

A Dissertation

On

Development of Methodology for Characterization of Roll and Pitch Damping Behaviour in a Commercial Vehicle

Submitted in partial fulfilment of requirements for the degree of

Master of Engineering

in

CAD / CAM Engineering

Submitted by

Rupin Sharma

Registration No.: 801784015

Under the Supervision of

Mr. Saurabh Singh

Deputy General Manager
Vehicle Engineering Department
Engineering Research Centre, CVBU,
Tata Motors Ltd.
Pimpri, Pune 411018, India

Mr. Ajay Jadhav

Senior Manager
Vehicle Engineering Department,
Engineering Research Centre, CVBU,
Tata Motors Ltd.
Pimpri, Pune 411018, India

Dr. Vivek Jain

Associate Professor
Department of Mechanical Engineering
Thapar Institute of Engineering & Technology
(Deemed to be University)



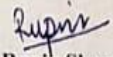
THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

Mechanical Engineering Department
Thapar Institute of Engineering and Technology
(Deemed to be University)
Patiala-147004, India
July 2019

DECLARATION

I hereby declare that the work done in thesis report entitled, "Development of Methodology for Characterization of Roll and Pitch Damping behaviour in a commercial vehicle" submitted towards partial fulfilment of award of Master of Engineering degree in CAD/CAM Engineering in Department of Mechanical Engineering of Thapar Institute of Engineering and Technology, Patiala is an authentic record of work carried out by me under the supervision and guidance of Mr. Ajay Jadhav, Senior manager, TATA Motors Ltd., Pune, Mr. Saurabh Singh, Deputy General manager, TATA Motors Ltd. and Dr. Vivek Jain, Associate Professor, Mechanical Engineering Department of Thapar Institute of Engineering and Technology, Patiala.

Date: 30/7/19


Rupin Sharma

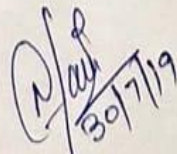
This is to certify that above declaration made by the student concerned is correct to the best of our knowledge and belief.



Mr. Saurabh Singh
Deputy General Manager
Vehicle Engineering Department
Engineering Research Centre, CVBU,
Tata Motors Ltd.
Pimpri, Pune 411018, India



Mr. Ajay Jadhav
Senior Manager
Vehicle Engineering Department,
Engineering Research Centre, CVBU,
Tata Motors Ltd.
Pimpri, Pune 411018, India



Dr. Vivek Jain
Associate Professor
Department of Mechanical Engineering
Thapar Institute of Engineering &
Technology
(Deemed to be University)
Patiala - 147001, India

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Abstract

Vehicle dynamics have been studied by many researchers for the purpose of enhancing passenger comfort in a vehicle. Studies have been conducted into varying suspension parameters and tuning suspension characteristics so as to maximize the passenger's comfort. In this study, a methodology for characterization of vehicle's rolling and pitching damping behaviour and for the evaluation of comfort values of roll and pitch characteristics of a vehicle during dynamic maneuvers have been proposed and validated. Several characterization tests, namely, Step Input, Double Lane Change, Straight Line, Dive, Squat, Single Speed Bump and Start Stay Stop Test which simulate several real life driving maneuvers performed by real life driver have been performed on several test vehicles and output parameters such as roll angle, pitch angle, roll rate and pitch rate have been captured and analysed. Subjective Ratings of driver and co-driver are also taken immediately after the maneuvers. After analyzing and tabulation of the output parameters data obtained from characterization tests, correlation between subjective ratings and objective vehicle output data is established. Upon correlation, characterization test is validated and output data is used for evaluation of roll and pitch comfort values for various dynamic maneuvers and objective characterization of vehicle's roll and pitch damping behaviour.

x	-	Forward Direction of the vehicle
y	-	Right Side of the driver and perpendicular to x axis
z	-	Downwards to driver and perpendicular to both x and y axis
p	-	Roll velocity about x axis of the vehicle
q	-	Pitch velocity about y axis of the vehicle
r	-	Yaw velocity about z axis of the vehicle
C_a	-	Coefficient of Air Resistance
V_x	-	Wind velocity in x axis direction
h_a	-	Height of aerodynamic drag force
R_{xf}	-	Rolling resistance force in direction x (front)
R_{xr}	-	Rolling resistance force in direction x (rear)
F_{xf}	-	Tractive force in direction x (front)
F_{xr}	-	Tractive force in direction x (front)
m	-	Mass of the vehicle
h	-	Centre of gravity height
v_x	-	Velocity of vehicle in x direction
L_f	-	Longitudinal distance from front axle to centre of gravity
L_r	-	Longitudinal distance from centre of gravity to rear axle
F_{zf}	-	Dynamic weight on front axle
F_{zr}	-	Dynamic weight on rear axle
α_f	-	Tire slip angle (front)
α_r	-	Tire slip angle (rear)
δ_f	-	Steer angle (front)
δ_r	-	Steer angle (rear)

F_f	-	Lateral force on front axle
F_r	-	Lateral force on rear axle
a	-	Longitudinal distance from front axle to centre of gravity
b	-	Longitudinal distance from centre of gravity to rear axle
u	-	Vehicle velocity in x direction
v	-	Vehicle velocity in y direction
r	-	Angular velocity of vehicle about z axis
z_g	-	Displacement of ground in z direction
z_u	-	Displacement of unsprung mass in z direction
z_s	-	Displacement of sprung mass in z direction
z	-	Total displacement of vehicle in z direction
k_t	-	Tire Stiffness
k_s	-	Spring Stiffness
c	-	Damping coefficient
F_z	-	Force applied to sprung mass in z direction
m_u	-	Unsprung mass of the vehicle
m_s	-	Sprung mass of the vehicle
θ	-	Pitch angle of the vehicle

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Chapter 1

Introduction

Vehicle dynamics is the study of vehicle's response to various stimuli. Stimuli can be driver induced or environment induced.

Driver Induced stimuli are the forces which are exerted upon the vehicle as a result of driver's actions to control the vehicle. Driver induced stimuli are mainly divided into two categories:-

1. Steering
2. Acceleration & Braking

Environment Induced Stimuli are the forces exerted upon the vehicle which are external to the vehicle and are beyond the control of the driver. Environment Induced stimuli can be divided into these categories:-

1. Road Conditions:- Road Roughness, Potholes, Ditches, Road Grade etc.
2. Wind Conditions:- Wind Velocity, Wind Direction etc.
3. Ambient Temperature

In lieu of studying this interaction of vehicle with the above-mentioned stimuli and response of vehicle to these stimuli, Society of Automotive Engineer described a standard fixed right hand orthogonal coordinate system [1] for defining vehicular motions as shown in Fig. 1.1.

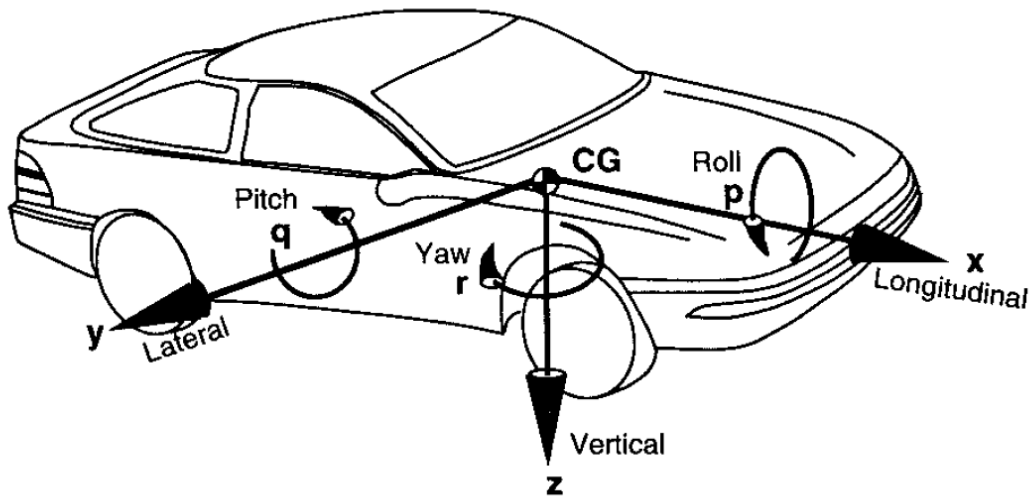


Fig. 1.1. Pictorial Representation of SAE Axis System

x - Forward Direction of the vehicle

y - Right side of the driver and perpendicular to x axis

z - Downwards to the driver and perpendicular to both x and y axis

Roll - Rotation about x axis of the vehicle

Pitch - Rotation about y axis of the vehicle

Yaw – Rotation about z axis of the vehicle

x, y and z directions are also termed as Longitudinal, Lateral and Vertical directions respectively in some of the literature & books.

Study of vehicle dynamics can also be divided into three categories depending upon direction of forces acting upon the vehicle, namely:-

1. Longitudinal Dynamics
2. Lateral Dynamics
3. Vertical Dynamics

Longitudinal Dynamics

Study of a vehicle's response to the forces exerted upon the vehicle during its motion in x direction. As an example, basic forces acting upon a vehicle in x direction are illustrated in the Fig. 1.2. Many important concepts are evaluated using longitudinal dynamics study such as roll resistance of the vehicle, slip of tire, stopping distance during braking, gradeability of the vehicle etc.

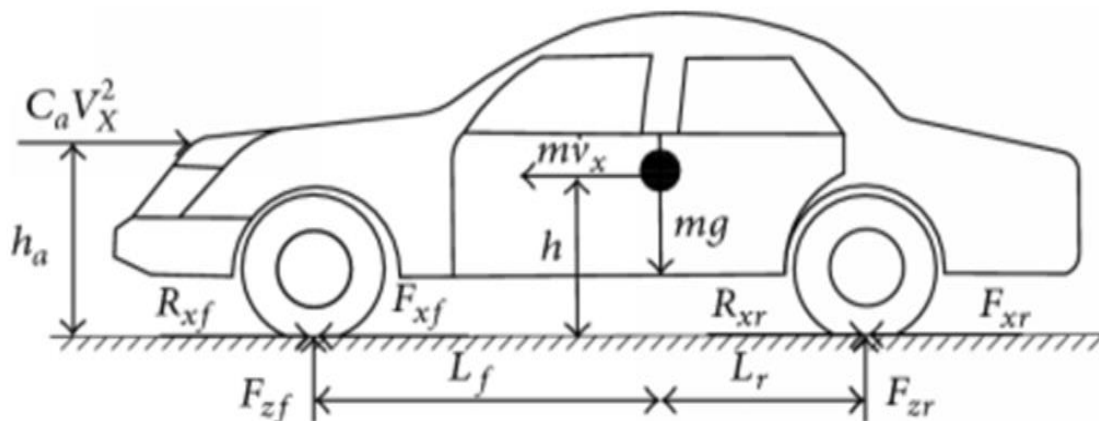


Fig. 1.2. General Forces exerted in Longitudinal Dynamics

Lateral Dynamics

Study of forces trying to displace the vehicle in y direction and vehicle's response to those forces. Generally, Bicycle model is used in order to study lateral dynamics. It is the most basic and simplistic model to study dynamics of the vehicle in lateral direction as can be seen in Fig. 1.3. Complex models used in simulations of vehicle behaviour are generally an expansion of bicycle model. Lateral dynamics is used to study various phenomenon experienced by the vehicle on-road such as side slip of vehicle, understeer/oversteer behaviour of the vehicle, vehicle spinout behaviour (excessive yawing of vehicle) etc.

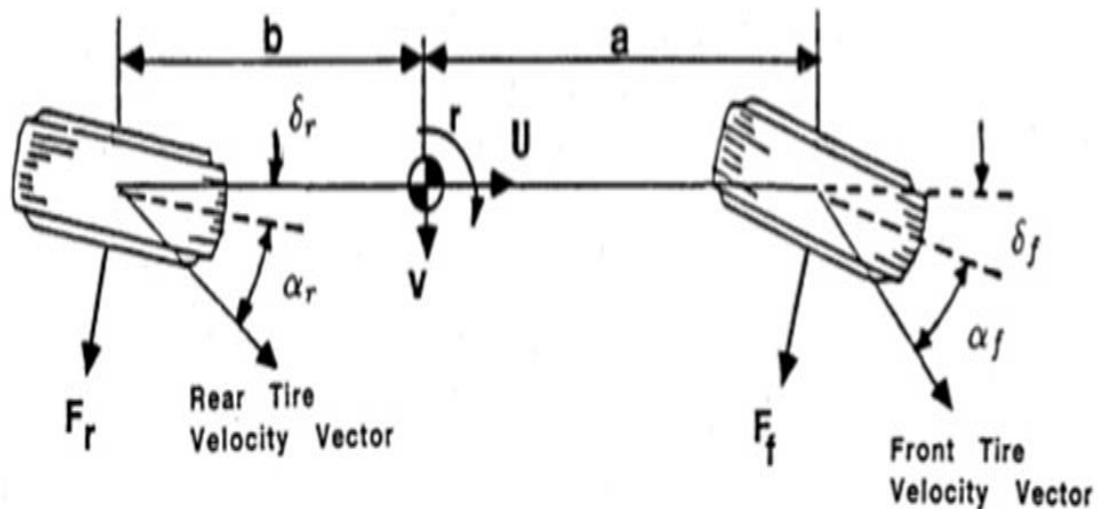


Fig. 1.3. Bicycle Model for Lateral Dynamics

Vertical Dynamics:-

Vertical dynamics is the study of forces which cause the movement of vehicle in z direction and the vehicle's response to these forces. Generally, a Quarter Car, Half Car or a Full Car Model is used for theoretical evaluation of vehicle's behaviour in z axis direction.

Quarter car model assumes that vehicle's behavior at all four corners is identical.

Half car model assumes that vehicle behaviour is symmetric about its longitudinal axis. It is the most commonly used model for the study of basic vertical dynamics and therefore shown below in Fig. 1.4.

Full car model assesses each tire-suspension assembly individually and recognizes that responses at each corner of vehicle might be different and they can also experience different road conditions individually.

Vertical Dynamics plays a major role in the passenger comfort of the vehicle as it determines the vehicle's response to the road undulations. It also determines the rolling response of the vehicle, which hugely contributes to the rollover (vehicle tipping to its left or right side) mitigation studies conducted for the commercial vehicles and passenger vehicles alike. Vertical dynamics of a vehicle also gives an insight into the handling capabilities of the vehicle as it is used to study bounce (upward travel in z direction) behaviour of a vehicle. If a vehicle bounces too much due to road conditions and if this results in a loss of contact between road surface and tires of the vehicle then in the time where tire is not touching the ground, vehicle is not controllable by the driver as it cannot be steered or braked for that brief period of time. Thus, vertical dynamics of a vehicle is very important for its handling capabilities.

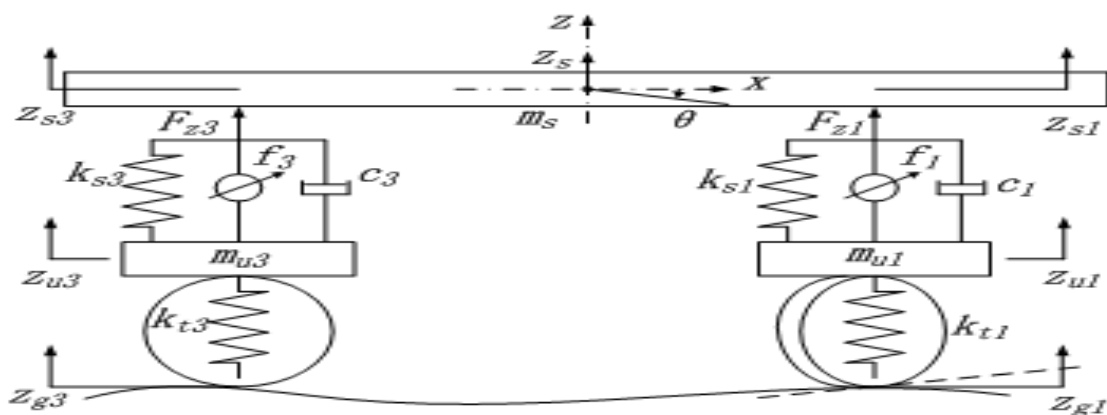


Fig. 1.4. Half Car Model for Vertical Dynamics

Vehicle Dynamics is primarily studied so that vehicle should always remain in driver's control i.e. vehicle should not spinout or rollover etc. so that the passenger's safety can be ensured. Secondary reason to study vehicle dynamics is to ensure the comfort of the passengers sitting in the vehicle throughout their journey inside the vehicle.

Spinning out and Rolling over has almost been counteracted by Electronic Stability Control (ESC) module present in vehicles as a safety measure. ESC continuously monitors yaw angle, roll angle, roll rate and several other parameters during vehicle's operation using various sensors (such as wheel rate sensors) placed inside modern day vehicles so as to determine and predict that either vehicle is going to spin out or rollover. Whenever the ESC feels that a vehicle is going to spin out or roll over, it reduces the power of engine and in severe cases it also uses selective braking in order to prevent rollover or spinout.

In India, ESC module is generally absent in most of the vehicles and is only available in few of the premium cars. However, GNCAP (Global New Car Assessment Programme) and

MoRTH (Ministry of Road Transport and Highways) recently announced that it will be a mandatory safety feature from 2022 in India.

Now, passenger safety has been ensured by ESC from a vehicle dynamics point of view, passenger comfort is the key component that distinguishes a good vehicle from a great vehicle.

In modern day era, companies are competing on the basis of technological advances in safety and features which can make passenger feel right at home inside a vehicle.

Passenger Discomfort inside road vehicles due to dynamics of a vehicle is generally associated with the vertical vibrations or vertical acceleration produced in the vehicle. Innumerable studies have been conducted to find out the vertical vibrations of a vehicle and the factors/characteristics that contribute towards vertical movement of a vehicle. Although vertical vibrations might be the major source of passenger discomfort due to vehicle dynamics, studies have shown that other types of vibrations also cause passenger discomfort.

In 2013, G.F. Beard and M.J. Griffin conducted a study involving 15 male and 15 female volunteers between the age of 19 and 30 years. It used a 6-axis motion simulator to create lateral, roll and roll compensated lateral acceleration oscillations (combination of lateral and roll oscillation in a phase such that resulting acceleration in the plane of seat of simulator is zero) and mapped volunteer's discomfort to the motion stimuli [2]. Study found that rolling oscillations in the frequency range 0.4 to 1 HZ caused most discomfort to the volunteers.

In 2016, M. Mulder and D.A. Abbink studied the discomfort caused by oscillations produced in vertical, longitudinal and pitch directions using a motion simulator having 6 degrees of freedom. 27 participants were subjected to the pitch oscillations of magnitude ranging from 0 to 140.3 deg/s^2 and frequency ranging from 0 to 12 Hz [3]. It was found the passenger discomfort increased with increasing amplitude as well as increasing frequency.

In 2016, X. Shao et al studied the effect of Anti Pitch Anti Roll Hydraulically Interconnected Suspension (AAHIS) on Vehicle Handling and Ride. Steering and Braking maneuver (driving at constant speed of 110 kmph and braking with 4m/s^2 constant deceleration for 2 seconds and step input is given in order to generate 4 m/s^2 lateral acceleration) is performed in this study [4] and vehicle roll response is captured. It can be clearly seen in the roll angle time history graph shown below that after gaining maximum roll angle, vehicle undergoes roll oscillations. Also, maximum roll angle achieved and settling time of roll oscillations is reduced using AAHIS as can be seen in Fig. 1.5.

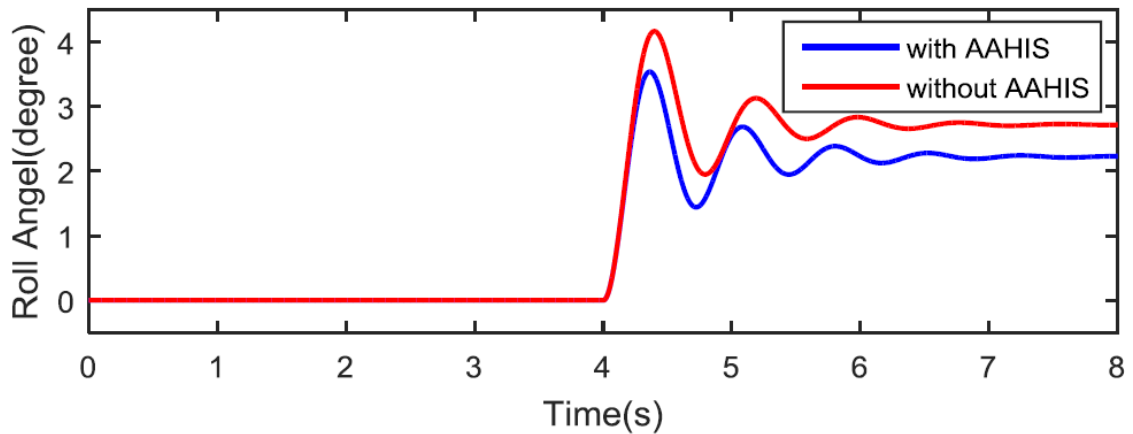


Fig. 1.5. Roll Response in Steering and Braking Maneuver

In 2018, A.E. Mohan et al studied the effect of varying suspension parameters (spring stiffness and damping level) on pitch performance of a vehicle in order to increase passenger comfort. Vehicle is passed over a single speed bump at a constant vehicle speed and pitch angle is observed[19]. It can be clearly seen in the Fig. 1.6 that after achieving maximum pitch angle, vehicle experiences pitch oscillations for some time. Also, study showed that upon increasing either spring rate or damping level, the maximum vertical acceleration observed in the vehicle also increased and lowering the spring rate/ damping levels resulted in lower pitch angle in the vehicle.

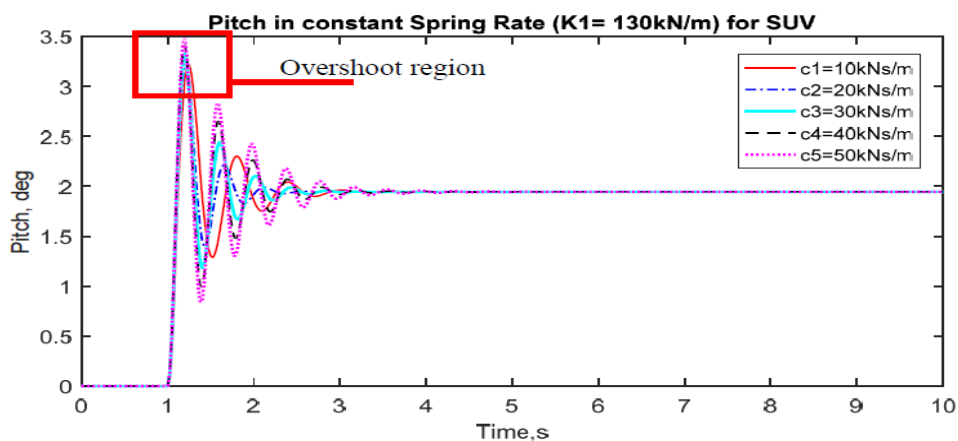


Fig. 1.6. Pitch Response of Vehicle to Speed Bump Test

Research studies above tell us two things. First, roll and pitch oscillations produced in the road vehicles play a crucial role towards passenger comfort. Second, a balance must be struck between vehicle's handling and roll/pitch oscillations of the vehicle in order to propose a safe and comfortable driving experience. Thus, roll and pitch oscillations must be optimized so as to enhance passenger comfort.

Chapter 2

Literature Review

2.1 Introduction

Several researchers have studied the effect of varying suspension parameters, wheelbase, wheel track and tire characteristics on dynamics of a vehicle. Several studies have been conducted into varying the spring stiffness and/or damping levels and their effect on pitch and roll behaviour of vehicle. Some researchers have also studied the various ways of controlling an active suspension so as to improve roll and pitch behaviour of a vehicle. Brief reviews of researches carried out to characterize and optimize the roll and pitch behaviour of a vehicle is presented here. Also, methods used to characterize the roll and pitch behaviour are discussed and highlighted.

2.2 Literature Review

T.D. Gillespie and R.D. Ervin (1983) used a mathematical model of a vehicle in order to calculate rollover threshold i.e. lateral acceleration required to cause vehicle rollover. Steady state turning maneuver (driving vehicle around a constant radius circle from stationary condition and increasing speed slowly until vehicle leaves the circle due to centrifugal force) was used in the simulation model for determination of rollover threshold of a vehicles of variety of vehicles ranging from passenger car of 1.1 ton to 6.8 ton step van. They also studied the effect of varying track width on rollover threshold of a vehicle and discovered that an increase in track width resulted in corresponding increase in rollover threshold.

R.W. Allen et al (1990) used computer simulations as well as field tests in order to study directional and roll stability of a vehicle under dynamic maneuvering conditions. They used several maneuvers for the validation of computer simulations. Steady State Cornering Test was used to test the roll response of a vehicle while cornering. Sinusoidal Steer Test (driving vehicle at a constant speed and sinusoidal input of increasing frequency step by step till the maximum limit of steering frequency possible) was used to determine lateral response (yaw rate, roll rate and lateral acceleration) of vehicle under dynamic input. Switch Back Steering Test (hard turn in one direction followed by hard turn in other direction and then returning to the center position at a constant vehicle speed) is used to test limit lateral performance of a vehicle under dynamic conditions. Study concluded that directional and roll stability is highly influenced by track

width ratio(track width/(2 x CG Height)) and wheel base ratio (wheel base/ CG Height). “A low track width ratio is clearly related to the propensity for rollover, and the load transfer sensitivity defined by the track width ratio and wheel base ratios definitely relates to directional stability”.

J. Ackermann and D. Odenthal (1999) studied the effects of using active steering with PD controller feedback of roll rate on roll dynamics of a vehicle during certain emergency maneuvers such as double lane change. Active steering system proposed here, used an actuator which added an auxiliary steering angle that is calculated using PD controller feedback of roll rate, to the driver’s steering input. They observed that the roll dynamics was significantly improved by the use of active steering and it also reduced the risk of rollover in case of transient driving maneuvers.

J.E. Larson et al (2000) devised a test in order to recreate vehicle rollover and study the rollover dynamics of a vehicle. Generally, rollover occurs in three phases. First phase usually begins with a steering maneuver, usually accompanied with braking which causes the vehicle to yaw excessively, generates body roll and lateral acceleration. Second phase is when combination of excessive yawing, rolling and lateral accelerations causes wheels to lift off the ground and vehicle is about to tip up. In third phase, vehicle starts rolling over and decelerating until the vehicle finally stops. In this study, a test was devised in which a driverless vehicle was accelerated to 120 kmph using a guide and tow mechanism and then it is released unto a skid pad where a 3 step steering maneuver was provided to vehicle after 3 seconds of its release. Trapezoidal form of steering maneuver is shown below in Fig 2.1:-

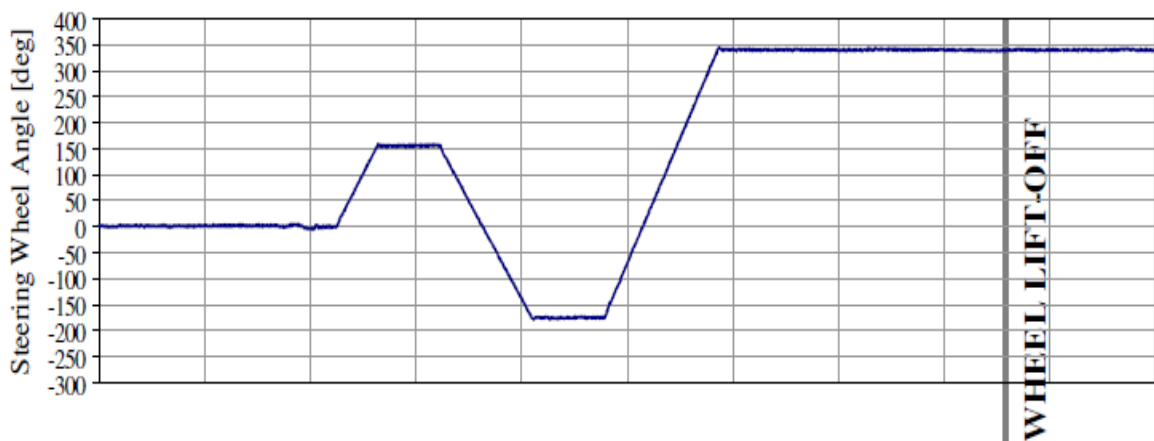


Fig. 2.1. Three Step Trapezoidal Steering Maneuver for Rollover

Trapezoidal input of 160° towards right is given first with a steering rate of $800^\circ/\text{s}$ and then 180° towards left with steering rate of $755^\circ/\text{s}$ proceeded by 350° towards right with a steering rate of $964^\circ/\text{s}$ to cause a rollover i.e. 4 wheel lift-off.

