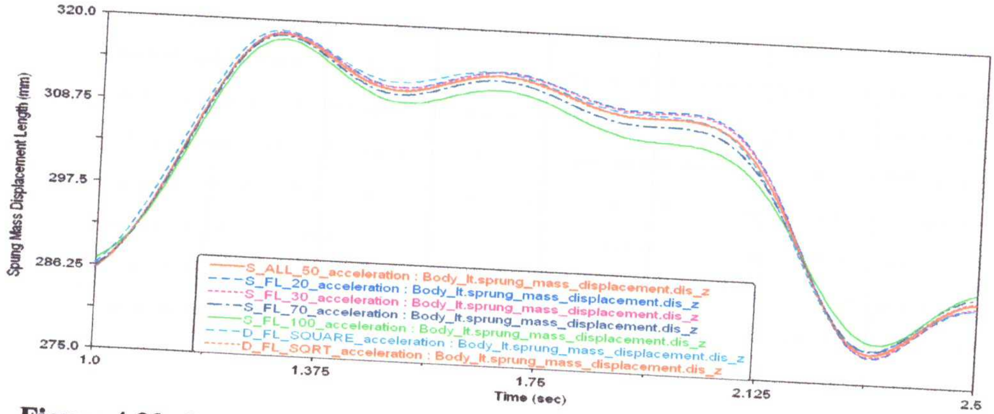


Figure 4.33- Sprung mass vertical displacement during front-left wheel bump.

But, as stiffness/damping increase, this will transmit all the forces directly to the body to cause more yawing and rolling angles, that may cause instability during driving. Yaw and roll angles have a noticeable change, but the system of control must taken into account the driving condition of the wheel under study. Here as the obstacle with 100mm height for one wheels act as a large problem since its CG height is only 300mm, which leads to noticeable change in some value. Some angles as yaw, must studied with reference to wheelbase of the vehicle, that is the vehicle will move with half the wheelbase multiplied to yaw angle tangent.

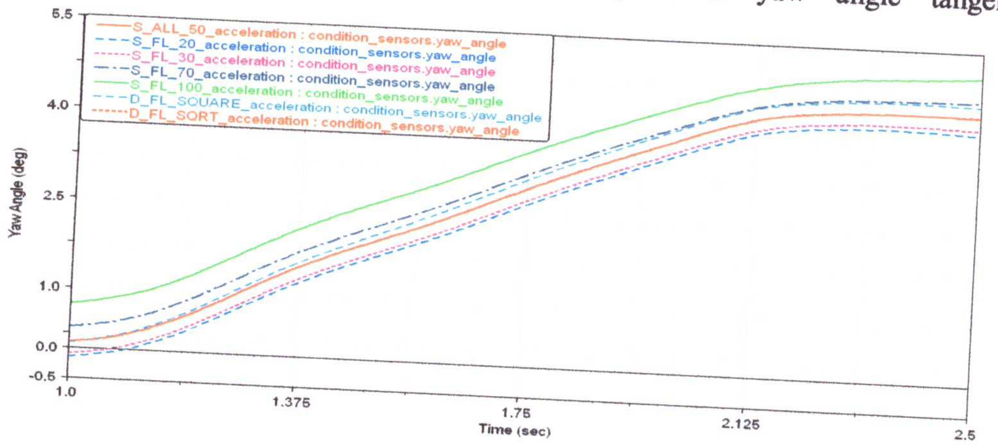


Figure 4.34- Yaw angle during front-left wheel bump.

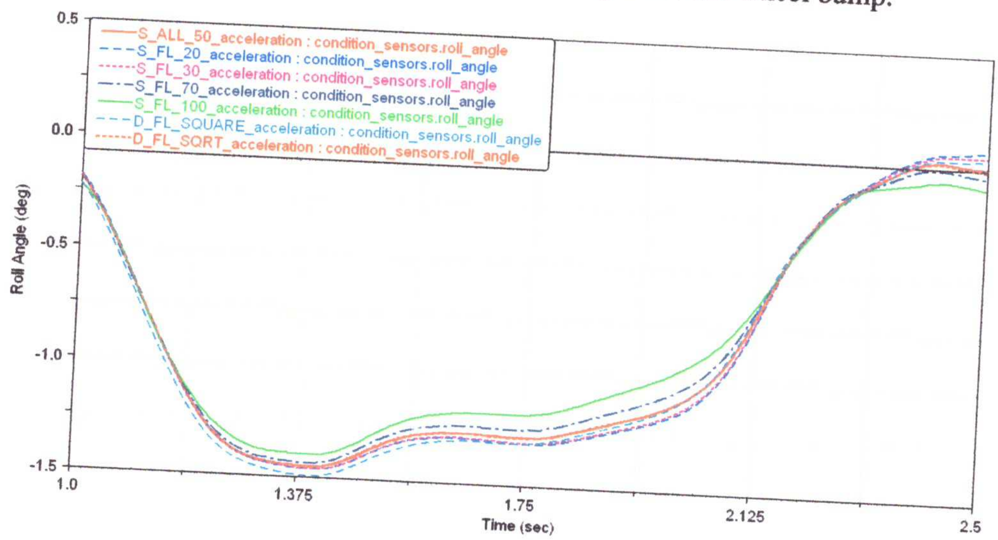


Figure 4.35- Roll angle during front-left wheel bump.

Chapter Five

Automotive Stability Control and Riding Comfort using ADAMS/Car

Chapter Content:

Chapter Five

Automotive Stability Control and Riding Comfort using ADAMS/Car

5.1 General Outlook

As the worldwide use of automotives increases rapidly, it has become ever more important to develop vehicles systems, to provide safe and comfortable transportation and at the same time have minimal impact on the environment. To meet these diverse and often conflicting requirements, automobiles are increasingly relying on electromechanical systems that employ sensors, actuators and feedback control(fig. 5.1), so engineering activities must acting on the active and/or semi-active systems in automotive field.

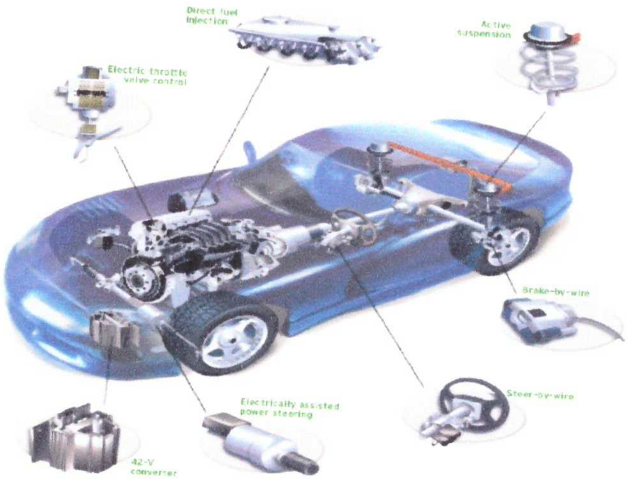


Figure 5.1- Automotive Modern Trend (Hybrid vehicle).

An ever decreasing design effort for such systems, coupled with increasing amounts of equipment, is only possible due to the far-reaching use of computer simulations in the design of new vehicles, also computer monitoring, communications, and continuous diagnosing system. The aim of computer models, such as the one shown schematically in figure 5.2 is to reveal, as early as possible in the design phase, the effect on the dynamic behavior of the vehicle.

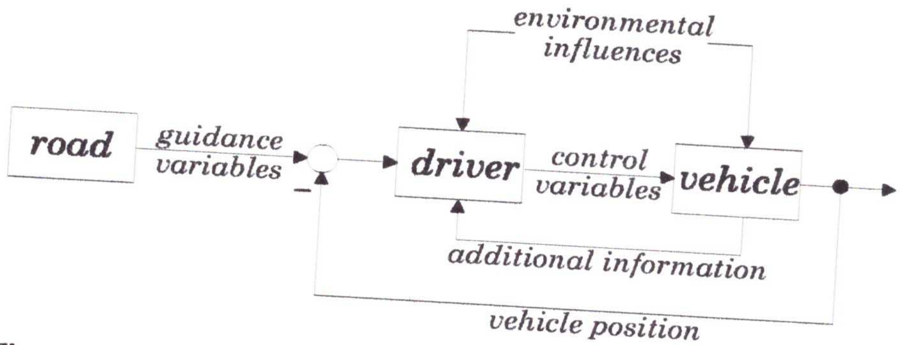


Figure 5.2- The standard vehicle-driver-road control loop.[3]

In any area of technology, control systems design is an interplay between reality, physics, modeling, and design methods. This is also true in automotive control, and there has been extensive work done in research and development leading to a number of descriptions, models, and design methodologies suited for control. The study in this field doesn't stop in any point, which is the end of any is a start of a new study with improving environment.

A control/mechatronics engineer needs models that are both simple enough to use for control system design, but also at the same time, rich enough to capture all the essential features of the dynamics, which must be ready from the automotive engineer.

In this chapter, ADAMS/Car results taken into account in order to extract data of the vehicle handling and riding characteristics, study it, processing according to literature, and then propose control scheme that makes a useful addition to the electronic stability and comfort programs now available. The proposed scheme which adjusts the vehicle height/damping automatically with air/hydraulic control and damping forces continuously according to driving conditions, using monitoring system that composed of sensors on the vehicle systems under considerations. The system proposed is equipped with four wheel independently controlled semi-active dampers with four air springs as a unit, one ECU and related sensors.

5.2 System Configuration

The system is composed of an automatic air leveling system and a four-wheel independently controlled semi-active suspension system, and a group of monitoring sensors. figure 5.3 show the simple configuration of the proposed control system.

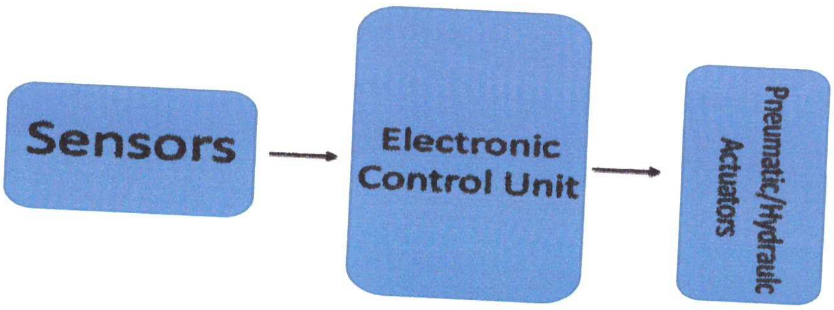


Figure 5.3- Proposed control system block diagram.

5.3 Proposed Semi-Active Control System

The semi-active suspension consists of four continuously variable dampers with four air leveling springs, a control module, three acceleration/motion sensors, a steering wheel sensor, a speed sensor, a throttle position sensor, roll sensor, and brake switch.

