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Enabler Methodology to Use a Dynamic Simulator to Develop Global Vehicles

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ABSTRACT

The international car manufacturer Stellantis designs and produces vehicles for fourteen brands. Some brand characteristics satisfy both the European and North American market (e.g., Jeep), while others primarily target one market or the other. Efforts have been made recently to harmonize design and development processes within the global company. The cornerstone of this project is the subjective assessment procedure performed on the dynamic driving simulator, a newly developed technology that reduces time and cost during the development phase of a new car model. The technology can be used prior to the production of physical prototypes, allowing the assessment of handling and dynamic qualities continuously during the design phase as various parameters are changed. The purpose of the current research is to determine the most relevant differences in assessments as they are performed in Italy and in North America (i.e., Canada) and to understand the effect on vehicle design as it pertains to the location of the development processes.

It was found that the main discriminating factor among the drivers when performing the assessment of a vehicle in design phase is their sensitivity, or their ability to clearly identify the change in behaviour of a vehicle after the design of a component has been modified (e.g., the dampers). If the driver's sensitivity is high enough, their next concern is to find a balance between the brand identity research (i.e., which kind of customers are targeted and their expectations towards the driving experience) and the safety of the customer (vehicles that are easier to maneuver for the average driver). Eventually, their individual preferences enter the picture; some people simply find sporty driving more appealing while others prefer a vehicle designed with a focus on better ride characteristics.

DEDICATION

This was all possible due to my family's tremendous support and their outstanding ability to give unconditional love, support, trust, and acceptance. My dear parents, Antonella and Maurizio, and my siblings, Gianluca and Serena, are truly my best friends. It is their love, that has set me up for success. I would like to also thank my loving aunt Francesca and uncle Alessandro, who have always believed in my goals. I thank my nonna Ponina (even though she tells her friend that I have been doing research in Alaska) for being so funny and supportive in her own way.

To the Italian immigrants in Windsor, I want to apologize on behalf of our country for failing in rewarding your hard work adequately and forcing you to search elsewhere for a better life. The love and pride you still bear in your hearts for Italy is incredible. I will keep the memories of your endeavours in my heart forever and make sure people back home know how strong, creative, and generous the Italian community in Canada is.

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LIST OF ABBREVIATIONS

ADAS	-	Advanced Driver Assistance Systems
ARB	-	Antiroll Bar
CRC	-	Constant Radius Cornering
CRT	-	Car Real Time
DiM	-	Driver in Motion
DOF	-	Degree of Freedom
EMEA	-	Europe, Middle East, Africa
FCA	-	Fiat Chrysler Automobiles
FFT	-	Fast Fourier Transform
FWD	-	Front Wheel Drive
ICE	-	Internal Combustion Engine
ISO	-	International Organization for Standardization
L/R	-	Left/Right
NA	-	North America
OCH	-	On-Center Handling
OMs	-	Objective Metrics
P2P	-	Peak to Peak
PSA	-	Peugeot Société Anonyme
R&D	-	Research and Development
SA	-	Subjective Assessment

SSQ	-	Simulator Sickness Questionnaire
SWA	-	Steering Wheel Angle
SWT	-	Steering Wheel Torque
UK	-	United Kingdom
VR	-	Virtual Reality

NOMENCLATURE

Symbol	Description
g	Gravitational constant
u	Longitudinal speed
v	Lateral speed
r	Yaw rate
m	Vehicle mass
I_{zz}	Yaw moment of inertia
a	Distance of the front axle from the center of gravity
b	Distance of the rear axle from the center of gravity
c_f	Damping rate of the front suspension
c_r	Damping rate of the rear suspension
m_s	Sprung mass
m_u	Unsprung mass
z_s	Vertical displacement of the sprung mass
z_u	Vertical displacement of the unsprung mass
c_s	Damping rate of the suspension
k_t	Tire stiffness
k_s	Suspension stiffness
Z_f	Vertical load on the front axle
Z_r	Vertical load on the rear axle
u_f	Vertical displacement of the front axle
u_r	Vertical displacement of the rear axle
I_{yy}	Pitch moment of inertia

CHAPTER 1

Introduction

The tests taking place during the design and development phase of a vehicle are mainly divided in three macro areas: virtual testing, testing on a driving simulator, and on-road testing. Currently, engineers use simplified but reliable mathematical models to describe the systems and subsystems that make up a vehicle, tires, the road and their mutual interaction. Furthermore, the computational power of an average laptop is enough to manage large amounts of data. These tools make virtual simulations accurate; when inspecting how a change in a component design affects the performance of the vehicle, it is sufficient to modify the parameters targeted in the virtual model and run a simulation, from which numerical results can be extrapolated. However, numerical results are "just" numbers; they give a good idea of how the behaviour of the vehicle has been affected by the change, but that doesn't necessarily inform the engineer of the driver's perceived change. Subjective assessment (SA) tests are still the state of the art and one of the most reliable methods of obtaining good handling qualities during the design and development phase.

Before driving simulators reached a technology advanced enough to be included in the development phase, eventual issues in the vehicle ride and handling qualities were found only after a prototype was tested on the road. At this stage of the vehicle design cycle, manufacturing resources have been employed, and applying modifications takes time and additional financial resources. During the intermediate step of the real time testing on the driving simulator, engineers are able to make changes and they have more room to be creative and attempt new solutions without being concerned about the cost of realizing a physical prototype.

The subjective dimension of the driving experience is still a broadly unexplored field, and this project stems from a necessity coming from industry to try and understand if there is a link between the way in which test drivers assess the ride and handling quality of a car and their geographic location. International car manufacturers like Stellantis are born from the merging of car manufacturers located all over the world. Each one of them serves a narrow or broad market niche. As a result, the performance engineers and test drivers are trained to develop vehicles that address the needs and expectations of the targeted niche. Despite the fact that these manufacturers are now merged under one name, the lead in the development process of a new model is still given to the engineers of the area that always had the product design responsibility for that model and brand. What if the process is changed? Would the subjective assessment of engineers from another geographic area be the same? Where will the major differences lie, and what can be their root cause?

The challenge posed by the industry is to exploit this powerful technology to investigate the major differences in the way the assessment is carried out in two different teams of test drivers: one in Italy, one in Canada, respectively representing two of the regions in which Stellantis is active: EMEA (Europe, Middle East, Africa) and NA (North America). The aim is to get a better understanding of the factors that influence a driver's judgement of the ride and handling qualities of a vehicle, with a focus on their geographic location. In the next chapter, the major differences between European and North American automotive markets are listed, but do they impact the way in which a driver assesses a vehicle, their preferences and expectations? Being able to have a deeper understanding of this opens new possibilities: for the development of global vehicles (i.e. vehicles sold in both regions), SA testing on the driving simulator can be used as a tool to interpret the market and make sure the final product meets requirements, taste and expectations of customers from different areas.

1.1 European and North American markets

The profile of the typical North American car displays some major differences compared to the European favorite vehicle models. North American cars are planned for the most extreme use case [1]; they are larger in size and employ more driver assistance systems. The footprint of North America has more rural areas; on average, the distances to be covered are bigger, so space constraints are not really a limiting factor. In contrast, most European cities developed at a time before modern urban planning existed [2]; their roads are generally narrower and there are more constraints related to the availability of parking spots due to the higher population density of the territory. Furthermore, many European countries tax vehicles on size, engine dimension and fuel consumption at a far higher rate than North America, which explains why the typical choice of Europeans falls on more compact, fuel-efficient cars. Another factor to consider is the speed limits [3]: North American limits are generally lower, so the handling at high speeds is not a big concern for buyers like it is for their overseas counterpart.

Stellantis is a mega auto conglomerate created on Jan 16, 2021. It's a new company formed by the merger of France's Groupe PSA and Italian-American auto conglomerate Fiat Chrysler Automobiles (FCA). The merger of the two auto groups combined approximately 4.8 million vehicles from FCA with 4.1 million vehicles of Groupe PSA, making it the fourth-largest automaker in the world [4]; at this time, Stellantis offers fourteen vehicle brands. Some of them display characteristics that satisfy both the European and North American market (e.g., Jeep), while others are typical of one market or the other. The Dodge brand, for example, was withdrawn by the European market in 2011 due to slow sales [5]; the same action was taken with Chrysler vehicles in 2009 (except for UK and Ireland) [6]. Currently, when looking to buy a Fiat vehicle in Canada, the only available choice is the 500X model, while on the Italian market there are currently seven options available, the majority of which are hybrid. Another circumstance that makes it harder to market an expensive product to customers who are loyal to other existing brands is the fact that among these two continents there are different government emissions, safety and lighting requirements, making it expensive for a company to develop market-specific models that ensure compliance in both macro-areas. Table 1 lists Stellantis brands and their Country of origin.

Table 1. List of Stellantis brands and country of origin.

Brand	Country
Abarth	Italy
Alfa Romeo	Italy
Chrysler	USA
Citroen	France
Dodge	USA
DS Automobiles	France
Fiat	Italy
Jeep	USA
Lancia	Italy
Maserati	Italy
Opel	Germany
Peugeot	France
Ram	USA
Vauxhall	UK

When it comes to assigning the leadership of the development process for a new model, the tendency is to respect the loyalty that customers of a specific area show to some brands or models. The subjective assessment of ride and handling has always been task of engineers who are fully familiar with the product they are dealing with, the driving circumstances in which it needs to be tested, and the expectations and skills of an average customer. The aim of this study is to investigate the major differences in the way in which the ride and handling assessment is carried out in Europe and North America. The results of this study will provide the company with more data to exploit in the process of harmonizing the testing procedure and company standards on a global level.