Vehicle was equipped with instruments to accumulate several vehicle parameters that are given below:-

- Steering Wheel Angle
- Steering Wheel Torque
- Three Axes Accelerations
- Three Axes Angular Rate
- Roll Angle
- Longitudinal Velocity
- Lateral Acceleration

A pick up vehicle was tested through the above-mentioned process and vehicle rolled for 7 times before stopping, which included 3 severe ground impacts of the roof. This test is suitable for rollover studies but it is irrelevant in the study of roll damping since wheel lift off and then its impact with the ground would distort the roll angle damping readings by adding additional impact force input onto the roll angle.

D. J. M. Sampson (2000) implemented and tested an active roll control system in single unit as well as articulated heavy vehicles. He used various control techniques to control the hydraulic actuators attached to antiroll bar (ARB) connected to the drive axles of heavy vehicles as shown in Fig 2.2:-

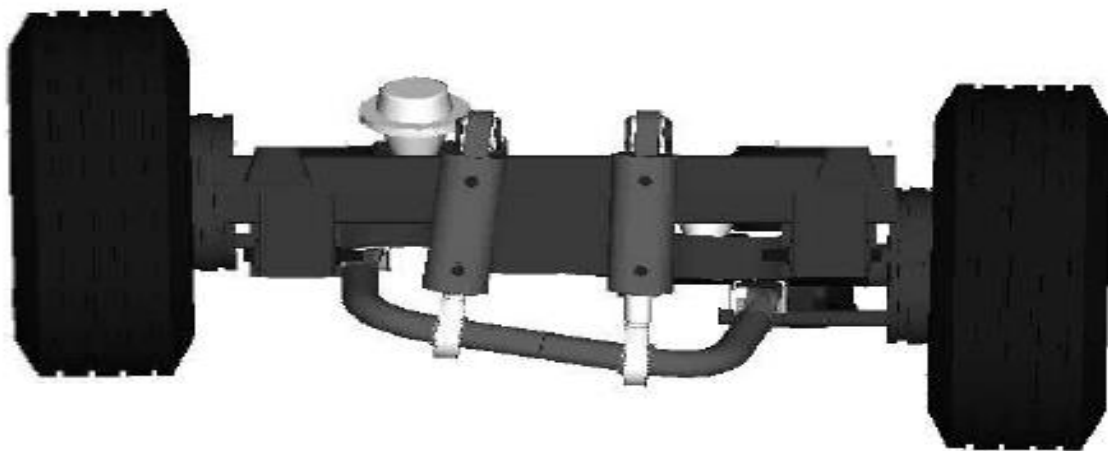


Fig. 2.2. Hydraulic Actuators & ARB Assembly in Active Roll Control System

A counteracting roll moment is applied to the vehicle body by extending one and retracting the other hydraulic actuator whenever vehicle body rolls beyond a certain limit. Amount of extension and contraction of hydraulic actuators is determined by a partial and full state feedback controller. Active Roll Control was tested using three types of test maneuvers:-

1. Steady State Test Maneuver
2. Step Input Test Maneuver
3. Double Lane Change Test Maneuver

J.G. Howe et al (2001) of National Highway Traffic Safety Administration (NHTSA) conducted an “Experimental Examination of Selected Maneuvers That May Induce On-Road, Untripped Light Vehicle Rollover” which stated that “A vehicle’s rollover (two-wheel lift) behavior in a complex maneuver (such as a double lane change) depends strongly upon the precise steering inputs provided by the driver. At a given speed, a driver can use different sets of steering inputs to follow the same course. These different sets of steering inputs can result in a vehicle having a completely different rollover behavior. For example, one set of steering inputs may allow the driver to proceed completely through a course without any two-wheel lift while a second set of steering inputs, at the same speed, may result in large two-wheel lift and rollover.” Thus, NHTSA began researching the tests which would initiate a rollover in a vehicle. Initially, they investigated 8 test maneuvers that may induce rollover, namely:-

1. J-Turn Test Maneuver
2. J-Turn with Pulse Braking Test Maneuver
3. Brake & Steer Test Maneuver
4. Steering Reversal Test Maneuver
5. Toyota Fishhook Test Maneuver
6. Double Lane Change Test Maneuver
7. Split Mu Off-Road Recovery Simulation Test Maneuver
8. Toyota Fishhook with Pulse Braking Test Maneuver

NHTSA’s rollover study was conducted in 8 phases as follows:-

1. **Phase 1-A:** Firstly, it determined that whether the test procedures aforementioned, induced rollover in some vehicles, all vehicles or no vehicles at all. It also checked objectivity and repeatability of the test maneuvers i.e. whether the same vehicle will produce same results upon testing with same procedure. Also, it was checked whether the test performed in the study will be performed by a real driver on road.

2. **Phase 1-B:** It determined the effects of using different drivers, outriggers, fuel levels in vehicles on the results of test maneuvers. It also focused on procuring a programmable steering controller so that exact same steering input can be given every time. Finally, it narrowed down the test maneuver which are objective, repeatable, portrays a real driving scenario.
3. **Phase 2:** It tested a wide range of vehicles using the test maneuvers defined in Phase 1-B and determined their rollover resistance and metrics that affected rollover propensity i.e. ease with which rollover is initiated in a particular vehicle, of these vehicles. It used the testing data of vehicles and their rollover propensities to correlate their rollover propensity with static & dynamic rollover metrics such as Tilt Table Ratio, Static Stability Ratio and Critical Sliding Velocity.
4. **Phase 3:** It focused on improving the severity of fishhook maneuver by initiating steering reversal at the point when roll rate of vehicle is reduced to zero after the initial steer instead of determining steering reversal timing through vehicle's roll frequency at 50 mph. It also focused on improve repeatability of pulse braking during J-Turn Test Maneuver using Automated Pulse Braking instead of test drivers initiating the brake.
5. **Phase 4:** It graded test maneuvers defined in Phase 1-A based upon following criteria:-
 - i. Objectivity and Repeatability
 - ii. Performability
 - iii. Discriminatory Ability
 - iv. Appearance of Reality

Four tests were finalized at end of Phase 4, namely:-

- NHTSA J-Turn
 - Fishhook 1-a
 - Fishhook 1-b
 - Nissan Fishhook
6. **Phase 5:** It investigated the effects of different outrigger designs, ambient temperature and test surfaces on the test maneuvers. It also finalized the testing methodology to be used in phase 6 of this study.
 7. **Phase 6:** It focused on determining the rollover resistance of various vehicles using the testing methodology defined in phase 5 of the testing and using the result from the tests to assist in the development of the rollover resistance rating test.
 8. **Phase 7:** It devised a new loading pattern of the vehicle because when vehicle was loaded for maximum occupancy using earlier loading pattern, vehicle could not meet

front load limit/rear load limit/vehicle load limit or both. It also modulated severity of fishhook test by adjusting the steering magnitude in fishhook test according to the vehicle as vehicles did not produce two wheel lift in some cases due to tire saturation before steering reversal and in others since the steering input was not high enough to produce a two wheel lift off.

- 9. Phase 8:** Objective of this phase of testing was to use the fishhook test maneuver in order to generate results of testing to evaluate rollover resistance of several vehicles and provide relative rollover risk of these vehicles for its NCAP rollover ratings.

Hac et al (2004) developed an algorithm to prevent rollover in dynamic situations. A Rollover Index is defined by the author which is an estimate of probability of rollover in a dynamic condition using the estimated roll angle, side slip velocity and measured roll rate and lateral acceleration of the vehicle. For validation of algorithm, vehicle tests were performed and results obtained from experimentation were compared with simulated results. Vehicle test maneuvers used while testing include J-Turn Test and Fishhook maneuver but test maneuvers used for simulations in order to improve upon the algorithm include Double Lane change maneuver, Ramp road input and Harmonic road input.

“In dynamic rollover tests many vehicles experience sustained body roll oscillations during a portion of road edge recovery maneuver, in which constant steering angle is maintained.”

A.E. Mohan et al (2018) studied the effect of changing spring stiffness values and damping levels of a vehicle using a computer simulation using a single speed bump maneuver wherein vehicle is passed over a single speed bump at a constant speed and vehicle's pitch angle response and vertical acceleration response is studied. Study showed that upon increasing either spring rate or damping level, the maximum vertical acceleration observed in the vehicle also increased and lower spring rate/ damping levels resulted in lower pitch angle in the vehicle.

F. Ahmad and K. Hudha (2009) used a gain scheduling PID controller with pitch moment rejection in order to reduce dive and squat response of a vehicle. A 14 DOF model was used for simulation of vehicle's response to sudden acceleration achieving squat and sudden braking achieving dive in a vehicle.

M. T. Long et al (2017) studied the relationships between pitch/heave and roll/heave of a vehicle while travelling on a highway in a straight line. Straight Line Test was used with speeds varying from 60 to 100 kmph. A strong relationship was observed between the pitch angular velocity and heave acceleration. A weaker, yet still evident relationship was observed between

the roll angular velocity and heave acceleration. It was also found that the pitch/heave and roll/heave relationships are influenced by vehicle speed.

G.F. Beard and M.J. Griffin (2013) conducted a study involving 15 male and 15 female volunteer between the age of 19 and 30 years. It used a 6-axis motion simulator to create lateral, roll and roll compensated lateral acceleration oscillations (combination of lateral and roll oscillation in a phase such that resulting acceleration in the plane of seat of simulator is zero) and mapped volunteer's discomfort to the motion stimuli. Study found that rolling oscillations in the frequency range 0.4 to 1 HZ caused most discomfort to the volunteers.

M. Mulder and D.A. Abbink (2016) studied the discomfort caused by oscillations produced in vertical, longitudinal and pitch directions using a motion simulator having 6 degrees of freedom. 27 participants were subjected to the pitch oscillations of magnitude ranging from 0 to 140.3 deg/s² and frequency ranging from 0 to 12 Hz. It was found the passenger discomfort increased with increasing amplitude as well as increasing frequency.

2.3. Literature Gap

Researches mentioned above only focused on optimizing the roll and pitch behaviour of vehicle and also mentions that roll and pitch oscillations also influence the passenger comfort. Roll and Pitch behaviour is characterized only using roll angle, pitch angle, roll rate and pitch rate. No research found in this literature review points to characterizing and studying the damping of roll and pitch oscillations generated in the vehicle.

2.4 Scope and Objective of the Present Work

Most of the research which emphasize on passenger comfort, it only talks about vertical acceleration generated by the vehicle. Above mentioned research studies clearly state that roll and pitch oscillations also have an impact upon the comfort of the passenger. Thus, roll and pitch damping behaviour of vehicles must be studied in order to understand the passenger comfort more profoundly and thereafter optimization of roll and pitch damping behaviour must be carried out. Mentioned below are the objective of this study:-

- Development of methodology for characterization of pitch and roll damping behaviour in dynamic maneuvers
- Determination of pitch and roll comfort values and damping characteristics of pitch and roll oscillations

Chapter 3

Methodology & Vehicle Setup

3.1 Introduction

In this section, firstly, a brief summary of the methodology adopted for the completion of this study is mentioned. Secondly, vehicle setup and instruments mounted onto the vehicle for studying the roll and pitch damping behaviour of a vehicle is highlighted. Also, detailed information about the parameters captured, process and objective of test maneuvers performed for characterization of roll & pitch damping behaviour of vehicle is compiled.

3.2 Project Methodology

Process followed for step by step completion of the dissertation work is depicted in the flow chart in Fig. 3.1.

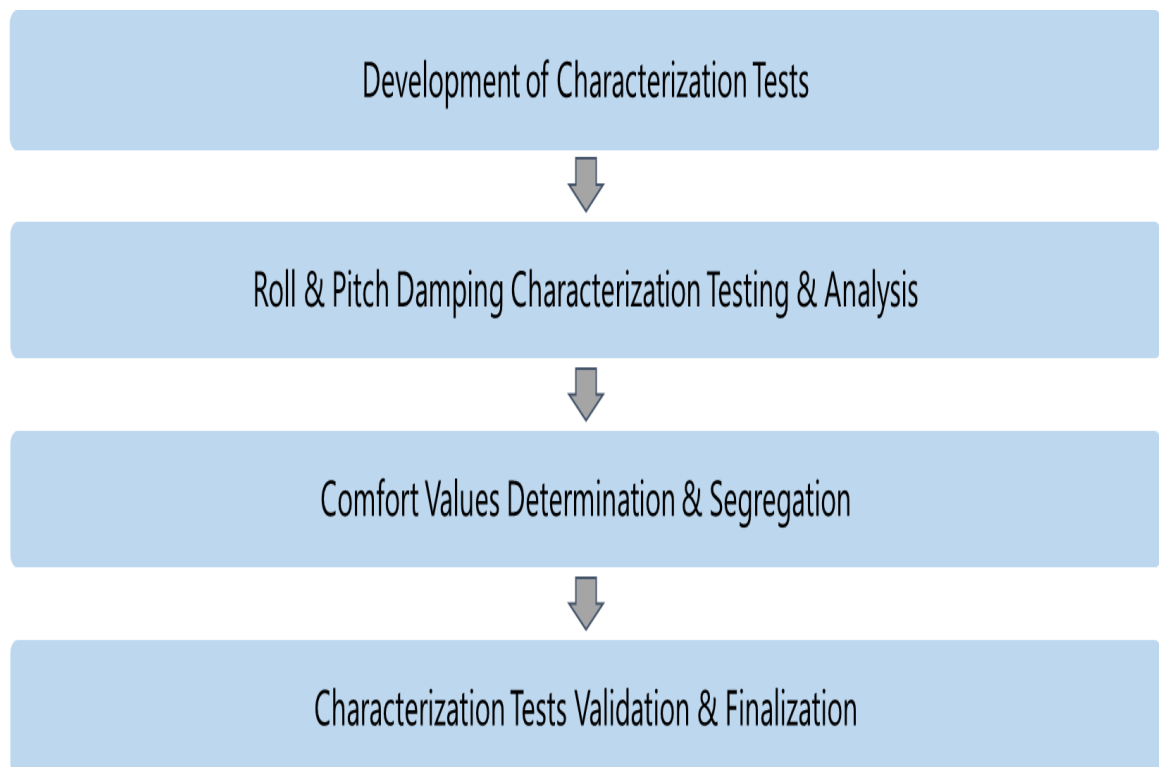


Fig. 3.1. Project Methodology

3.2.1 Development of Characterization Tests

A list of tests conducted by other researchers in their studies was compiled. Test which were relevant to our study were separated from the list of test maneuver conducted by fellow researchers. Tests maneuvers which will be performed by a real driver during daily driving and maneuvers which resulted into roll and pitch oscillations were formulated. All of the tests were performed using a vehicle and they were analyzed of the basis of following criteria:-

1. **Objectivity:-** Test maneuver should not be driver dependent. If two different drivers are performing the same test maneuver then it should not affect the outcome of the test i.e. values of parameters collected during testing
2. **Repeatability:-** If same driver repeats the same driving maneuver then the resulting vehicle behaviour should remain same every time i.e. parameter values should not differ the second time.
3. **Realness of Test:-** It is the likelihood of a real life driver performing a maneuver on a road while driving either in an emergency or just for fun.
4. **Discernibility:-** Test maneuver's ability to create roll/pitch oscillations so that it can be analyzed to study roll/pitch damping behaviour of a vehicle.

A list of tests which meet the requirements of this study were selected, which are mentioned in Characterization Test section of this chapter.

3.2.2 Roll & Pitch Damping Characterization Testing & Analysis

A fleet of vehicles were tested using test maneuvers defined for the characterization of roll & pitch damping behaviour of the vehicle in the previous phase were performed using various vehicles.

Before testing, static measurements of parameters which affect the rolling and pitching behaviour of a vehicle were measured and compiled e.g. Tire characteristics, Suspension characteristics etc.

Shortlisted test maneuvers defined in previous phase were performed on the test vehicle and data was collected on roll & pitch oscillations damping behaviour of vehicle.

A subjective rating sheet is also prepared for test engineer and co-driver to objectively rate their discomfort level due to oscillations produced in vehicle during test maneuvers. Subjective rating is immediately given after performing each test maneuver.

3.2.3 Comfort Values Determination & Segregation

In this phase, testing data was closely analysed so that a vehicle's roll & pitch damping behaviour can be defined objectively using certain parameters such as max. value of roll/pitch angle achieved during testing and settling time of oscillations produced by the vehicle.

Objective data collected from the vehicle's behaviour is then correlated with subjective rating of the test engineer and the co-driver so as to discern a comfort zone of passenger.

A value range/threshold value of a parameter is defined wherein the passenger feels comfortable and unbothered by the roll and pitch oscillation of the vehicle.

3.2.4 Characterization Test Validation & Finalization

Characterization Tests which resulted in the amalgamation of the objective and subjective results were documented and finalized for 1:1 objective comparison of vehicle's rolling & pitching damping behaviour.

3.3 Vehicle Setup

Prior to vehicle testing, test vehicle is equipped with certain sensors in order to characterize vehicle behaviour during testing. A list of instruments/sensors mounted onto vehicle for testing & capturing vehicle's behaviour are as follows:-

3.3.1 Speed Sensor

An optical speed sensor is mounted on the vehicle in order to measure the vehicle speed. Depicted below is the used sensor and its specifications in Fig 3.2 and Table 3.1 respectively.



Fig. 3.2. Kistler Optical Speed Sensor

Table 3.1. Speed Sensor Specifications

Specification	Units	Value
Speed Range	kmph	0 to 250
Distance Resolution	mm	2.47
Measurement Frequency	Hz	250
Working Distance	mm	350±100
Operating Temperature Range	°C	-25 to 50

Speed Sensor is mounted in front of the front bumper of the vehicle using a suction type sensor mount. Sensor's longitudinal axis is aligned with vehicle's longitudinal axis when it is mounted on the test vehicle as shown in Fig 3.3:-



Fig. 3.3. Speed Sensor Mounting Position

3.3.2 Measuring Steering Wheel (MSW)

MSW is used to measure the position of steering wheel. MSW used in this study is an optical type of measuring steering wheel. Picture depicting the MSW & mounting position of MSW onto the steering wheel of the vehicle is shown below in Fig.3.4.



Fig. 3.4. MSW Sensor & Mounting Position

Specifications of the MSW used for the study has been mentioned in Table 3.2.

Table 3.2. MSW Specifications

Specification	Units	Value
Steering Angle Range	°	-1250 to 1250
Steering Speed	°/s	≤2000
Resolution	°	0.015
Accuracy	°	±0.1
Operating Temperature Range	°C	-20 to 80

3.3.3 Height Sensor

Four laser type height sensors are mounted on the vehicle in order to calculate the body roll angle as well as pitch angle during dynamic testing maneuvers. Typical height sensor used in the study has been shown in Fig. 3.5.



Fig. 3.5. Height Sensor for calculation of Roll & Pitch Angle

Specifications of the height sensor used for the study has been mentioned in Table 3.3.

Table 3.3. Height Sensor Specifications

Specification	Units	Value
Measuring Range	mm	150 to 900
Resolution	mm	0.3
Sampling Rate	kHz	0.3 to 8
Light Source	-	Laser
Operating Temperature Range	°C	-5 to 60

Height sensors are mounted at each corner of the vehicle i.e. Front Left Hand Side (FLH), Front Right Hand Side (FRH), Rear Left Hand Side (RLH) and Rear Right Hand Side (RRH) as shown in Fig.3.6:-

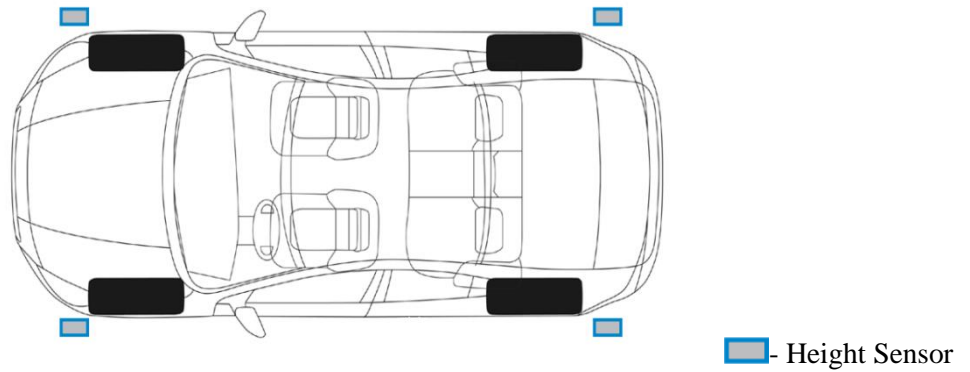


Fig. 3.6. Height Sensor Mounting Positions on test vehicle

Height sensors measure the distance between the ground and the position of the sensor continuously. Whenever vehicle rolls or pitches, as a result, height sensors are either deflected towards the ground or away from the ground depending upon the direction of motion of vehicle body. For example, if a vehicle pitches towards the front i.e. it dips in front and elevates in rear then front height sensors move towards the ground and rear sensors move away from ground as shown in Fig. 3.7.



Fig. 3.7. Vehicle Pitching Forward

Now, pitch angle of the vehicle can be easily calculated using simple underlying mathematical formula:-

$$Pitch\ Angle = \tan^{-1} \left[\frac{Height\ of\ Front\ Sensor - Height\ of\ Rear\ sensor}{Distance\ between\ the\ Front\ \&\ Rear\ sensors} \right]$$

Similarly, whenever the vehicle rolls towards left or right side, the roll angle can be calculated.

$$Roll\ Angle = \tan^{-1} \left[\frac{Height\ of\ LH\ Sensor - Height\ of\ RH\ sensor}{Distance\ between\ the\ Front\ \&\ Rear\ sensors} \right]$$

Before performing any testing maneuvers, distances between FLH & FRH Height Sensor, RLH & RRH Height Sensor are measured for Front Roll Angle & Rear Roll Angle calculations

respectively. Also, distances between FLH & RLH Heights Sensors, FRH & RRH Height Sensors are also measured to calculate LH Pitch Angle & RH Pitch Angle of the vehicle respectively.

3.3.4 Lateral Acceleration Sensor

A capacitive type of accelerometer is mounted at CG (x & y direction) location of the vehicle. A typical accelerometer is shown in Fig. 3.8.



Fig. 3.8. Accelerometer used to capture lateral acceleration

Accelerometer is used to measure lateral acceleration experienced by the vehicle during transient test maneuvers and specifications of accelerometer used in the study have been mentioned in Table 3.4.

Table 3.4. Latac Sensor Specifications

Specification	Units	Value
Acceleration Range	g	-2 to 2
Frequency Range	Hz	0 to 250
Resolution	mg _{rms}	0.100
Operating Temperature Range	°C	-55 to 125

3.3.5 Gyro Sensor

A gyroscopic capacitive type angular rate sensor is used to measure roll rate and pitch rate of the vehicle. It is placed at the CG (x & y direction) location of the vehicle alongside latak sensor. A typical accelerometer is shown in Fig. 3.9.



Fig. 3.9. Gyro Sensor used to capture roll rate and pitch rate of test vehicle

Specifications of the gyro sensor used in testing to measure roll & pitch rate of the vehicle are mentioned in Table 3.5.

Table 3.5. Gyro Sensor Specifications

Specification	Units	Value
Measuring Range	°/s	-150 to 150
Operating Temperature Range	°C	-40 to 85

3.4 Characterization Test Maneuvers

Roll & Pitch Damping Characterization Test identified, developed, used in this study are mentioned in Table 3.6 below:-

Table 3.6. Roll & Pitch Damping & Comfort Characterization Tests

Roll Damping Evaluation Tests		
1.	Step Input Test	Roll damping response of vehicle during abrupt lane change
2.	Double Lane Change Test	Roll behavior of vehicle during double lane change
Pitch Damping Evaluation Tests		
1.	Dive Test	Pitch damping response of vehicle travelling in forward direction & braking
2.	Squat Test	Pitch damping response of vehicle travelling in reverse direction & braking
3.	Single Speed Bump Test	Pitching behaviour & its damping while negotiating a single speed bump
Roll & Pitch Coupled Damping Evaluation Tests		
1.	Straight Line Test	Rolling & pitching behaviour of a vehicle travelling in straight line
2.	Start Stay Stop Test	Vehicle behavior during acceleration, deceleration and rough road inputs in a straight line

Testing Procedure and other details of the test maneuvers used for the roll & pitch damping characterization mentioned in Table 3.6 are elaborated below.

3.4.1 Step Input Test Maneuver

Objective: - Evaluation of roll damping behaviour of a vehicle during a abrupt emergency lane change.

Procedure: -

1. Drive the vehicle in a straight line with no steering wheel input at a constant vehicle speed of 30 kmph.
2. Steering Wheel must be turned to a predetermined angle as rapidly as possible so as to generate 0.2g lateral acceleration in the vehicle.
3. Hold Steering Wheel at the predetermined angle until roll oscillations stops.

Vehicle Path Trajectory:-

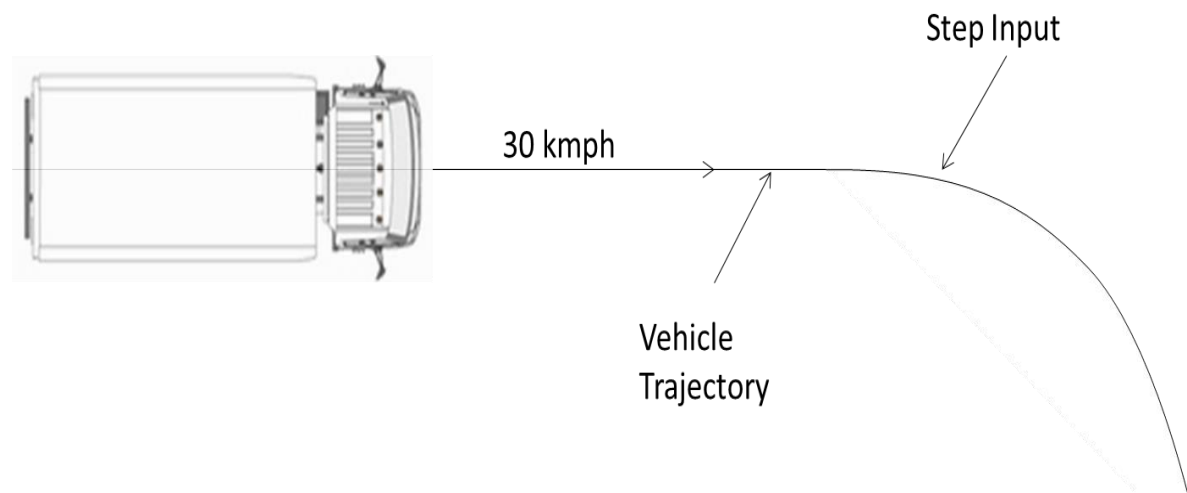


Fig. 3.10. Step Input Test Maneuver Vehicle Path Trajectory

Parameters Observed:-

1. Roll Angle
2. Roll Rate
3. Lateral Acceleration (Latac)
4. Vehicle Speed
5. Steering Wheel Angle

3.4.2 Double Lane Change Test Maneuver

Objective:- Evaluation of roll response of vehicle during double lane change.