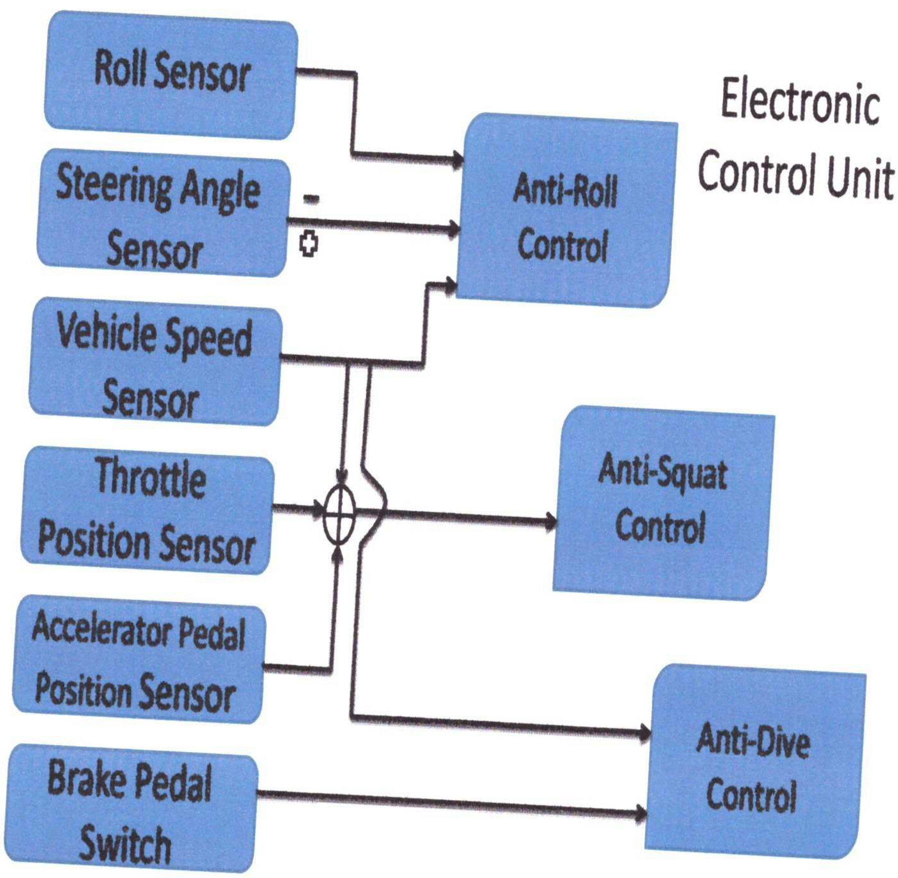


Figure 5.4- Inside ECU.

5.4 Schematic Control

The proposed control system shown schematically in figure 5.4, will be now divided into specific functions, so the three main considerations will be shown and described, and of course, the result of proposed action during this control will be shown through ADAMS/Car compromising results.

5.4.1 Anti-Roll schematic Control

The vehicle system will undergoes a force during cornering and other irregular driving situation, that cause the vehicle rolling around its longitudinal axis, this causes unstable driving and may be converted to dangerous case, so unsafe condition.

Anti-roll control will resist the vehicle ability to roll to increase its stability, improve the comfort for driver and occupants of the vehicle, and of course, less stress on them also.

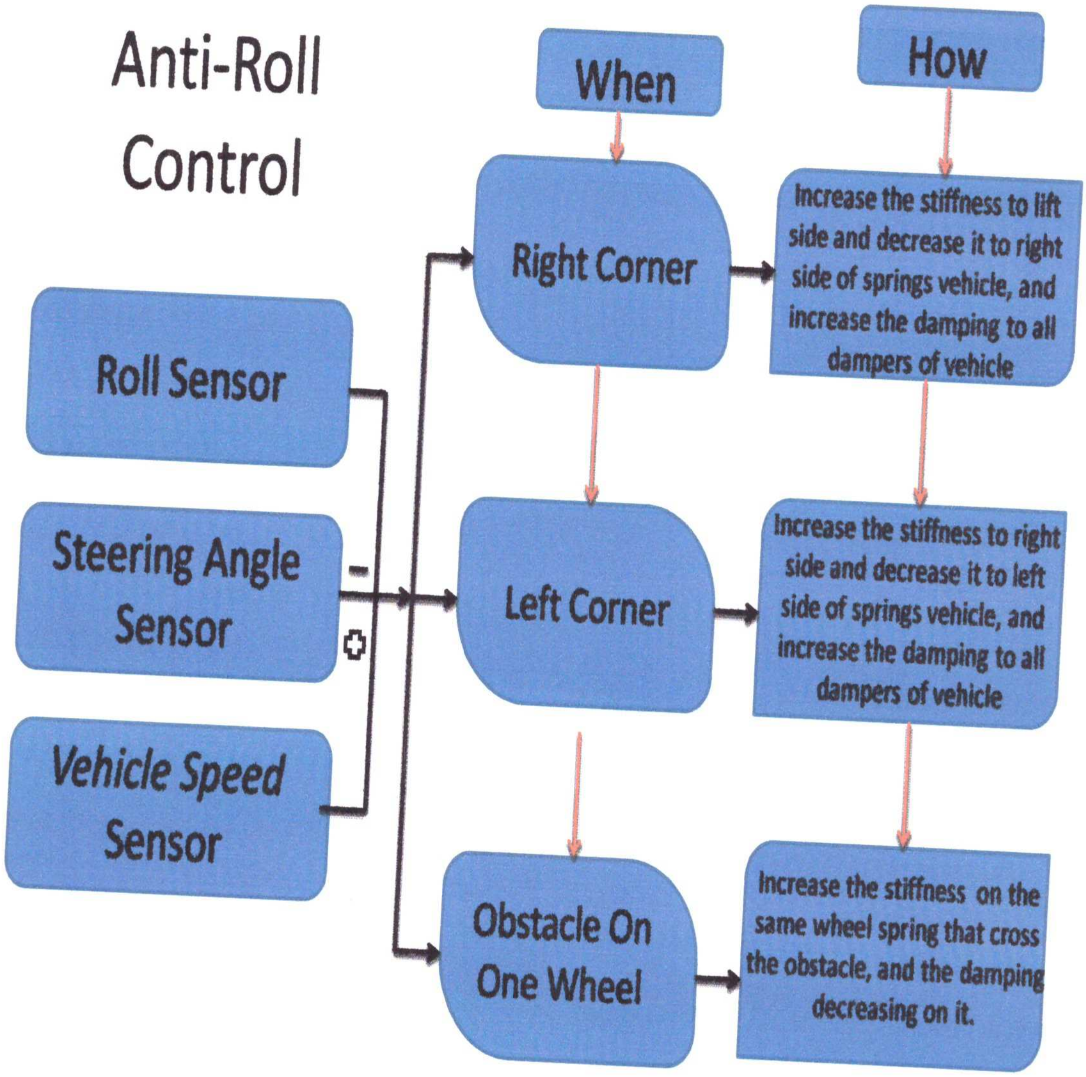


Figure 5.5- Anti-Roll Control.

Right corner:

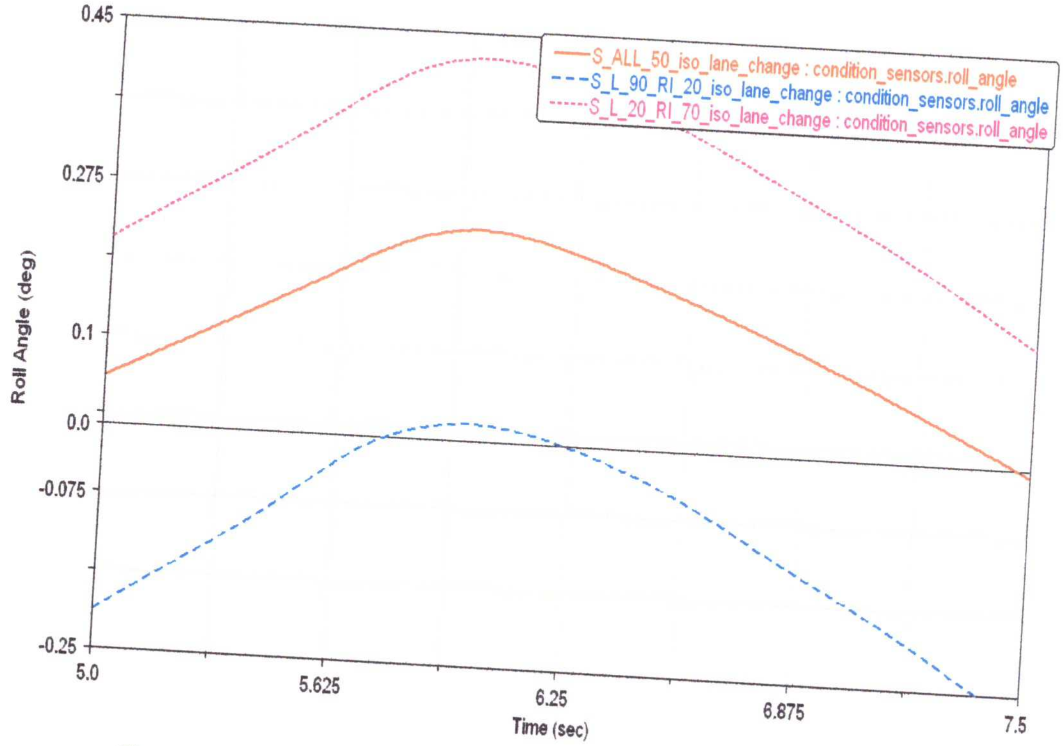


Figure 5.6- Roll Angle During Right Corner/Spring Results.

To make the vehicle more stable and not to roll, the roll angle must be minimum as possible (around zero). In the above curve, the increasing of the stiffness in the left side of vehicle and decreasing it in the right side, will make the roll angle approaches zero, so when the controller know the vehicle in this case (right corner) by the sensor monitoring systems shown schematically in the fig(5.5), it will increase the stiffness in left side and decrease it in right side, in order to achieve the desired goal of minimum roll angle. The reason is that changes will resist the effect of the centrifugal force produced by this corner that also cause a weight transfer outside the cornering center.