1.2 Virtual Simulations

While it is true that the focus of this project is on the subjective dimension of the driving experience and how environmental factors such as the operating market might affect a driver's judgement of the ride and handling quality of a vehicle, a big part of the work done required a good understanding of vehicle dynamics. Many simulations were run offline, and existing car models were altered in order to achieve a different behaviour, so that the feedback to such change provided by the test driver when it came to perform a subjective assessment of the vehicle could be gauged and compared to the one given by overseas colleagues. Simulation and post processing software played a big role in this first, offline stage of the work.

In Chapter 2, an explanation of the basic models to describe vehicles and their dynamics is provided to the reader. When it comes to a virtual simulation environment, the components of a vehicle are grouped into subsystems, each one modelled in a different way, so that the behaviour of the whole system (the vehicle) when subjected to a certain input is computed. The inputs are the driver's commands (steering wheel angle, throttle, brake) and the road profile. For this project, the software employed is CarRealTime (CRT) by VI-Grade, which allows engineers to develop virtual models, perform analyses and tune the vehicle's subsystem, and execute virtual driving maneuvers to mimic real world testing.

The vehicle model used for this project is the one of the Jeep Renegade ICE. Figure 1shows the tree view of the model on the CRT interface. The vehicle is subdivided into the following subsystems: body, brakes, suspensions, wheels, powertrain and steering.

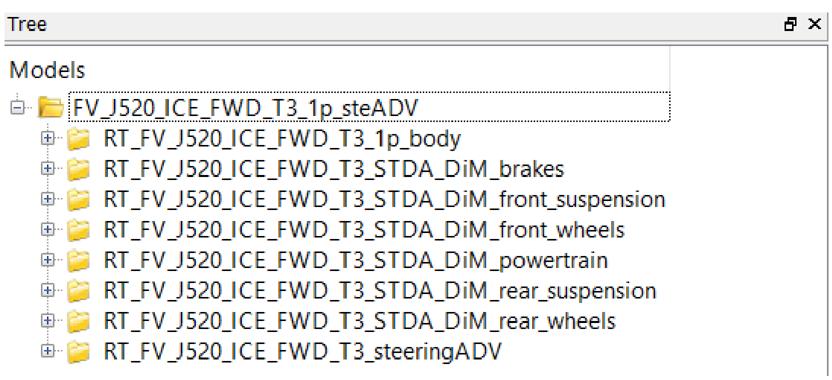


Figure 1. Tree view of the Jeep Renegade model on VI- CRT.

1.3 Driving Simulators

The aim of this project is exploring one of the multiple, possible applications of this relatively new technology that is driving simulators, which nowadays is becoming an essential part of car manufacturers' research and development (R&D) activities.

Regardless of its application domain, this technology is designed to offer a realistic driving experience.

Driving simulators have multiple applications, ranging from the ride and handling assessment to the development and validation of Advanced Driver Assistance Systems (ADAS), in-vehicle information systems, adaptive cruise control and obstacle avoidance devices. Driving simulators can also be used to investigate the impact of these systems on human factors and test drivers' performance under various circumstances (when they are subject to stress, distraction, drowsiness, fatigue, etc.). Studies on simulators have been conducted for developing driving quality standards and regulations, as well as in the context of product litigation and recalls. Their main advantage is the repeatability and the possibility to obtain useful data without risking drivers' safety [7].

Driving a vehicle might be mistaken as a task dominated by visual information. However, it is well established that other sensory information, such as that provided by the vestibular and proprioceptive channels (organs located in the inner ears, that detect the motion of the head and body in space), also contributes to the perception and control of self-motion [8].Figure 2 represents the vestibular system: the three semi-circular canals (red, orange and pink) are filled with a viscous liquid, the endolymph. When the head is moved, the liquid exerts a pressure on the cupula, a specialized structure localized at the end of each canal. Pressure stimuli is transformed into nerve discharge, encoding the angular acceleration of the head. Similarly, the otolith receptors (blue and green), which are composed of a mass of crystals floating in the endolymph, encode both linear acceleration and tilt of the head [8].

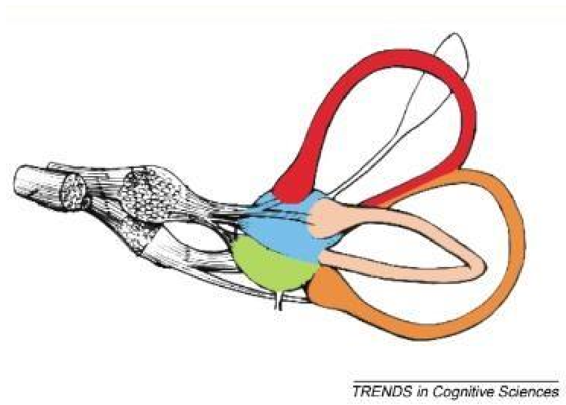


Figure 2. The vestibular system and its measurement principles.

Due to workspace and actuator limitations, driving simulators cannot perfectly reproduce the motion of the vehicle being simulated. Different strategies are used in order to immerse the driver in the simulation environment and to increase the degree of authenticity of the simulation: motion cueing, a completely enclosed environment, a large field of view, visual and audio cues, etc. [9]

The state of art for simulators is a very complex technology, featuring 4k projectors and conical screens. VI-Grade is a leading provider in the field. Figure 3 represents the main systems in their latest model, Driver-in-Motion (DiM) 250 dynamic driving simulator.

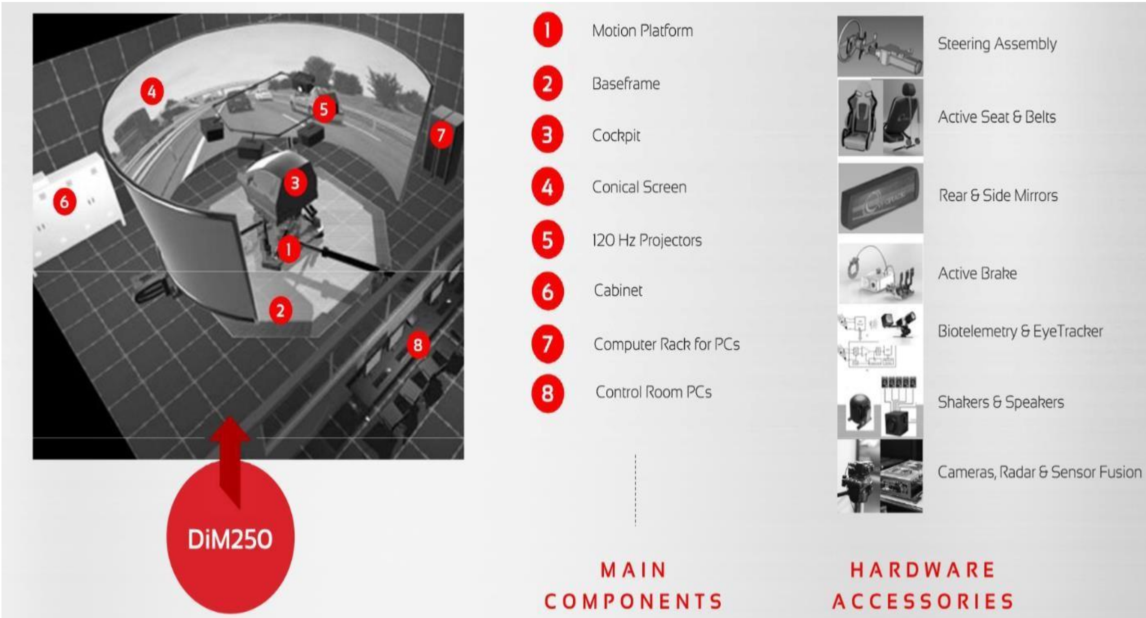


Figure 3.DiM250 simulator ecosystem. by VI Grade [10].

Motion cueing can be obtained thanks to a movement platform which is controlled by a set of six electromechanical linear actuators mounted in a hexapod configuration, also known as Stewart platform. It generates linear acceleration in the longitudinal, lateral, and vertical direction of the vehicle, as well as roll, pitch, and yaw angular accelerations. To extend the range of physical movement, a large linear actuator can be added to the Stewart platform in longitudinal and lateral direction.

That is the case for the simulator used in this study: the DiM 250 dynamic driving simulator in Figure 4, designed and installed by VI grade. This solution provides a faithful reproduction of the motions the driver is subjected to at both low and high frequencies which characterize automotive chassis design. New, extended linear actuators allow an increased travel of the tripod, providing a more accurate feeling at steady state accelerations [10]. The entire apparatus is electrically actuated to minimize latency and provide the massive and instantaneous torque required to produce events up to 2g.

The simulator became operative in early September 2019, before the completion of the FCA and Groupe PSA merge. It can be fitted with any vehicle body in the FCA line-up, from a Fiat 500 to a Ram Heavy Duty pickup truck, and any number of road surfaces or driving environments can be loaded into the simulator, supported by the adjacent control room. A curved, 180-degree screen in front of the pod fills the driver's field of view and five 4K projectors produce the image on the screen. The projected image shifts in real time using tracking data correlated to the position of the driver's line of sight; frequent users of the dynamic simulator get a personal calibration of the motion cueing to account for physiologic variables [11].