Procedure:-

1. Vehicle is maneuvered through standard DLC path.
2. Driver must try to maintain constant speed of 30 kmph all through the path.

Vehicle Path Trajectory:-

Standard DLC representation is depicted below.

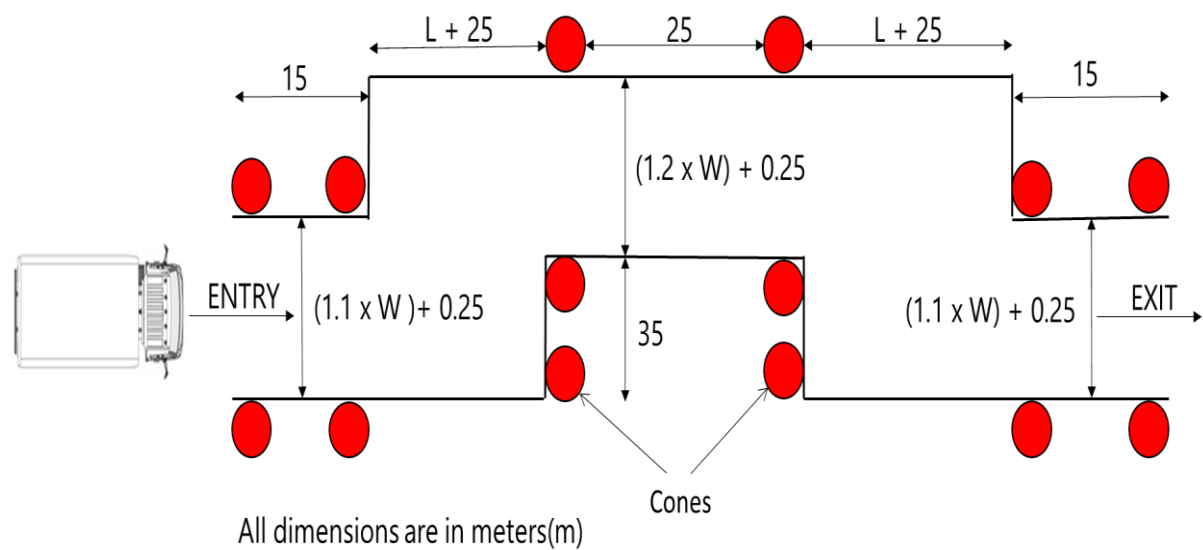


Fig. 3.11. Standard Double Lane Change Path

Parameters Observed:-

1. Roll Angle
2. Roll Rate
3. Lateral Acceleration (Latac)
4. Vehicle Speed
5. Steering Wheel Angle

3.4.3 Dive Test Maneuver

Objective:- Evaluation of pitch damping response of the vehicle during braking when vehicle is moving in forward direction.

Procedure:-

1. Drive vehicle at constant speed of 40 kmph in a straight line path.
2. While holding the steering at $0 \pm 10^\circ$, apply brake with a constant pedal effort of 15 ± 1 kg until vehicle stops.
3. Continue holding the brake position, until the vehicle stops pitching.

Vehicle Path Trajectory:-

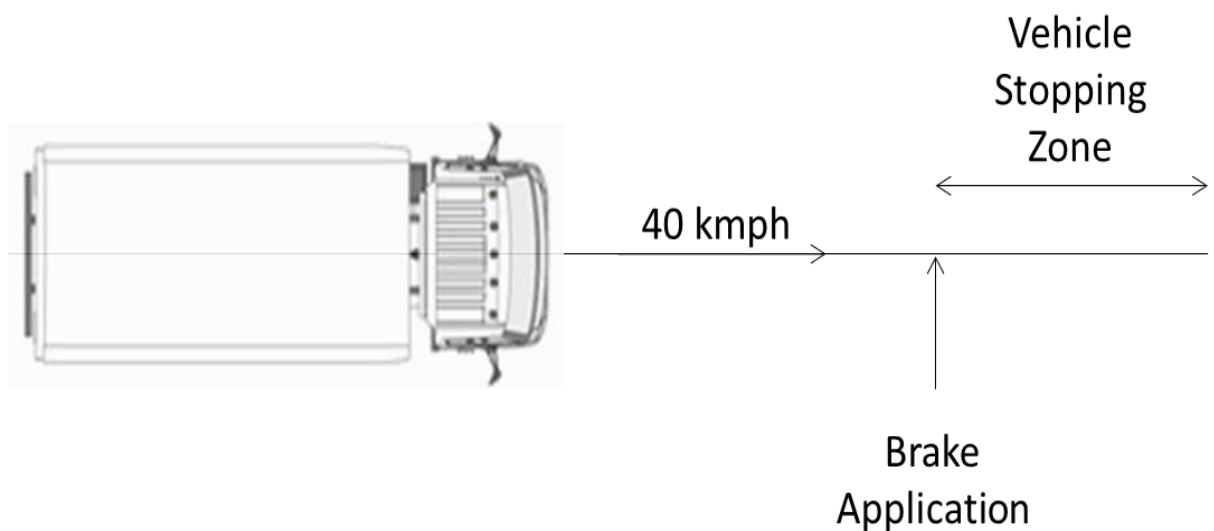


Fig. 3.12. Dive Test Maneuver Vehicle Path Trajectory

Parameters Observed:-

1. Pitch Angle
2. Pitch Rate
3. Vehicle Speed
4. Steering Wheel Angle

3.4.4 Squat Test Maneuver

Objective:- Evaluation of damping pitch response of the vehicle during braking when vehicle is moving in reverse direction.

Procedure:-

1. Drive vehicle at constant speed of 15 kmph or max. speed in reverse gear if max. speed is less than 15 kmph.
2. While holding the steering at $0 \pm 10^\circ$, apply brake with a constant pedal effort of 15 ± 1 kg until vehicle stops.
3. Continue holding the brake position, until the vehicle stops pitching.

Vehicle Path Trajectory:-

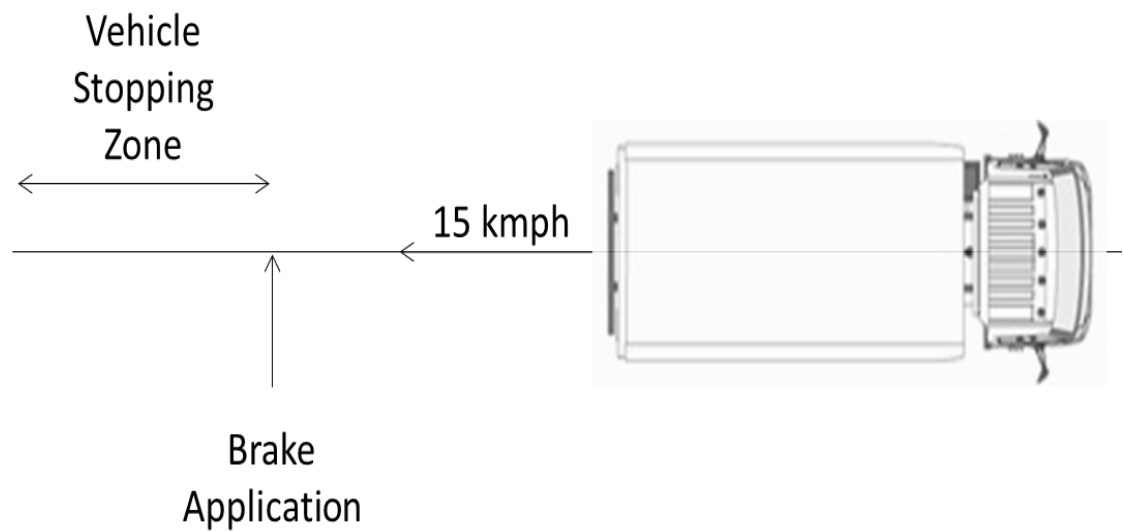


Fig. 3.13. Squat Test Maneuver Vehicle Path Trajectory

Parameters Observed:-

1. Pitch Angle
2. Pitch Rate
3. Vehicle Speed
4. Steering Wheel Angle

3.4.5 Single Speed Bump Test Maneuver

Objective:- Evaluation of vehicle pitching behavior while and after negotiating a speed bump.

Procedure:-

1. Drive the vehicle over the defined speed bump at a constant speed of 15 kmph in a straight line.
2. Throttle position must be kept constant before and after the bump.
3. Start data logging once the speed of 15 kmph is achieved and stop it after vehicle stops pitch oscillations.
4. Steering wheel must be held at $0 \pm 10^\circ$ position throughout the test.

Vehicle Path Trajectory:-

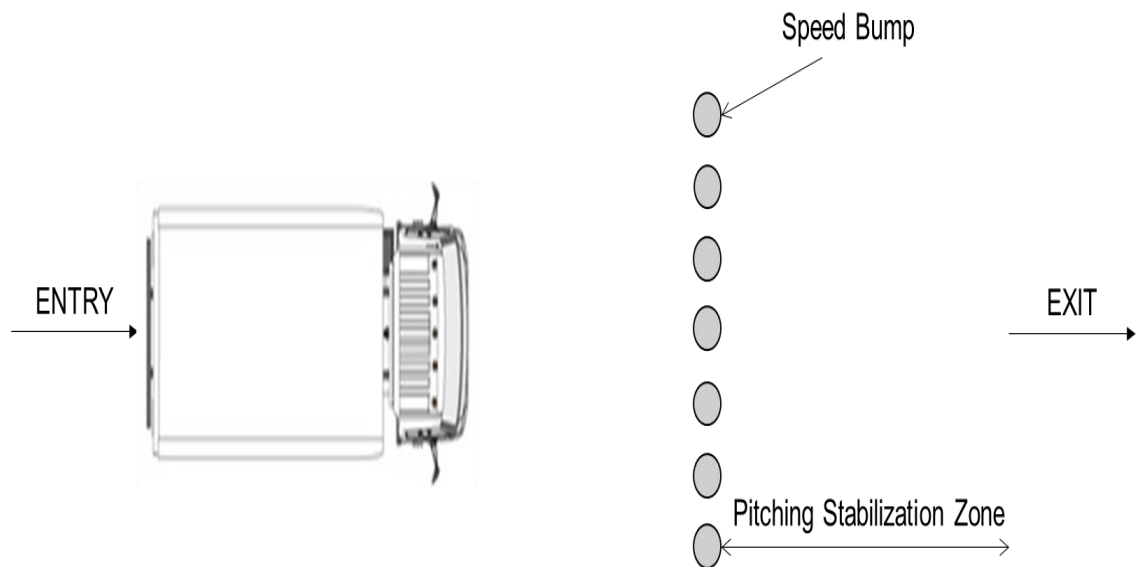


Fig. 3.14. Single Speed Bump Test Maneuver Vehicle Path Trajectory

Parameters Observed:-

1. Pitch Angle
2. Pitch Rate
3. Vehicle Speed
4. Steering Wheel Angle

3.4.6 Straight Line Test Maneuver

Objective:- Evaluation of vehicle roll and pitch behavior during straight line driving.

Procedure:-

1. Drive the vehicle at a constant speed of 40 kmph in a straight line on a dry asphalt road.
2. Start the data logging at data logging starting point and stop it at data logging stopping point marked on the test track.
3. Steering Wheel must be held at $0 \pm 10^\circ$ position throughout the test.

Vehicle Path Trajectory:-

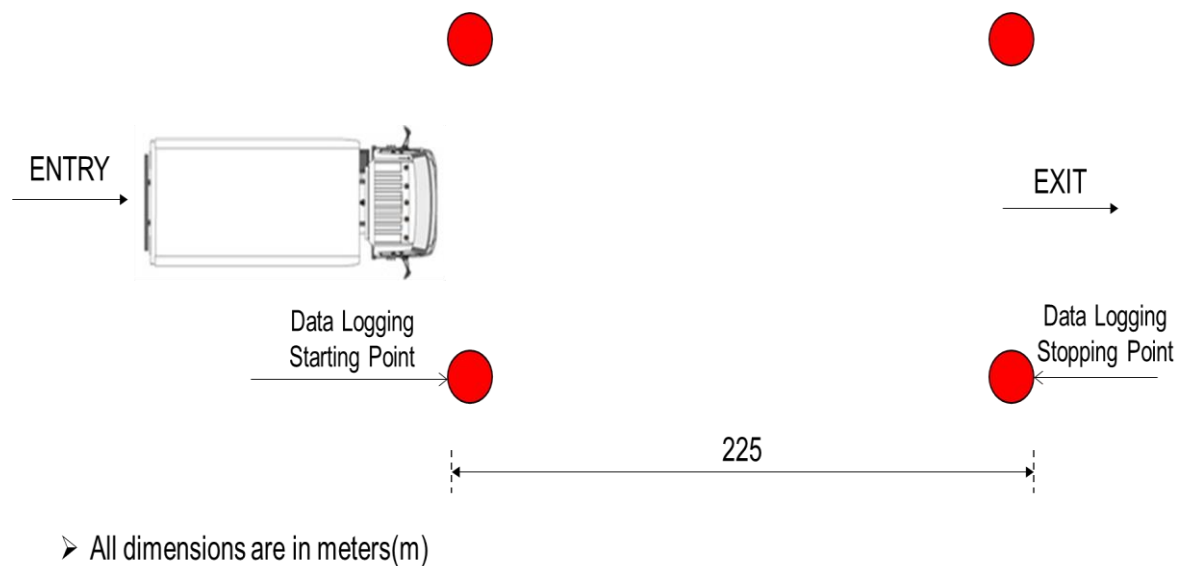


Fig. 3.15. Straight Line Test Maneuver Vehicle Path Trajectory

Parameters Observed:-

1. Roll Angle
2. Pitch Angle
3. Roll Rate
4. Pitch Rate
5. Vehicle Speed
6. Steering Wheel Angle

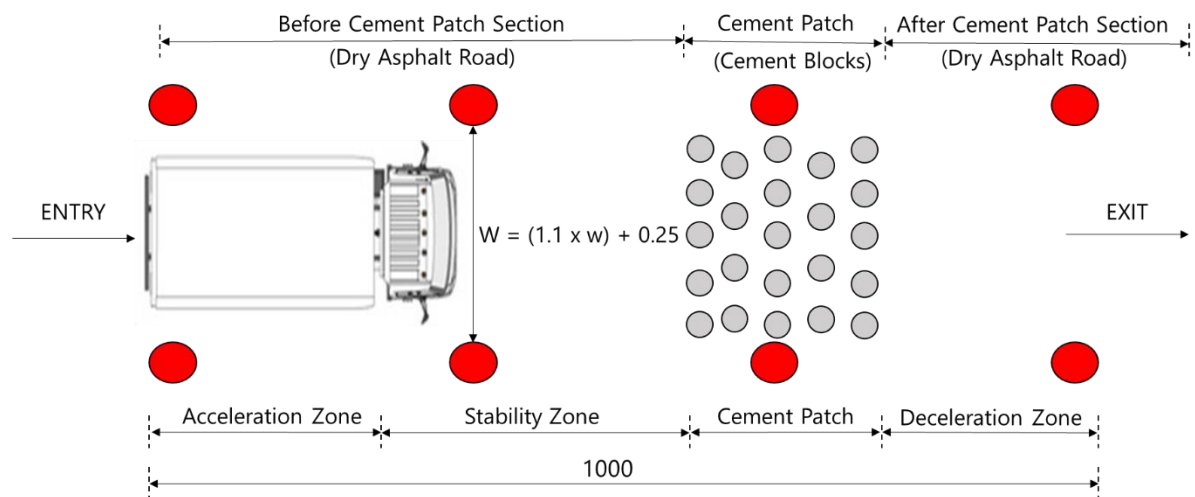
3.4.7 Start Stay Stop Test Maneuver

Objective:- Evaluation of vehicle roll and pitch behavior during accelerating, braking and rough road inputs.

Procedure:-

1. Accelerate the vehicle to 40 kmph as rapidly as possible from the halt position.
2. Once you reach a speed of 40 kmph, maintain and hold vehicle at a constant speed of 40 kmph before and through the cement patch (rough road input patch of road).
3. After vehicle has passed the cement patch section, apply brake with a constant pedal effort of 15 kg until vehicle stops.
4. Continue holding the brake position, until the vehicle stops pitching
5. Steering must be held at $0 \pm 10^\circ$ throughout the test.

Vehicle Path Trajectory:-



w = Width of the Vehicle

Fig. 3.16. Start Stay Stop Test Maneuver Vehicle Path Trajectory

Parameters Observed:-

1. Roll Angle
2. Pitch Angle
3. Roll Rate
4. Pitch Rate
5. Vehicle Speed
6. Steering Wheel Angle

Chapter 4

Results and Discussion

4.1 Introduction

Characterization Test identified in previous section were performed using different test vehicles and parameters such as pitch angle, roll angle, pitch rate, roll rate and lateral acceleration etc. were captured and analysed for the characterization of roll & pitch damping behaviour as well as roll & pitch comfort zones.

4.2 Vehicle Characterization

Static Measurements were conducted on each vehicle before performing characterization tests on a vehicle. Parameters measured on each vehicle before the characterization tests are mentioned below: -

1. Wheelbase
2. Wheel Track
3. Front Axle Weight (FAW)
4. Rear Axle Weight (RAW)
5. Gross Vehicle Weight (GVW)
6. F/R Ratio = FAW/RAW
7. CG of Vehicle (X)
8. Type of Springs
9. No. of Leafs
10. Spring Track
11. Spring Span
12. Spring Width
13. Thickness of Leaf
14. Anti-Roll Bar Diameter
15. Chassis Height
16. Damper
17. Tyre
18. Tyre Tread Pattern
19. Tyre Pressure

4.3 Characterization Test Results

Characterization Tests mentioned in the previous chapter were conducted on vehicles for the objectively capturing the roll and pitch behaviour of the vehicle and then the objective results were analyzed and correlated with the subjective ratings given by the test engineer and co-driver. Objective and subjective values captured in each test is subsequently mentioned and results on the basis of their correlation are discussed.

4.3.1 Subjective Ratings Criteria

Each vehicle is graded according to various criteria based upon its comfort level felt during testing by the test engineer and co-driver immediately after its objective testing. Subjective rating system used here has been mentioned in Table 4.1.

Table 4.1 Subjective Rating Criteria

Subjective Experience	Subjective Rating
Unacceptable	1-3
Customer Complaint	4
Borderline	5
Barely Acceptable	6
Fair	7
Good	8
Very Good	9
Excellent	10

4.3.2 Step Input Test

Step Input Test was performed as mentioned in the previous chapter. Typical roll angle time history has been shown in Fig. 4.1

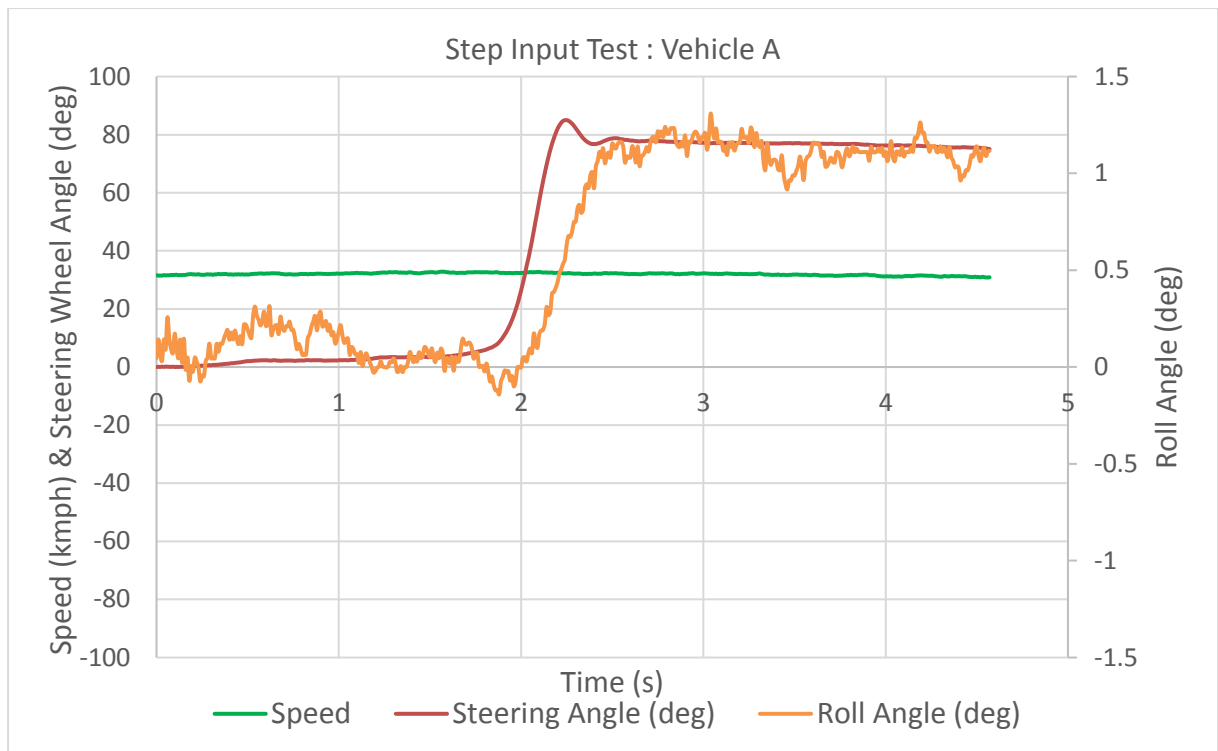


Fig. 4.1 Roll Angle Time History during Step Input Test

Roll angle and Roll rate has been normalized using peak lateral acceleration value achieved during the maneuver so as to nullify the effect of differences in steering rate and steering wheel angle between different vehicles. Table 4.2 mentions the Peak Roll Angle per Latac, Peak Roll Rate per Latac and Subjective Ratings captured during the step input test.

Table 4.2 Step Input Test Output Parameters and Subjective Ratings

Step Input Test : Output Parameters				
Vehicle	Peak Roll Angle per Latac (deg per g)	Peak Roll Rate per Latac (deg/s per g)	Subjective Rating	
			Roll Angle	Roll Rate
Vehicle A	5.590	3.678	8	9
Vehicle B	11.43	26.53	5	5
Vehicle E	8.07	37.18	7	3
Vehicle F	11.37	31.69	5	4
Vehicle I	10.57	29.05	6	5
Vehicle K	9.94	33.54	7	4

Fig. 4.2. And Fig. 4.3. depicts the above tabular data of Peak Roll Angle per Latac and Peak Roll Rate per Latac respectively in a graphical manner for the ease of comparison between vehicles.

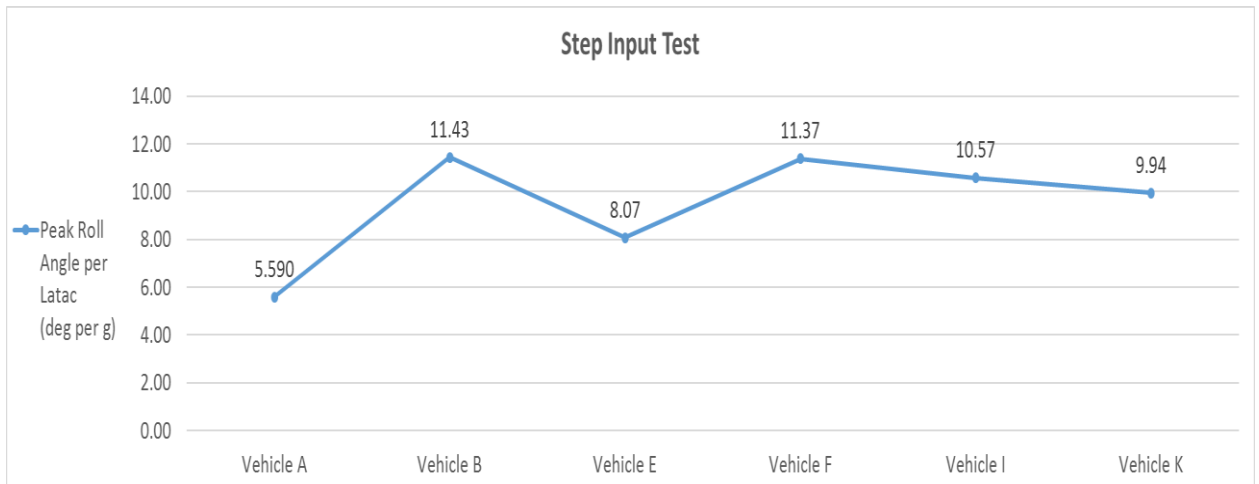


Fig. 4.2. Peak Roll Angle per Latac during Step Input Test

Roll angle was perceived comfortable in Vehicle E. Thus, vehicles having Peak roll angle per latac value less than 8.07 deg per g will be perceived comfortable by its passengers. Vehicle K was barely acceptable to the passengers. Thus, vehicle having peak roll angle per latac value more than 9.94 deg per g will be perceived uncomfortable by the passengers.

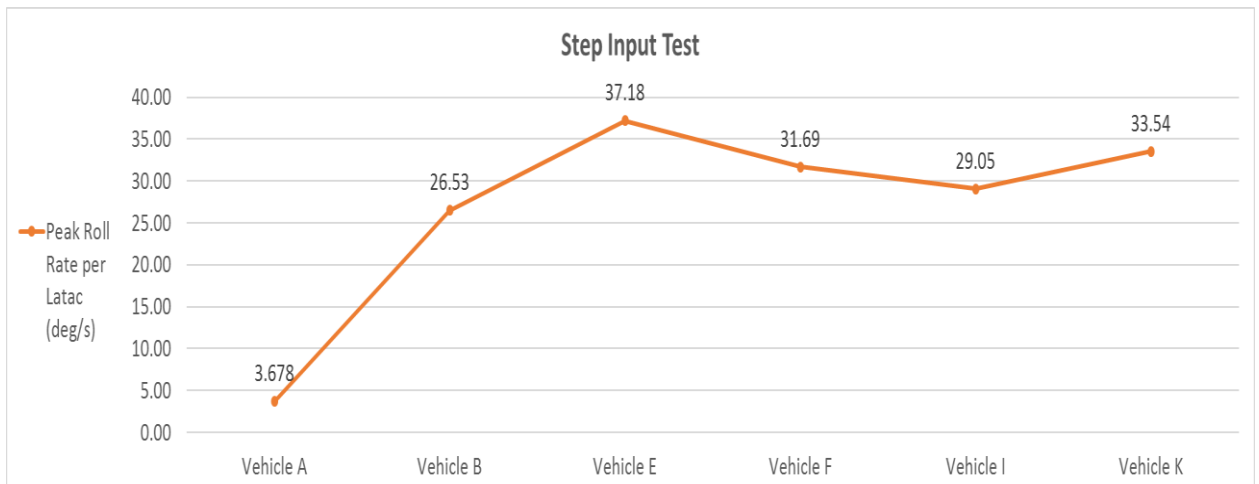


Fig. 4.3. Peak Roll Rate per Latac during Step Input Test

Roll rate was perceived extremely comfortable in Vehicle A. Thus, vehicles having Peak roll rate per latac value less than 3.678 deg/s per g will be perceived comfortable by its passengers. All the other vehicles were perceived uncomfortable by the passengers. Thus, vehicles having peak roll rate per latac more than 26.53 deg/s per g will be uncomfortable to the passengers.

4.3.3 Double Lane Change Test

Double Lane Change was performed as mentioned in the previous chapter. Passenger Discomfort caused during Double Lane Change is primarily due to rolling of the vehicle and lateral acceleration. Thus, roll angle, roll rate and lateral acceleration are mapped while performing DLC test. Typical Roll behaviour of vehicles during Double Lane Change Test is illustrated in Fig. 4.4. and Fig 4.5. using Roll Angle and Roll Rate Time Histories.