Left corner:

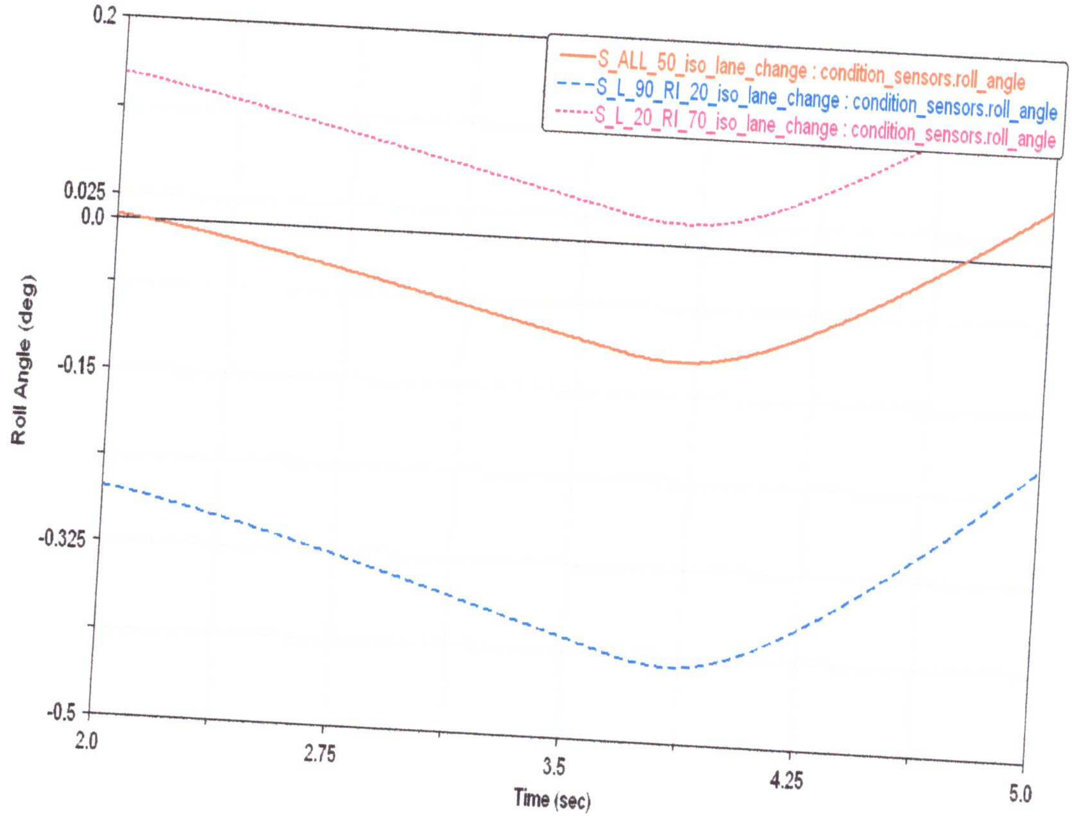


Figure 5.7- Roll Angle During Left Corner/Spring Results.

But, on the contrast, when the controller know that the vehicle will now passing through left corner, make the roll angle closely to zero by increasing the stiffness in right side and decreasing it in left side that make the vehicle more stable during this maneuver. This, as in right cornering, will resist the effect of centrifugal force and the weight transfer.

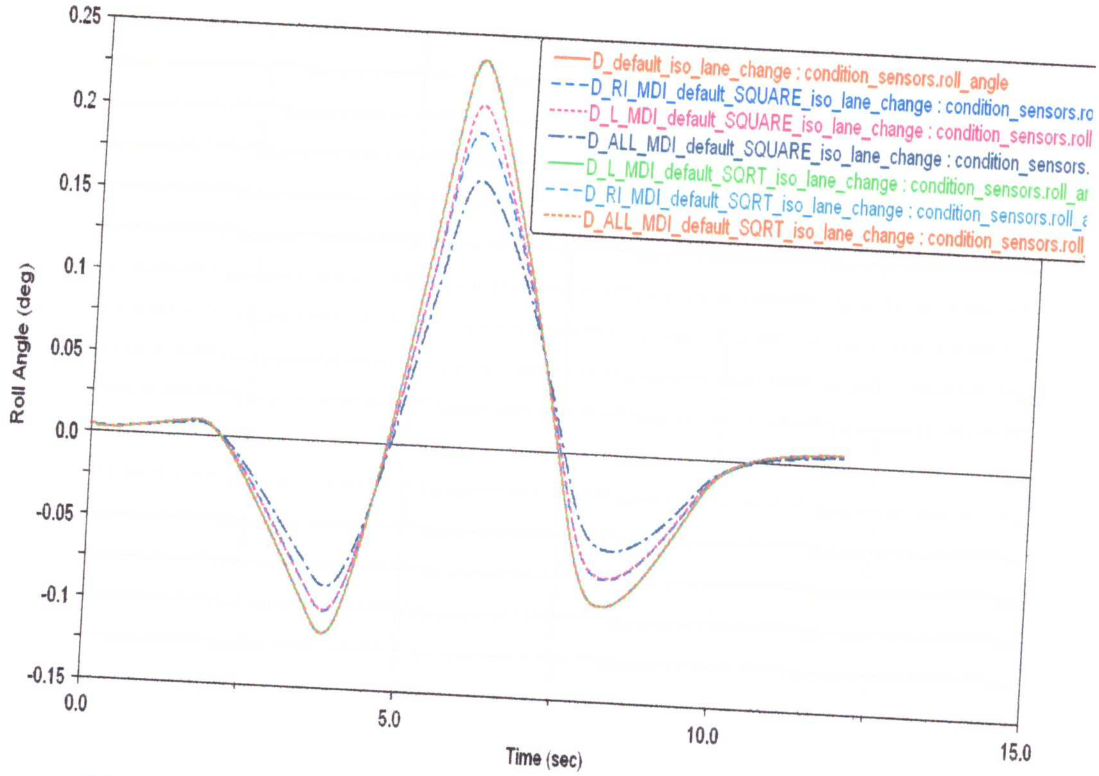


Figure 5.8- Roll Angle During ISO-lane Change/Damper Results.

When the controller know that the vehicle in right and/or left corner, it will function properly modifies the damping in required damper of vehicle, which means lowering of the center of gravity and/or increasing the damping of cornering resulted force. But this result give a contradiction to spring stiffness change results, this related to the core of spring work in vehicle suspension, that it must faces the forces first but the damper only deadens it, so the effect on the spring appear in more clarity than the damper.

Different road conditions for vehicle wheels:

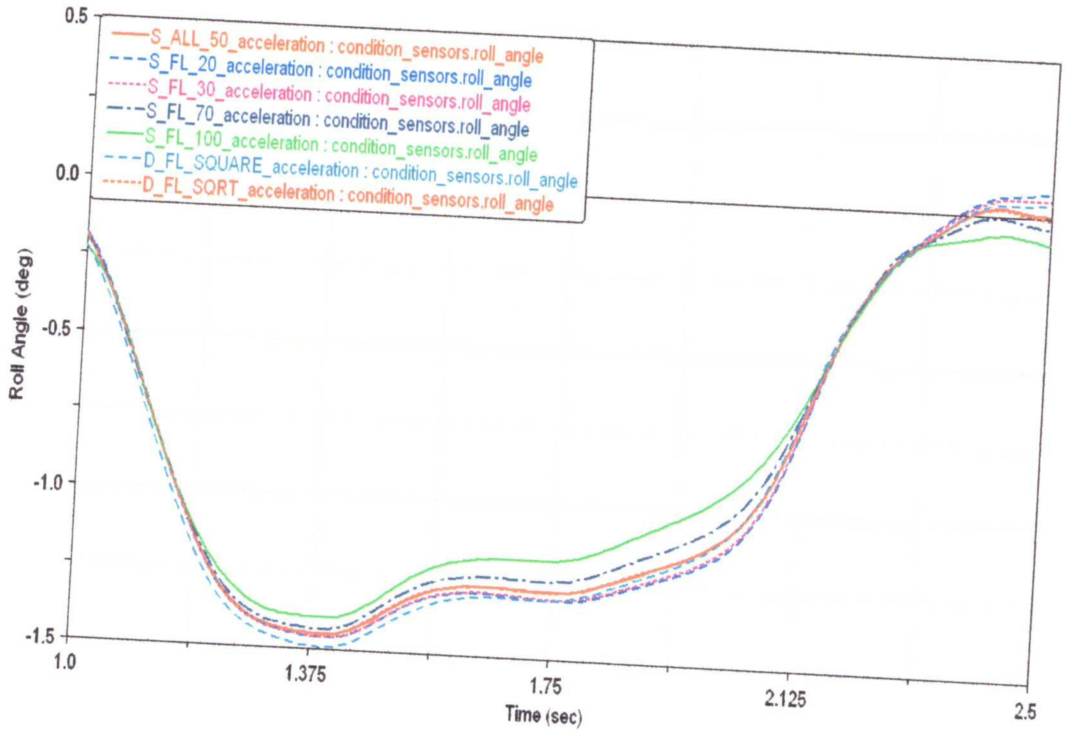


Figure 5.9- Roll angle during front-left wheel bump.

Obstacle **(Different road conditions for vehicle wheels)** means that a moment forces will exerted on the vehicle suspension, that must be continuously damped, so the control system must increase the stiffness and decrease the damping on the same wheel that cross the obstacle.

5.4.2 Anti-Squat schematic Control

This condition appears obviously when the vehicle starts acceleration from zero velocity, which increases the load on the rear wheels; because of weight transfer of vehicle inertia. Another situation implies another than zero start velocity, but this will be less obvious, but must be taken into account.

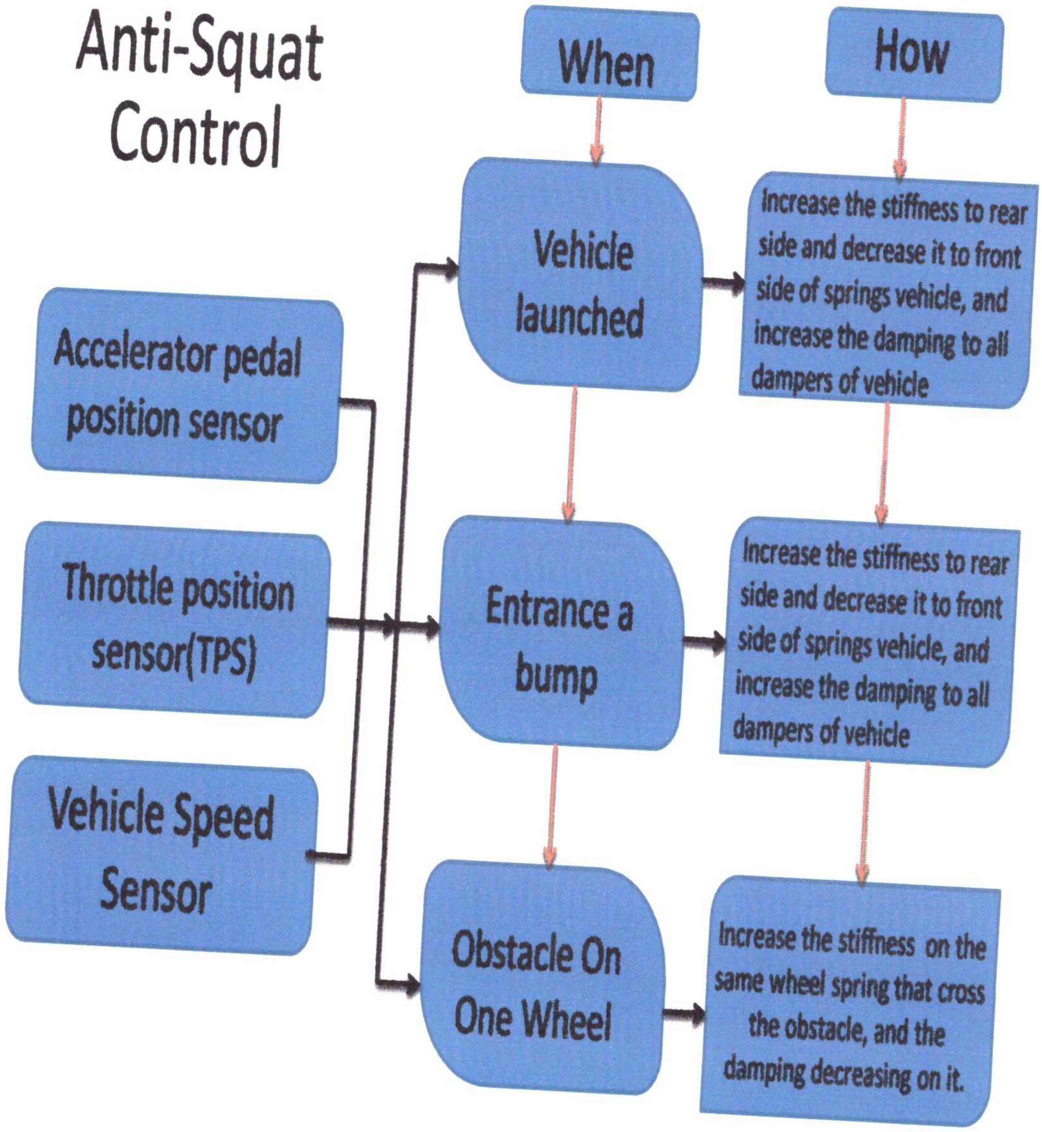


Figure 5.10- Anti-Squat Control.

