INTRODUCTION

In this chapter, a vehicle suspension system is introduced from the point of view of ride comfort, handling and safety. Also the perception of ride comfort has been presented using various standard graphs showing human tolerance criteria. Various types of vehicle models taken for analysis of ride dynamics have been presented. An overview of types of the shock absorbers has been presented along with introduction to modeling and simulation.

2.1 INTRODUCTION TO SUSPENSION SYSTEMS

In recent years, the tendency of the automobile manufacturers has been to produce upper end, high-grade automobiles. The suspension of these automobiles should be of appropriate isolation characteristics. This has made the automobile engineers to develop new approaches to the design of the dampers/shock absorbers [2], which play an important role in the control of vibration amplitude of the vehicle system, especially in the neighborhood on the resonance.

Although some active and semi-active suspension systems have been developed and successfully implemented in practice, the requirement of an external energy source and control systems with a large number of sensors limit the application of active suspension to the cases where the performance outweighs the disadvantages associated with costs and complexities. The cost, complexities and the chatter associated with semi active “on-off” control may still be prohibitive for its general applications [10]. Thus the designers have to consider appropriate changes in the passive suspension system to obtain better vibration isolation characteristics over a wide range of excitation frequency.

Traditionally, automotive suspension designs have been a compromise between the three conflicting criteria of road holding, load carrying and passenger comfort. The suspension system must support vehicle body, provide directional control during handling maneuvers and provide effective isolation of passenger/payload from road disturbances. Good ride comfort requires a soft
suspension, whereas insensitivity to applied loads requires stiff suspension, while good handling requires a suspension setting somewhere between the two. Due to these conflicting demands, suspension design has had to be something of a compromise. So a typical passive suspension system is usually a compromise between the aforementioned conflicting demands. That means once it is installed in the car, its character changes little.

A passive suspension system of a road vehicle traditionally consists of a spring and a damper mounted in parallel. The spring supports the static weight of the mass, while the damper/shock absorber dissipates the energy from disturbances. The damper and the spring are interposed on a vehicle between its sprung mass (the vehicle body) and the unsprung mass (wheels and wheels structure). In order to control the movements of these two distinct masses, the springs and dampers work in conjunction, as in an inseparable unit. In spite of its name, which it suggests the opposite; it is not the damper/shock absorber but the spring that absorbs shocks. When subjected to the external excitation, the spring does not manifest just one compression-rebound cycle, but relaxes and recompresses a few times in an oscillatory motion before recovering its initial position. In the meantime, new shocks that could reinforce or renew movement must be absorbed.

The damper has the specific task of slowing down and controlling these spring movements. In absence of good dampers many problems and dangerous phenomena can occur. As wheels would dance in an uncontrolled manner on the road, they would not maintain adequate contact with the road and it would thus become impossible to transfer the power of motor, to use the brakes with efficiency and even to maintain a trajectory.

As such the suspension systems are used

i) to transmit minimize vibration at the passengers/payload cabins,
ii) to maintain contact between tyre/track and road,
iii) to provide safe handling during maneuvers,
iv) to react changes in load,
v) to keep the suspension displacements within limits of travel,
v) to minimize the pitch and roll motion of vehicle body.
2.1.1 Compromise between Stability and Comfort

Automotive customers are demanding vehicles with both improved comfort and improved handling. The damping constant of the damper determines both stability of vehicle and the comfort of travelers. A heavy suspension with firm springs and dampers with high damping characteristics will yield good vehicle handling and stability keeping the tyres in contact with the road and preventing frame oscillations and other problems, but will also transfer most of road oscillations to the passengers causing an uncomfortable ride. However a light suspension with soft springs and dampers with low damping characteristics will yield a more comfortable ride, but at the same time can reduce the stability of the vehicle. Therefore, it is general practice to make a compromise between stability and comfort while designing a passive suspension system.

From the ride comfort considerations, it is observed that the human body is more sensitive to the vibrations generated within the range of 4-8 Hz in vertical directions and within the range of 1-2 Hz in other directions. Thus the damper bandwidth is desired to respond to body heave (2 Hz), body roll (5 Hz) and wheel hop (15 Hz).