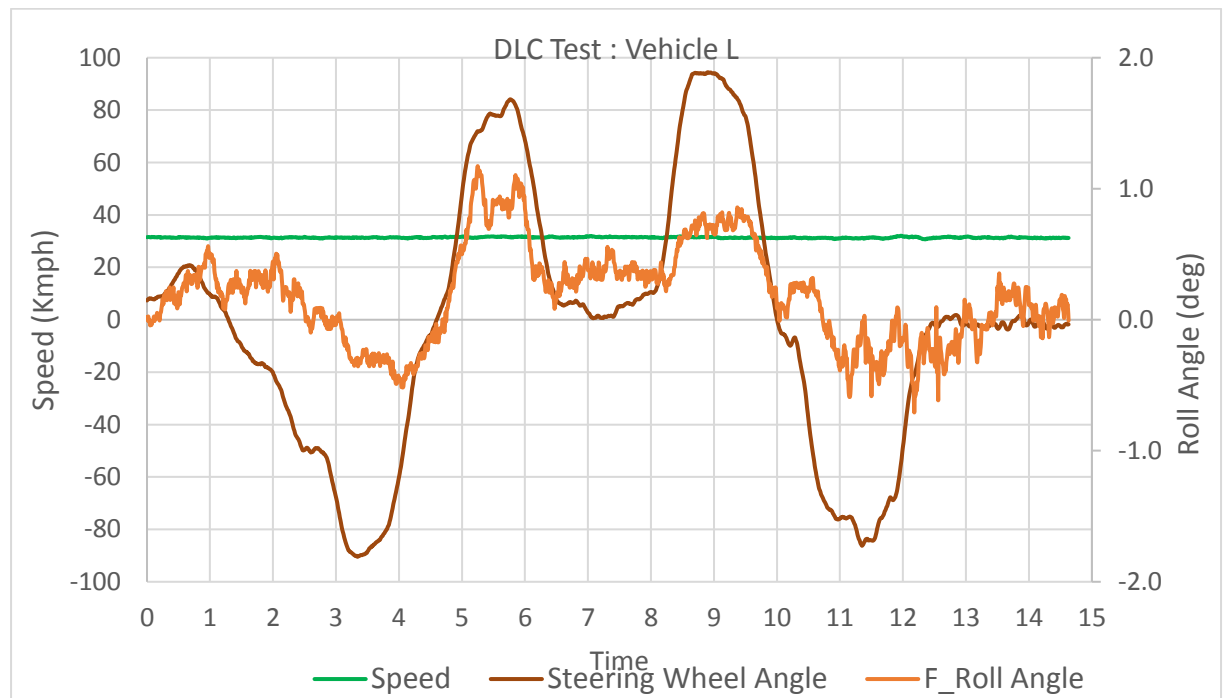


Fig. 4.4. Roll Angle Time History of Vehicle L during Double Lane Change Test

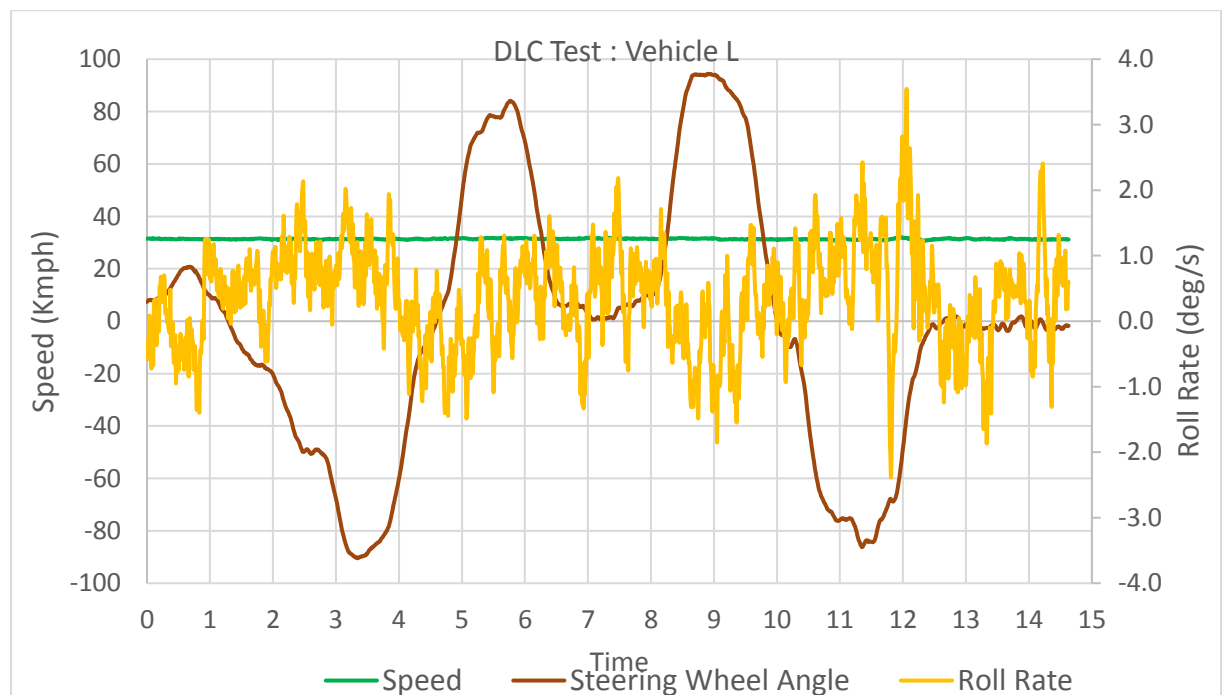


Fig. 4.5. Roll Rate Time History of Vehicle L during Double Lane Change Test

Table No. 4.3. mentions output parameters i.e. normalized peak roll angle and normalized peak roll rate achieved by the vehicles as well as subjective ratings given by test engineer during DLC test. Peak Roll Angle and Peak Roll Rate values have been normalized by maximum lateral acceleration (latac) generated during DLC Test maneuver as roll behaviour is generally directly proportional to the lateral acceleration generated inside a vehicle during a maneuver i.e. more the lateral acceleration generated, more is the roll angle.

Table 4.3. DLC Test Output Parameters & Subjective Ratings

DLC Test Output Parameters & Subjective Ratings						
Vehicle	Peak Roll Angle per latac (deg/g)	Peak Roll Rate per latac (deg/s per g)	Subjective Rating			
			Roll Angl e	Roll Rate	Roll Oscillations	Settlin g Time
Vehicle A	5.77	4.47	9	9	9	9
Vehicle B	9.46	21.96	6	7	7	7
Vehicle E	7.80	20.19	7	7.5	7.5	7.5
Vehicle F	9.77	25.44	6	6.5	7.5	7
Vehicle G	4.94	18.17	9	7	8.5	9
Vehicle H	8.20	18.71	6.5	7	8	9
Vehicle I	15.80	43.99	5	6	6	8
Vehicle J	7.63	26.38	7	6.5	6.5	7
Vehicle K	5.40	14.29	8.5	8	7	7
Vehicle L	8.62	11.29	6.5	8	8	8
Vehicle M	8.21	30.27	6.5	6	8	7
Vehicle N	7.45	13.35	7.5	8	9	9

Fig. 4.6. And Fig. 4.7. depicts the above tabular data of Peak Roll Angle per Latac and Peak Roll Rate per Latac respectively in a graphical manner for the ease of comparison between vehicles.

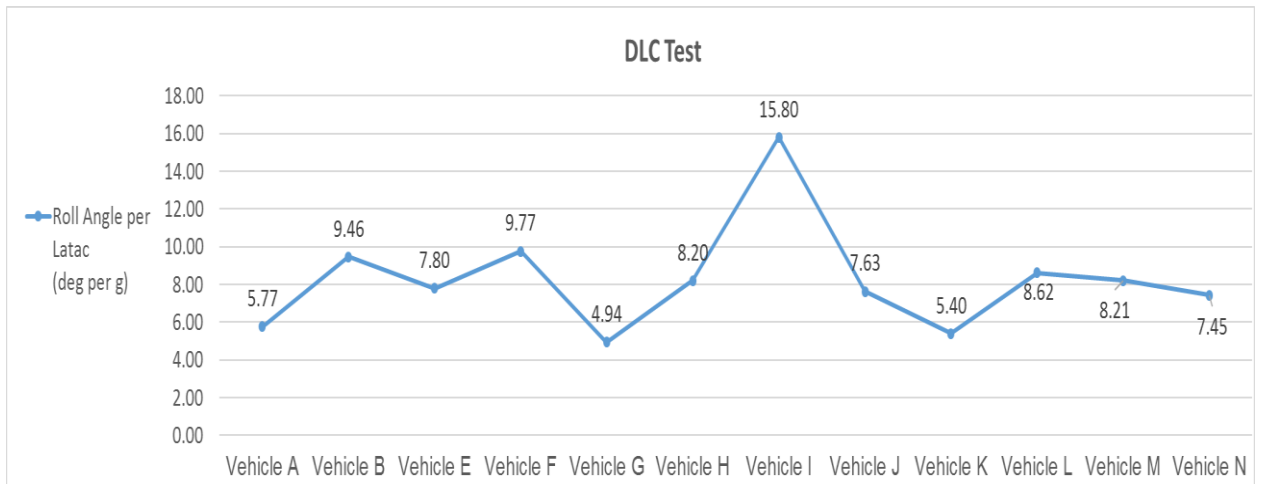


Fig. 4.6. Peak Roll Angle per Latac during DLC Test

Correlating the normalized data with the subjective ratings of test engineer and co-driver, Vehicle E had subjective rating that is acceptable by the passengers in terms of roll angle, beyond which Vehicle F had a subjective rating of barely acceptable. Vehicle I received the not acceptable subjective rating i.e. it was not comfortable at all in terms of roll angle. Therefore, a vehicle having a peak roll angle per latac higher than 9.77 deg per g will definitely be uncomfortable to the passengers whereas vehicle having a peak roll angle per latac lower than 7.45 deg per g is acceptable by the passengers during a double lane change.

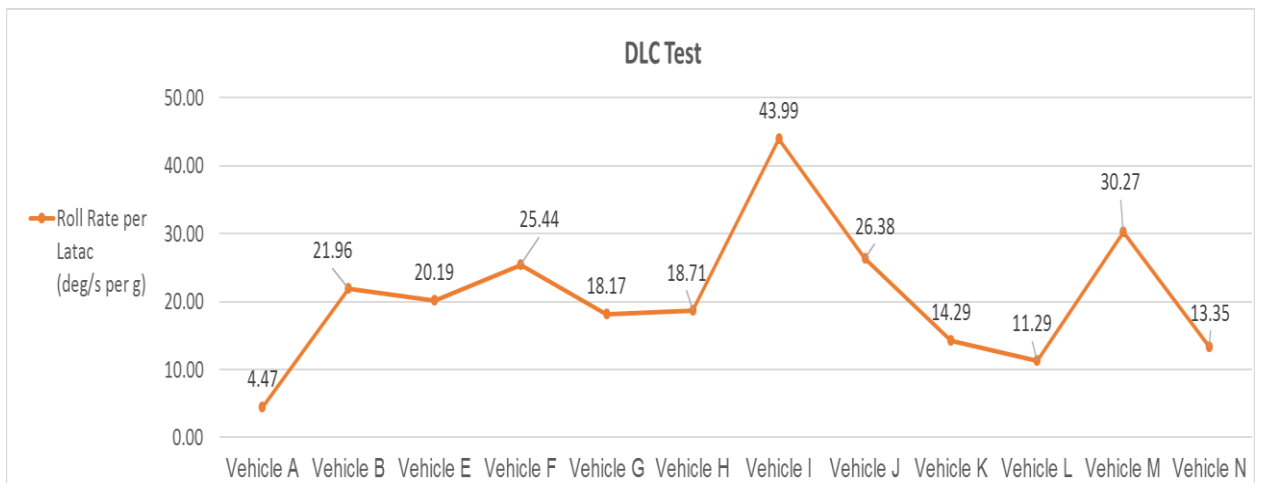


Fig. 4.7. Peak Roll Rate per Latac during DLC Test

Vehicle I was the worst case scenario in terms of roll rate as per the subjective rating and Vehicle A was the best case scenario. Vehicle B had the minimum rating to be qualified as acceptable. Vehicle G was barely acceptable in terms of roll rate. Therefore, vehicle having peak roll rate per lateral acceleration more than 25.44 deg/s per g will be uncomfortable to the passengers and vehicle having peak roll rate per lateral acceleration lower than 21.96 deg/s per g is comfortable to the passengers.

4.3.4 Dive Test

Dive Test was performed as discussed in the previous chapter on the test vehicles. Pitch Angle and Pitch Rate Time Histories of each vehicle was plotted for the evaluation of pitch damping characteristics and pitch comfort values of each vehicle. Pitch Damping characteristics are *No. of Pitch oscillations* observed post stoppage of the vehicle and *Pitch Oscillations Settling Time* i.e. Time elapsed between pitch oscillation initiation and completion of pitch oscillation after stoppage of vehicle. Pitch Comfort values are based upon Peak Pitch Angle and Peak Pitch Rate observed during the Dive Test. As an example, Pitch Angle Time History plot and Pitch Rate Time History plot of Vehicle K during Dive Test is shown below in Fig 4.8 and Fig. 4.10. respectively.

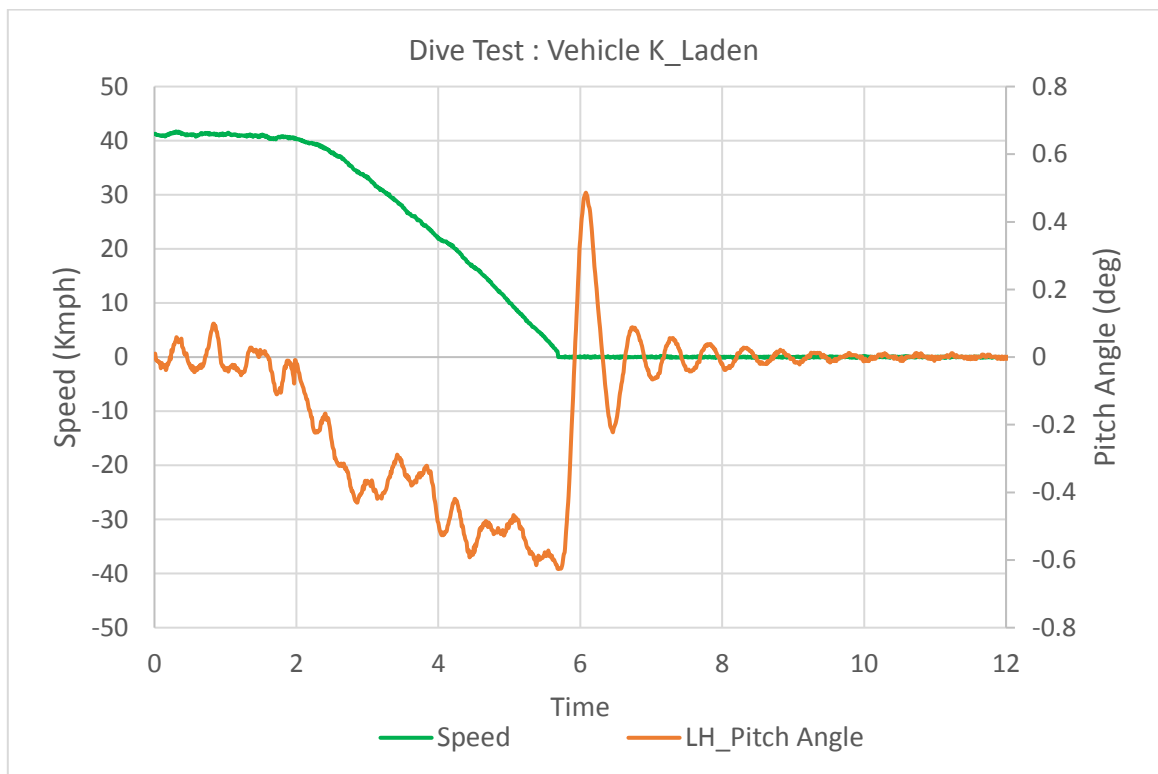


Fig. 4.8. Pitch Angle Time History of Vehicle K during Dive Test

No. of Pitch Oscillations is no. of oscillations between the point where “line representing pitch angle” crosses zero datum line first time after vehicle speed has been reduced to zero and point beyond which pitch angle oscillates between +0.02 deg and -0.02 deg and does not leave this band as depicted in Fig. 4.9.

Pitch Oscillations Settling Time is time elapsed between point where “line representing pitch angle” crosses zero datum line first time after vehicle speed has been reduced to zero and point beyond which pitch angle oscillates between +0.02 deg and -0.02 deg and does not leave this band as depicted in Fig. 4.9.

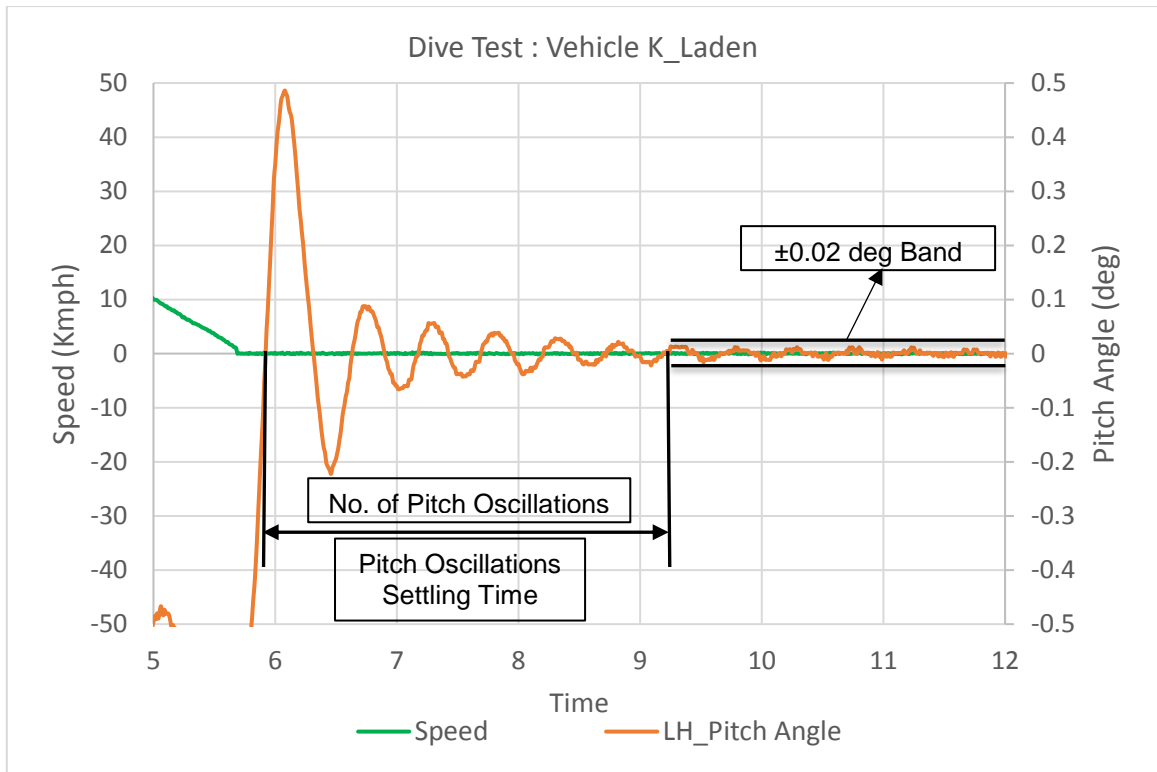


Fig. 4.9. No. of Pitch Oscillations and Pitch Oscillations Settling Time

Peak Pitch Angle, Peak Pitch Rate, No. of Pitch Oscillations and Pitch Oscillations Settling Time achieved during Dive Test is dependent upon the braking intensity/brake pedal effort. Tests were conducted while trying to maintain the pedal effort at 15 kg but the rate of applying the brake differed even if the constant pedal effort of 15 kg could be maintained by test engineer. Thus, Peak Pitch Angle, Peak Pitch Rate, No. of Pitch Oscillations and Pitch Oscillations Settling Time were tabulated and normalized with vehicle deceleration i.e. rate of deceleration of vehicle.

$$\text{Vehicle Deceleration} = \frac{\text{Constant Vehicle Speed before Braking}}{\text{Time Taken by vehicle to stop}}$$

Typical Pitch Rate Time History of a vehicle during Dive Test is shown in Fig. 4.10. using the Pitch Rate Time History of Vehicle K.

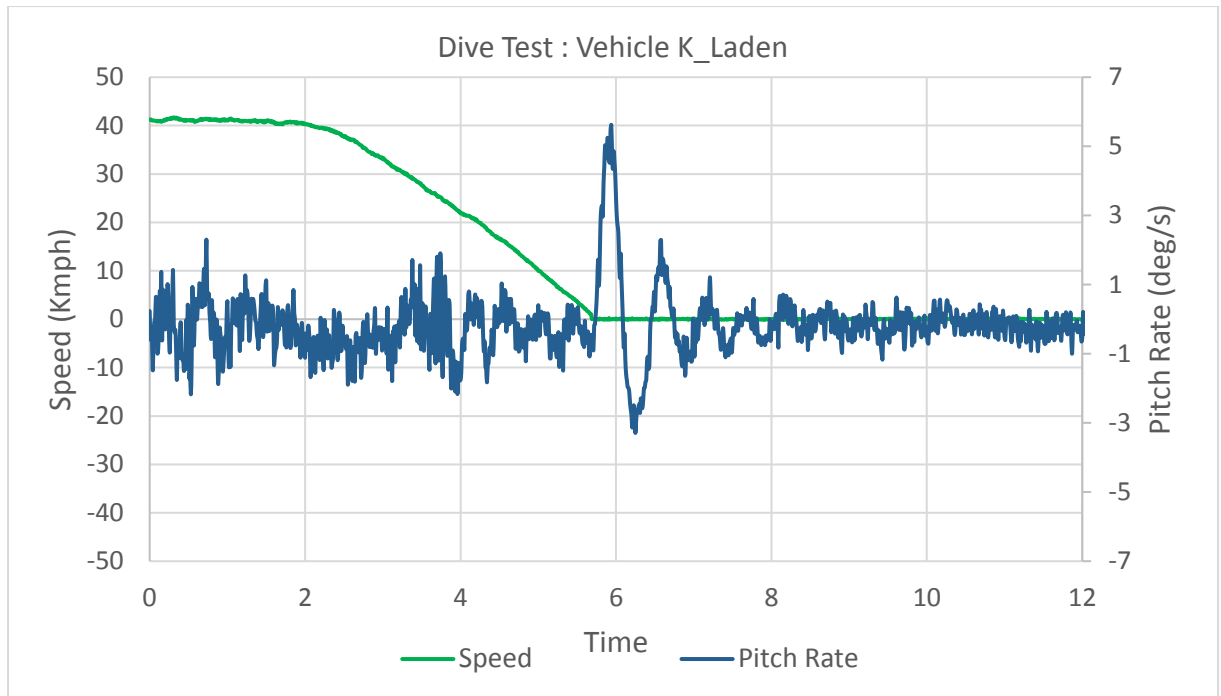


Fig. 4.10. Pitch Rate Time History of Vehicle K during Dive Test

Table 4.4. mentions the values of Pitch Angle per Deceleration, Peak Pitch Rate per Deceleration, No. of Pitch Oscillations per Deceleration and Pitch Oscillations Settling Time per Deceleration for all of the vehicles tested. Table 4.5 mentions the subjective ratings of pitch angle, pitch rate, no. of pitch oscillations and settling time of pitch oscillations during dive test.

Table 4.4. Dive Test Output Parameters

Dive Test: Output Parameters				
Vehicle	Peak Pitch Angle per Deceleration (deg per m/s²)	Peak Pitch Rate per Deceleration (deg/s per m/s²)	No. of Oscillations per Deceleration (per m/s²)	Settling Time per Deceleration (sec per m/s²)
Vehicle A	0.49	2.88	1.05	0.60
Vehicle B	0.25	1.81	0.56	0.45
Vehicle C	0.12	1.65	0.59	0.31
Vehicle D	0.45	3.74	1.58	1.29
Vehicle E	0.20	1.70	0.88	0.44
Vehicle F	0.18	1.08	1.57	0.70
Vehicle G	0.20	1.92	1.52	0.70
Vehicle H	0.18	1.59	1.27	0.62
Vehicle I	0.25	1.51	1.86	1.47
Vehicle J	0.19	1.54	1.55	0.82
Vehicle K	0.23	1.90	1.69	0.94
Vehicle L	0.18	1.14	1.52	0.86
Vehicle M	0.12	1.21	2.32	1.39
Vehicle N	0.13	0.86	1.32	0.73

Table 4.5. Dive Test Subjective Ratings

Dive Test: Subjective Ratings				
Vehicle	Pitch Angle	Pitch Rate	Pitch Oscillations	Settling Time
Vehicle A	5	5	8	8
Vehicle B	6	6	9	8
Vehicle C	7	6	9	9
Vehicle D	5	5	6.5	6
Vehicle E	8	5	8	8
Vehicle F	7	8	7	7
Vehicle G	7	5.5	7	7
Vehicle H	7	6	7	7
Vehicle I	6.5	5	6	5
Vehicle J	7	6	7	7
Vehicle K	6.5	6	6	7
Vehicle L	7	7	7	7
Vehicle M	7	6	5	5
Vehicle N	7	5	8	8

Fig. 4.11. and Fig. 4.12. are the graphical representation of Pitch Comfort parameters i.e. Peak Pitch Angle per Deceleration and Peak Pitch Rate per Deceleration respectively.

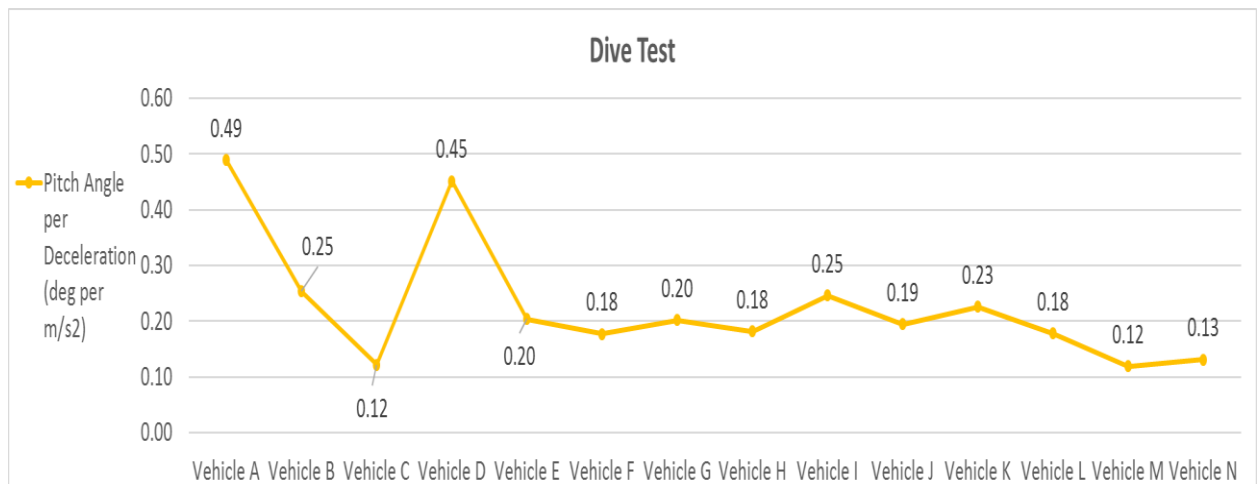


Fig. 4.11. Peak Pitch Angle per Deceleration of vehicle during Dive Test

Upon Correlation of the above obtained vehicle data with the subjective ratings, it was found that vehicles having Peak Pitch Angle per Deceleration of the vehicle below 0.25 deg per m/s² was borderline acceptable to the passengers i.e. vehicle having Peak Pitch Angle per Deceleration higher than 0.25 deg/m² caused discomfort to passengers.