Vehicle launching:

In vehicle launching from rest, by connecting the response of main variables especially pitch angles, the lowering of the front stiffness with higher rear stiffness will produce an acceptable result, so decreasing the pitch angle, as shown in the following figure.

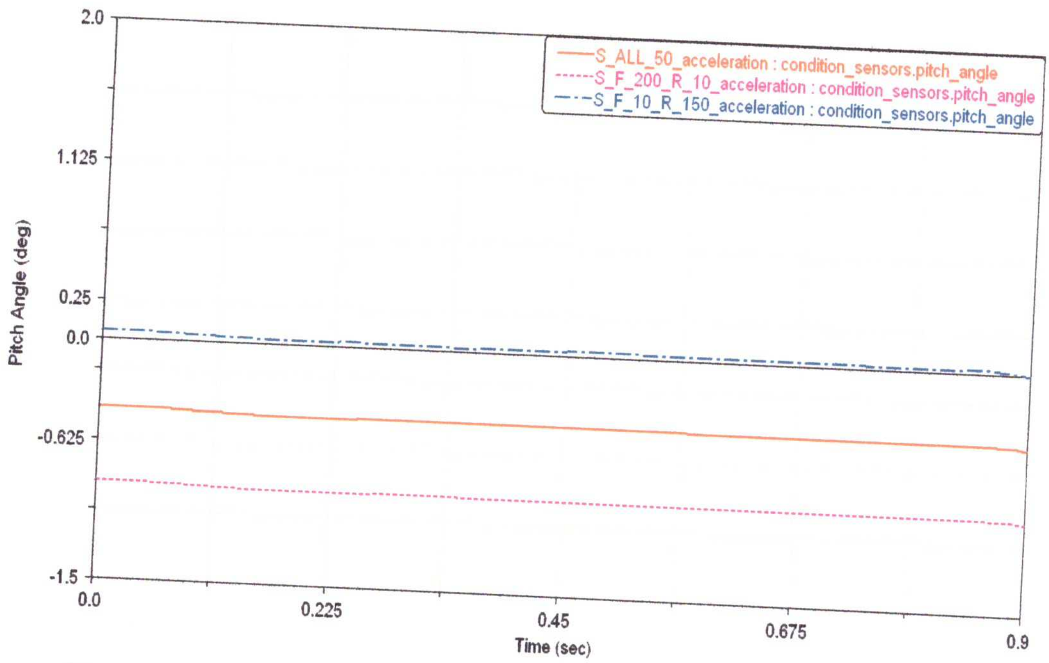


Figure 5.11- Launching over longitudinal path/Stiffness compromise.

To show the complete effect of suspension parameters, the damper change must be considered as the following figures appear:

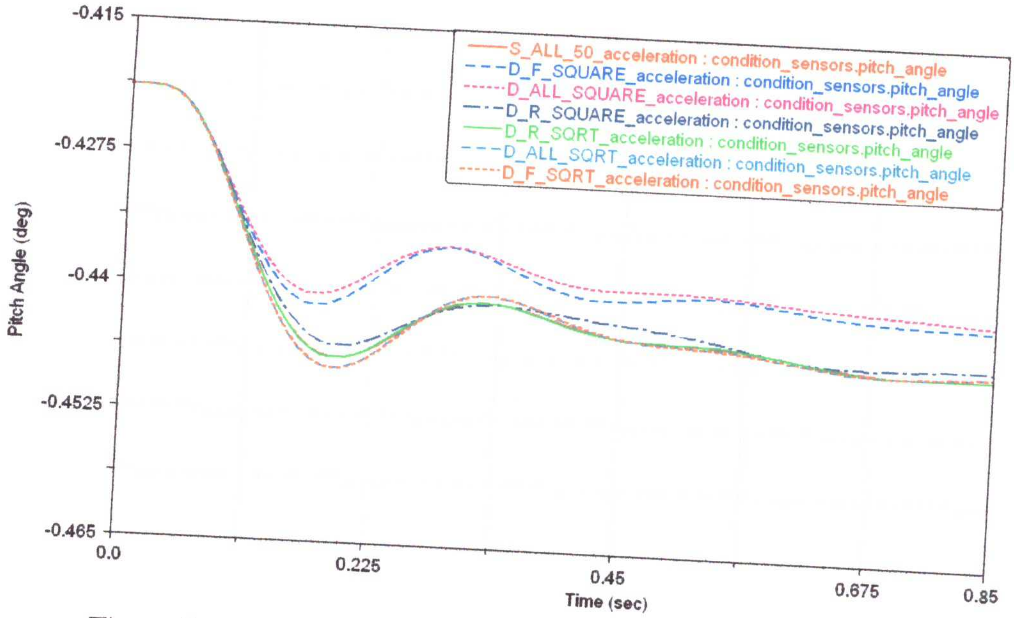


Figure 5.12- Launching over longitudinal path/ Damping change.

Figure 5.12, a solution of the vehicle suspension engineering problem is obtainable, that relates to the same effect for changing of damper and/or stiffness, so an increase of front or all suspension damping will decrease the pitch angle produced during launching of the vehicle, and also, minimizing the overshoot appear in other situation, that is the work of controller will be done.

Entrance a bump:

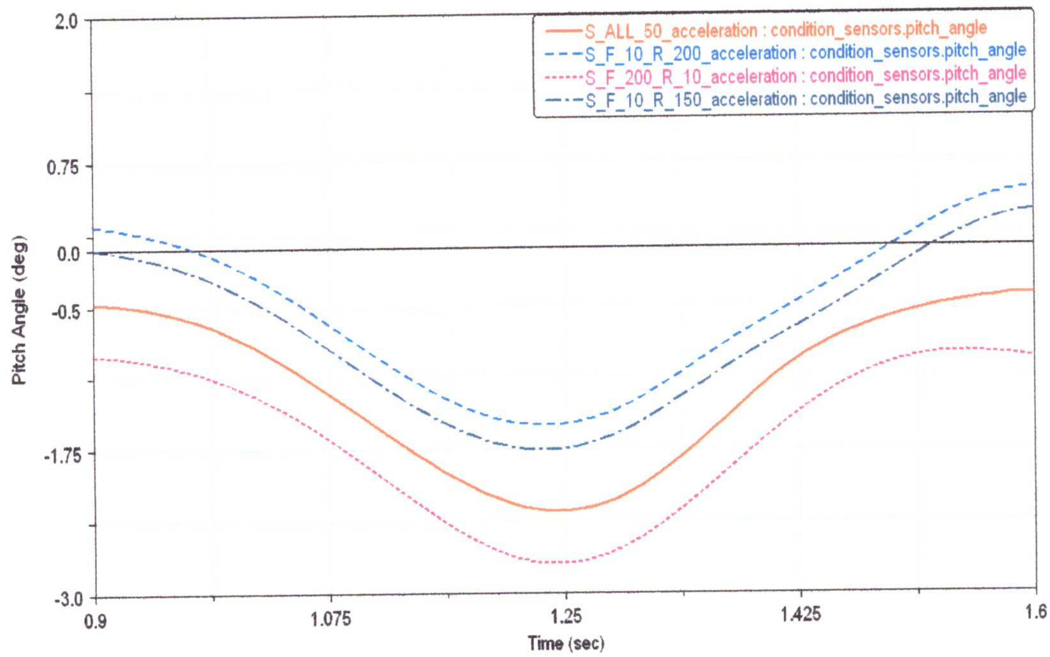


Figure 5.13- Pitch angle in vehicle entering a bump during acceleration/Stiffness compromise.

In Figure 5.13, curves show a required function from a control system, that is the control system must be continuously monitor and vary the system stiffness parameter, to incorporate the change in system response for having best case. The increase of rear stiffness and decrease the front, will give the best result of improving the pitch angle decreasing. The reason of this, that the rear spring limited the rotation of the vehicle around the lateral axis (the rear spring approximate rigid link characteristics), and the front will dissipate the bump response profile. Taking into account, that the changing (increase-decrease) must instantly monitoring and changing to desired response (less pitch angle).

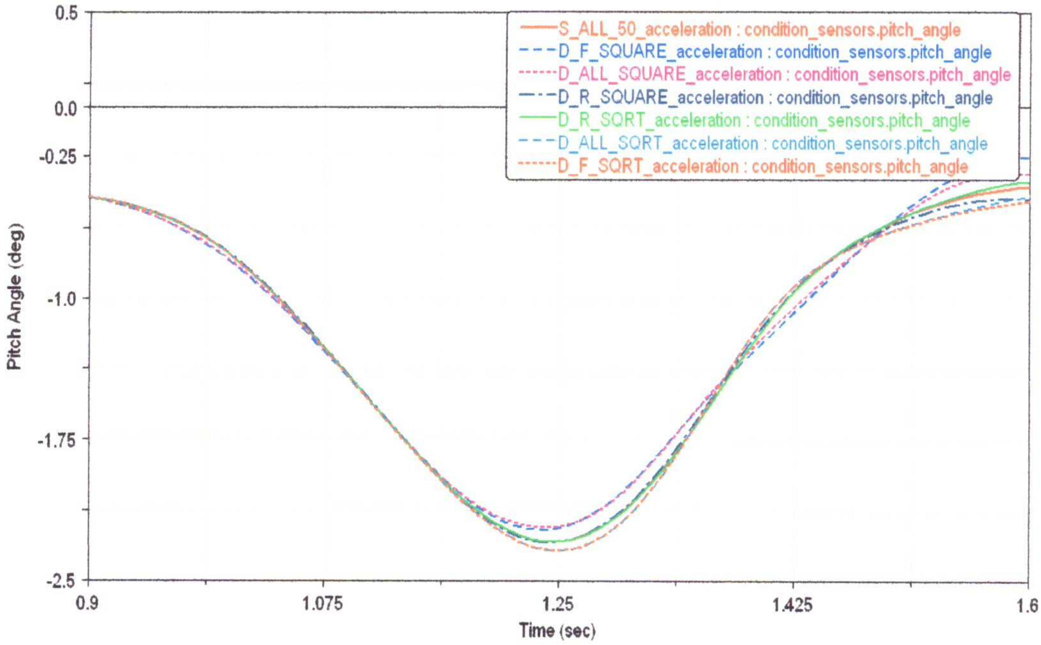


Figure 5.14- Pitch angle in vehicle entering a bump during acceleration/Damping compromise.