2.2 PERCEPTION OF RIDE

The final assessment of ride vibrations deals with the issue of how the ride is perceived. The evaluation of ride comfort involves assessment of human sensitivity to vibration, which depends not only on the physiological and biomechanical response of human body, but also on a number of psychological and environmental factors. Ride is a subjective perception, normally associated with the level of comfort experienced when traveling in a vehicle. Therefore, in its broadest sense, the perceived ride is the cumulative product of many factors.

2.2.1 Tolerances to Seat Vibrations

The judgment of ride vibration in a vehicle is still an area of controversy in the automotive community. Pure sinusoidal inputs are often used in attempts to establish quantified levels of discomfort, or equal levels of sensation, as a
function of frequency. Yet no universally accepted standards exist for judgment of ride vibrations in regard to the consideration of the following variables:

- Seating position
- Influence of hand and foot vibration input
- Single - versus multiple-frequency input
- Multi-directional input
- Comfort scaling
- Duration of exposure
- Sound and visual vibration input

Fig. 2.2.1 shows lines of constant comfort as determined by the researchers. Because of the different interpretations of the comfort in each study, the nominal level of one curve in not comparable to the others, nor is it especially meaningful. Nevertheless, majority shows a minimum tolerance (maximum sensitivity) of the human body to vertical vibration in the frequency range between 4 and 8 Hz. This sensitivity is well recognized as the result of vertical resonance of the abdominal cavity. At frequencies above and below this range the tolerances increase in proportion to frequency. The actual shape of the boundaries will often be small inflections in the 10 to 20 Hz range due to other organ resonance, especially head resonance near 10 Hz [35].

The International Standard Organization (ISO 2631, 1978 (E)) has specified numerical values for the limits of exposure to vibrations transmitted from solid surface to human body in frequency range 1-80 Hz. These limits cover human sensitivity to vertical, lateral and fore-aft vibration to periodic vibrations over exposure time ranging from 1 minute to 24 hrs.

The ISO defines three criteria corresponding to:

i) The preservation of working efficiency (Fatigue Decreased Proficiency Boundary);

ii) The preservation of health and safety (Exposure Limit); and

iii) The preservation of comfort (Reduced Comfort Boundary) [37].
Fig. 2.2.2 shows the fatigue-decreased proficiency boundary for vertical vibrations. It can be seen that as the average daily exposure time increases, the boundary lowers. The fatigue decreased proficiency boundaries for lateral vibrations are shown in Fig. 2.2.3. When the vibration takes place in more than one direction simultaneously, corresponding boundaries apply to each vectorial component in three axes. The exposure limits for safety (or health) reasons are obtained by raising the fatigue or decreased proficiency boundaries shown in Fig. 2.2.2 and Fig. 2.2.3 by a factor of two (6 DB higher), whereas the reduced comfort boundaries are obtained by lowering the boundaries shown in Fig. 2.2.2 and Fig. 2.2.3 by a factor of 3.15 (10 DB lower). Most of the data used in establishing ride comfort were obtained using sinusoidal inputs, whereas actual vehicle vibration is usually of a random nature [34].

NASA obtained very interesting findings in research on comfort in mass transport vehicles, notably airplanes. The constant comfort lines for vertical vibration taken from that work are shown in Fig. 2.2.4. The significant point observed is that the sensitivity as a function of frequency is dependent on the acceleration level. At high levels of vibration, the tolerance curves generally match those of other researchers. But at low amplitudes the horizontal nature of the curves implies that the discomfort is rather independent of frequency. Therefore, low levels of vibration are equally objectionable regardless of their frequency over the indicated range.

Human sensitivity to fore/aft vibrations is somewhat different from that of the vertical. Fig. 2.2.5 shows tolerance limits for fore/aft vibrations as determined from a number of sources. Again the nominal level of each curve is not especially meaningful, but similar sensitivities are indicated. The most remarkable difference seen is that the region of maximum sensitivity occurs in the 1 to 2 Hz range. This sensitivity is generally recognized to the result from the fore/aft resonance of the upper torso. When the vertical and fore/aft boundaries from individual, researchers are compared, the minimum tolerance is observed in the fore/aft direction.