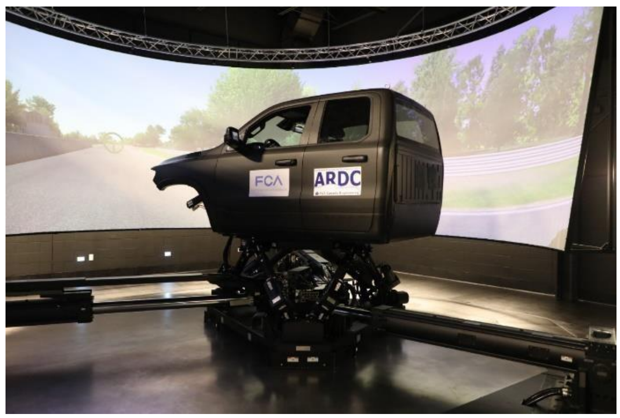


Figure 4. DiM 250 Dynamic Simulator as installed at the Automotive Research and Development Center in Windsor, Ontario [12].

CHAPTER 2

Theory

Simplified linear models to describe the subsystems of a vehicle and their interactions are employed in the software CarRealTime (CRT) by VI-Grade, used for this project. For the sake of providing the reader with a better understanding of the design choices made in this project, in this theory chapter will be explained the way in which some subsystems are modelled on CRT. Before then, a briefing on the main simplified models used to describe the dynamics of a vehicle is given.

2.1 Vehicle Dynamics

There is not a unique way to lump vehicle subsystems (tires, suspensions…) and their properties (damping, stiffness) into masses, springs and dampers; it highly depends on the target behaviour of the study (yaw stability, ride quality..). Adding more masses, springs and dampers to a model increases its degrees of freedom, alongside with the time required to manage a higher number of equations. For the models described here, the main reference is Minaker[13].

2.1.1 Vehicle motions

The reference frames and coordinates system adopted on VI- CRT comply to the standards [14] and [15].

A global reference system is defined; a Newtonian (i.e. inertial) frame that does not accelerate in translation nor rotate. This frame has origin point N_0 and unit vectors n_x, n_y, n_z. The use of the letter “N” for this reference system stands for “Newtonian”.

The vehicle reference system has origin S_0, located at Z=0 of the global reference frame and at half of the front vehicle track (Figure 5).

In design conditions, the two systems coincide. The orientation of the triad axes is the following:

- X+ axis pointing forward in the direction of motion
- Y+ axis pointing leftward
- Z+ axis pointing upward

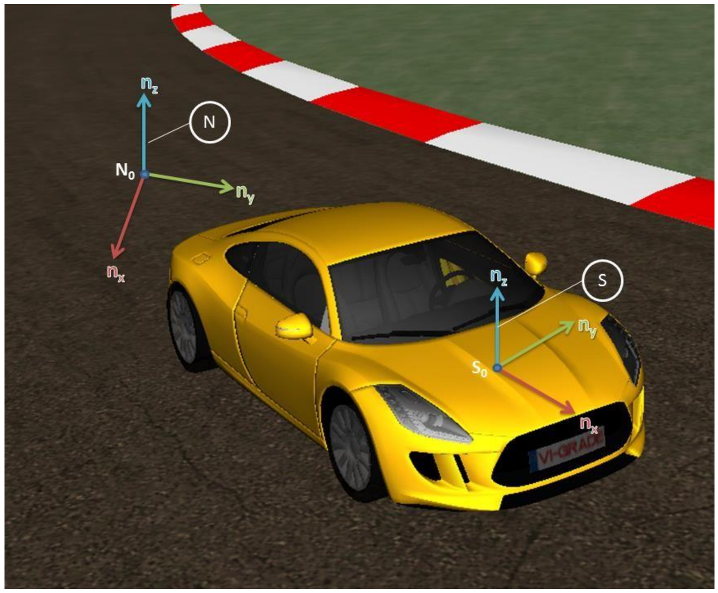


Figure 5. Global and Vehicle Reference System. From [16]

The vehicle responses to road excitations and maneuvers consist in the sum of six different motions: three translations and three rotations along the X, Y, Z axis as shown in Figure 6. Three terms are used to address the rotational displacements:

- Yaw, the rotation of the vehicle about the Z axis
- Pitch, the rotation of the vehicle about the Y axis
- Roll, the rotation of the vehicle about the X axis

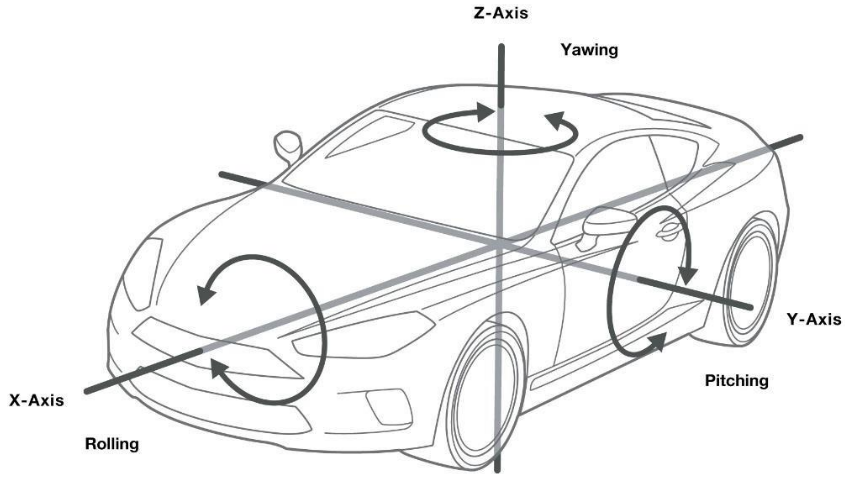


Figure 6. Motions about the three axes of the reference frame of a vehicle. From [17]

2.1.2 Yaw Plane Model

The yaw plane model is also widely known as “bicycle model” due to the fact that the effect of the track width is considered negligible when studying the vehicle lateral and yaw response for lateral accelerations up to 0.4g [18], so when picturing the vehicle from a top view and collapsing each axle in a single tire, it looks like a bicycle. In Figure 7, the orientation of the Y and Z axis adopted is the opposite with respect to the one established on CRT (i.e., the SAE standard).

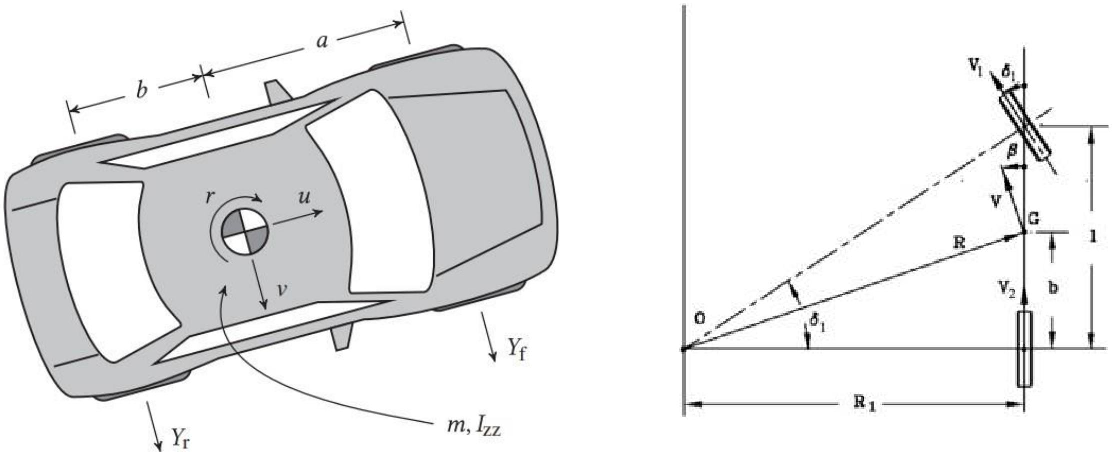


Figure 7. Yaw Plane model, from [13] and bicycle model, from [19].

The degrees of freedom of this model are the lateral velocity v and the yaw velocity r, gathered in the vector $\boldsymbol{x} = [v \quad r]'$. The longitudinal speed u is assumed to be under driver control, and held constant, and as a result is treated as a parameter of the model rather than a variable. The parameters needed for this model are listed in Table 2:

Table 2. Parameters needed for the bicycle model

Symbol	Parameter
m	Vehicle mass
I_{zz}	Yaw moment of inertia
a	Distance of the front axle from the CG
b	Distance of the rear axle from the CG
c_f	Front tires cornering stiffness
c_r	Rear tires cornering stiffness

The first order model to describe the system is the following, where the steering angle applied to the front wheel is defined as δ_f:

$$\boldsymbol{M}\dot{\boldsymbol{x}} + \boldsymbol{L}\boldsymbol{x} = \boldsymbol{F}\delta_f \tag{1}$$

With:

$$\boldsymbol{M} = \begin{bmatrix} m & 0 \\ 0 & I_{zz} \end{bmatrix} \tag{2}$$

$$\boldsymbol{L} = \frac{1}{u}\begin{bmatrix} c_r + c_r & ac_f - bc_r + mu^2 \\ ac_f - bc_r & a^2c_f + b^2c_r \end{bmatrix} \tag{3}$$

$$\boldsymbol{F} = \begin{bmatrix} c_f \\ ac_f \end{bmatrix} \tag{4}$$

Despite the fact that certain factors have been ignored in order to develop a usable linear model, this equation has proved to be reasonably accurate and suitable to predict the fundamental dynamic characteristics of a typical passenger car.

2.1.3 Quarter Car Model

The quarter car model has been used for many years to predict ride quality. It is a simple two degree of freedom model, with two bodies constrained to vertical translation, representing the sprung mass m_s (the chassis, powertrain, driver, cargo, etc.) and the unsprung mass m_u (the wheel, hub, brake rotor or drum, etc.).