All the mentioned simulations occur on the stiffness changing, but in figure 5.14, the system undergoes a damping change. The increase in front or all wheel damping, will produce a low pitch angle, but, rear damping increase/decrease will show the same bad response of the originally used damping curve/value. The high value damper will deaden the bump response at the entrance, but the rear undergoes no visible effect.

Different road conditions for vehicle wheels:

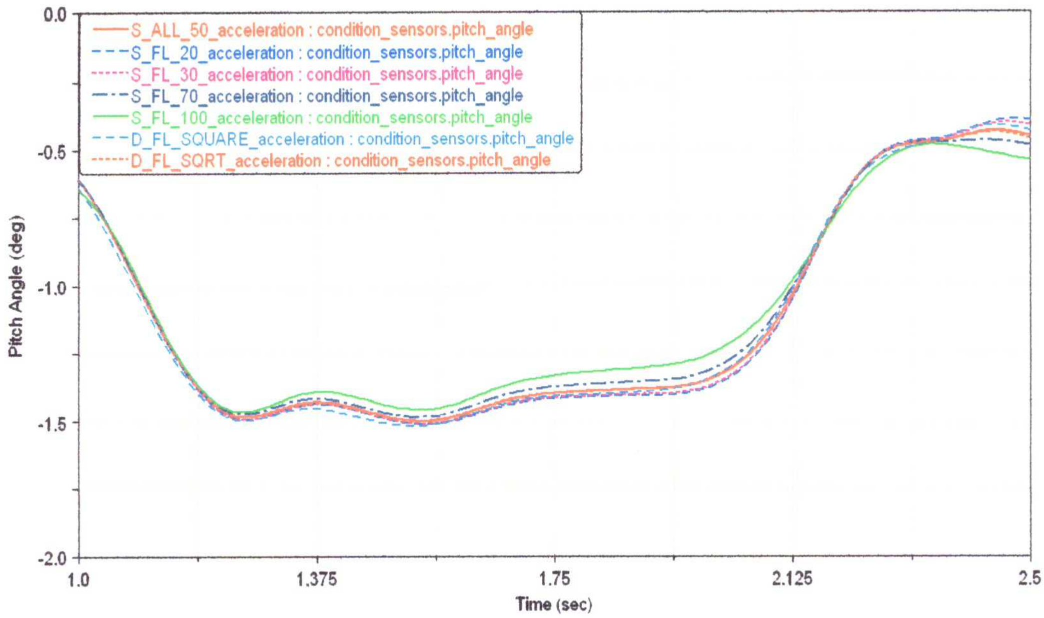


Figure 5.15- Pitch angle during front-left wheel bump.

Pitch angle, that is continuously an important factor in suspension design, is taken here also. Its negative value related to its upward vertical direction during the entering of the bump. The sensor that measure this angle doesn't measure pitch angle for this wheel only but it measures the whole vehicle CG pitch angle, as it located there.

5.5.3 Anti-Dive schematic Control

Dive phenomena is an important vehicle characteristic, that appear during braking and an instant change of velocity to stop the vehicle, as a result of weight transfer. Also the exit of bump may be assumed as dive, taking into account that dive has large time than the assumed dive in the exit of a bump.

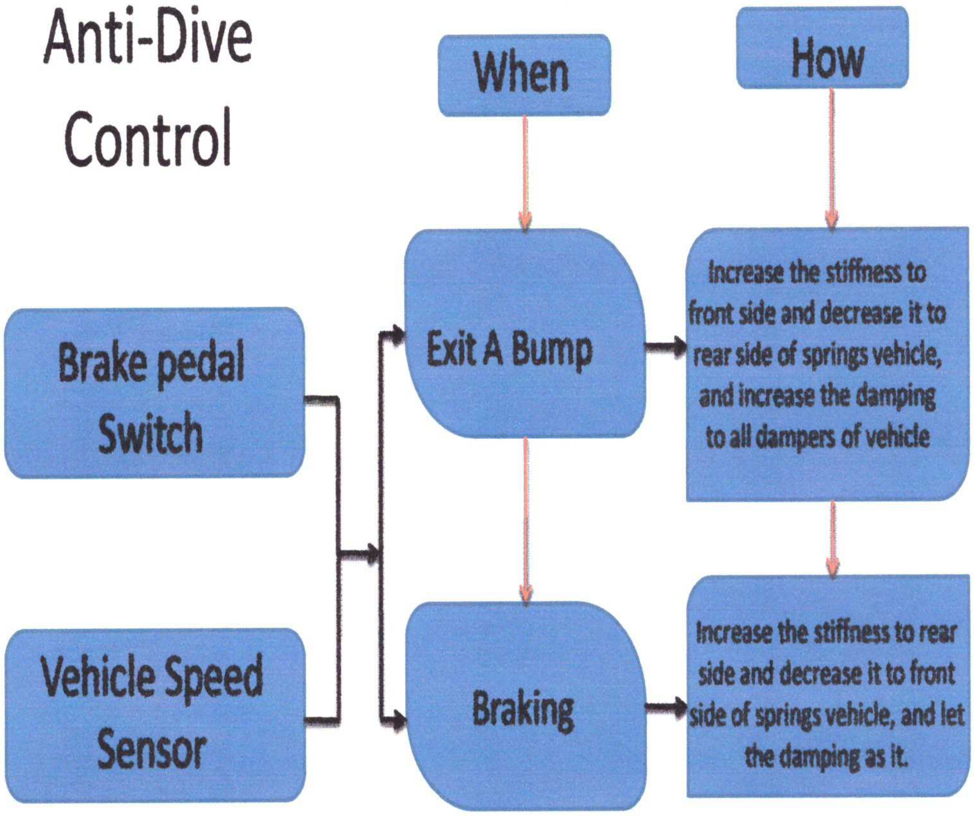


Figure 5.16- Anti-Dive Control.

Exit a bump:

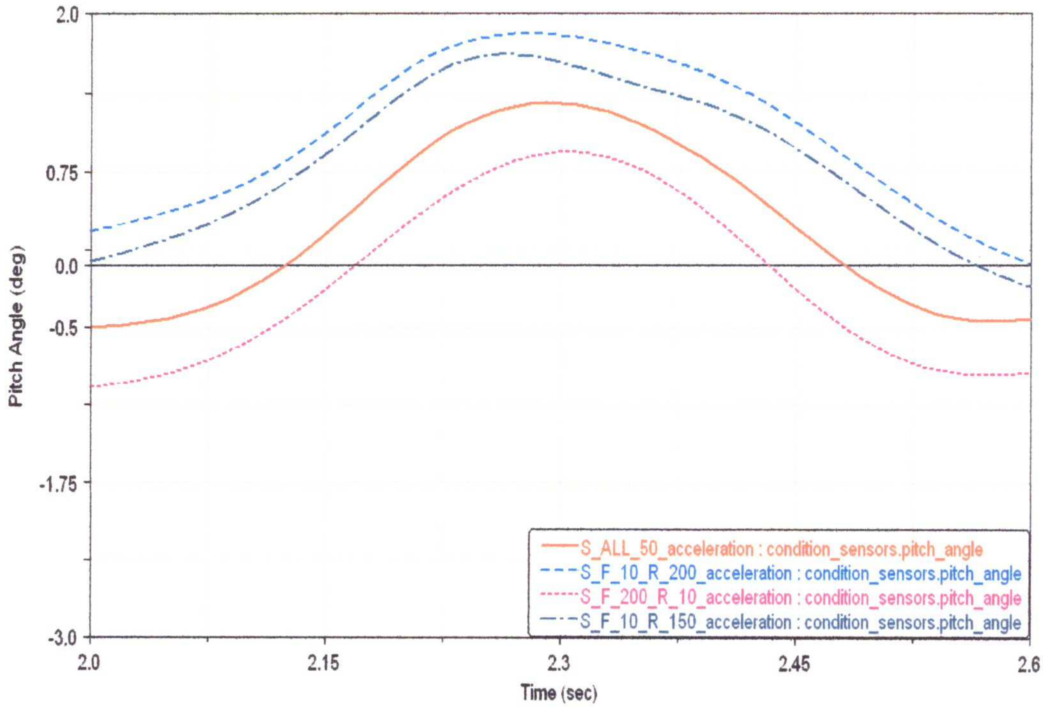


Figure 5.17- Pitch angle in vehicle exist a bump during acceleration/Stiffness compromise.

The curves in figure 5.17 give indications for an engineering system that must continuously monitor and vary the system parameter, to incorporate the change in system response for obtaining an ideal case. The increase of front stiffness and decreasing the rear will give the best result of improving the pitch angle decreasing.

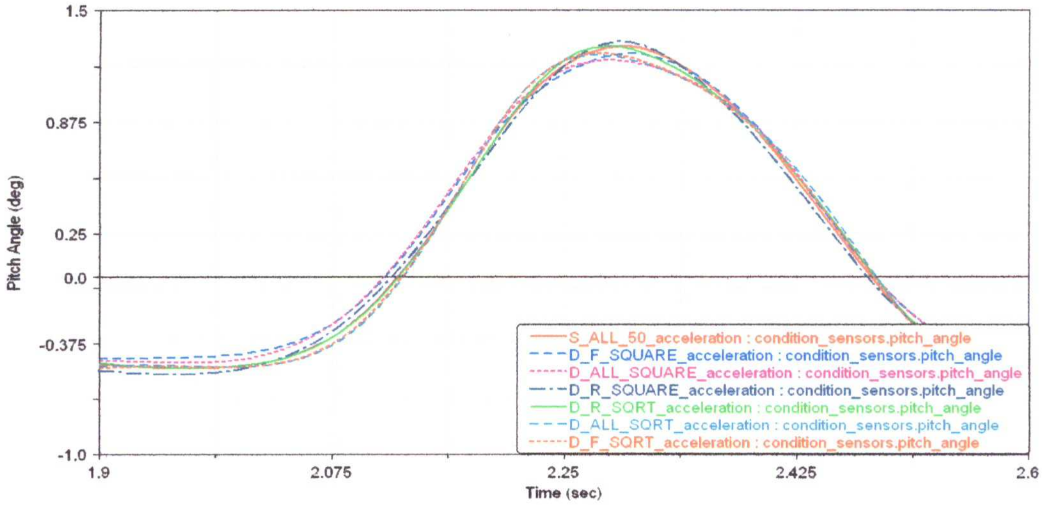


Figure 5.18- Pitch angle in vehicle exist a bump during acceleration/Damping compromise.