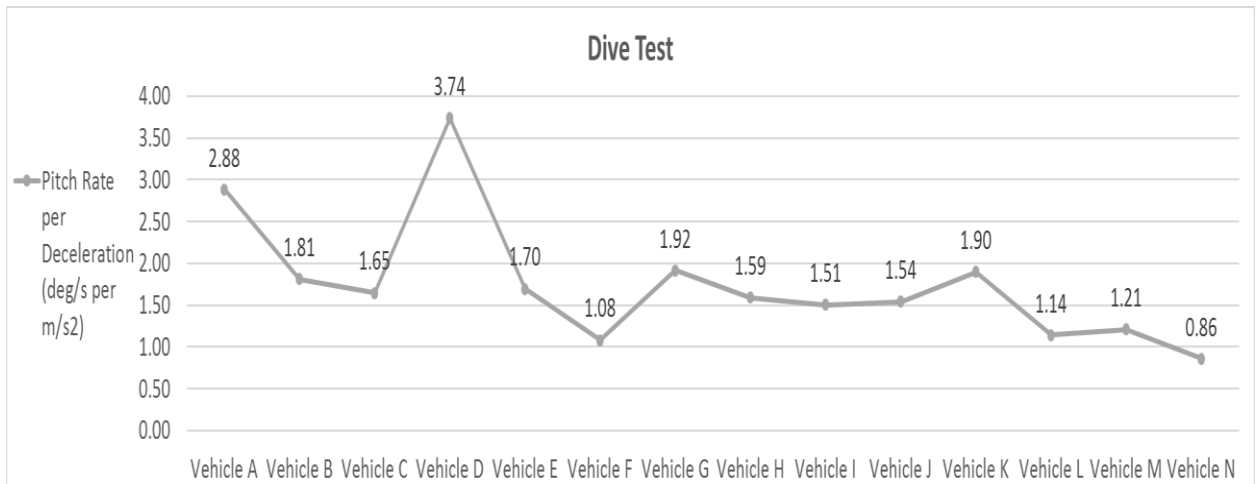


Fig. 4.12. Peak Pitch Rate per Deceleration of vehicle during Dive Test

Vehicles having Peak Pitch Rate per Deceleration of 1.14 deg/s per m/s² was found acceptable by the passengers. Vehicles having Peak Pitch Rate per Deceleration more than 1.92 deg/s per m/s² was not at all acceptable to the passengers.

No. of Pitch Oscillations per Deceleration and Pitch Oscillations Settling Time per Deceleration values have been represented in Fig. 4.13 and Fig. 4.14 respectively.

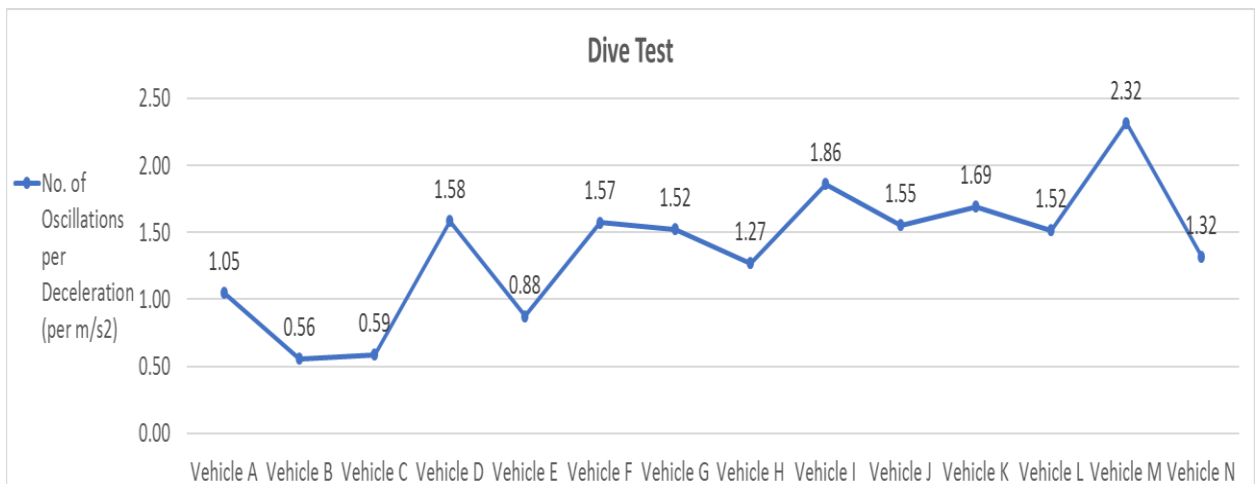


Fig. 4.13. No. of Pitch Oscillations per Deceleration of vehicles during Dive Test

In terms of No. of Pitch Oscillations per Deceleration of vehicle, vehicles having Pitch Oscillation per Deceleration more than 1.86 per m/s² are definitely perceivable by the passengers and caused discomfort to passengers. Vehicle D having No. of Pitch Oscillation per Deceleration equal to 1.58 per m/s² was also perceivable by passengers and caused mild discomfort to the passengers. Vehicle having good subjective rating with highest No. of Pitch Oscillations per Deceleration equal to 1.32 per m/s² is Vehicle N. Thus, vehicles having No. of Pitch Oscillation per Deceleration less than 1.32 per m/s² caused no perceivable discomfort to the passengers.

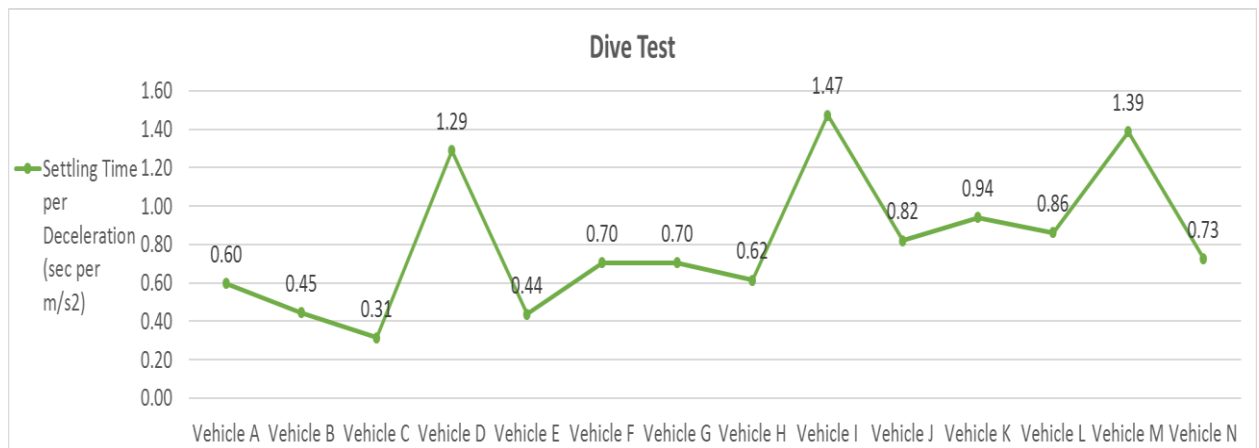


Fig. 4.14. Pitch Oscillations Settling Time per Deceleration of vehicles during Dive Test

Vehicle K having Pitch Oscillations Settling Time per Deceleration of 0.94 seconds per m/s² was acceptable to the passengers. Thus, vehicles having Pitch Oscillations Settling Time Per Deceleration less than 0.94 seconds per m/s² will be acceptable to the passengers. Least value of Pitch Oscillation Settling Time per Deceleration was 1.29 seconds per m/s² which was unacceptable to passengers.

In Dive Test, No. of Pitch Oscillations per Deceleration and Pitch Oscillations Settling Time per Decelerations data collected could be perfectly correlated with the subjective ratings of test engineer and co-driver. Thus, Dive Test can be used for characterization of Pitch Damping Characteristics of a vehicle and is thus validated for this purpose.

4.3.5 Squat Test

Squat Test was performed as discussed in the previous chapter on test vehicles. Pitch Angle and Pitch Rate Time Histories of each vehicle was plotted for the evaluation of pitch damping characteristics and pitch comfort values of each vehicle. Pitch Damping Characteristics and Pitch Comfort values are evaluated similarly as in Dive Test. Typical Pitch Angle and Pitch Rate Time History during Squat Test is shown below in Fig. 4.15. And Fig. 4.16.

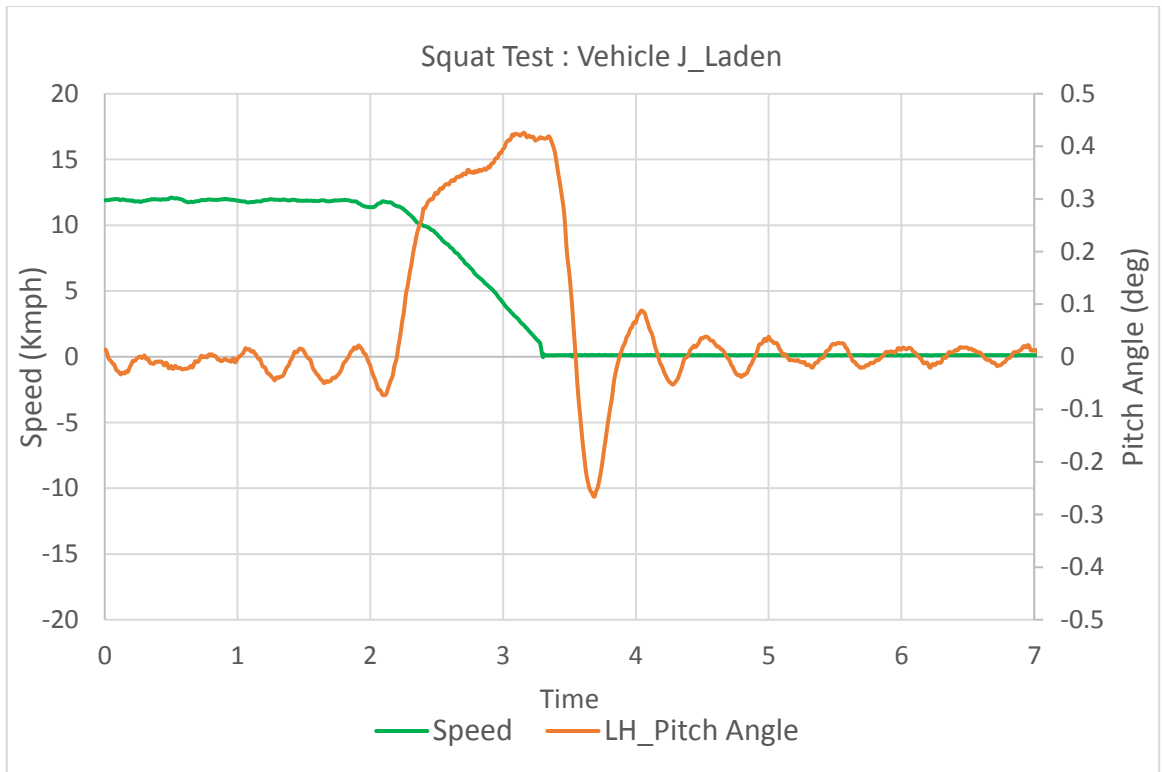


Fig. 4.15. Pitch Angle Time History of Vehicle J during Squat Test

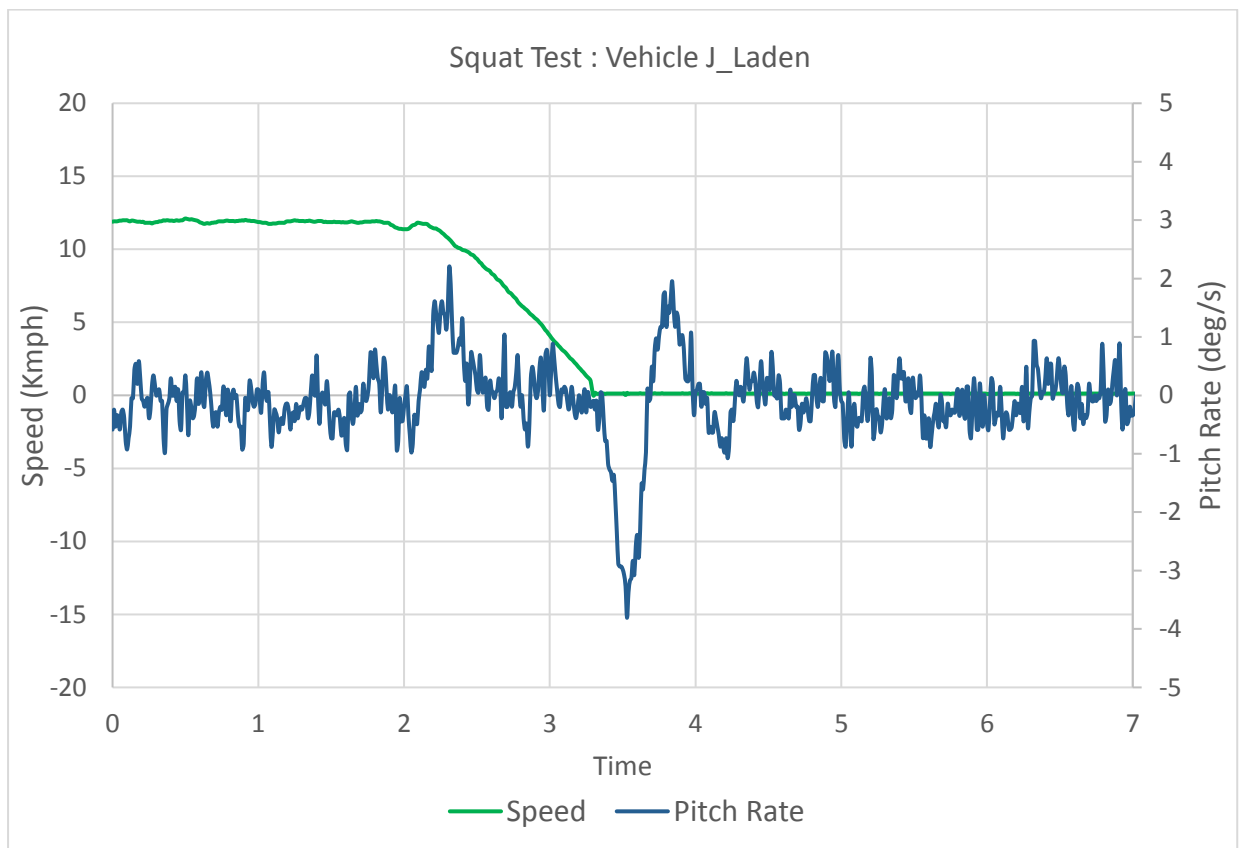


Fig. 4.16. Pitch Rate Time History of Vehicle J during Squat Test

No. of Pitch Oscillations, Pitch Oscillations Settling Time and Vehicle Deceleration are calculated similarly as in the *Dive Test*. Peak Pitch Angle, Peak Pitch Rate, No. of Pitch

Oscillations, and Pitch Oscillations Settling Time is tabulated and normalized similarly as in Dive Test using Vehicle Deceleration.

Table 4.6. mentions Pitch Angle per Deceleration, Peak Pitch Rate per Deceleration, No. of Pitch Oscillations per Deceleration and Pitch Oscillations Settling Time per Deceleration achieved by test vehicles during Squat Test.

Table 4.7 mentions subjective ratings of pitch angle, pitch rate, no. of pitch oscillations and settling time during squat test of all the vehicles.

Table No. 4.6. Squat Test Output Parameters

Squat Test Output Parameters				
Vehicle	Peak Pitch Angle per Deceleration (deg per m/s²)	Peak Pitch Rate per Deceleration (deg/s per m/s²)	No. of Oscillations per Deceleration (per m/s²)	Settling Time per Deceleration (sec per m/s²)
Vehicle A	0.733	3.913	1.23	0.69
Vehicle B	0.317	2.129	0.85	0.65
Vehicle C	0.183	3.062	1.45	0.76
Vehicle D	0.841	4.325	1.99	1.58
Vehicle E	0.196	1.366	1.40	0.65
Vehicle F	0.182	0.892	1.07	0.45
Vehicle G	0.224	1.844	0.64	0.36
Vehicle H	0.352	1.824	1.65	0.82
Vehicle I	0.242	1.789	1.81	1.46
Vehicle J	0.213	1.695	2.22	1.15
Vehicle L	0.318	1.968	1.75	1.09
Vehicle M	0.143	2.312	2.11	1.24
Vehicle N	0.218	1.309	1.38	0.86

Table 4.7 Squat Test Subjective Ratings

Squat Test Subjective Ratings				
Vehicle	Subjective Rating			
	Pitch Angle	Pitch Rate	Pitch Oscillations	Settling Time
Vehicle A	5	5	7	8
Vehicle B	8	5	8	8
Vehicle C	9	5	6	8
Vehicle D	4	3	5	5.5
Vehicle E	7.5	7.5	7	8
Vehicle F	8	8.5	8	8
Vehicle G	7	5	9	9
Vehicle H	6	5	6	8
Vehicle I	7	6	6	6
Vehicle J	8	6	5	7
Vehicle L	6	6	6	7
Vehicle M	8	5	6	6
Vehicle N	8	6	7	8

Peak Pitch Angle per Deceleration and Peak Pitch Rate per Deceleration of various vehicles have been illustrated in Fig. 4.17. and Fig. 4.18. respectively.

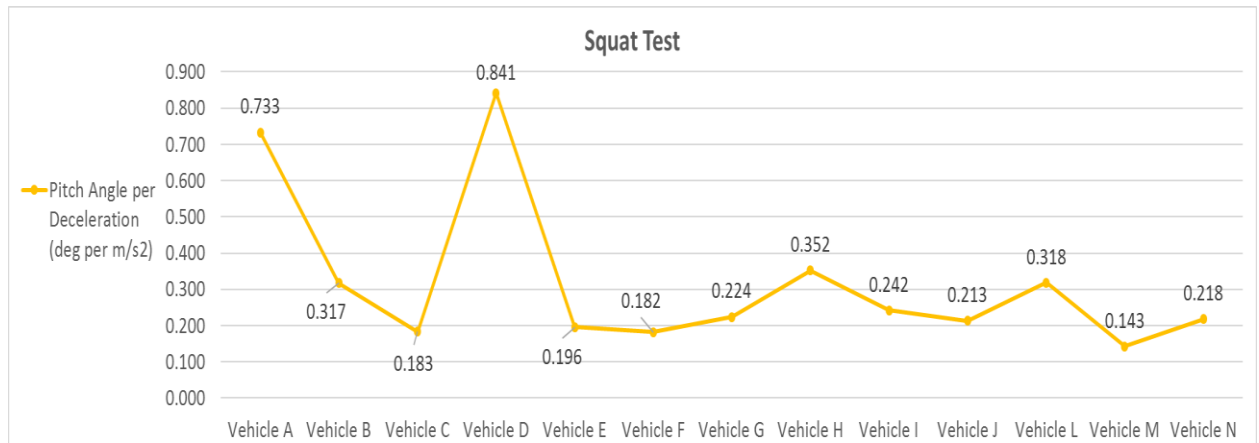


Fig. 4.17. Peak Pitch Angle per Deceleration of vehicle during Squat Test

Vehicle I had highest Peak Pitch Angle per Deceleration value amongst all the vehicles that were acceptable to the test engineer and co-driver. Thus, vehicle having Peak Pitch Angle per Deceleration value lower than 0.242 deg per m/s² will be comfortable to the passengers.

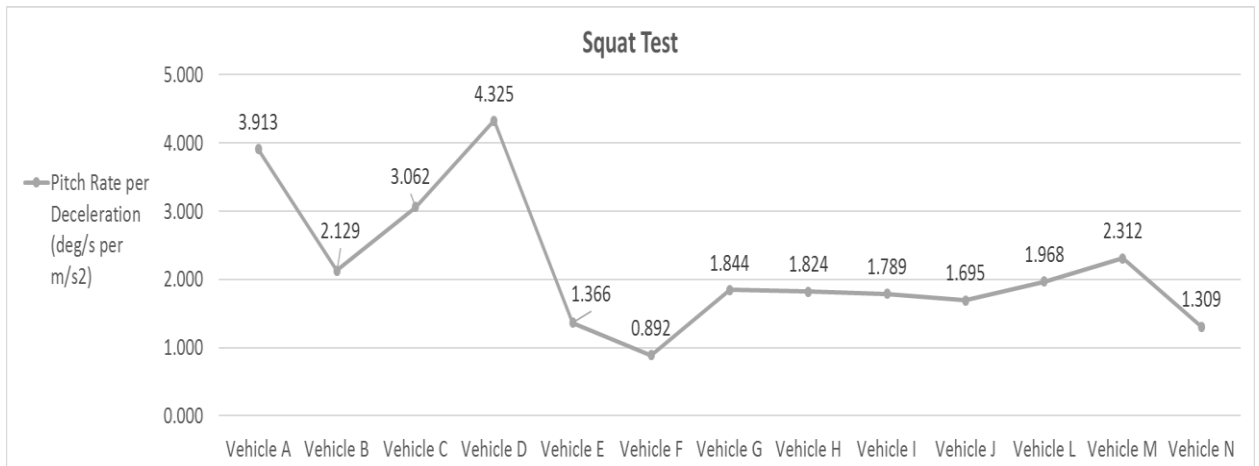


Fig. 4.18. Peak Pitch Rate per Deceleration of vehicle during Squat Test

Least barely acceptable value of Peak Pitch Rate per Deceleration of vehicle was 1.695 deg/s per m/s². Thus, vehicles having Peak Pitch Rate per Deceleration more than 1.695 per m/s² will cause discomfort to the passengers. Max. Value of Peak Pitch Rate per Deceleration at which passengers were comfortable was 1.366 deg/s per m/s². Thus, vehicles having Peak Pitch Rate per Deceleration less than 1.366 per m/s² will cause no discomfort to the passengers.

No. of Pitch Oscillations per Deceleration and Pitch Oscillations Settling Time per Deceleration values have been represented in Fig. 4.19 and Fig. 4.20 respectively.

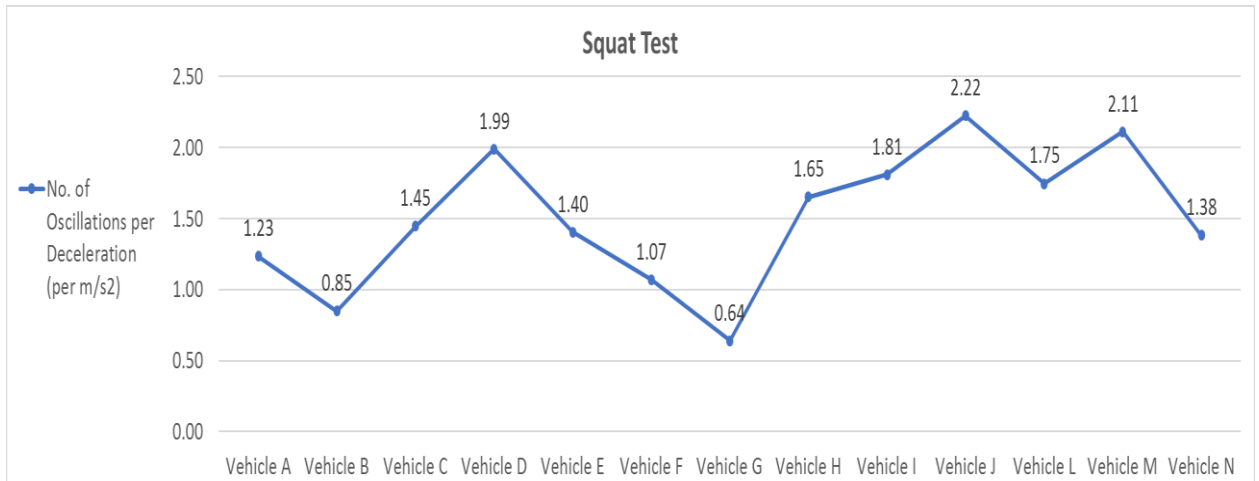


Fig. 4.19. No. of Pitch Oscillations per Deceleration of vehicles during Squat Test

Highest No. of Pitch Oscillations per Deceleration of vehicles acceptable to the passengers was 1.40 per m/s² and the least No. of Pitch Oscillations per Deceleration value that caused definite discomfort to the passenger was 1.99 per m/s² during Squat Test.

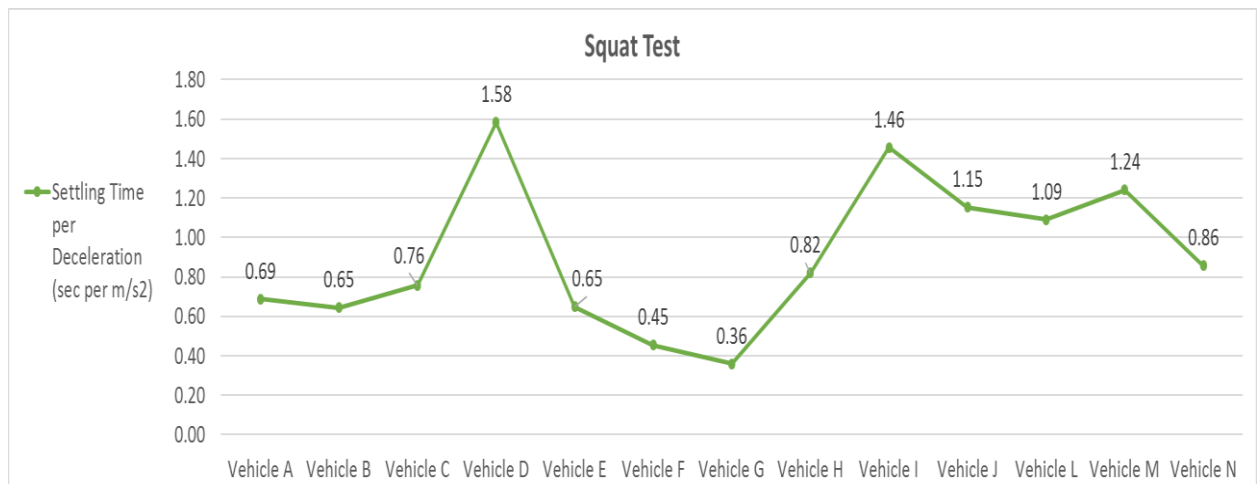


Fig. 4.20. Pitch Oscillations Settling Time per Deceleration of vehicles during Dive Test

Highest value of Pitch Oscillations Settling Time per Deceleration where passengers were comfortable is 1.15 seconds per m/s². Thus, vehicles having Pitch Oscillations Settling Time per Deceleration less than 1.15 seconds per m/s² would cause no perceivable discomfort to the passengers. Least value of Pitch Oscillations Settling Time per Deceleration that caused perceivable discomfort to the passengers was 1.46 seconds per m/s².

In Squat Test, No. of Pitch Oscillations per Deceleration, Pitch Oscillations Settling Time and Peak Pitch Angle per Deceleration data perfectly correlated with the subjective ratings given by test engineer and co-driver. Thus, Squat Test is validated for characterization of Pitch Damping and Pitch Comfort Characteristics.

4.3.6 Single Speed Bump Test

Single Speed Bump Test was performed as discussed in the previous chapter on test vehicles. Pitch Angle and Pitch Rate Time Histories of each vehicle was plotted for the evaluation of pitch damping characteristics and pitch comfort values of each vehicle. Pitch Comfort values are evaluated similarly as in Dive Test. Typical Pitch Angle and Pitch Rate Time History during Squat Test is shown below in Fig. 4.21. And Fig. 4.22.