The bodies are linked by a linear spring with stiffness k_s and a damper with coefficient c_s, representing the suspension, and the wheel is held to the ground by a spring that represents the tire elasticity, with the stiffness denoted as k_t. With reference to Figure 8, the input variable is the ground displacement z_g, while the state variables are the displacement of sprung and unsprung mass $\{z_s \quad z_u\}'$.

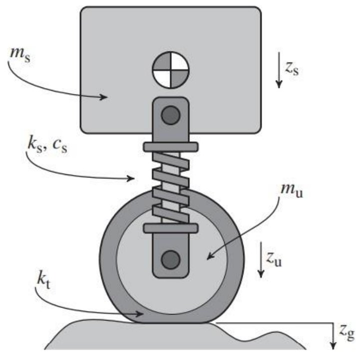


Figure 8. Quarter car model, from [13].

The vectorial equation that results from the equilibrium analysis of this system is the following:

$$\boldsymbol{M}\ddot{\boldsymbol{z}} + \boldsymbol{L}\dot{\boldsymbol{z}} + \boldsymbol{K}\boldsymbol{z} = \boldsymbol{F}\{z_g\} \tag{5}$$

With:

$$\boldsymbol{M} = \begin{bmatrix} m_s & 0 \\ 0 & m_u \end{bmatrix} \tag{6}$$

$$\boldsymbol{L} = \begin{bmatrix} c_s & -c_s \\ -c_s & c_s \end{bmatrix} \tag{7}$$

$$\boldsymbol{K} = \begin{bmatrix} k_s & -k_s \\ -k_s & k_s + k_t \end{bmatrix} \tag{8}$$

$$\boldsymbol{F} = \begin{bmatrix} 0 \\ k_t \end{bmatrix} \tag{9}$$

The transient analysis of this model shows that two resonance frequencies are found: one in the neighbourhood of 1 Hz and one around 10 Hz. The lower frequency is associated to a motion in which the unsprung is ignored and the sprung mass bounces against the suspension and tire as two springs in series, the higher frequency is associated with a system where the sprung mass is held fixed while the unsprung mass bounces against the suspension and tire as two parallel springs. The first motion is called bounce or heave mode, while the second one is called wheel hop; when driving over an obstacle such as a bump at low speed, the impact felt by the driver in terms of displacement is major compared to an obstacle taken at high speed, where the displacement of the tire is prominent instead. A good ride quality implies adherence of the wheel to the road and minor impact felt by the driver and their passengers when driving over road irregularities.

2.1.4 Bounce-Pitch Model

From the analysis of the quarter car model, it was highlighted how the body motion (bounce mode) and unsprung motion (wheel hop mode) occur at different resonance frequencies. The simplified Bounce-Pitch model (Figure 9) considers both bounce and pitch motion of the vehicle body, ignoring any suspension or unsprung mass effect. Those effects are accounted for in the Bicycle Vibrating model (Figure 10).

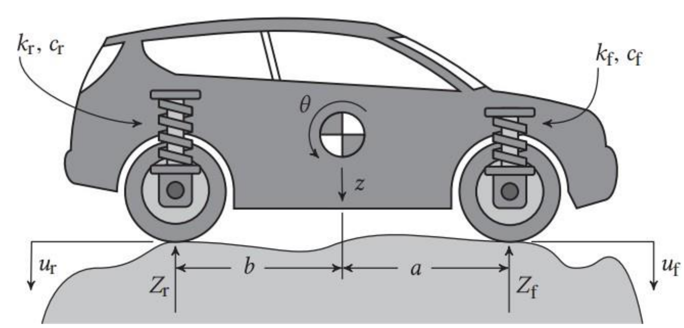


Figure 9. Bounce-Pitch Model, from [13].

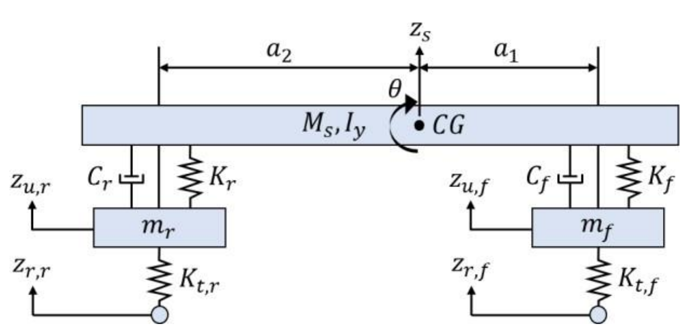


Figure 10. Bicycle Vibrating Model, from [20].

The bounce pitch model is accurate enough to provide information on the ride quality. The state variables of this model are the vertical displacement of the center of mass and the pitch angle $\boldsymbol{z} = [z \quad \theta]'$, while the input variables are the vertical displacement of the road at the front and rear axle $\boldsymbol{u} = [u_f \quad u_r]'$.

The model is described by the following equation:

$$\boldsymbol{M\ddot{z}} + \boldsymbol{L\dot{z}} + \boldsymbol{Kz} = \boldsymbol{Fu} + \boldsymbol{G\dot{u}} \tag{10}$$

With:

$$\boldsymbol{M} = \begin{bmatrix} m_s & 0 \\ 0 & I_{yy} \end{bmatrix} \tag{11}$$

$$\boldsymbol{L} = \begin{bmatrix} c_f + c_r & bc_r - ac_f \\ bc_r - ac_f & a^2 c_f + b^2 c_r \end{bmatrix} \tag{12}$$

$$\boldsymbol{K} = \begin{bmatrix} k_f + k_r & bk_r - ak_f \\ bk_r - ak_f & a^2 k_f + b^2 k_r \end{bmatrix} \tag{13}$$

$$\boldsymbol{F} = \begin{bmatrix} k_f & k_r \\ -ak_f & bk_r \end{bmatrix} \tag{14}$$

$$\boldsymbol{G} = \begin{bmatrix} c_f & c_r \\ -ac_f & bc_r \end{bmatrix} \tag{15}$$

The resonance frequencies of this model are associated with two modes: both are a combination or bounce and pitch, in different measure. For each vector $[z \quad \theta]'$, a center of oscillation *l* can be defined, whose distance from the center of mass is given by the ratio of bounce and pitch. Small values of *l* are associated to a pitch motion, while a center of oscillation which lays outside the axles means mostly bounce.

Experience has shown that most passengers find pitching motions to be more uncomfortable than bounce, so the properties are chosen to discourage pitch.

2.1.5 Full Vehicle Model

There is not just one model to represent the whole vehicle; it always depends on the aim of the study and the level of complexity deemed necessary for the analysis in question (unsprung masses were neglected on the bounce-pitch model because the goal was to carry out an analysis of the ride comfort). The aim of the model embedded in VI-CRT is to accurately predict the overall vehicle behavior for cornering, braking, and acceleration-performance studies for four-wheeled vehicles with independent-front and independent-rear suspensions.

Figure 11 represents a simplified vehicle model on VI-CRT; it consists of 5 rigid bodies: a sprung mass and four unsprung masses.

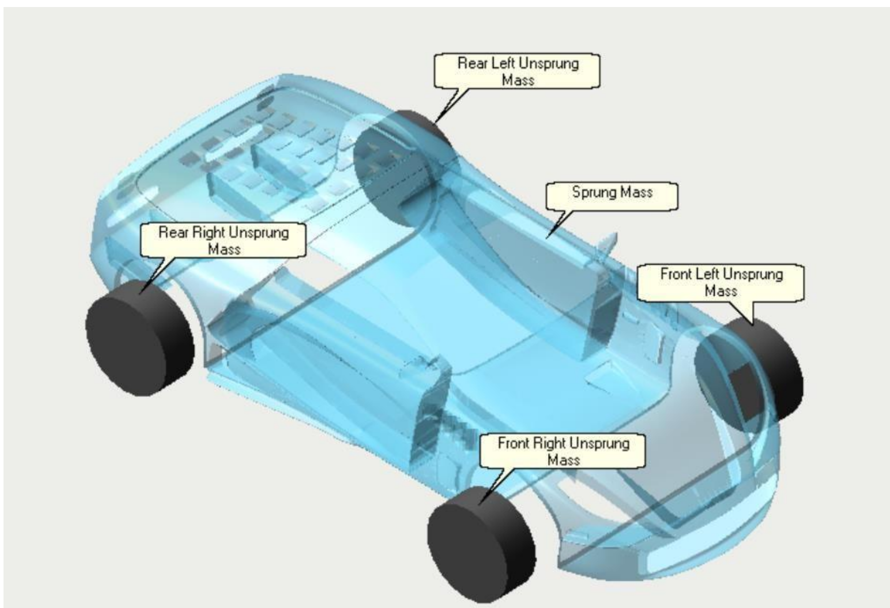


Figure 11. Vehicle model in VI-CRT. From [21]

The model has 14 degrees of freedom (DOFs): 6 for the chassis (three rotations and three translations) and 2 for each wheel (motion with respect to the vehicle body and wheel spin).

The number of DOFs in this model can be increased in the following ways:

- An additional stiffness in series to the main spring can be considered for each suspension, providing 4 further DOFs
- Body chassis torsional compliances may be included, adding up to 6 more DOFs

- For each suspension it is possible to enable an additional longitudinal degree of freedom, adding up to 4 more DOFs.

2.2 Design Features

Part of this project consisted in creating variants of a Jeep Renegade model in CRT. This was done with the intent of causing a change in the behaviour of the vehicle during a certain maneuver. The goal of this chapter is to provide the reader with a basic knowledge on the design features that were targeted, how that translates to a physical change in the mechanical components of the vehicle, and the behaviours directly affected by such change.