All the mentioned simulations occur on the stiffness changing, but in figure 5.18, the system undergoes a damping change. The increase in front or all wheel damping, will produce a low pitch angle, but, rear damping increase/decrease will show the same bad response of the originally used damping curve/value. The high value damper will deaden the bump response at the entrance, but the rear undergoes no visible effect.

Braking:

Braking, as in the main dive result, produce large amount of weight transfer to the front wheels. Braking is affected by the design of brake system, the distribution over the wheels, the braking area of the wheels, and the road conditions.

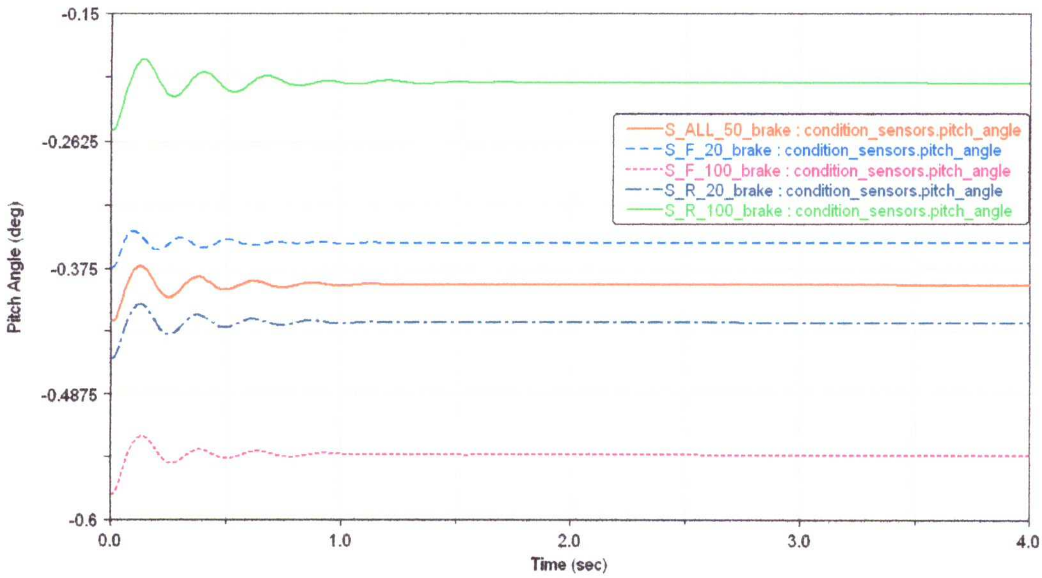


Figure 5.19- Pitch angle during Braking/Stiffness.

As shown in figure 5.19, to decrease the vehicle rotation around its lateral axis (that is pitch motion), the rear wheels spring must become more stiff and the front become less stiff, so low weight transfer occurring during the braking, but the ripple will be more (the *green* line show three shots that have a higher amplitude than the other ones), since the change occur during approximately rigid links at rear wheels.

To show the complete effect on the suspension response, the damper change must be considered as the following figures appear (the red line is the best response that means the default damper is the best damping):

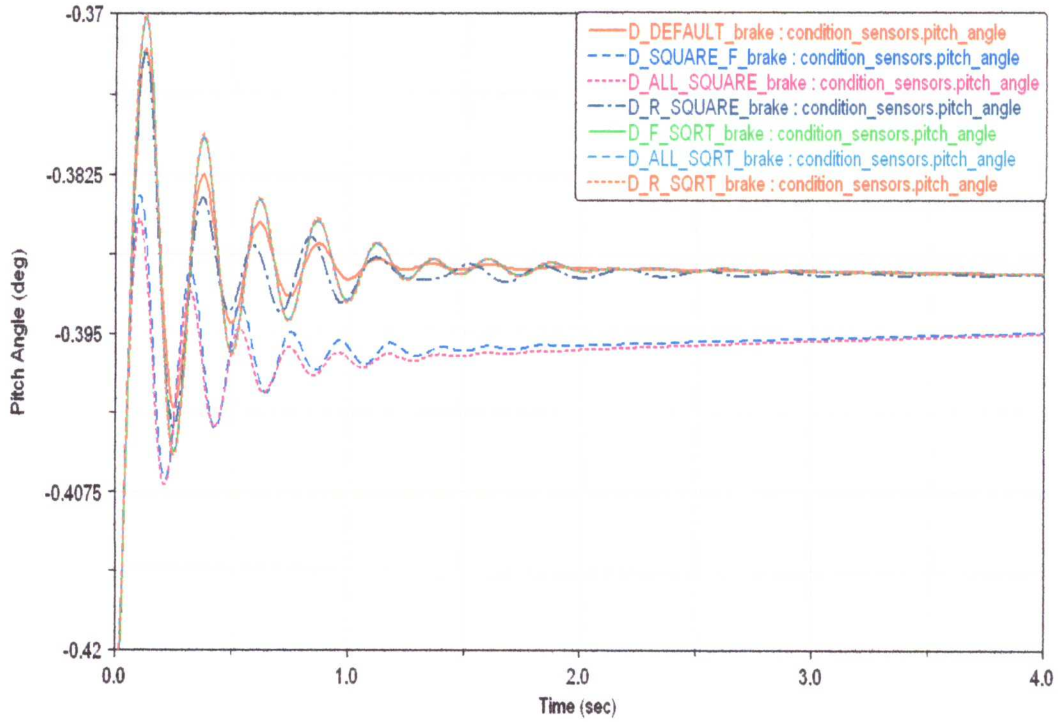
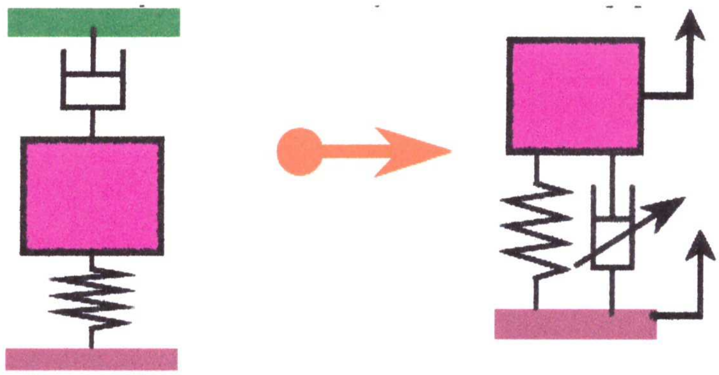


Figure 5.20- Pitch angle during Braking/Damping.

5.5 Height Control Logic

The control logic for the system has two separate parts: semi-active damper control logic and height control logic. The electronic control system logic consists of ride control, anti-roll control, anti-dive and anti-squat control. The ride control is based on the skyhook damper model, which is realized with the continuously variable damper as shown in the figure 5.21:



(a) Ideal sky-hook damper (b) Practical realization

Figure 5.21- Realization of sky-hook damper.

The anti-roll control logic detects the vehicle's cornering motion from the steering wheel angle sensor, and sets the inner rebounding dampers hard to reduce the body roll motion and to lower the vehicle's center of gravity position. The anti-squat and dive control logic sustains the body pitch motion when the vehicle is accelerated or decelerated rapidly.

The height control logic receives relative distance between the vehicle body and wheel from the height sensor. The high frequency component is filtered out so that it captures the spring deflection resulting only from the static vehicle weight variation, and neglects the other. Then PI (proportional-integral) controller and valve selector decide whether the compressed air should be supplied into the spring from the air compressor, or exhaust the air inside the spring to the atmosphere. Finally, the air compressor and the on/off type solenoid valve assembly are driven correspondingly.

5.6 Air Springs

Air springs have good properties compared to the conventional coil or leaf springs. First of all, they can adjust or maintain the height with an auxiliary air supply system. The equivalent spring constant, as depicted in the following equation, increases as the spring load is added so that the ride frequency remains almost the same irrespective of the vehicle weight:

$$K_{eq}=P_i(dA_e/dx) + n\,(P_a+P_i)(A^2_e/V)\ \ [N/m]$$

where P_i is the internal pressure (that produced from the change of weight or weight adding), P_a is the atmospheric pressure, A_e is the effective area, x is the stroke (vertical movement), V is the air volume, and n=1.38 is the polytrophic constant. As for the static conditions, n must equal one (n=1.0), which implies a less soft spring constant.

The dynamic model of the air spring is linked to the ADAMS/Car vehicle model. The dynamic stiffness is shown in figure 5.22 with respect to wheel stroke. When the spring is compressed, that is positive wheel stroke, the stiffness is increased parabolically.

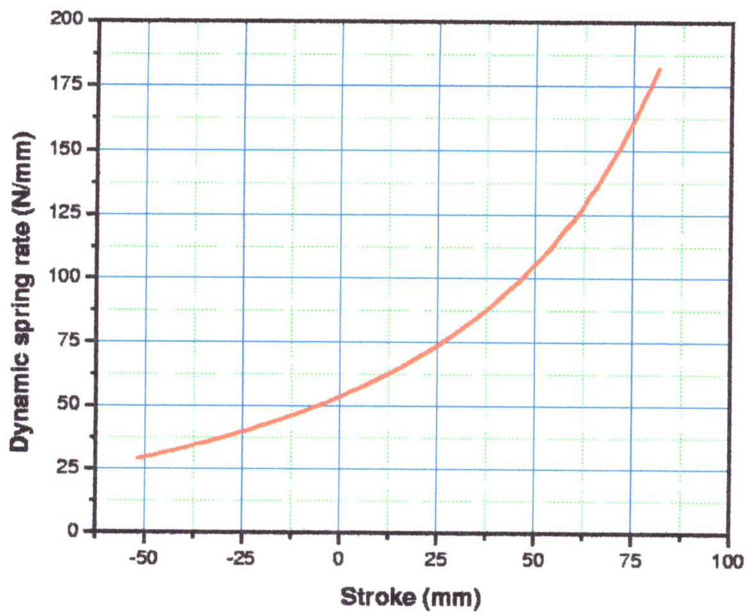


Figure 5.22- Air Spring Characteristic curve.

But, taking in mind, that ADAMS/Control is not completely capable for this type of controlling, so an advance stage of the project may be relies on ADAMS/Car/Control connections with MATLAB/Simulink that will improve the purpose of the project.

5.7 The Damper Control

The control system for the damping regulator uses wheel acceleration sensors and three body acceleration sensors (yaw, roll, and pitch) to monitor the road condition through vehicle movement.

The characteristic curves of the individual vibration dampers are adjusted according to the calculated damping requirement. Here the dampers work as semi-active components in extend and compress mode.

Continuous damping regulation is based on vibration dampers that have characteristic curves which can be adjusted electrically. These vibration dampers are integrated into the air spring dampers.

The damping force is adjusted according to the characteristic diagram using a proportional valve positioned on the vibration damper. Thus, within milliseconds it is possible to adapt the damping force to the driving situation and the road conditions.