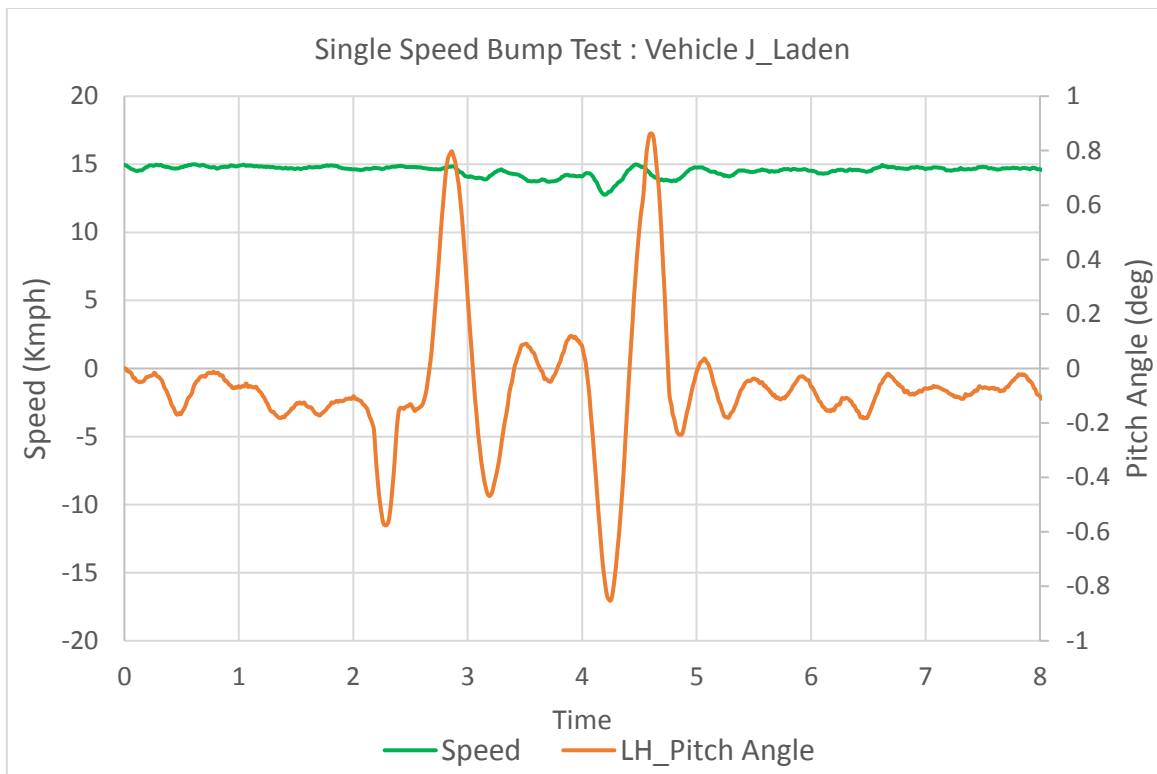


Fig. 4.21. Pitch Angle Time History of Vehicle J during Single Speed Bump Test

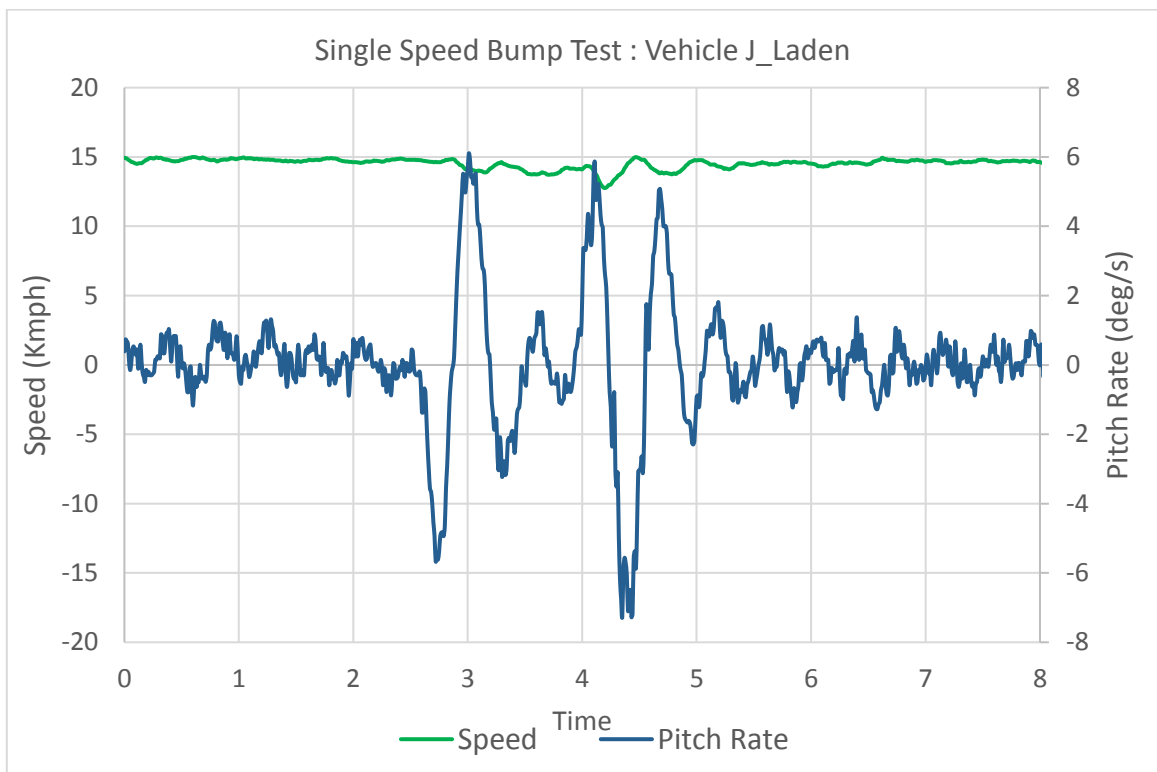


Fig. 4.22. Pitch Rate Time History of Vehicle J during Single Speed Bump Test

Peak Pitch Angle and Peak Pitch Rate achieved during Single Speed Bump is dependent upon the vehicle speed while negotiating the speed bump. Thus, Peak Pitch Angle and Peak Pitch Rate values achieved during Single Speed Bump Test are normalized by vehicle speed while negotiating the speed bump. Since these values were very small, they were multiplied by a

factor of 100 to achieve Peak Pitch Angle and Peak Pitch Rate value per 100 kmph. Objective values and subjective ratings obtained during single speed bump test are mentioned in the Table 4.8.

Table 4.8. Single Speed Bump Test Output Parameters & Subjective Ratings

Single Speed Bump Test				
Vehicle	Pitch Angle per Vehicle Speed (deg per 100 kmph)	Pitch Rate per Vehicle Speed (deg/s per 100 kmph)	Subjective Rating	
			Pitch Angle	Pitch Rate
Vehicle A	27.80	201.40	5	4
Vehicle B	6.41	53.02	9	7
Vehicle C	8.24	103.37	8	5
Vehicle D	16.07	105.59	6	5
Vehicle E	11.74	125.68	7	4.5
Vehicle F	6.37	41.14	9	8.5
Vehicle G	11.36	99.65	7	5
Vehicle H	11.33	111.96	7	5.5
Vehicle I	8.34	44.89	8	8
Vehicle J	6.82	49.19	9	8
Vehicle K	8.85	69.32	8	7
Vehicle L	20.40	97.92	5	6
Vehicle M	12.47	79.22	5.5	6.5
Vehicle N	3.71	27.32	8	7

Fig. 4.23. and Fig. 4.24. illustrates the Peak Pitch Angle per Vehicle Speed and Peak Pitch Rate per Vehicle Speed for various vehicles tested using single speed bump test respectively.

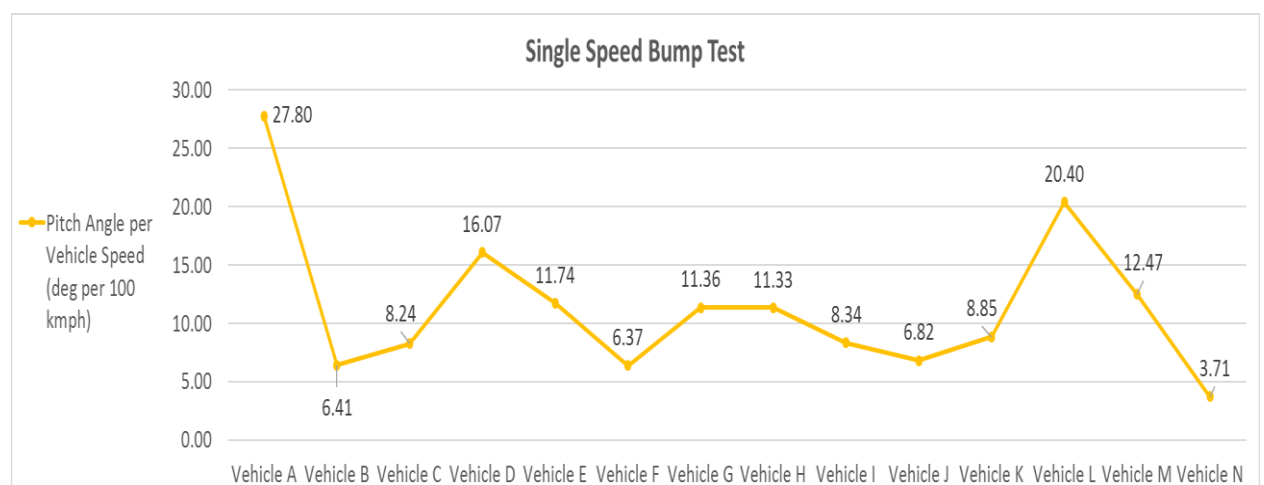


Fig. 4.23. Peak Pitch Angle per Vehicle Speed during Single Speed Bump Test

Vehicle E has the highest acceptable value of Peak Pitch Angle per Vehicle Speed, which did not cause any discomfort to the passengers. Thus, vehicles having Peak Pitch Angle per Vehicle Speed value less than 11.74 deg per 100 kmph during Single Speed Bump Test will cause no discomfort to the passengers. Least value of Peak Pitch Angle per Vehicle Speed which was barely acceptable to the passengers is 16.07 deg per 100 kmph. Thus, vehicles having Peak Pitch Angle per Vehicle Speed more than 16.07 deg per 100 kmph will cause definite discomfort to the passengers.

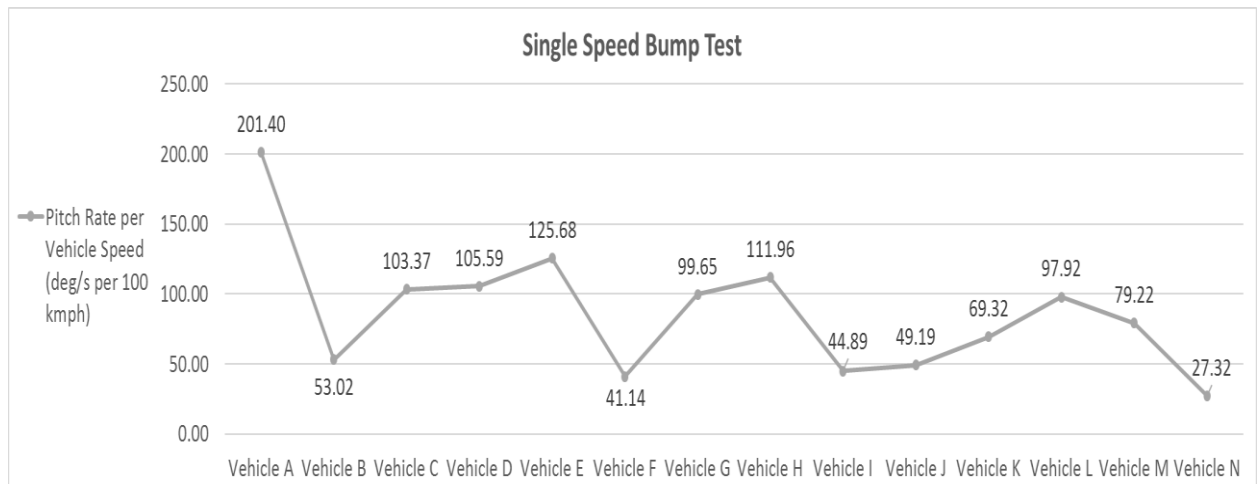


Fig. 4.24. Peak Pitch Rate per Vehicle Speed during Single Speed Bump Test

Vehicle K has the highest Peak Pitch Rate per Vehicle Speed value which was acceptable to the passengers. Thus, vehicles having Peak Pitch Rate per Vehicle Speed value less than 69.32 deg/s per 100 kmph will be comfortable to the passengers. Least value of Peak Pitch Rate per Vehicle Speed which was found to uncomfortable by the passengers was 97.92 deg/s per 100 kmph. Thus, vehicles having Peak Pitch Rate per Vehicle Speed more than 97.92 deg/s per 100 kmph will be perceived as uncomfortable by the passengers.

Peak Pitch Angle per Vehicle Speed and Peak Pitch Rate per Vehicle Speed values achieved during Single Speed Bump Test proved to be a great indicative of the passenger discomfort.

4.3.7 Straight Line Test

Straight Line Test was conducted as explained in previous chapter on test vehicles so as to evaluate and characterize a vehicle's roll and pitch behavior when travelling on a smooth road at a constant speed without any steering input, which is the condition on highways. Typical roll and pitch behavior of a vehicle during Straight Line Test is illustrated below using Roll Angle Time History, Roll Rate Time History, Pitch Angle Time History, Pitch Rate Time History in Fig. 4.25, Fig. 4.26, Fig. 4.27. and Fig. 4.28. respectively. Same patch of road was

used for the purpose of objectivity during Straight Line Test i.e. Data Logging Starting Point is always kept same and Data Logging is stopped after 25 seconds each time and data was analyzed of the first 20 seconds. Vehicle must achieve constant speed of 40 kmph well before the Data Logging Starting Point.

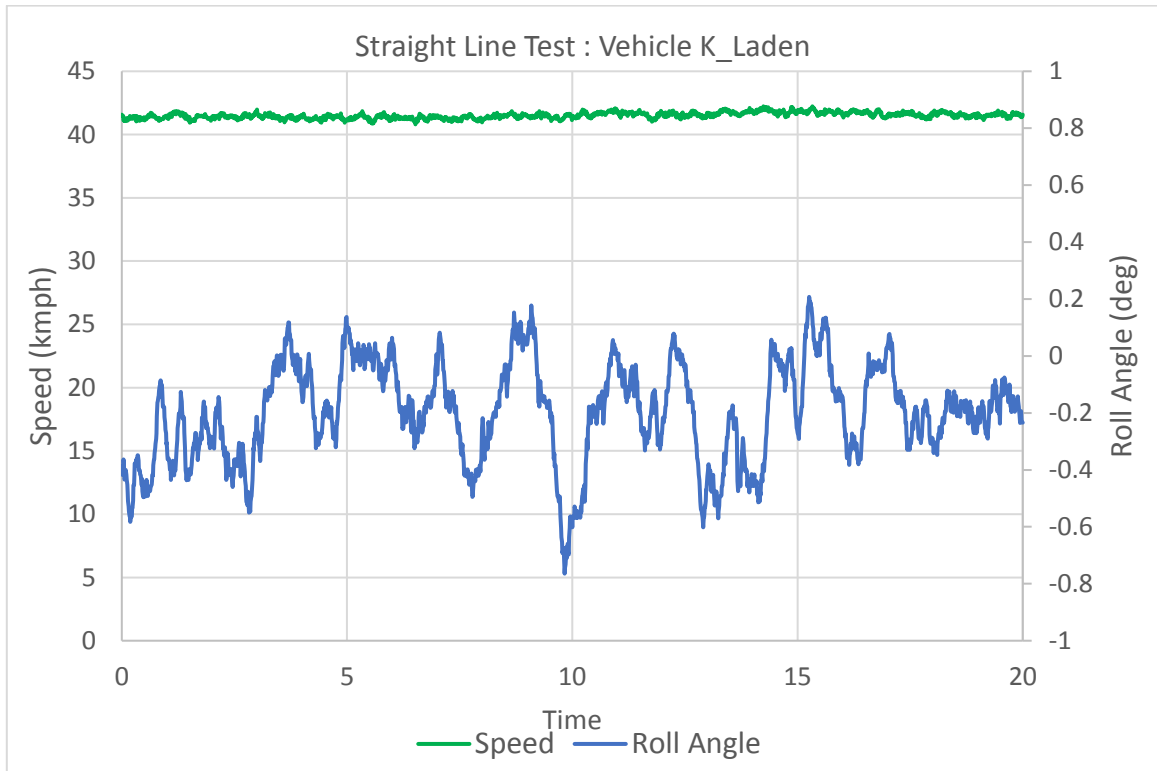


Fig. 4.25. Roll Angle Time History of Vehicle K during Straight Line Test

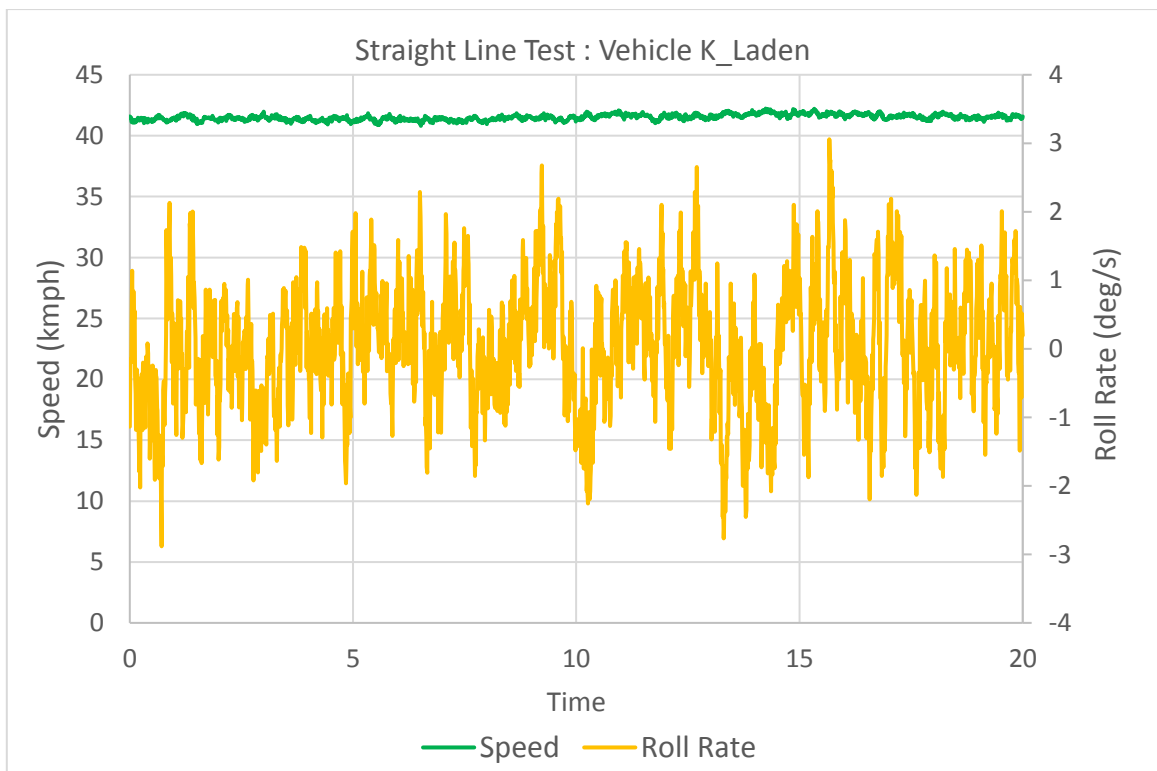


Fig. 4.26. Roll Rate Time History of Vehicle K during Straight Line Test

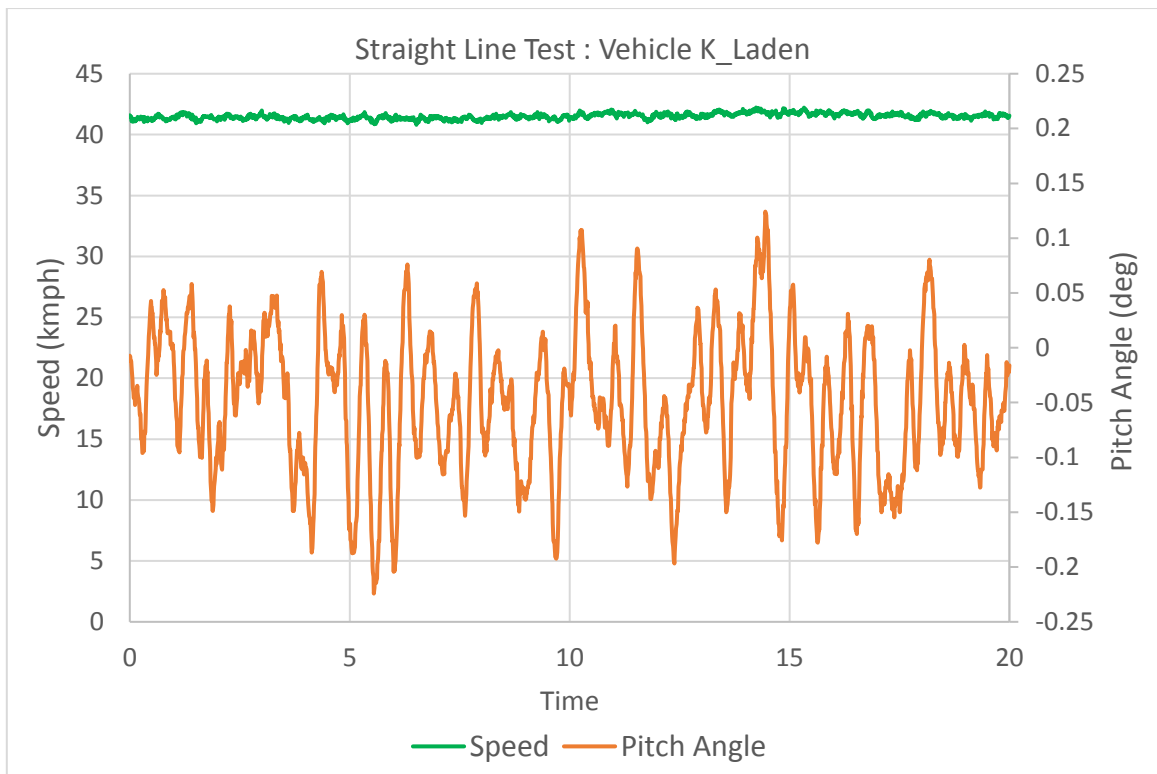


Fig. 4.27. Pitch Angle Time History of Vehicle K during Straight Line Test

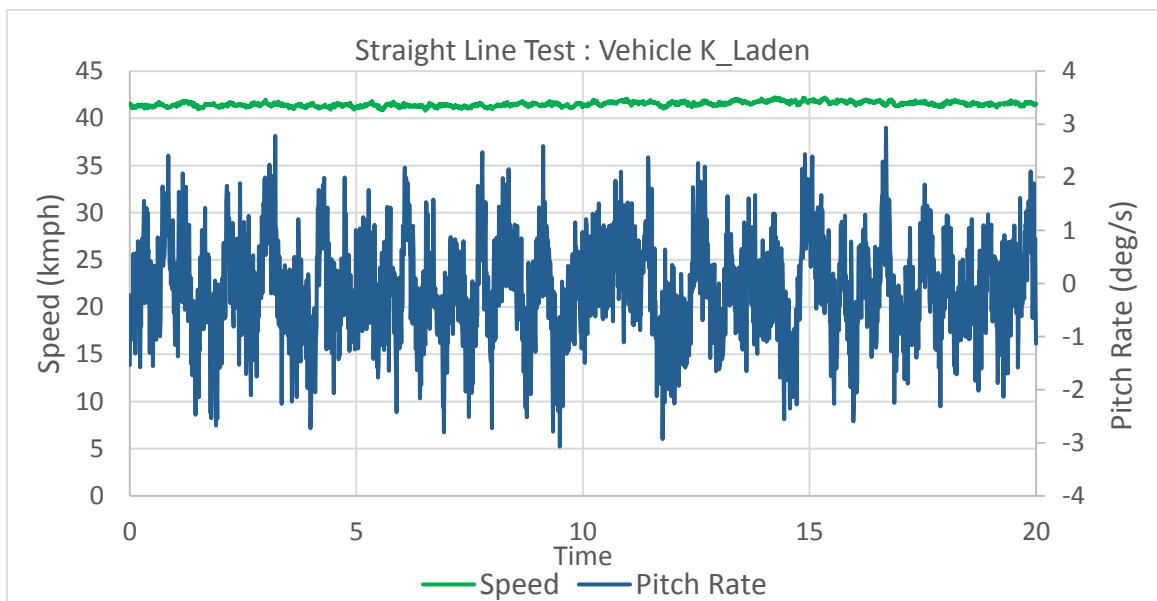


Fig. 4.28. Pitch Rate Time History of Vehicle K during Straight Line Test

Table 4.9 shows the Peak Roll Angle, Peak Roll Rate, Peak Pitch Angle and Peak Pitch Rate of 14 vehicles tested via Straight Line Test maneuver. Peak Roll Angle, Peak Roll Rate, Peak Pitch Angle and Peak Pitch Rate values have been normalized by max vehicle speed as vehicle speed influences the below-mentioned values when vehicle is travelling on a smooth road in a straight line. Since values obtained after normalization were very small, they have also been multiplied by a factor of 100.

Table No. 4.9. Straight Line Test Output Parameters

Straight Line Test				
Vehicle	Peak Roll Angle per Vehicle Speed (deg per 100 kmph)	Peak Roll Rate per Vehicle Speed (deg/s per 100 kmph)	Pitch Angle per Vehicle Speed (deg per 100 kmph)	Pitch Rate per Vehicle Speed (deg/s per 100 kmph)
Vehicle A	0.283	0.363	0.294	3.416
Vehicle B	1.895	2.446	0.460	1.751
Vehicle C	0.240	2.276	0.193	1.954
Vehicle D	0.684	2.263	0.086	1.426
Vehicle E	2.193	6.493	0.234	1.937
Vehicle F	0.889	2.540	0.194	1.399
Vehicle G	0.534	2.298	0.236	1.716
Vehicle H	0.557	2.470	0.199	1.758
Vehicle I	1.797	2.733	0.266	1.702
Vehicle J	0.761	1.905	0.243	1.323
Vehicle K	0.637	2.181	0.23	2.31
Vehicle L	1.437	2.479	0.163	1.864
Vehicle M	0.623	2.616	0.390	3.078
Vehicle N	0.613	2.055	0.219	1.858

Table 4.10 shows the subjective ratings of roll angle, roll rate, pitch angle and pitch rate obtained during straight line test.

Table 4.10. Straight Line Test Subjective Ratings

Straight Line Test				
Vehicle	Subjective Rating			
	Roll Angle	Roll Rate	Pitch Angle	Pitch Rate
Vehicle A	8	9	8	8
Vehicle B	5	8	7	8
Vehicle C	8	8	8	8
Vehicle D	7	8	9	9
Vehicle E	4	5	7	7
Vehicle F	7	8	8	9
Vehicle G	8	8	8	8
Vehicle H	8	8	8	8
Vehicle I	5	7	7	8
Vehicle J	7.5	8	8	9
Vehicle K	8	8	8	8
Vehicle L	6	8	8	8
Vehicle M	7	8	6	8
Vehicle N	7	8	6	6

Fig. 4.29. and Fig. 4.30. illustrates the Peak Roll Angle per Vehicle Speed and Peak Roll Rate per Vehicle Speed for various vehicles which underwent straight line test respectively.