2.2.1 The Antiroll Bar (ARB)

The antiroll bar, also known as roll bar, anti-sway bar, sway bar or stabilizer bar, is a mechanical device used to improve the handling quality of a vehicle. It consists in a metal bar or tube with two control arms which connect together the suspensions on the right and left side of an axle (Figure 12). The metal tube is attached to the vehicle chassis in the middle, usually with rubber bushings [22, 23]. This device acts as a torsion spring, increasing the roll stiffness of the axle. The way this is achieved is by redistributing the vertical load applied on a tire between the two tires of the axle. The aim is to force each side of the vehicle to lower or rise at similar heights, reducing the roll of the vehicle on curves, sharp corners, large bumps.

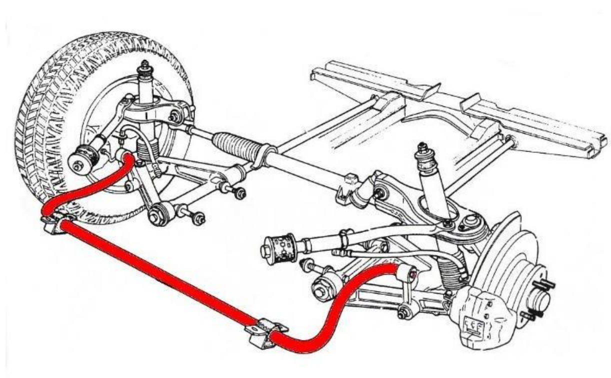


Figure 12. Antiroll bar, from [24]

The torsional stiffness of the bar affects the roll stiffness of its axle. Because the roll angle is approximately proportional to the lateral acceleration, as is the weight transfer, it is a common misconception that increasing the roll stiffness will reduce the lateral weight transfer, but this is not the case; the only thing that is reduced is the magnitude of the roll angle. A more important factor is the relative weight transfer, the ratio between front and rear axle, which is a function of the relative roll stiffness of the two axles. When the vehicle is subjected to a lateral acceleration, the tire that bears more weight is the outer one in the axle with higher roll stiffness. Upon reaching the saturation point, a loss in the lateral grip exerted by this tire is experienced (Figure 13).

- If the front axle loses grip prior to the rear one, the vehicle displays an understeering behaviour
- If the rear axle loses grip before the front one, the vehicle displays an oversteering behaviour

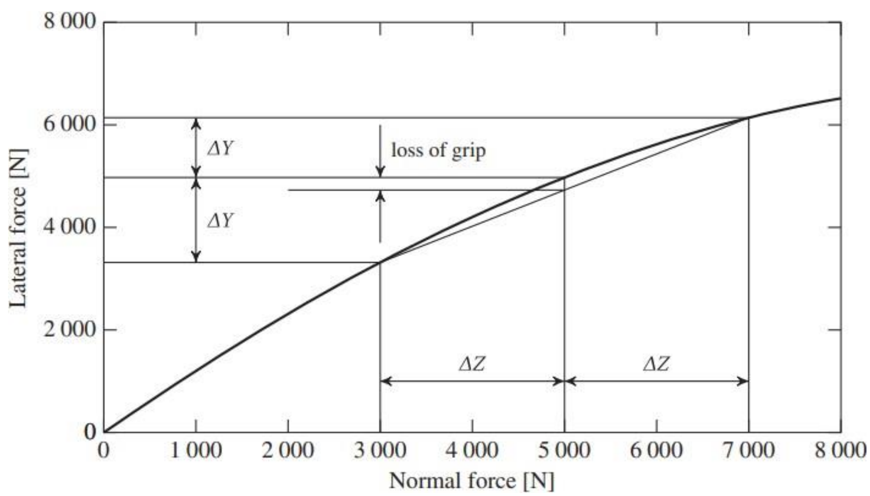


Figure 13. Lateral force exerted by the tire with respect to the normal force applied on it, from [13].

The bicycle model is used to study the equilibrium of forces acting on a car which is cornering at steady state. The following equation is found [25]:

$$\delta = \frac{57.3L}{R} + Ka_y \tag{16}$$

Where

- δ is the steer angle applied by the driver
- L is the wheelbase of the vehicle
- R is the radius of turn
- K is the understeering gradient
- a_y is the lateral acceleration experienced during turn

The understeering gradient is defined as

$$K = \frac{1}{g}\left(\frac{Z_f}{c_f} - \frac{Z_r}{c_r}\right) \tag{17}$$

With Z_f and Z_r representing the normal force applied on the front and rear axle, and g is the gravitational acceleration. Note that the ARB effects don't directly appear in the bicycle model, but only directly through changes in c_f and c_r, which in turn affect K.

Considering the same curvature radius, a vehicle will experience larger lateral acceleration if turning at higher speed. According to Eq.16, with increasing values of lateral acceleration (and longitudinal speed), if the driver wants to keep the trajectory of the curve, the steer angle applied will have to increase or decrease depending on the sign of the understeering gradient; in the first case the vehicle is understeering, in the second case it's oversteering. The sign of the understeering gradient depends on the weight borne by each axle (Eq.17).

In CRT, the ARB can either be characterized as a component of its own, or it can be included in the "Auxiliary Anti-Roll Force" panel, in the suspension subsystem, to characterize the suspension anti-roll effect. Auxiliary anti-roll forces are used in CRT to introduce the effect of elastic elements connecting left and right paired wheels (typically ARBs).

Depending on the conceptual suspension model the force is projected at the wheels as a pair of opposite vertical forces acting between the wheel (unsprung mass) and the body chassis [21].

The value of the force is related to the left/right (L/R) wheel jounce (jounce is the upward movement or compression of suspension components, rebound is the downward movement or extension of suspension components) difference and can be input using three methods:

- Rate**:** the force intensity is computed by the product of the rate value and the L/R jounce difference.
- Single Table: the force is introduced using a spline having as first independent variable (X) the L/R jounce difference (delta jounce). It is also possible to have a second independent variable (Z) which is the L/R average jounce. This allows one to take into account the non-linear behaviour of the ARB due to suspension geometry.
- Dual Table: the force is introduced using two splines having as first independent variable (X) the wheel travel of one wheel and as second independent variable (Z) the other wheel travel. The Dual Table option supports the possibility of asymmetric auxiliary anti-roll forces.

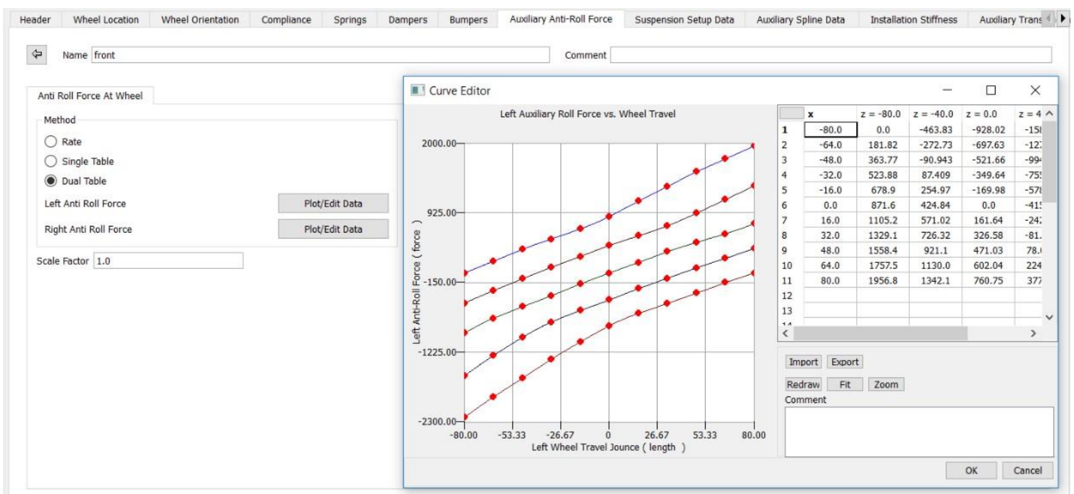


Figure 14. Auxiliary Anti-Roll Force panel, from [21].

2.2.2 The Steering System

In the case of a front wheel drive (FWD) vehicle, the function of the steering system is to steer the front wheels in response to driver command inputs in order to provide overall directional control of the vehicle. However, the actual steer angles achieved are modified by the geometry of the suspension system, the geometry and reactions within the steering system and the geometry and reactions from the drivetrain.

While the design of steering systems may vary, their functionality is similar. The design described in this chapter is the rack and pinion linkage, represented in Figure 15, because it is the kind of modelling for the steering subsystem used in CRT for the vehicle in this case study.

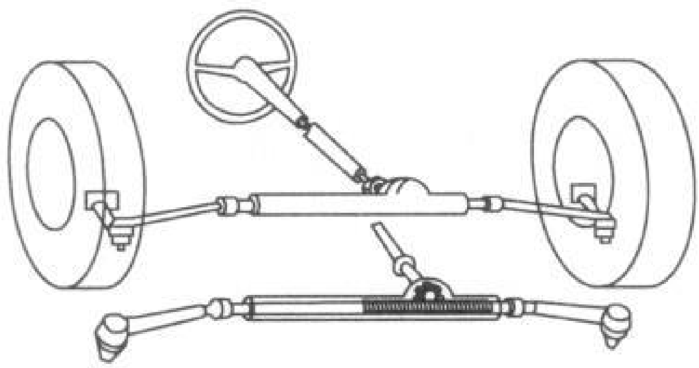


Figure 15. Rack- and- pinion linkage, from [26]

The rack and pinion system consists of a linearly moving rack and pinion, mounted on a firewall or a forward cross member, which steers the left and right wheels directly by a tie-rod connection.