2.3 VEHICLE RIDE MODELS
To study the ride quality of ground vehicles, various ride models have been developed. For a passenger car with independent front suspension, a seven degrees-of-freedom model as shown in Fig. 2.3.1 may be used. In this model, the pitch, bounce and roll of the vehicle body, as well as the bounce of the two front wheels, and the bounce and roll (tramp) of the solid rear axle are taken into consideration. The mass representing the wheel, tyre, brakes and part of the suspension linkage mass is referred to as unsprung mass and mass of the frame, body, engine, transmission and any part that moves directly with the frame and body is referred to as sprung mass. For a cross-country military tracked vehicle shown in Fig. 2.3.2 a fifteen degrees-of-freedom model may be used, which includes the pitch, bounce, and roll of the vehicle body and the bounce of the each road wheel.

To study the vibrational characteristics of the vehicle, equations of the motion using Newton’s second law of motion for each mass can be formulated. Natural frequencies and amplitude ratio can be determined by considering the principal modes of vibration of the system. When the excitation of the system is known, the response can be determined by solving the equations of motion. However, as the degrees-of-freedom of the system increase, the analysis becomes increasingly complex.

A vehicle represents a complex vibration system with many degrees-of-freedom. It is possible to simplify the system by considering only some of the major motions of the vehicle. For instance, to obtain a qualitative insight into the functions of the suspension, particularly the effects of the sprung mass and unsprung mass on vehicle vibrations, a linear model with two degrees-of-freedom as shown in Fig. 2.3.3 may be used. On the other hand, to reach a better understanding of the pitch and bounce vibrations of the vehicle body, two degrees-of-freedom model as shown in Fig. 2.3.4 may be used.

A 2DOF quarter car model suspension is a model with a spring and damper connecting the vehicle body to a single wheel, which in turn is connected to the ground via tyre spring. Important features of the quarter car model are that it includes a proper representation of the problem of controlling wheel load
variations and contains suspension system forces, which are properly applied between wheel mass and body mass.  

The vibration isolation performance of the suspension system in terms of displacement, velocity and acceleration transmissibility can be determined easily by further simplifying the quarter car model to single degree of freedom system subjected to harmonic excitation as in Fig. 2.3.5 [34].  

In case of a quarter car model, according to typical modern vehicle, with independent suspension, the sprung mass is around eight times the unsprung mass, while the tyre spring stiffness is around 12.5 times suspension spring stiffness. With moderate damping rates, this leads to two distinct modes of vibration, a body mode around 1.2 Hz and a wheel hop mode around 12 Hz [29].  

A four degrees-of-freedom half car model can also be used by taking into consideration the bounce and pith motion of the sprung mass and only bounce motion for unsprung mass as shown in Fig. 2.3.6.  

A five degrees-of-freedom half car model as shown in Fig. 2.3.7 is used to study the dynamic response characteristics at driver’s seat.  

Depending upon the vibration isolation performance requirements an appropriate type of car model can be taken for dynamic response analysis.  

2.3.1 Vehicle Damper Model  

An accurate Computer Numerical Simulation and Modeling of a suspension system helps to speed up the design process. For this reason, the industry started to develop a fully Computer Aided Approach (CAE) to deal with the design problems like tuning. This approach can be broken down into consecutive steps for the suspension study. In the first step, the actual physical system is studied. This system possesses the true dynamic response characteristics that correspond to the exact linear or non-linear behaviour of the system. In second step, the engineer’s perception of the system about the linearity and its dynamic characteristics is considered. In third step, by using a set of tunable parameters the Characteristics Diagram (Damping force v/s Velocity) and Work Diagram (Damping force v/s Displacement) of shock absorber are obtained. In the fourth step, the behaviour of the vehicle is characterized using the computer simulation techniques typically by means of a
set of displacement, velocity and acceleration response from a given road input. Finally, the time histories of these displacement and acceleration are then used to measure ride and handling quality of the suspension system.

2.3.2 Tracked Vehicle Model

Movement of vehicle is unavoidably related to shock and vibrations, the extent of which depends upon the type of vehicle, the surface with which it interact during its travel and the operating speed of the vehicle. The vehicle body transmits these vibrations to different locations of the vehicle with varying levels of intensities due to the inherent design characteristics of the materials of construction and component designed and fitted for different purposes.