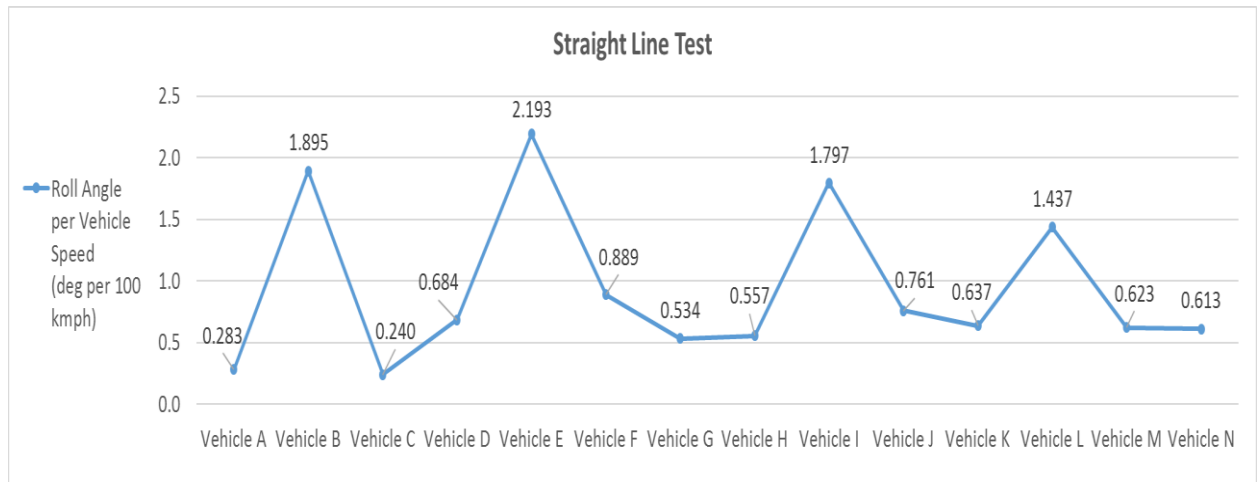


Fig. 4.29. Peak Roll Angle per Vehicle Speed during Straight Line Test

Vehicle Roll was perceivable by test engineer and co-driver in vehicle L. All the vehicles having Peak Roll Angle per Vehicle Speed less than 0.889 deg per 100 kmph had no perceivable roll. Thus, vehicles driving in straight line and having Peak Roll Angle per Vehicle Speed less than 0.889 deg per 100 kmph will be absolutely comfortable to the passengers. All vehicles having peak roll angle per vehicle speed more than 1.437 deg per 100 kmph will cause definite discomfort to its passengers.

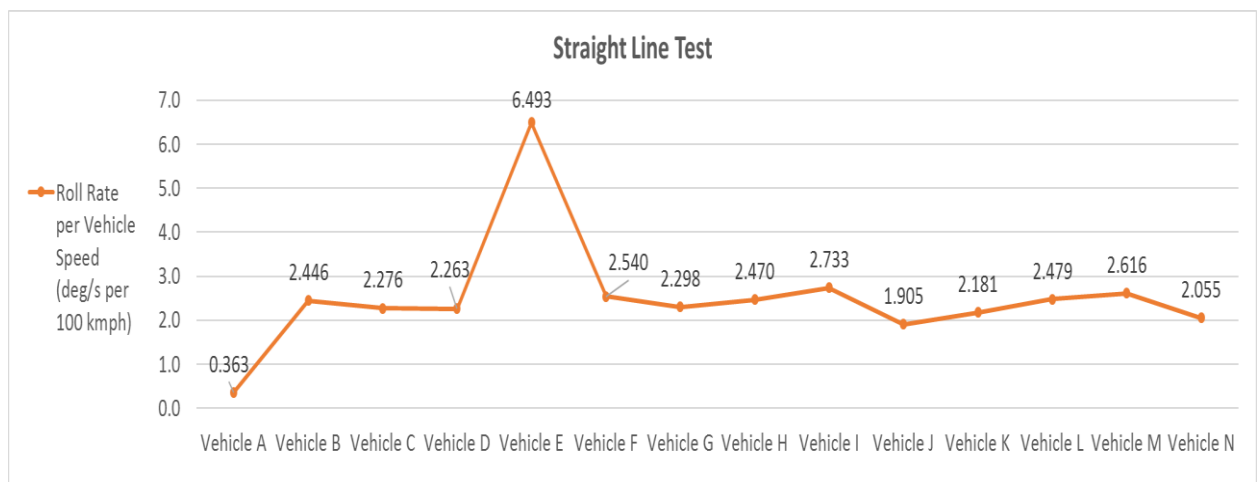


Fig. 4.30. Peak Roll Rate per Vehicle Speed during Straight Line Test

All vehicle did not cause any perceivable discomfort due to roll rate in a straight line test except Vehicle E, which could be confirmed by a sufficient lower subjective rating than other vehicles. Highest Peak Roll Rate per Vehicle Speed value which did not cause any discomfort to the passengers is 2.733 deg/s per 100 kmph. Thus, vehicles having Peak Roll Rate per Vehicle Speed lesser than 2.733 deg/s per 100 kmph will not cause any perceivable discomfort to its

passengers. All the vehicles having peak roll rate per vehicle speed more than 6.493 deg/s per 100 kmph will cause definite discomfort to its passengers.

Fig. 4.31. and Fig. 4.32. illustrates the Peak Pitch Angle per Vehicle Speed and Peak Pitch Rate per Vehicle Speed for various vehicles which underwent straight line test respectively.

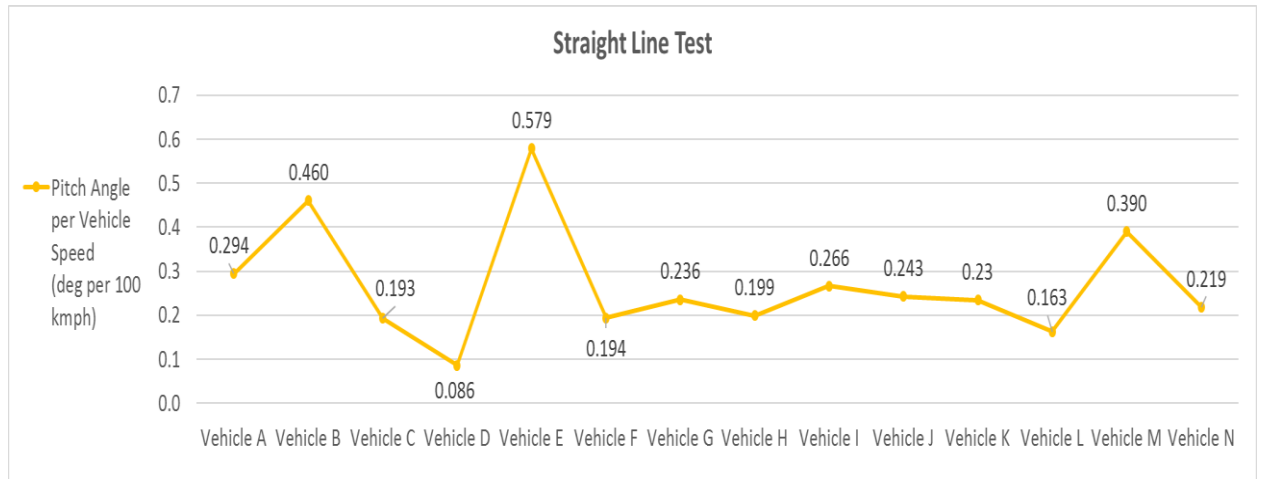


Fig. 4.31. Peak Pitch Angle per Vehicle Speed during Straight Line Test

All the vehicle showed no perceivable pitching except Vehicle B and Vehicle E. Pitching of vehicles E and B was only perceivable if it is closely observed. Otherwise, no observable pitching was found. Thus, Peak Pitch Angle per Vehicle Speed is perceivable only, if it is more than 0.460 deg per 100 kmph.

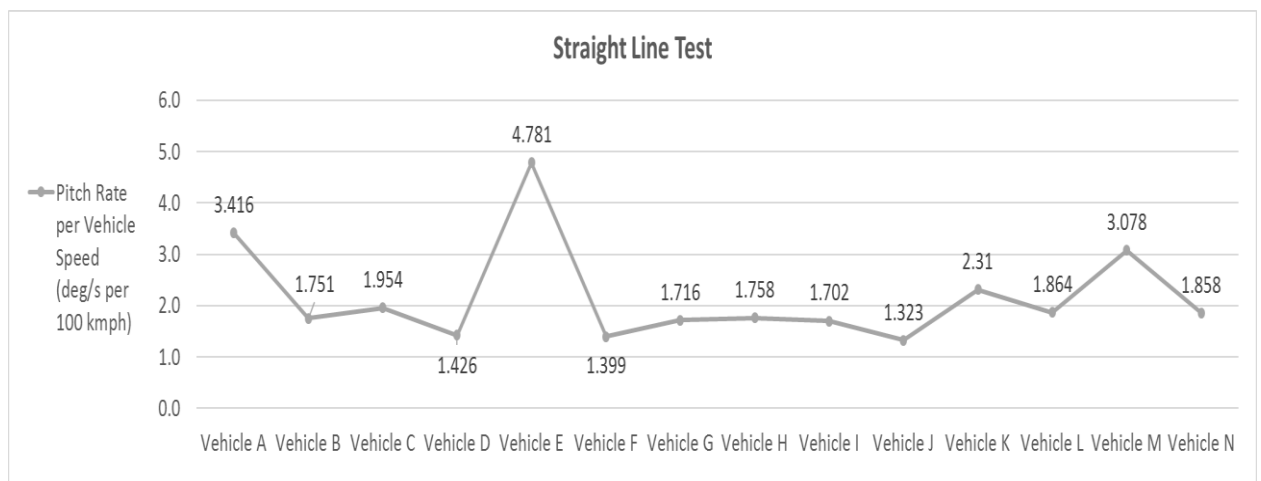


Fig. 4.32. Peak Pitch Rate per Vehicle Speed during Straight Line Test

Although, all the vehicle showed no perceivable discomfort due to pitch rate, in author's opinion above values of Peak Pitch Rate per Vehicle Speed provides an apt measure to differentiate between comfort levels of vehicles due to pitch rate.

4.3.8 Start Stay Stop Test

Start Stay Stop Test is performed using 14 vehicles. Typical roll and pitch behavior of a vehicle during Start Stay Stop Test is illustrated below using Roll Angle Time History, Roll Rate Time History, Pitch Angle Time History, Pitch Rate Time History in Fig. 4.33, Fig. 4.34, Fig. 4.35. and Fig. 4.36. respectively.

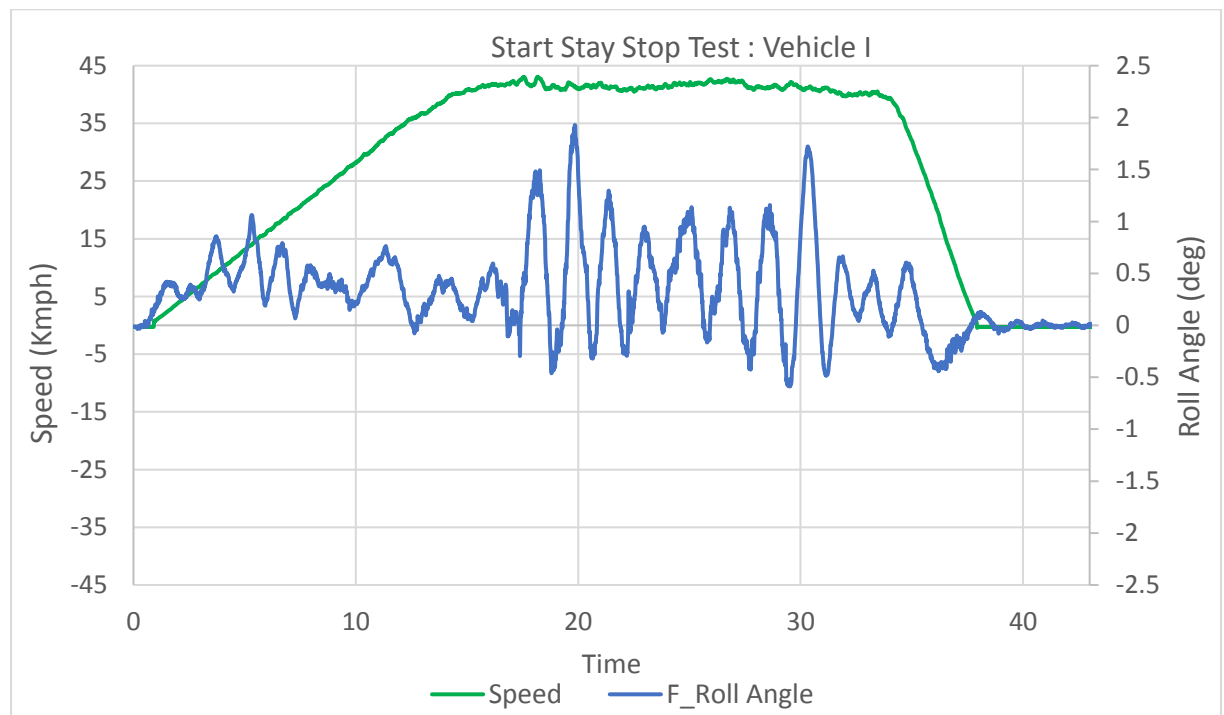


Fig. 4.33. Roll Angle Time History of Vehicle I during Start Stay Stop Test

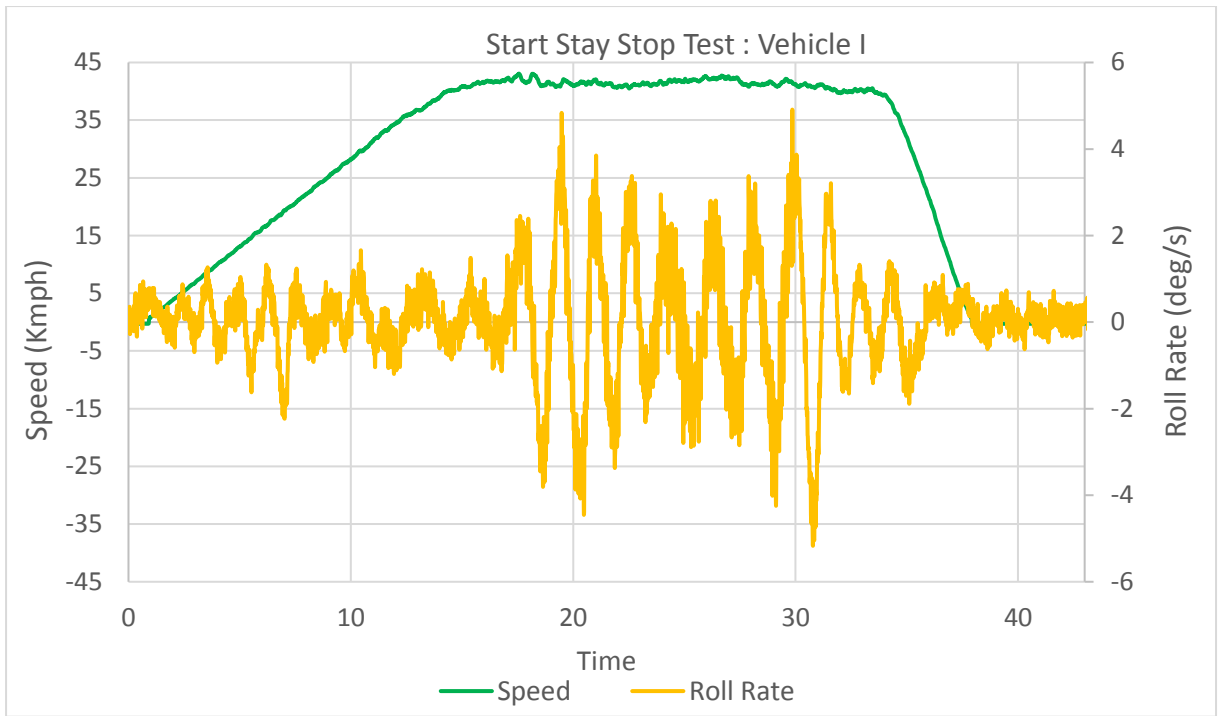


Fig. 4.34. Roll Rate Time History of Vehicle I during Start Stay Stop Test

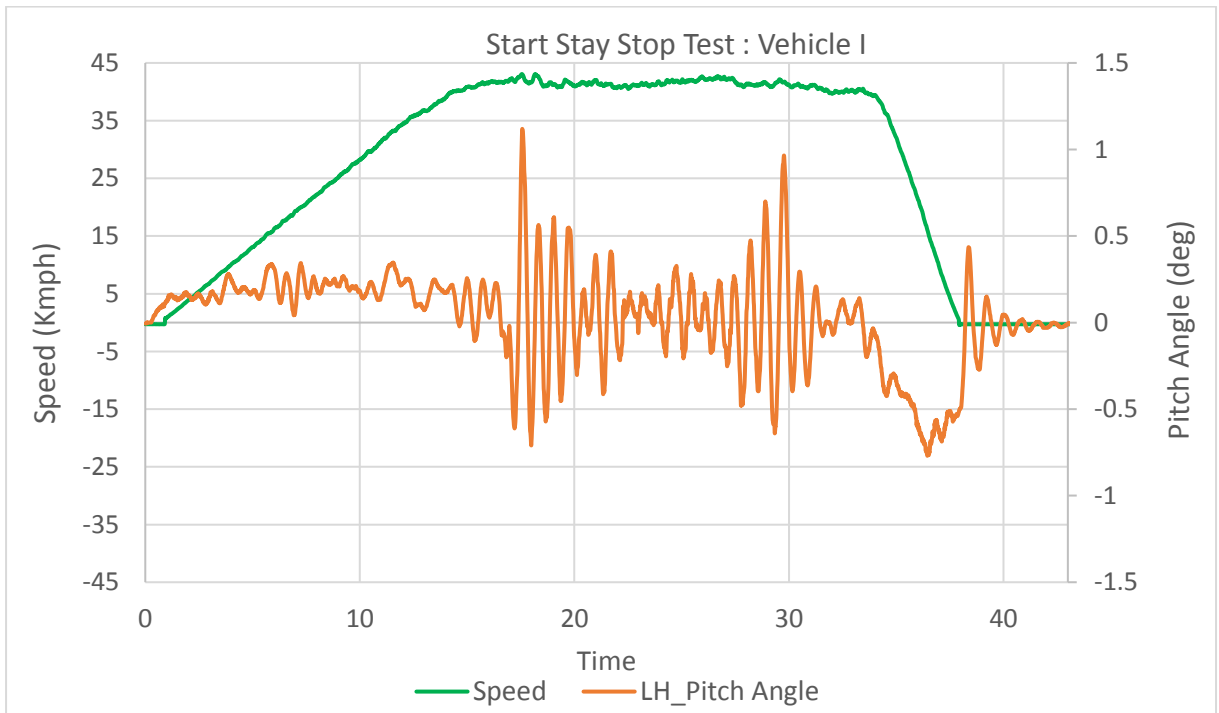


Fig. 4.35. Pitch Angle Time History of Vehicle I during Start Stay Stop Test

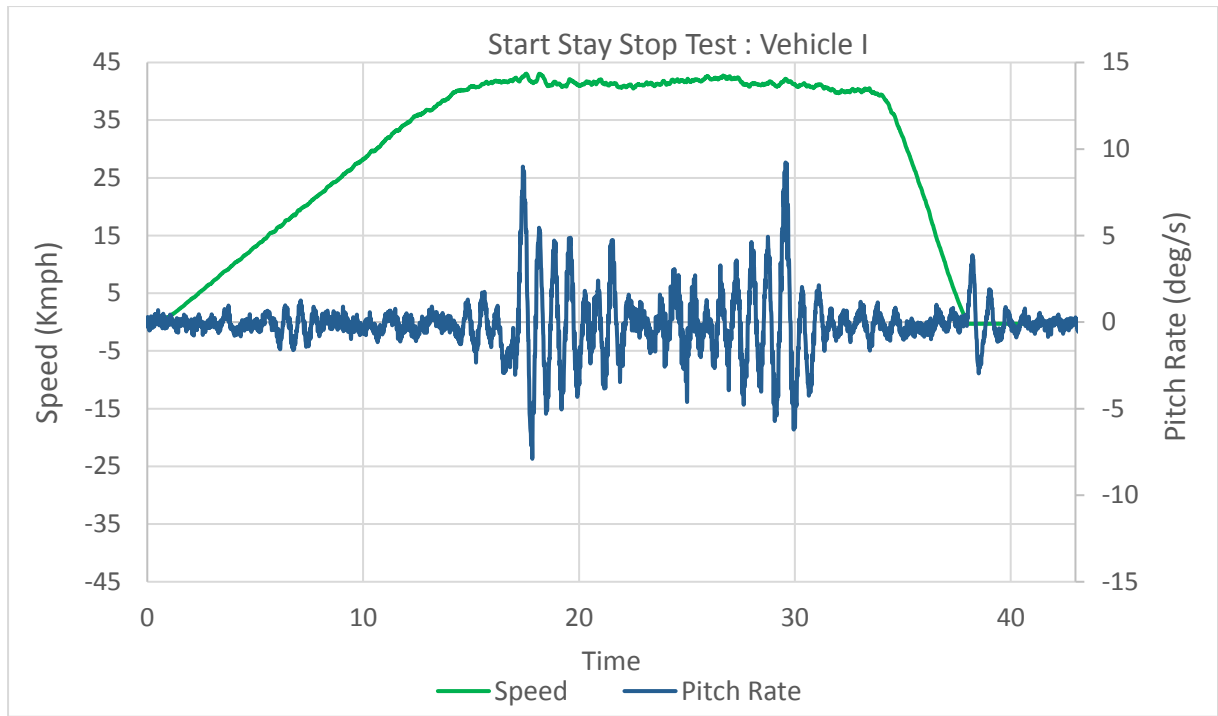


Fig. 4.36. Pitch Rate Time History of Vehicle I during Start Stay Stop Test

For analysis of data from Start Stay Stop Test, test was divided into 4 parts, namely: -

1. Before Concrete Blocks Road
2. Transition from Dry Asphalt Road to Concrete Blocks Road
3. Concrete Blocks Road
4. Transition from Concrete Blocks Road to Dry Asphalt Road

4.3.8.1 Before Concrete Blocks Road

Table No. 4.11. shows the peak values of pitch angle and pitch rate of vehicle before entering the cement patch and subjective ratings. Objective Parameter values have been normalized by vehicle acceleration.

Table No. 4.11. Output Parameters & Subjective Ratings during Before Concrete Blocks Section

Start Stay Stop Test: Before Concrete Blocks Road				
Vehicle	Peak Pitch Angle per Acceleration (deg per m/s ²)	Peak Pitch Rate per Acceleration (deg/s per m/s ²)	Subjective Rating	
			Pitch Angle	Pitch Rate
Vehicle A	1.11	5.04	6	6
Vehicle B	0.63	3.41	8	8
Vehicle C	0.31	4.29	9	7
Vehicle D	1.13	7.62	6	5
Vehicle E	0.62	3.03	7	7.5
Vehicle F	0.40	3.41	8	8

Vehicle G	0.40	3.01	8	8
Vehicle H	0.45	4.22	8	6
Vehicle I	0.51	3.97	7	6
Vehicle J	0.37	2.80	9	7
Vehicle K	0.95	8.97	7	5
Vehicle L	0.47	5.69	8	6
Vehicle M	0.51	8.31	8	8
Vehicle N	0.69	11.98	9	9

Fig. 4.37. and Fig. 4.38. illustrates the Peak Pitch Angle per Vehicle Acceleration and Peak Pitch Rate per Vehicle Acceleration values achieved by vehicles during before concrete blocks section of start stay stop test respectively.

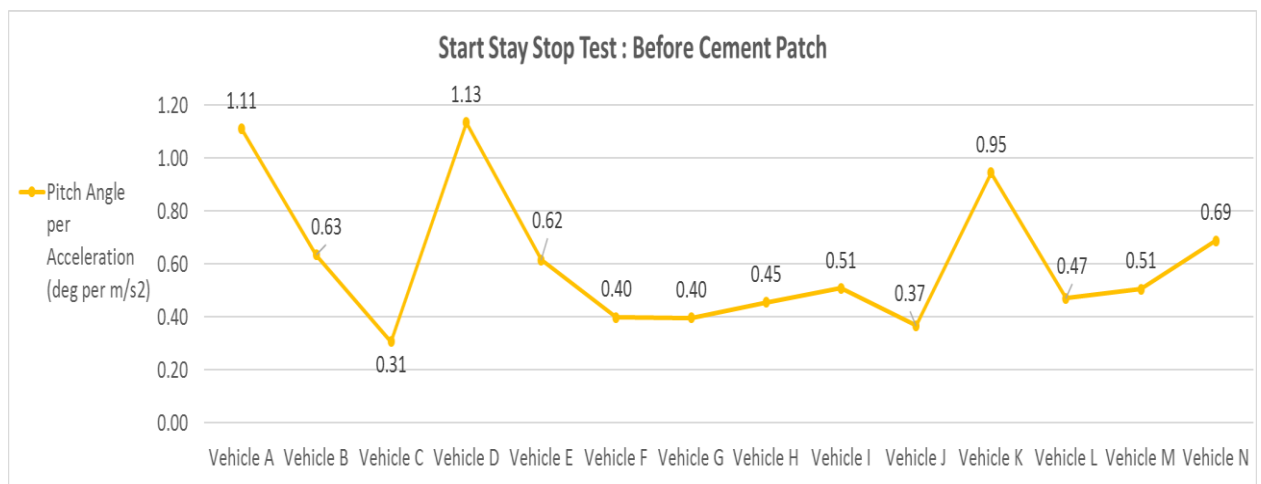


Fig. 4.37. Peak Pitch Angle per Vehicle Acceleration during Before Concrete Blocks Road Section

Least Peak Pitch Angle per Vehicle Acceleration which caused a slightly perceivable pitching of vehicle was 1.13 deg per m/s² in Vehicle D. All the vehicles except vehicle D did not produce any perceivable discomfort while accelerating in Before Concrete Blocks Road Section of Start Stay Stop Test.

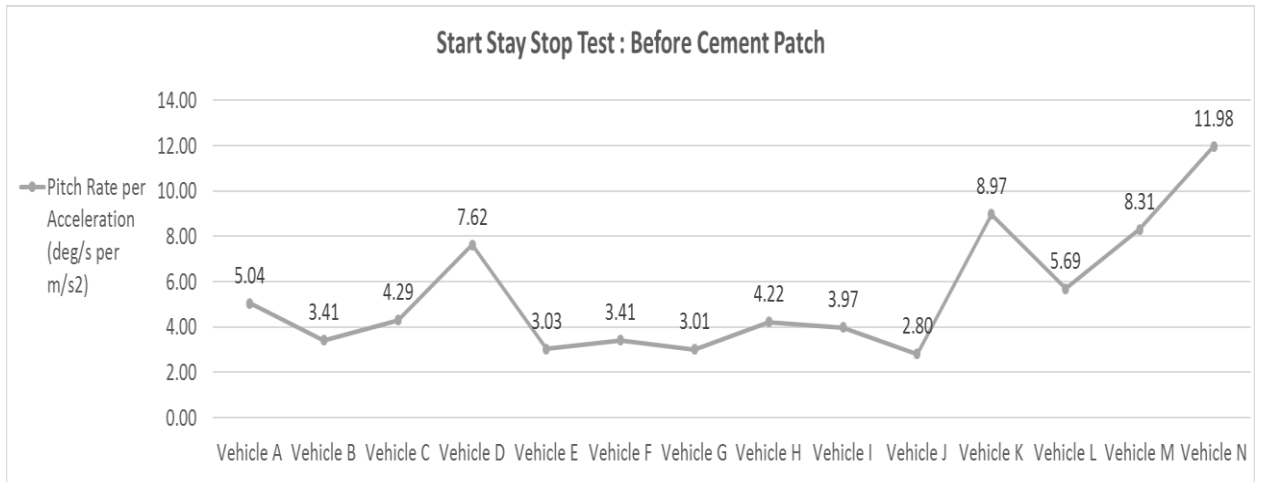


Fig. 4.38. Peak Pitch Rate per Vehicle Acceleration during Before Concrete Blocks Road Section

Least perceivable Peak Pitch Rate per Vehicle Speed is 3.97 deg/s per m/s² of Vehicle I. Vehicles having Peak Pitch Rate per Vehicle Acceleration less than 3.97 deg/s per m/s² do not cause any discomfort to the passengers.