A rack-and-pinion is a type of linear actuator, used to translate rotational motion into linear one. Two elements are needed: a cylindrical gear, called pinion, and a linear gear, called rack (elements 1 and 2 in Figure 16).

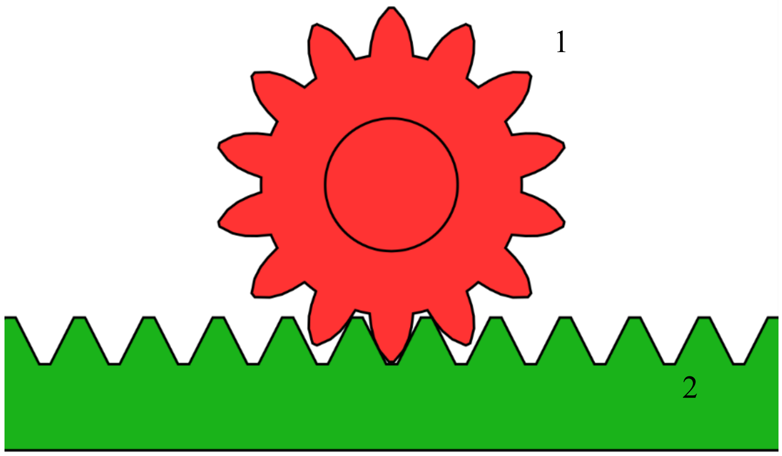
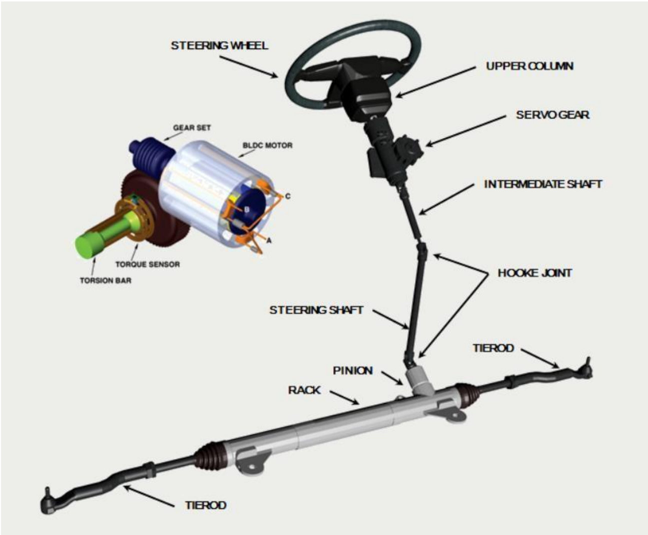


Figure 16. Rack and pinion, from [27].

The basic steering system modelling in CRT presents no physical part or linkage; the steering and other movements of the wheels are related to steering wheel (or rack) motion and wheel jounce by lookup tables. Besides the basic model, an advanced rack-pinion steering model which models the steering in terms of mechanical and electric/hydraulic components is available. This model has 2 DOFs and allows to capture the dynamics of the steering system [28]; the first DOF represents the inertia of the steering wheel down to the torsion bar and the other is the steering rack with pinion. Figure 17 shows the way the steering system is modelled on CRT and how every mechanical component is represented by a spring and/or a damper.



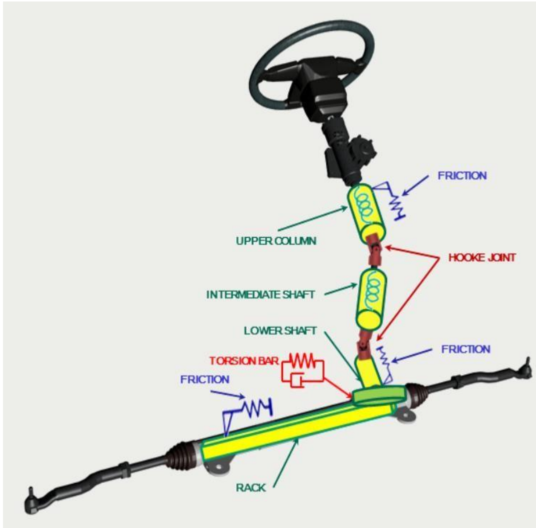


Figure 17. Advanced steering system model - Rack-and-Pinion, from [29].

With reference to Figure 17, the element of interest for this project, which is the one whose parameters were tuned, is the torsion bar.

The torsion bar is modelled as a bi-linear spring element with linear damping. Figure 18 shows the main parameters that can be modified to affect the torsion bar behaviour:

- Torsion Bar Stiffness: the stiffness of the torsion bar until the torsion bar twist limit
- Torsion Bar Twist Limit: transition value of the torsion bar twist angle for the torsion bar stiffness
- Torsion Bar Limit Stiffness: stiffness of the torsion bar when the twist limit angle is exceeded
- Torsion Bar Damping: damping of the torsion bar

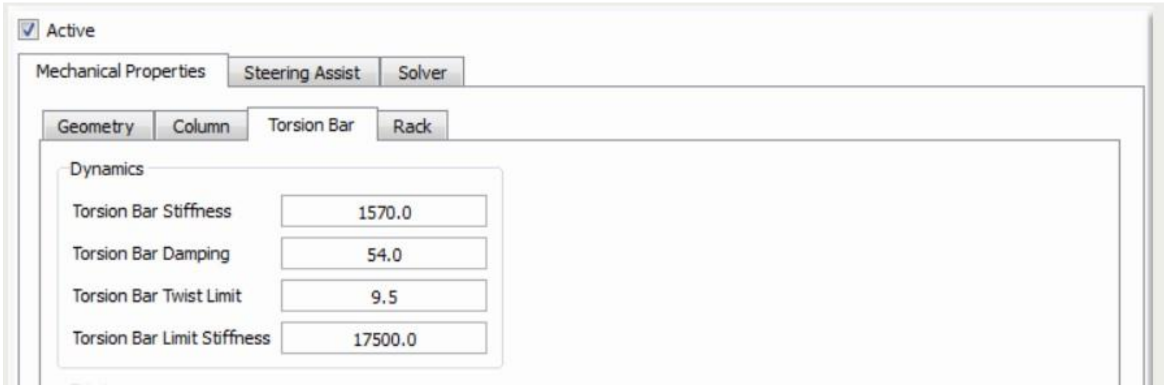


Figure 18. Torsion bar panel, from [30].

Throughout this project, the parameters of the torsion bar were altered in order to change the steering feel of the driver, like the effort required to carry out a maneuver or the steering returnability. Acting on the Torsion Bar Stiffness, specifically changes the Steering Wheel (SWT) versus Steering Wheel Angle (SWA) characteristics, which has been proved to affect the driver's assessment, as it will be explained in the next chapter.

2.2.3 Dampers

Dampers, also known as "shock absorbers", are hydraulic devices installed in vehicles' suspensions. If a suspension was to be made up of only spring elements, the energy stored when the tire overcomes a road irregularity, causing the spring to elongate or compress, would not be dissipated and the tire would keep bouncing up and down. Hence why a damping element is needed to dissipate this energy.

When describing some popular vehicle dynamics models in 2.1, damping behaviours were attributed to tires and suspensions, which were modelled using a linear relationship between force and speed.

$$F = c\dot{z} \tag{18}$$

In common applications, the damping coefficient is not constant. A real damper's force vs speed characteristics looks more like the one depicted in Figure 19.

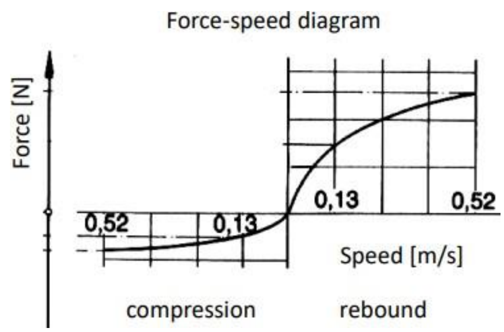


Figure 19. Force versus Speed characteristics, from [31]

There are different designs to a damper (monotube, twin tube…), but the basic functioning principle is the following: a cylinder filled with mineral oil (viscosity slightly higher than water) and gas, and a piston whose rod is linked to the rest of the suspension that slides up and down in such chamber (Figure 20). The piston presents two unidirectional valves which require a certain pressure drop for the fluid to cross them. One valve allows the piston to move downward, while the other lets the piston move upward. The design parameters of the valves can be tuned in such a way that the pressure drop required to let the oil pass in the two directions is different. The aim is to determine an asymmetric force vs speed characteristics for the damper.