The majority of the analytical models and simulation packages use a 4 degree of freedom (DOF) in plane model. In the present project work a six wheel tracked vehicle is modeled as two degree of freedom (1 Hull), one degree of freedom (each bogie wheel) dynamical system, incorporating one degree of freedom in each hydro-pneumatic strut initially. Subsequently to obtain the detailed insight the model is studied for 15 DOF. The wheel is modeled as a point contact model representing parallel combination of equivalent vertical spring, where the terrain contact occurs at a single point vertically beneath the wheel center. The net foot-print force resulting from the vertical motion of wheel relative to the terrain, is assumed to act normal to the local terrain surface. Thus, a horizontal component is generated whenever the local terrain profile is inclined to the horizontal, and is related to the vertical component through the tangent of local profile angle. The track tensile forces are modeled considering track as spring and restoring forces generated by relative springs. Hydro-pneumatic strut connected to hull and road arm are modeled as a non-linear spring and damper. The model is designed incorporating dynamical pressures and damping forces generated in the strut for optimization of location of hydro-pneumatic strut on the vehicle to minimize the acceleration of vehicle.

2.3.3 Physical Description
Although military tracked vehicles vary widely in size, shape, general physical appearance and performance characteristics, they share many commonalities in basic principle of construction and operation. A typical tracked vehicle can be divided into two major groups namely track and suspension components and hull components. The schematic of a tracked vehicle is shown in Fig 2.7.

The first group includes track, hull wheels (drive sprocket, idler and support rollers), bogie wheel assemblies and suspension components including hydro-pneumatic strut. Track and suspension components constitute the unsprung mass of the system. The track is a multiple link chain having rubber pads fitted on each link. These pads act as a cushion between the terrain and the track. The vehicle selected for the simulation is a tracked vehicle with six bogie stations. Each bogie wheel is mounted on axle arm or road arm pivoted to the hull chassis. Hydro-pneumatic struts are mounted between axle arm and hull chassis. Rubber bump stops are mounted at upper and lower bounds of axle arms to prevent road wheel interference with the track which is assumed to be a mass less continuous belt constituting stiffness due to the initial track tension and tension caused by the stretching of the track. The road wheels ride on this endless track that completes its circuit by passing over the drive sprocket, three support rollers and adjusting idler. The hull represents collectively all the remaining components of the vehicle and has been referred to sprung mass.

2.3.4 Tracked Vehicle Dynamic Model

In order to develop a dynamic model, suspension component such as axle arm and hydro-pneumatic strut connecting the wheels to the superstructure are to be identified along with unsprung mass inertia and sprung mass inertia, elastic properties of tyres, bump stops, track pads, etc are to be taken into account for modelling.

In this thesis, vehicle suspension units are modeled using independent suspension configuration with non-linear spring characteristics linearised in its operating range. The equivalent road wheel stiffness is computed taking into account the stiffness due to track pad in parallel combination with the radial
spring of bogie wheel. The dynamic track tensioning effects are modeled as local tensioning effects, while neglecting the overall track tension. The intermediate track segments (between bogie wheels) are modeled as vertical springs interconnecting each adjacent bogie wheel pair, which restricts the relative vertical motion of the bogie wheels. The springs are bi-directional springs, which effectively generate a vertical force proportional to the relative displacement between adjacent bogie wheels. Consequently, when the bogie wheels centers are all lined up on the same horizontal axis, there is no force contribution due to the track tension model. The stiffness of this equivalent vertical spring depends on inter spacing of the bogie wheels.

2.4 SUSPENSION SYSTEMS BASED ON METHOD OF ISOLATION

In practice, following types of suspension systems, based on method of isolation, are used in the road vehicles

2.4.1 Passive Suspension System

A passive suspension system has the ability to store energy via a spring and to dissipate it via a damper. Its parameters are fixed, being chosen to achieve a certain level of compromise between road handling, load carrying and comfort. Fig. 2.3.3 shows a quarter car model for passive suspension system.