4.3.8.2 Transition from Dry Asphalt Road to Concrete Blocks Road

Table No. 4.12. shows the peak values of pitch angle and pitch rate of vehicle during transition from tar road to cement patch. Values have been normalized by vehicle speed and multiplied by a factor of 100.

Table No. 4.12. Output Parameters & Subjective Ratings during Transition from Dry Asphalt to Concrete Blocks Section

Start Stay Stop Test: Transition from Dry Asphalt Road to Concrete Blocks Road				
Vehicle	Peak Pitch Angle per Vehicle Speed (deg per 100 kmph)	Peak Pitch Rate per Vehicle Speed (deg/s per 100 kmph)	Subjective Rating	
			Pitch Angle	Pitch Rate
Vehicle A	5.04	60.28	5	5
Vehicle B	2.51	24.61	6.5	7
Vehicle C	1.34	30.12	7	6.5
Vehicle D	3.05	33.03	5.5	6
Vehicle E	2.48	25.62	6.5	7
Vehicle F	2.51	17.09	6.5	8
Vehicle G	2.37	26.95	6.5	7
Vehicle H	2.23	24.20	7	7
Vehicle I	2.62	20.86	6.5	8
Vehicle J	1.95	14.08	7.5	9
Vehicle K	2.39	21.10	7	7
Vehicle L	1.35	11.54	8	9
Vehicle M	1.60	44.68	7	5
Vehicle N	2.06	15.69	9	9

Fig. 4.39. and Fig. 4.40. illustrates the Peak Pitch Angle per Vehicle Speed and Peak Pitch Rate per Vehicle Speed values achieved by vehicles during Transition from Dry Asphalt Road to Concrete Blocks Road of start stay stop test respectively.

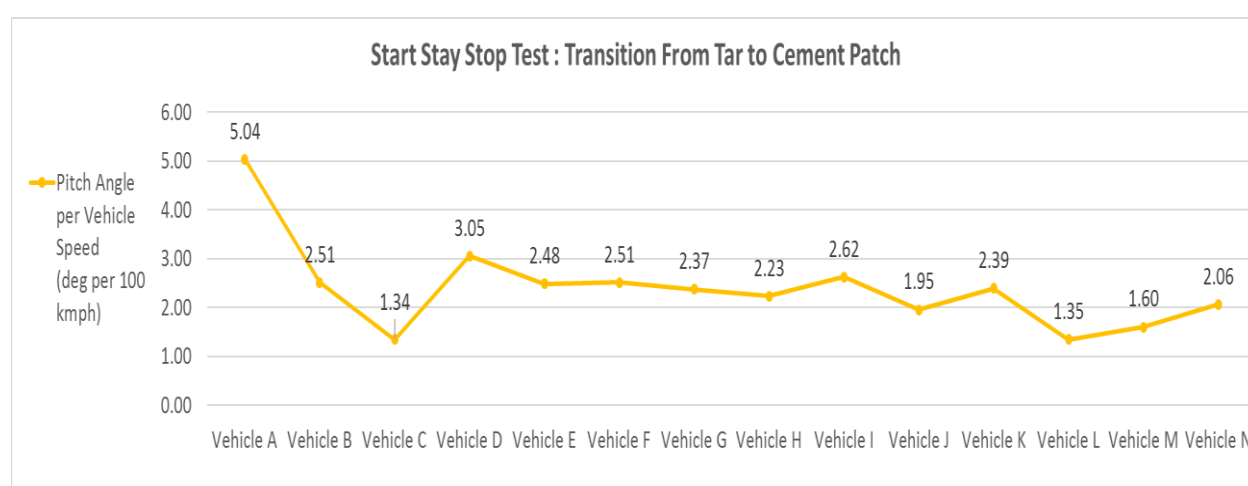


Fig. 4.39. Peak Pitch Angle per Vehicle Speed during Transition from Dry Asphalt Road to Concrete Blocks Road Section

Highest value of Peak Pitch Angle per Vehicle Speed which is acceptable to passengers is 2.39 deg per 100 kmph of vehicle K. Least value of Peak Pitch Angle per Vehicle Speed which caused discomfort to the passengers was 3.05 deg per 100 kmph of vehicle D.

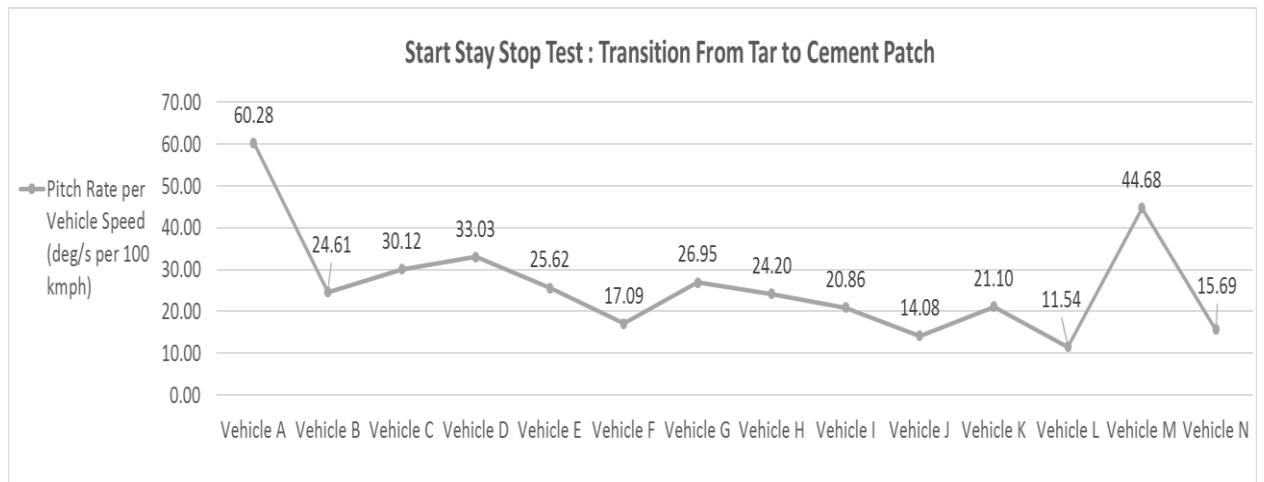


Fig. 4.40. Peak Pitch Rate per Vehicle Speed during Transition from Dry Asphalt Road to Concrete Blocks Road Section

Highest value of Peak Pitch Rate per Vehicle Speed which did not cause any perceivable discomfort to the passenger was 26.95 deg/s per 100 kmph. Thus, vehicles having Peak Pitch Rate per Vehicle Speed less than 26.95 deg/s per 100 kmph will cause no discomfort to the passengers during Transition from Tar Road to Cement Patch Section of Start Stay Stop Test. Least value of Peak Pitch Rate per Vehicle Speed where perceivable discomfort was felt by passengers was 30.12 deg/s per 100 kmph.

4.3.8.3 Concrete Blocks Road

Table No. 4.13. shows the normalized peak values of roll angle, roll rate, pitch angle and pitch rate of vehicle during Concrete Blocks section. Values have been normalized by vehicle speed and multiplied by a factor of 100.

Table No. 4.13. Output Parameters during Concrete Blocks Section

Start Stay Stop Test: Concrete Blocks				
Vehicle	Peak Roll Angle per Vehicle Speed (deg per 100 kmph)	Peak Roll Rate per Vehicle Speed (deg/s per 100 kmph)	Peak Pitch Angle per Vehicle Speed (deg per 100 kmph)	Peak Pitch Rate per Vehicle Speed (deg/s per 100 kmph)
Vehicle A	2.07	2.09	2.19	24.00
Vehicle B	1.85	10.87	1.43	13.41
Vehicle C	1.18	11.40	0.67	13.64
Vehicle D	2.18	11.36	1.64	17.28
Vehicle E	2.71	11.88	1.26	12.11
Vehicle F	2.08	29.00	2.14	10.86
Vehicle G	3.13	13.52	1.20	13.76
Vehicle H	1.96	11.87	1.08	16.95
Vehicle I	4.51	11.31	1.43	11.81
Vehicle J	2.08	9.46	0.98	10.86
Vehicle K	1.80	7.88	1.19	14.76
Vehicle L	1.89	7.72	1.20	9.94
Vehicle M	3.75	28.01	0.98	34.89
Vehicle N	2.53	9.82	1.81	11.55

Table 4.14 shows the subjective ratings of roll angle, roll rate, pitch angle and pitch rate during Concrete Blocks section of start stay stop test.

Table 4.14. Start Stay Stop Test: Concrete Blocks Section Subjective Ratings

Start Stay Stop Test: Concrete Blocks				
Vehicle	Subjective Rating			
	Roll Angle	Roll Rate	Pitch Angle	Pitch Rate
Vehicle A	8	9	5	5
Vehicle B	8	6.5	7	6
Vehicle C	8	6	9	6
Vehicle D	7	6	6.5	5
Vehicle E	7	6	7.5	7
Vehicle F	8	5	6	7
Vehicle G	6.5	6	8	6
Vehicle H	8	6	8	5.5
Vehicle I	6	6	7	7
Vehicle J	8	7	8	7
Vehicle K	8	8	8	6
Vehicle L	8	8	8	8
Vehicle M	6	6	8	6
Vehicle N	7	7	8	8

Fig. 4.41. and Fig. 4.42. illustrates the Peak Roll Angle per Vehicle Speed and Peak Roll Rate per Vehicle Speed values achieved by vehicles during Concrete Blocks section of start stay stop test respectively.

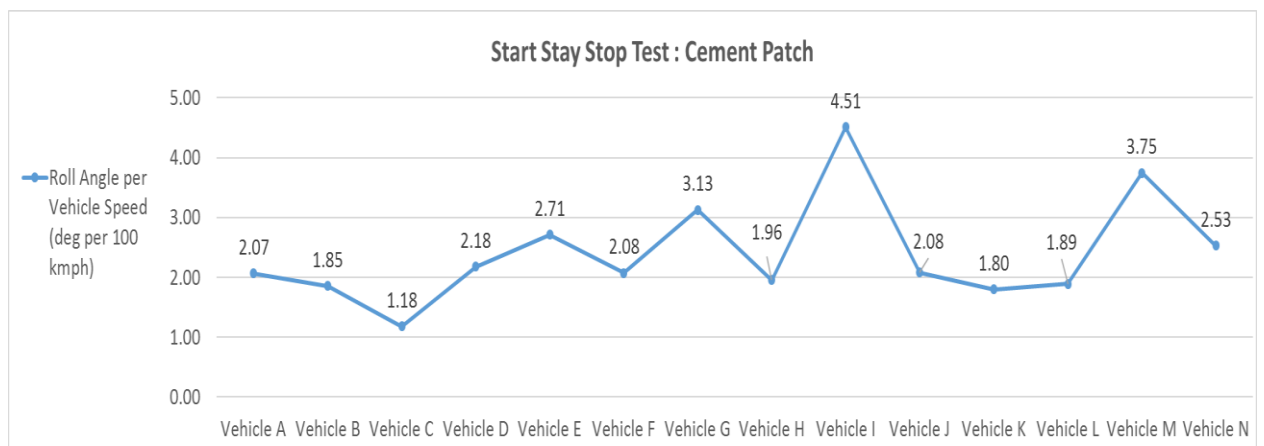


Fig. 4.41. Peak Roll Angle per Vehicle Speed during Concrete Blocks Section

Vehicle G having a Peak Roll Angle per Vehicle Speed value equal to 3.13 deg per 100 kmph had a perceivable roll. Thus, vehicles having Peak Roll Angle per Vehicle Speed value higher or equal to 3.13 deg per 100 kmph will definitely experience discomfort. Vehicles having peak roll angle per vehicle speed less than 2.71 deg per 100 kmph will definitely not cause any discomfort to the passengers.

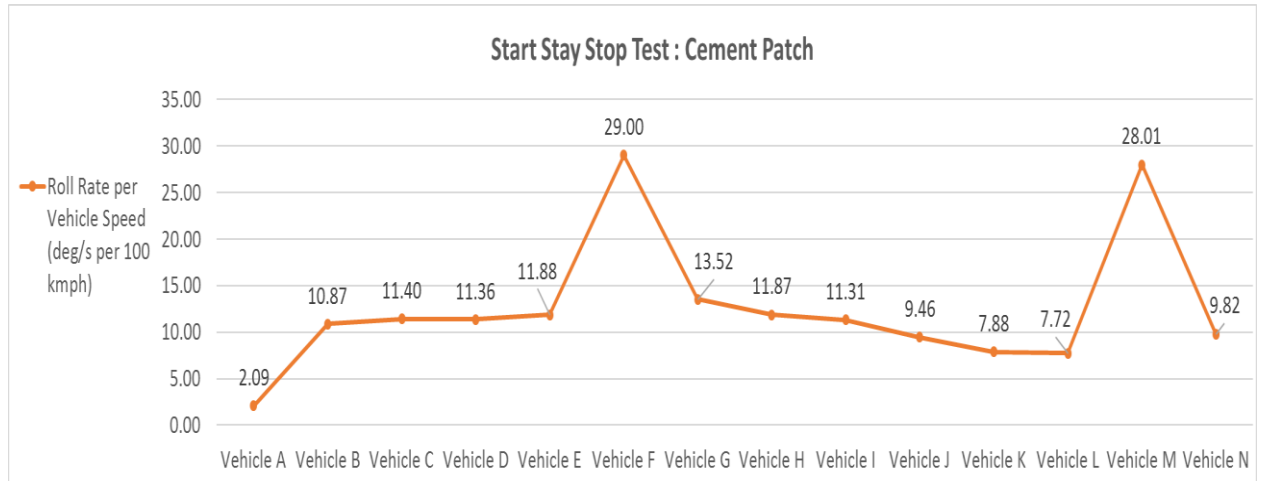


Fig. 4.42. Peak Roll Rate per Vehicle Speed during Concrete Blocks Section

Highest acceptable value of Peak Pitch Rate per Vehicle Speed is 9.46 deg/s per 100 kmph of Vehicle J. Least non-acceptable value of Peak Pitch Rate per Vehicle Speed is 10.87 deg/s per 100 kmph.

Fig. 4.43. and Fig. 4.44. illustrates the Peak Pitch Angle per Vehicle Speed and Peak Pitch Rate per Vehicle Speed values achieved by vehicles during cement patch section of start stay stop test respectively.

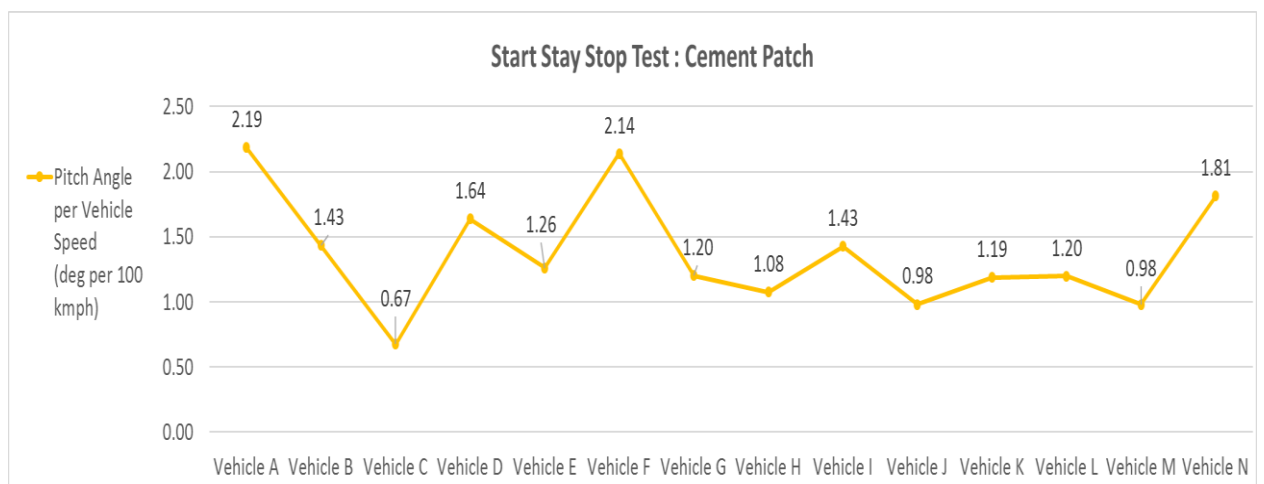


Fig. 4.43. Peak Pitch Angle per Vehicle Speed during Concrete Blocks Section

Vehicle I has the highest value that does not cause any discomfort to the passengers due to Peak Pitch Angle achieved by the vehicle while vehicle is treading the Cement Patch Section

of Start Stay Stop Test. Thus, passengers of vehicles having Peak Pitch Angle per Vehicle Speed value less than 1.43 deg per 100 kmph will not experience any discomfort due to Pitch Angle achieved by the vehicle. Least value of Peak Pitch Angle per Vehicle Speed which was perceivable by the test engineer and co-driver is 1.64 deg/s per 100 kmph.

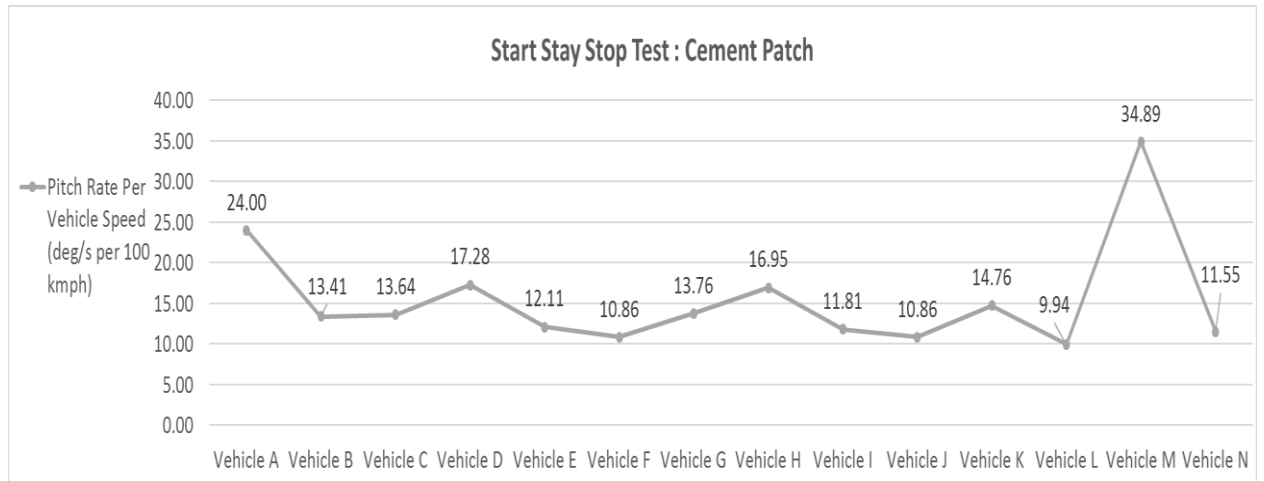


Fig. 4.44. Peak Pitch Rate per Vehicle Speed during Concrete Blocks Section

Vehicle E having Peak Pitch Rate per Vehicle Speed of 12.11 deg/s per 100 kmph has the highest value of Peak Pitch Rate per Vehicle Speed which was acceptable by the passengers. Least value of Peak Pitch Rate per Vehicle Speed which was unacceptable by the passenger is 13.41 deg/s per 100 kmph.

4.3.8.4 Transition from Concrete Blocks to Dry Asphalt Road

Table No. 4.15. shows the peak values of pitch angle and pitch rate of vehicle and subjective ratings during Transition from Concrete Blocks to Dry Asphalt Road section. Values have been normalized by vehicle speed and multiplied by a factor of 100.

Table No. 4.15. Output Parameters & Subjective Ratings during Transition from Concrete Blocks to Dry Asphalt Section

Start Stay Stop Test: Transition from Concrete Blocks to Dry Asphalt Road				
Vehicle	Peak Pitch Angle per Vehicle Speed (deg per 100 kmph)	Peak Pitch Rate per Vehicle Speed (deg/s per 100 kmph)	Subjective Rating	
			Pitch Angle	Pitch Rate
Vehicle A	3.96	38.55	6	5
Vehicle B	1.37	15.51	9	9
Vehicle C	0.90	16.20	9	9
Vehicle D	2.26	24.07	8	6
Vehicle E	2.50	20.47	7.5	7.5
Vehicle F	2.08	18.68	8	8
Vehicle G	2.08	22.22	8	7
Vehicle H	2.06	23.29	8	6.5
Vehicle I	2.39	21.87	8	7
Vehicle J	1.24	14.38	9	9
Vehicle K	1.65	16.61	8	9
Vehicle L	2.19	15.74	8	9
Vehicle M	1.27	32.54	9	9
Vehicle N	1.72	13.66	9	9

Fig. 4.45. and Fig. 4.46. illustrates the Peak Pitch Angle per Vehicle Speed and Peak Pitch Rate per Vehicle Speed values achieved by vehicles during Transition from Concrete Blocks to Dry Asphalt Road section of start stay stop test respectively.

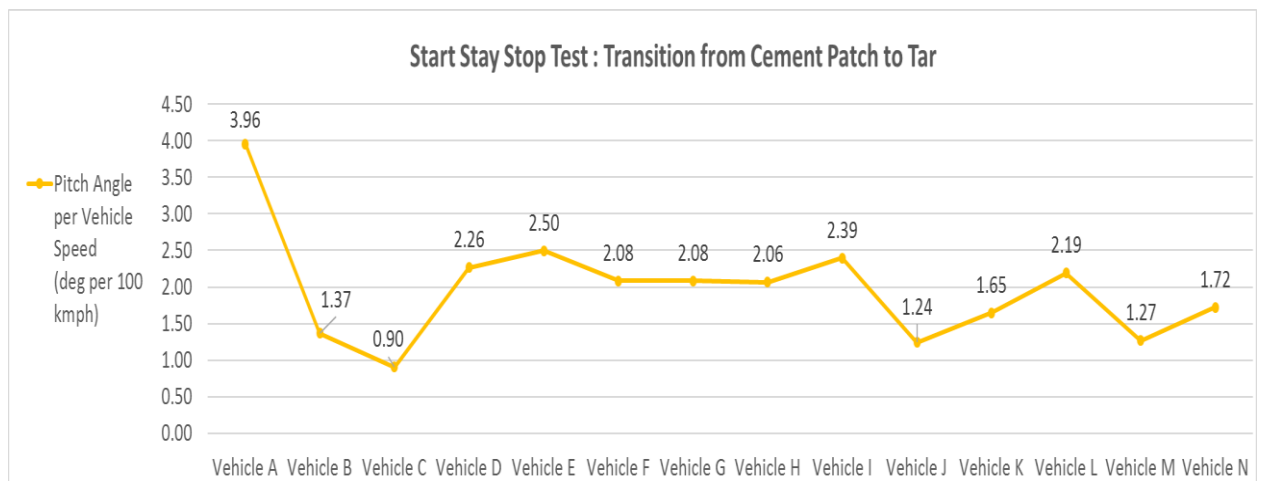


Fig. 4.45. Peak Pitch Angle per Vehicle Speed during Transition from Concrete Blocks to Dry Asphalt Section

All the vehicles were comfortable as far as pitch angle is concerned except vehicle A, where discomfort was perceivable due to pitch angle. Thus, vehicles having Peak Pitch Angle per Vehicle Speed more than 3.96 deg per 100 kmph will cause perceivable discomfort to the

passengers. Vehicle having peak pitch angle per vehicle speed less than 2.50 deg per 100 kmph will not cause any perceivable discomfort to the passengers.

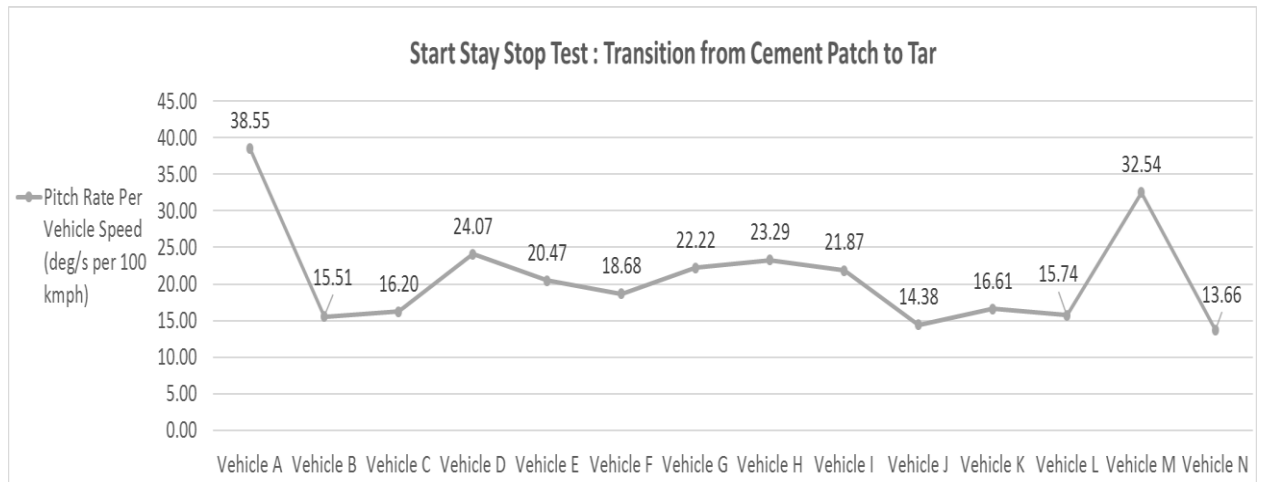


Fig. 4.46. Peak Pitch Rate per Vehicle Speed during Transition from Concrete Blocks to Dry Asphalt Road Section

Vehicle D has the least Peak Pitch Rate per Vehicle Speed where discomfort was perceivable by the passengers. Thus, vehicle having Peak Pitch Rate per Vehicle Speed more than 24.07 deg/s per 100 kmph will have perceivable discomfort. Vehicle G having Peak Pitch Rate per Vehicle Speed value of 22.22 deg/s per 100 kmph has the highest value of Peak Pitch Rate per Vehicle Speed which was acceptable to the passengers.

Chapter 5

Conclusion and Future Scope

Conclusion

On the basis of previous chapter's results & their analysis following conclusions can be drawn from this study:-

- Passenger comfort is greatly influenced by roll and pitch rate rather than roll and pitch angle
- Dive Test provides an excellent way to characterize both pitch comfort values and pitch damping behaviour of a vehicle
- Squat Test was similar to Dive Test and it was helpful in characterizing the pitch damping behaviour as well as pitch comfort values of a vehicle
- Squat and Dive Test resulted in similar values of comfort and damping characteristics of vehicles
- Single Speed Bump Test showed good correlation between captured output parameters and subjective rating of passengers. Thus, it can be used for characterization of pitching behaviour and pitching comfort values while negotiating a speed bump
- Straight Line Test provides an efficient way of differentiating and objectively map the roll and pitch behaviour of vehicle driving on a smooth road without any driver's inputs
- Start Stay Stop Test provides a complete way of evaluation of comfort values for pitching behaviour of vehicle during acceleration, speed bumps and rough road inputs
- Step Input Test has been used to characterize roll damping characteristics and proved to be good way of characterizing roll damping behaviour of a vehicle
- Double Lane Change Test is a good way to characterize the roll comfort values
- Characterization methodology highlighted in this research can be applied for evaluation of objective comfort ranges of roll and pitch behaviour of vehicles
- Characterization methodology can be used for the evaluation of objective roll and pitch damping characteristics of vehicles

Future Scope

Further, this methodology can be tested for objective 1 on 1 comparison of vehicle's rolling and pitching behaviour during dynamic maneuvers and then optimization of vehicles based on comparison and modification of static measures of vehicle design. Also, separate gyro sensor

might be placed inside the cabin of the vehicles having wheelbase more than 5.4 m so as to map the pitch and roll rate comfort values.

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