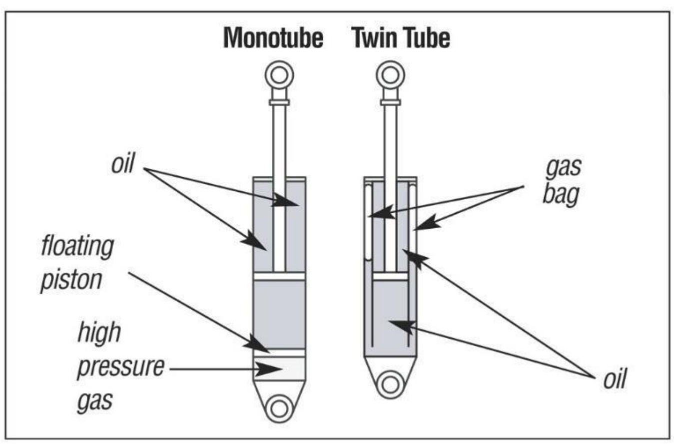


Figure 20. Two different damper designs: monotube (more expensive) and twin tube (cheaper), from [32]

The reason why dampers are designed to exert larger forces in the rebound phase is the following: in a scenario in which a tire drives over an obstacle such as a road bump, there are mainly two phases: the tire climbing up the bump, causing the suspension to compress, and the tire climbing down the bump, causing the suspension to elongate again. If dampers were to have a steeper curve in the Force vs Speed characteristics in the climb-up phase, that would translate into a higher vertical acceleration perceived by the driver, which is deemed uncomfortable. If the dampers were to exert low forces in the rebound phase, when the obstacle is overcome, that would mean more time required before the energy is dissipated, causing the car to bounce up and down. Hence why they are designed to dampen less in compression and more in rebound. However, there are some drawbacks in choosing this asymmetric characteristic, like when a roll motion is considered rather than a pitch- bounce motion. Let's picture the case in which the driver must perform a slalom maneuver. That can be broken down into a series of quick maneuvers (steer and countersteer). When cornering around the slalom obstacles, the wheels experience a load transfer. An asymmetric force vs speed characteristics might cause the bottoming of the suspensions; the out-of-band suspensions will compress more than the in-band ones extent, then, when cornering on the other side, the situation is the opposite but if the maneuver takes place very quickly, the suspensions that were prior compressed might not manage to restore the original length. Hence why in many race cars dampers are tuned to have a symmetric characteristic [31].

The vehicle model used in this project is the one of the Jeep Renegade: a FWD, front- heavy subcompact SUV, with gas-filled passive dampers. To study the test drivers' feedback to a change in the dampers, the damping curve of the vehicle was altered, but with some practical constraints; too low damping rates would make the vehicle unsuitable to dissipate disturbances, while high damping rates would basically transform the damper element into a rigid link between the wheel and the chassis, resulting in low yaw stability due to poor tire grip.

On the VI-CRT software, the Dampers panel is subdivided in two areas (Figure 21):

- Suspension data; used to project the effect of damper component at wheel center. The compression ratio method is used to convert the damper deformation to the equivalent wheel jounce, since on CRT the suspension is conceptual.

- Property file; used to describe the component's specific properties. The damping curve can either be modelled in a linear fashion, or in a non-linear one (more accurate). VI-CarRealTime solver supports both 2D damper and 3D damper curves. 2D damper curve defines the damper element force as a function of damper velocity (positive in extension); 3D damper curve defines the damper element force as a function of damper velocity (first independent variable, positive in extension) and damper displacement (second independent variable, positive in extension). Damper displacement is the damper deflection with respect to the design condition (0 damper displacement) [33].

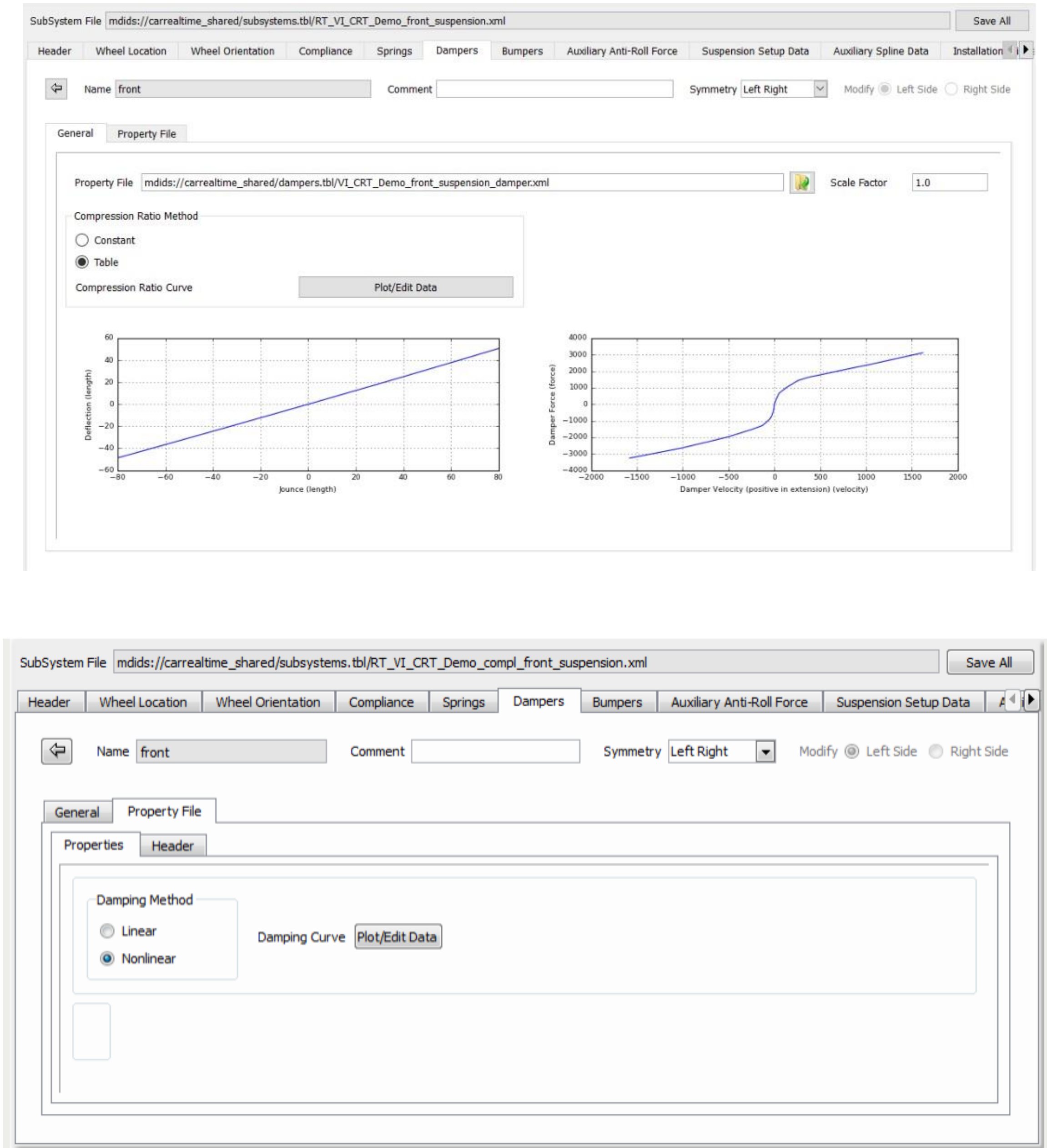


Figure 21. Dampers panels on CRT, from [33].

CHAPTER 3

Literature Review

The preliminary research conducted before the experimental part of this project was articulated in four main sections:

1) Driving simulators and subjective assessment tests
2) Correlation between objective metrics (OMs) and subjective assessment (SA)
3) Test maneuvers
4) Non-professional drivers on simulators

The first section was aimed at building a general background knowledge of the technology involved and the state of the art for the subjective assessment testing.

The way in which the case study of this project was approached consists in an extensive testing procedure; in the first stage it was only virtual, and then on the simulator with test engineers. Running virtual simulations implies not only being able set up a model and a maneuver scenario, but also provide an interpretation of the results; that is not a straightforward process because it requires correlating an objective field (numerical data) with a subjective one (the drivers' feel and perception). Reading about previous studies (that will be listed throughout this chapter) in which the link among some objective metrics and the drivers' feedback was experimentally found served this purpose.

The maneuvers employed for subjective assessment studies are multiple and follow different standards. Each maneuver highlights a vehicle behavior and is a good indicator of how the vehicle will behave in a certain scenario. The third section of the literature review was aimed at learning about the different standards and goals of SA maneuvers.

The goal of the fourth section of the literature review is to know where the current research about the driver-simulator interaction stands and evaluate the possibility of future introduction of non-professional drivers in the development phase of a vehicle.

The four sections were listed following the chronological order of the research process that led to the elaboration of the final methodology, but in order to provide the reader with the background necessary to understand the work that was done and why some experiments were carried out, sections 1, 2 and 3 are the most important at this stage and the way in which information is delivered in this chapter aims at building up towards an organic, logic understanding of the experimental set up and the design choices made during the offline virtual simulation stage.

3.1 Subjective Assessment Testing

Subjective evaluation of vehicles during the development process requires highly skilled and experienced test drivers because they can understand each question thoroughly by connecting them with the sensations perceived during the tests, performing more advanced maneuvers and still having enough mental capacity left for evaluation and to show lower variation in their subjective assessment (SA) [34]. Typical drivers may spend many years honing their abilities by accumulating thousands of hours of driving seat time on vehicles. Development of vehicles through subjective means remains the critical aspect of a vehicle design cycle – it is inevitably a human driver that ultimately decides whether a car performs suitably. Besides being the final sign-off test, subjective evaluations also remain one of the most reliable methods of obtaining good handling qualities during design and development. Vehicle dynamics, and more specifically steering and handling, cannot yet totally be completely described analytically and by performance criteria. These objective parameters are necessary to understand and improve the vehicular system; however, to understand the 'vehicle-driver' system, the subjective driving experience must be included in the evaluation.

An experienced test driver is often able to suggest changes after a relatively short evaluation which will result in improved handling. Often modifications will be made to the suspension, tires, chassis and steering system which would have not presented themselves through objective evaluations [35].

Subjective assessment tests are usually carried out following standard maneuvers. The standards can be federal, International Standards Organization (ISO), or even just within the company itself. There are two main ways to classify maneuvers: open/closed loop and "situational".