2.4.2 Semi-Active Suspension System

The semi-active suspension system covers a range of configurations, most commonly a slow self-leveling system often combined with controllable dampers. These dampers may simply be switched according to road conditions and driver inputs or may be controlled to achieve further ride quality improvements. Semi-active systems are the easiest to implement and have minimal power requirements, but offer few of the potential benefits. They are, however, the only class to have achieved a significant market penetration at the present time. A quarter car model for semi-active suspension system is shown in Fig. 2.3.8.
2.4.3 Active Suspension System

An active suspension system has the ability to store, dissipate and to introduce energy to system. It may vary its parameters depending upon its operating conditions. Active suspensions are characterized by the addition of external power sources, such as compressor or pumps, to achieve superior ride and/or handling performance. They are considered as a means of replacing the spring and dampers of passive suspension systems by actuators as part of or a complete suspension. These actuators act as force generators, according to a control law and operate with various transducers, providing inner loop feedback signals, to their controllers and to track faithfully force demand signals determined by control law. A quarter car model for active suspension system is shown in Fig. 2.3.9.

2.5 COMPUTER SIMULATION AND MODELING

The methodology of computer simulation and modeling and its validation has been described. Further the modeling approach of vehicle damper and tracked vehicle along with its physical description and dynamic model has been discussed in chapter III and IV.

Simulation is a technique for using computers to imitate, or simulate, the operations of various kinds of real world facilities or processes. The facility or process of interest is usually called a system, and in order to study it scientifically we often have to make set of assumptions about how it works. These assumptions, which usually take the form of mathematical or logical relationship, constitute a model that is used to try to gain some understanding of how the corresponding system behaves, under some projected set of environment and/or operating conditions.

Thus simulation in general is to pretend that one deals with a real thing while really working with an imitation.

To use a simulator is safer and cheaper than the real life system. For precisely this reason, models are used in industry, commerce and military systems. It is very costly, dangerous and often impossible to make experiments with real
systems. It is assumed that the models are adequate descriptions of reality and experimenting with them can save money, suffering and even time.

2.5.1 Some Concepts in Modeling and Simulation

2.5.1.1 System
A system is defined as an aggregation or assemblage of objects joined in some regular interaction or interdependence, or

2.5.1.2 Modeling
- Modeling is an attempt to replicate the way in which real system work.
- 'M' is called a model of a system 'S' for the observer 'O' if the observer can use 'M' to answer questions that interest him about ‘S’.
- A model mimics a real system.
- Simulation replaces a system to be studied by some other representation called a model.
- We define a model as the body of information about a system gathered for the purpose of studying the system.

2.5.1.3 Types of Models
- Static vs. Dynamic Simulation Models
- Deterministic vs. Stochastic Simulation Models
- Continuous vs. Discrete Simulation Models

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<td>Algebraic Equation</td>
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<tr>
<td>Probabilistic</td>
<td>Statistical Relationship</td>
<td>Queuing System</td>
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2.5.1.4 Simulation
Simulation is a technique of solving problems. In the broadest sense, it is a form of imitation in which a problem that needs solving is represented by a model, which in effect, replaces the problem by a second problem that is easier to solve.

In a simulation we use computer to evaluate a model numerically, and data are gathered in order to estimate the desired true characteristics of the model.

To simulate is to copy the behavior of a system or phenomenon under study i.e. to experiment with a system in terms of mathematical model on computer.

In any simulation experiment we have a system whose behavior we are studying. There is not a "Unified Theory" of computer simulation. Learning simulation does not consist of learning a few fundamental theorems and their corollaries and using them to solve problems. There are no set guiding rules/principles for simulation studies. Each simulation is "adhoc" to great extent. In this sense simulation is an art.

### 2.5.2 Steps in Simulation Study

The steps in simulation study are as follows.

1) Formulate the problem and plan the study.
   a) Overall objectives of study.
   b) Specific questions to be answered by the study.
   c) Performance measures that will be used to evaluate the efficacy of different system configurations.
   d) Scope of the model.
   e) System configurations to be modeled.
   f) Software to be used.
   g) Time frame for the study and the required resources.

2) Collect data and define a model.
   a) Collect information on the system layout and operating procedures.
b) Collect data on the performance of the existing system (for validation purposes in step 6).

3) Validation of the conceptual model.

4) Construct a computer program and verify.

5) Make pilot runs.
   a) Make pilot runs for validation purposes in step 6.