On principle, the system tries to adjust the damping force according to the sky-hook control strategy. The damper is adjusted in proportion to the vertical acceleration of the wheels and the vehicle body. Ideally, damping is regulated so that the vehicle body hangs on a sky-hook and floats above the road with almost no disruptive movements, thus, maximum driving comfort is achieved.

5.8 Sensor Technology

The advent of electrically power assisted steering systems introduced the steering torque sensor which can also be integrated with a steering position sensor. A number of torque sensing technologies have been used including inductive and optical technologies. In the case of the optically-based sensor, the pattern of light transmitted through two disks attached to the torsion bar is processed by the electronic control unit to determine both steering torque and position.

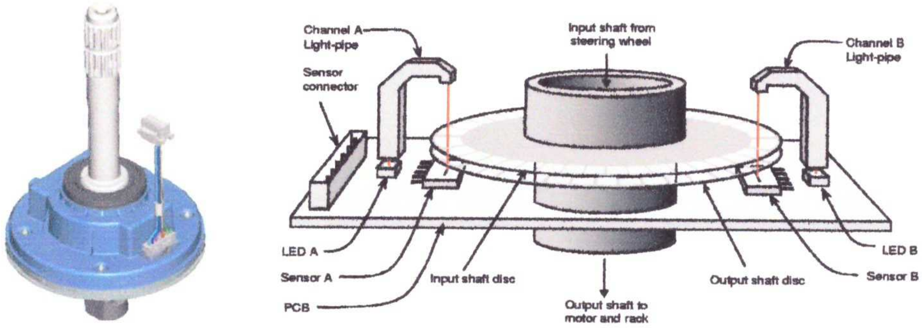


Figure 5.23- Optical Torque and Position Sensor.

Advanced vehicle stability control systems will include an inertial sensor cluster module that comprises a yaw rate sensor (sometimes also a roll rate sensor) and one or two acceleration (lateral/longitudinal) sensors. The yaw sensor can measure the rotation of a vehicle and has a measuring range of +/- $75^{o/s}$. The acceleration sensors measure the lateral and longitudinal acceleration of a vehicle in the range +/-1.5 g. All sensor elements can perform a self test to check their functionality. For future control systems, both the gyroscopes and accelerometers are being integrated with the main circuit board for the application, thus avoiding the need for a separately packaged sensor cluster.

Figure 5.24- Inertial Sensing Module.

Figure 5.25- Slip Control System *ECU* with Integrated Inertial Sensors.

Chapter Six

Conclusions and Recommendations

Chapter Six

Conclusions and Recommendations

6.1 Discussion

The question of handling and riding of automotive is very big to be handled in this thesis, it needs one time and considering of other parameters like functional handling tire models, complete real vehicle characteristics in order to give complete answer.

Working with a project like this, requires that the results are validated qualitatively against each other. It is a balance walk when considering the validity of the results.

The main hidden problem in vehicle dynamics simulation in ADAMS/Car, is the required knowledge to make a first simulation, and to set up a vehicle assembly and perform the simulation, an engineer with no earlier knowledge in the program, will be able to do this in a good time. As a result it is also very simple to plot and post process because of the existing test rig and defined requests from the templates.

The problem arises when the pre-defined templates will not match the design to be simulated and work needs to be done in the template builder, or ever the result cannot be understood. The same happens when something old should be plotted or revised in the postprocessor and the required request does not exist. In that phase the level of knowledge in ADAMS/Car need to be improved a lot, that require years and years to capable for this.

Plotting is much simpler if the user knows what he is looking for. In ADAMS/Car all requests have names and it is much harder to know what the graphs contain or what to choose or let. In some cases the question can be answered in the help, if not the template must be opened and the request investigated manually.

6.2 Conclusions and Remarks

During working on the project introduction, some remarks and notices must be presented:

1. Vehicle handling and riding improvement is an important topic that must be addressed continuously to make the vehicle more comfort, economic, less pollutant and powerful.
2. The design of a new automotive system or even control it means the contribution must be available between automotive and mechatronics engineers, to make the output suitable for its future purpose.
3. ADAMS software is an important simulation tool that helps to carry out a full vehicle simulation, not only for dynamics; but also for its parts and systems.
4. In this study handling and riding characteristics of a concept vehicle have been deeply analyzed through the variation of the main parameters like inertia, center of gravity, stiffness, and damping in the considered vehicle.
5. This study also adopted the standard tests recognized in scientific literature for simulating vehicle dynamics due to parameters change.
6. The obtained results show very clearly that stiffness is much influential on the vehicle stability than damping, which becomes more and more important to improve vehicles dynamics.
7. The obtained results by ADAMS/car software is used to propose a control scheme.

8. The control scheme is built on when the controller must intervene and how to intervene to make the response stability more accurate and good.
9. By using ADAMS/car simulation the time that we need to study the behavior of any part of vehicle or even design it would be minimized.
10. Using ADAMS/car software in study of vehicle is more effective and economic as it will not need to lose a lot of money to make any study of vehicle on real.
11. In ADAMS/car checking for any mistakes and error that can be found at any time by simple review.

6.3 Recommendations

After completing this thesis, the team has the following recommendations:

1. Applying ADAMS/car software for supporting courses in automotives that studied in Palestine Polytechnic University.
2. Establishing computer labs that concerns with simulation projects to improve students' learning environment.
3. Usage of other tools of MSC. ADAMS software like aircraft, chassis, engine, .etc.
4. Connect ADAMS software with other programs like CATIA software and MATLAB software.
5. Develop proposed the control scheme to obtain control of other parameters like sideslip angle, vertical displacement, lateral acceleration……etc.
6. Develop the proposed control scheme in other maneuvers like braking in turn, acceleration on sine road….etc.
7. Follow-up the obtained result and use them in designing a controller.

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Appendix

Appendix

1- Characteristics of springs used:

```
$----------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 ANGLE   =  'degrees'
 FORCE   =  'newton'
 MASS    =  'kg'
 TIME    =  'second'
$----------------------------------------------------------------SPRING_DATA
[SPRING_DATA]
 STIFFNESS    =  100.0 (or any value used)
 FREE_LENGTH  =  205.7 for front and 204.7for rear
```

2- Characteristics of dampers used:

```
$----------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 ANGLE   =  'degrees'
 FORCE   =  'newton'
 MASS    =  'kg'
 TIME    =  'second'
$----------------------------------------------------------------------CURVE
[CURVE]
```

{ vel	force}	or		or	
-1270.0	-1495.5	-1270.0	-38.67169508	-1270.0	-2236520.25
-254.0	-809.5	-254.0	-28.45171348	-254.0	-655290.25
-152.4	-654.8	-152.4	-25.58906016	-152.4	-428763.04
-127.0	-587.1	-127.0	-24.23014651	-127.0	-344686.41
-101.6	-533.8	-101.6	-23.10411219	-101.6	-28942.44
-76.2	-455.5	-76.2	-21.34244597	-76.2	-207480.25
-50.8	-370.1	-50.8	-19.23798326	-50.8	-136974.01
-25.4	-206.4	-25.4	-14.366628	-25.4	-42600.96
0.0	0.0	0.0	0.0	0.0	0.0
25.4	462.6	25.4	21.50813799	25.4	213998.76
50.8	695.4	50.8	25.40472397	50.8	483581.16
76.2	854.0	76.2	29.22327839	76.2	729316
101.6	966.4	101.6	31.08697476	101.6	933928.96
127.0	1085.1	127.0	32.94085609	127.0	1177442.1
152.4	1171.4	152.4	34.22572132	152.4	1372177.96
254.0	1423.4	254.0	37.72797371	254.0	2026067.56
1270.0	3218.1	1270.0	56.72829982	1270.0	10356167.61

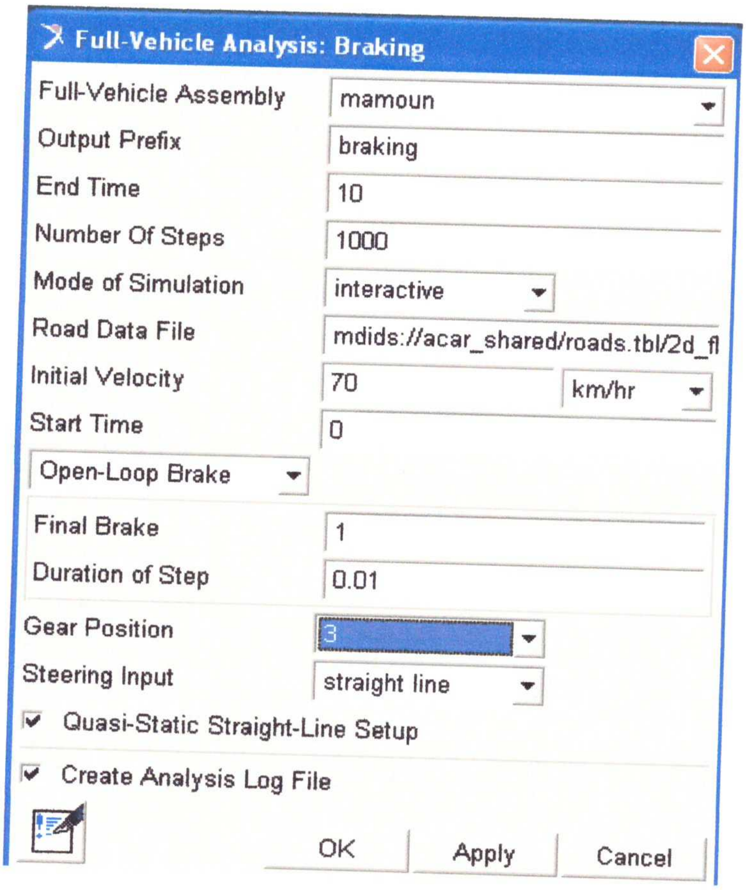
3- **Straight line Acceleration characteristics:**

```
$---------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 FORCE   =  'newton'
 ANGLE   =  'deg'
 MASS    =  'kg'
 TIME    =  'sec'

$---------------------------------------------------------------EXPERIMENT
[EXPERIMENT]
EXPERIMENT_NAME = 'Straight line Acceleration'
STATIC_SETUP    = 'STRAIGHT'
INITIAL_SPEED   = 8333.400000
INITIAL_GEAR    = 3
(MINI_MANEUVERS)
{mini_manuever    abort_time   step_size}
'ACCELERATION'      8.0          0.01

$---------------------------------------------------------------STEP_STEER
[ACCELERATION]
(STEERING)
 ACTUATOR_TYPE    =  'ROTATION'
 METHOD           =  'OPEN'
 MODE             =  'ABSOLUTE'
 CONTROL_TYPE     =  'CONSTANT'
 CONTROL_VALUE    =  0.0
(THROTTLE)
 METHOD           =  'MACHINE'
(BRAKING)
 METHOD           =  'MACHINE'
```

4- Braking characteristics:



5- ISO-Lane Change characteristics:

```
$---------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'meter'
 FORCE   =  'newton'
 ANGLE   =  'deg'
 MASS    =  'kg'
 TIME    =  'sec'
$----------------------------------------------------------------EXPERIMENT
[EXPERIMENT]
EXPERIMENT_NAME = 'ISO-Lane Change'
STATIC_SETUP    = 'STRAIGHT'
INITIAL_SPEED   = 16.667
```

```
INITIAL_GEAR   = 3

(MINI_MANEUVERS)
{mini_manuever   abort_time  step_size}
'LANE_CHANGE'    12.0       0.01
$---------------------------------------------------------------LANE_CHANGE
[LANE_CHANGE]
(STEERING)
 ACTUATOR_TYPE     = 'ROTATION'
 METHOD            = 'MACHINE'
(THROTTLE)
 METHOD            = 'MACHINE'
(BRAKING)
 METHOD            = 'MACHINE'
(GEAR)
 METHOD            = 'OPEN'
 MODE              = 'ABSOLUTE
 CONTROL_TYPE      = 'CONSTANT'
 CONTROL_VALUE     = 3
```

6- **bump used characteristics:**

```
$--------------------------------------------------------------------UNITS

[UNITS]

 LENGTH        = 'meter'

 FORCE         = 'newton'

 ANGLE         = 'radians'

 MASS          = 'kg'

 TIME          = 'sec'

$--------------------------------------------------------------------DEFINITION

[MODEL]

 METHOD        = '3D_SPLINE'

 VERSION       = 1.00
```

```
$-------------------------------------------------------------------------
ROAD_PARAMETERS

[GLOBAL_PARAMETERS]

CLOSED_ROAD        = 'nO'

SEARCH_ALGORITHM   = 'fast'

ROAD_VERTICAL      = '0.0 0.0 1.0'

FORWARD_DIR        = 'NORMAL'

MU_LEFT            = 0.5

MU_RIGHT           = 0.5

WIDTH              = 7.000

BANK               = 0.0
```

6- vehicle used characteristic :

```
$---------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE    = 'asy'
 FILE_VERSION = 1.0
 FILE_FORMAT  = 'ASCII'
 HEADER_SIZE  = 9
(COMMENTS)
{comment_string}
'Adams/Car full_vehicle assembly'
$----------------------------------------------------------ASSEMBLY_HEADER
[ASSEMBLY_HEADER]
 ASSEMBLY_CLASS = 'full_vehicle'
 TIMESTAMP      = '2008/12/15,16:18:13'
 HEADER_SIZE    = 5
$------------------------------------------------------------------PLUGINS
[PLUGINS]
 PLUGIN_LIST = 'acar'
 HEADER_SIZE = 4
$--------------------------------------------------------------------UNITS
```

```
[UNITS]
 LENGTH = 'mm'
 FORCE  = 'newton'
 ANGLE  = 'deg'
 MASS   = 'kg'
 TIME   = 'sec'
$---------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : suspension
$      Minor Role : front
$      Template   : _double_wishbone
USAGE = '<acar_shared>/subsystems.tbl/TR_Front_Suspension.sub'
$---------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : suspension
$      Minor Role : rear
$      Template   : _double_wishbone
USAGE = '<acar_shared>/subsystems.tbl/TR_Rear_Suspension.sub'
$---------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : steering
$      Minor Role : front
$      Template   : _rack_pinion_steering
USAGE = '<acar_shared>/subsystems.tbl/TR_Steering.sub'
$---------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : wheel
$      Minor Role : front
$      Template   : _handling_tire
USAGE = '<acar_shared>/subsystems.tbl/TR_Front_Tires.sub'
$---------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : wheel
$      Minor Role : rear
$      Template   : _handling_tire
USAGE = '<acar_shared>/subsystems.tbl/TR_Rear_Tires.sub'
$---------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
```

```
$      Major Role : body
$      Minor Role : any
$      Template   : _rigid_chassis_lt
 USAGE  =  '<acar_shared>/subsystems.tbl/Body_lt.sub'
$-----------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : powertrain
$      Minor Role : rear
$      Template   : _powertrain
 USAGE  =  '<acar_shared>/subsystems.tbl/Powertrain_lt.sub'
$-----------------------------------------------------------------SUBSYSTEM
[SUBSYSTEM]
$ Subsystem information:
$      Major Role : brake_system
$      Minor Role : any
$      Template   : _brake_system_4Wdisk
 USAGE  =  '<acar_shared>/subsystems.tbl/TR_Brake_System.sub'
$-----------------------------------------------------------------TESTRIG
[TESTRIG]
 USAGE  =  '__MDI_SDI_TESTRIG'
$-----------------------------------------------------------------HARDPOINT
[HARDPOINT]
{hardpoint_name              symmetry      x_value   y_value   z_value}
 'path_error_reference       ' 'single    '    0.0       0.0       0.0
 'upright_reference          ' 'left/right'    0.0       0.0       0.0
$-----------------------------------------------------------------PARAMETER
[PARAMETER]
{parameter_name              symmetry      type      value}
'initial_engine_rpm          ' 'single    '  'real'   2000.0
'throttle_lag_brake_demand   ' 'single    '  'real'   0.1
'brake_ratio                 ' 'single    '  'real'   0.55
'front_brake_max_torque      ' 'single    '  'real'   1700000.0
'rack_ratio                  ' 'single    '  'real'   174.5
'rear_brake_max_torque       ' 'single    '  'real'   1000000.0
'smart_driver_preview_time   ' 'single    '  'real'   0.5
'steering_ratio              ' 'single    '  'real'   27.6
$-----------------------------------------------------------SOLVER_SETTINGS
[SOLVER_SETTINGS]
 INTEGRATOR     =  'gstiff'
 CORRECTOR      =  'original'
 FORMULATION    =  'I3'
```

7. Tire front characteristic :

```
$------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE     =  'tir'
 FILE_VERSION  =  2.0
 FILE_FORMAT   =  'ASCII'
(COMMENTS)
{comment_string}
'Tire      - XXXXXX'
'Pressure  - XXXXXX'
'Test Date - XXXXXX'
'Test tire'
'New File Format v2.1'
$-----------------------------------------------------------------------UNITS
[UNITS]
 LENGTH           = 'mm'
 FORCE            = 'newton'
 ANGLE            = 'radians'
 MASS             = 'kg'
 TIME             = 'sec'
$-----------------------------------------------------------------------MODEL
[MODEL]
! use mode   1    2    3    4    11   12   13   14
! -------------------------------------------------
! smoothing            X    X              X    X
! combined        X         X         X         X
! transient              X    X   X   X
!
 PROPERTY_FILE_FORMAT   = 'PAC89'
 USE_MODE               = 4.0
$-------------------------------------------------------------------DIMENSION
[DIMENSION]
 UNLOADED_RADIUS        = 326.0
 WIDTH                  = 245.0
 ASPECT_RATIO           = 0.35
$-------------------------------------------------------------------PARAMETER
[PARAMETER]
 VERTICAL_STIFFNESS     = 310.0
 VERTICAL_DAMPING       = 3.1
 LATERAL_STIFFNESS      = 190.0
 ROLLING_RESISTANCE     = 0.0
$--------------------------------------------------------LATERAL_COEFFICIENTS
[LATERAL_COEFFICIENTS]
```

a0 = 1.65000
a1 = -34.0
a2 = 1250.00
a3 = 3036.00
a4 = 12.80
a5 = 0.00501
a6 = -0.02103
a7 = 0.77394
a8 = 0.0022890
a9 = 0.013442
a10 = 0.003709
a11 = 19.1656
a12 = 1.21356
a13 = 6.26206
$--longitudinal
[LONGITUDINAL_COEFFICIENTS]
b0 = 1.67272
b1 = -9.46000
b2 = 1490.00
b3 = 30.000
b4 = 176.000
b5 = 0.08860
b6 = 0.00402
b7 = -0.06150
b8 = 0.20000
b9 = 0.02990
b10 = -0.17600
$--aligning
[ALIGNING_COEFFICIENTS]
c0 = 2.34000
c1 = 1.4950
c2 = 6.416654
c3 = -3.57403
c4 = -0.087737
c5 = 0.098410
c6 = 0.0027699
c7 = -0.0001151
c8 = 0.1000
c9 = -1.33329
c10 = 0.025501
c11 = -0.02357
c12 = 0.03027
c13 = -0.0647
c14 = 0.0211329

c15 = 0.89469
c16 = -0.099443
c17 = -3.336941

8. Tire rear characteristic :

```
$-----------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE    = 'tir'
 FILE_VERSION  = 2.0
 FILE_FORMAT   = 'ASCII'
(COMMENTS)
{comment_string}
'Tire      - XXXXXX'
'Pressure  - XXXXXX'
'Test Date - XXXXXX'
'Test tire'
'New File Format v2.1'
$----------------------------------------------------------------------UNITS
[UNITS]
 LENGTH            = 'mm'
 FORCE             = 'newton'
 ANGLE             = 'radians'
 MASS              = 'kg'
 TIME              = 'sec'
$----------------------------------------------------------------------MODEL
[MODEL]
! use mode      1       2       3       4        11      12      13      14
! -------------------------------------------------------------------
! smoothing                      X       X                       X       X
! combined              X               X                X               X
! transient                         X      X     X      X
!
 PROPERTY_FILE_FORMAT    = 'PAC89'
 USE_MODE                = 4.0
$------------------------------------------------------------------DIMENSION
[DIMENSION]
 UNLOADED_RADIUS        = 340.6
 WIDTH                  = 255.0
 ASPECT_RATIO           = 0.35
$------------------------------------------------------------------PARAMETER
[PARAMETER]
 VERTICAL_STIFFNESS     = 310.0
 VERTICAL_DAMPING       = 3.1
 LATERAL_STIFFNESS      = 190.0
```

```
ROLLING_RESISTANCE   = 0.0
$---------------------------------------------------------LATERAL_COEFFICIENTS
[LATERAL_COEFFICIENTS]
 a0  =  1.65000
 a1  = -34.0
 a2  =  1250.00
 a3  =  3036.00
 a4  =  12.80
 a5  =  0.00501
 a6  = -0.02103
 a7  =  0.77394
 a8  =  0.0022890
 a9  =  0.013442
 a10 =  0.003709
 a11 =  19.1656
 a12 =  1.21356
 a13 =  6.26206
$---------------------------------------------------------------longitudinal
[LONGITUDINAL_COEFFICIENTS]
 b0  =  1.67272
 b1  = -9.46000
 b2  =  1490.00
 b3  =  30.000
 b4  =  176.000
 b5  =  0.08860
 b6  =  0.00402
 b7  = -0.06150
 b8  =  0.20000
 b9  =  0.02990
 b10 = -0.17600
$-----------------------------------------------------------------aligning
[ALIGNING_COEFFICIENTS]
 c0  =  2.34000
 c1  =  1.4950
 c2  =  6.416654
 c3  = -3.57403
 c4  = -0.087737
 c5  =  0.098410
 c6  =  0.0027699
 c7  = -0.0001151
 c8  =  0.1000
 c9  = -1.33329
 c10 =  0.025501
 c11 = -0.02357
```

c12 = 0.03027
c13 = -0.0647
c14 = 0.0211329
c15 = 0.89469
c16 = -0.099443
c17 = -3.336941