6) Validation of the program models.
   a) If there is an existing system, then compare model and system (from step 2) performance measures for the existing system.
   b) Use sensitivity analysis to determine what model factors have a significant impact on performance measures and, thus, have to be modeled carefully.

7) Design experiments.
   a) Specify the following for each system configuration of interest.
      i) Length of each run.
      ii) Length of the warm up period, if one is appropriate.
      iii) Number of independent simulation runs using different random numbers.

8) Make production runs.
   a) Production runs are made for use in step 9.

9) Analyze output data.
   a) Two major objectives in analyzing output data are:
      i) Determine the absolute performance of certain system configurations.
      ii) Comparing alternative system configurations in a relative sense.

10) Document, present, and use results.
    a) Document assumptions (see step 2), computer program, and study’s results for use in the current and future projects.
    b) Present study’s results.
       i) Use animation to communicate the model.
       ii) Discuss model building and validation process to promote credibility.
    c) Results are used in decision making process if they are both valid and credible.
2.5.3 Model Validation

Model validation means to substantiate that a computerized model within its domain of applicability possesses a satisfactory range of accuracy, consistent with the intended application of the model.

The problem entity is a system (real or proposed), idea, situation, policy, or phenomenon to be modeled; the conceptual model is the mathematical/logical/verbal representation (mimic) of the problem entity developed for a particular study; and the computerized model is the conceptual model implemented on a computer. The conceptual model is developed through an analysis and modeling phase, the computerized model is developed through computer programming and implementation phase, and inferences about the problem entity are obtained by conducting computer experiments on the computerized model in the experiment phase.

Conceptual model validity is defined as determining that the theories and assumptions underlying the conceptual model are correct and that the model’s structure, logic, mathematical and casual relationship, and model representation of the problem entity are reasonable for the intended use of the model. Computerized model verification is defined as ensuring that the computer program and implementation of the conceptual model is correct. Operational validity is defined as determining that the model’s output behavior has the sufficient accuracy for its intended purpose or use over the domain of the model’s intended application.

2.5.4 Principles of Valid Simulation Modeling

The issues to be investigated, the measure of performance for evaluation, the manner in which the model to be used, be carefully defined Models are not universally valid, but are designed for specific purposes. It is important to understand the need. A great model for the wrong problem will never be used.
• The “expert” and sensitivity analysis is used to help determine the level of model detail.

• It is desirable to start with a moderately detailed model, which can be embellished if needed. The adequacy of a particular model is determined in parts by presenting the model to experts.

• It is not necessary to have more details in a model than is necessary to address the issue of interest, subject to the proviso that the model must have enough detail to be credible.

• The level of model should be consistent with the type of data that are available.

• In some simulation studies, time and money constraints are a major factor in determining the amount of model detail.

If the number of factors for the study is large, then use a “coarse” simulation model or an analytic model to identify the important factors before developing a detailed simulation model.
Fig. 2.2.1 Human Tolerance Limits for Vertical Vibrations [35]

Fig. 2.2.2 Limits of Whole-Body Vibration for Fatigue or Decreased Proficiency in Vertical Direction Recommended by the ISO [34]
Fig. 2.2.3 Limits of Whole-Body Vibration for Fatigue or Decreased Proficiency in Transverse Direction Recommended by the ISO [34]

Fig. 2.2.4 NASA Discomfort Curves for Vibrations in Transport Vehicles [35]
Fig. 2.2.5 Human Tolerance Limits for Fore/Aft Vibrations [35]

Fig. 2.3.1 A Seven Degrees-of-Freedom Ride Model for Passenger Cars [34]
Fig. 2.3.2 A Ride Model for A Military Vehicle [34]

Fig. 2.3.3 A Two Degrees-of-Freedom Ride Model
Fig. 2.3.4 A Two Degrees-of-Freedom Ride Model for Pitch and Bounce Of the Sprung Mass

Fig. 2.3.5 Single Degree-Of-Freedom Car Model
Fig. 2.3.6 4 Degrees-of-Freedom Half-Car Model

Fig. 2.3.7 5 Degrees-of-Freedom Half-Car Model
Fig. 2.3.8  Semi - Active Control of Two Degree-of-Freedom System

Fig. 2.3.9  A Quarter Car Model - Active Suspension System