- During open loop maneuvers, the driver's input (throttle, brake, steering wheel angle) is prescribed to them. Most of the time, these maneuvers are employed for virtual testing and objective evaluations (e.g., after running an ISO Transition Test, some characteristics can be extracted from a Steering Wheel Torque vs Steering Wheel Angle graph, such as steering stiffness and steering wheel angle dead band [36]). During closed loop maneuvers, the driver is asked to perform a task (e.g., a slalom maneuver), usually with a prescribed longitudinal speed.

- During a "situational" maneuver, common driving scenarios are reproduced. There are three main categories: routine handling, highway handling, and limit maneuvers. They mostly differ in longitudinal speed and lateral acceleration.

Experiments have been conducted throughout the years to better understand the links between subjective and objective measures of vehicle handling, employing an extensive program of instrumented testing and driver evaluations, which were correlated via advanced statistical tools. Each driver has a different rating tendency; some drivers are more conservative with their scores, and some use a wider band of the rating scale, for example. However, it has been noted that some metrics have a consistently positive or consistently negative effect on the driver's feedback [35]. This information can be utilized by engineers to incorporate favourable handling characteristics in the early stages of design then as the basis for troubleshooting problems which arise in the later stages of vehicle development.

During subjective assessment procedures, the driver is prescribed one or more maneuvers to perform and then is asked to rate some aspects of the vehicle behaviour. In the case of an expert driver, they're usually provided with a 10-point rating scale and the target behaviour. Figure 22 is an example of a subjective assessment questionnaire [20].

In addition to the numeric rating, drivers are invited to leave comments and suggestions.

1. Straight Braking: 130 kph for 2sec, fully apply brakes (let go at 45kph), 2 runs

		Subjective Rating									
Mode 1	**Target**	Intolerable	Severe	Very Poor	Poor	Marginal	Barely Acc.	Fair	Good	Very Good	Excellent
Pitch Abruptness (ride) Evaluate the magnitude of the pitch motion in response to the braking input (focus on pitch acceleration).	Less Abrupt / Slower	1	2	3	4	5	6	7	8	9	10
Pitch Delay (handling) Evaluate the delay between the braking input and the pitch angle to reach steady state.	Minimal to No Delay	1	2	3	4	5	6	7	8	9	10

Figure 22. Example of SA questionnaire from [14]

3.1.1 Subjective Assessment Testing on the Simulator

The introduction of dynamic driving simulators in the development process is recent, so there still isn't a structured subjective assessment testing procedure. Common practice is that at least two drivers perform the test, make observations, and provide feedback. Usually, the development process is focused on tuning a specific design feature (e.g., dampers), so the maneuvers are chosen specifically to focus on the component(s) of interest (e.g., transient maneuvers involving roll and pitch or ride events).

As far as the company is concerned, when making a general vehicle assessment, there is a list of vehicle behaviour qualities to assess called a "Quality Profile", to which all the brands of the group should conform. Even though reference maneuvers are used, the highly subjective nature of this study does not leave much room for standardization. As mentioned in section 1.3, each driver has different gains values set in the motion cueing algorithm that depend on their individual sensitivity and perception thresholds, and in some cases they could slightly modify the prescribed maneuver if they feel like that would give them a better feel of the targeted vehicle behaviour.

One factor that can cause a bias in the subjective assessment between drivers is the type of training they underwent. They might have been instructed to seek a behaviour that makes the car safe and easy to drive for the average customer, or maybe they were taught to research for the brand identity. Furthermore, even among drivers who trained to become professionals, personal preferences play a role in the way they will interpret the questions and the kind of feedback they will provide.

3.2 Ride and Handling

The goal during the development process as far as the Vehicle Dynamics department is concerned is to ensure the final product has good ride and handling quality.

Ride is considered the motion environment involving the vehicle's vibration, shock, and translational and rotational accelerations in response to road excitations [37]. What mainly ensures a good ride feel is the ability of the vehicle's suspension to accommodate varying terrain while maintaining passenger comfort. Such comfort is mostly linked to the accelerations felt by the driver in the vertical, lateral, longitudinal, as well as the pitch and roll directions [20].

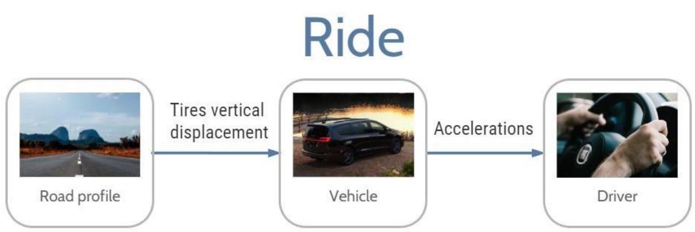


Figure 23. Ride (i.e., the study of the effect that road irregularities have on the driver)

While the study of ride is focused on the effect that the road irregularities have on the driver, the study of handling almost follows the opposite path; the main concern being the response of the vehicle to inputs from the driver [25]. The inputs considered are steering wheel angle, the position of accelerator or throttle, and the position of the brake pedal. The responsiveness of the vehicle generally consists of the magnitude of the vehicle's response characteristics and the delay of the response to driver inputs [20]. Directional stability is also a very important parameter for a good handling quality.

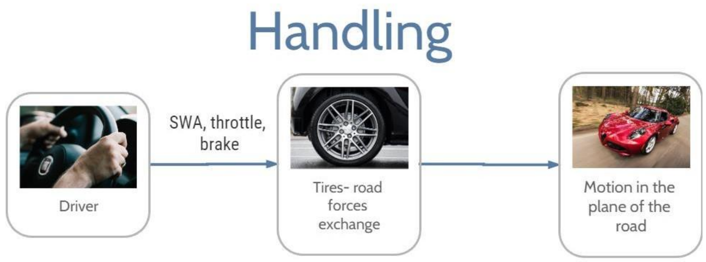


Figure 24. Handling (i.e., the study of the response of the vehicle to inputs from the driver)

A superior handling quality indicates that the vehicle reaches the motion state required by the driver more accurately and rapidly, while a superior stability indicates that the vehicle can rapidly restore the original motion state under external interference when it is running [38].

3.2.1 OMs and Tests Related to Ride and Handling Characteristics

In this section, the effect of some metrics on the handling behaviour perceived by the driver is reported, alongside with test procedures that have been elaborated precisely for the sake of evaluating a certain behaviour.

3.2.1.1 Yaw response

In [39], Jaksch led an investigation in which both theoretical analyses and experimental tests were comprised. The tests involved measuring of vehicle characteristics, subjective rating of steering control quality and measuring the performance of the system driver- vehicle, regarding the ability to follow a predicted course. Results have shown that there is a strong relationship between yaw velocity response time, steering wheel angle gradient and subjective rating. The results also show that yaw velocity response time is the dominating factor and greatly influences control quality in transient steering maneuvers with relatively high acceleration.

3.2.1.2 Roll Gradient

Huang and Tsai [38] constructed a full-vehicle analysis model incorporating a Short Long Arm strut front suspension system and a multi-link rear suspension system. A constant radius cornering simulation was run offline and compared with the experimental results. In the journal article about their work, the main objective metrics used to evaluate the performance of the vehicle are listed. The maneuver of their case study is a steady state one, while the slalom is highly transient, but some considerations still apply. The considerations made about an objective metrics called “Roll Gradient” are still very valid even for a transient test.

The Roll Gradient is the ratio between roll angle and lateral acceleration. An excessive roll angle degrades the vehicle stability and hence limits the ability of the driver to respond to any contingencies when steering around the corner. In extreme cases, the vehicle may even overturn. By contrast, a small roll angle increases the vehicle turning radius and reduces the offside wheel grip capability.

3.2.1.3 Phasing of Tire Forces

Another metric tightly linked to the driver’s perception during transient cornering is the phasing of tire forces. The effect of the phase lag is to allow the vehicle to yaw and change direction while moderating the level of lateral acceleration by spreading the acceleration over a longer time period. With passenger cars this effect contributes to a perception of lack of responsiveness (or sluggishness) in transient cornering [25].

3.2.1.4 Roll and Pitch Magnitude

Motion sickness caused by 0.2 Hz roll and pitch oscillation is dependent on the magnitude of the motion, with a trend for illness ratings to increase with increasing magnitude. The lowest magnitude of both roll and pitch oscillation caused the least sickness and the intermediate and higher magnitudes caused greater sickness. There were no significant differences in either illness ratings or symptoms caused by pitch and roll oscillation and the magnitudes studied [40].

3.2.1.5 On-center Handling

On-center Handling refers to the steering behaviour on and about the straight ahead driving position, and is important at high speeds. Passenger cars and commercial vehicles spend large percentage of their life under state and national highway conditions, at longitudinal speeds on the order of 100 kph.

One of the common driving situations is driving along a straight section (no lane change) of a highway at a very high speed characterized by low lateral acceleration. The ease and confidence with which a vehicle can be driven in such a situation is important. The vehicle behaviour on and about the “straight-ahead” driving position is referred to as On-Center Handling (OCH). A vehicle having poor OCH behaviour requires continuous steering inputs. Such a situation prevents the driver from getting true bearing of the vehicle and is not desirable [41]. Highway driving, during which OCH is an issue, can be simulated under test conditions using a weave test. Therefore, the weave maneuver is useful for judging vehicle characteristics; it consists in applying a sinusoidal steering input with a frequency of 0.2 Hz at a constant vehicle longitudinal speed of 100 kph. The steering wheel amplitude must be determined to produce a lateral acceleration of 2 m/s^2 [42].

The studies conducted in [43], [44] report a correlation between the subjective feel and the hysteresis width in the following graphs, represented in Figure 25:

- Lateral acceleration versus Steering torque
- Steering torque versus Steering angle

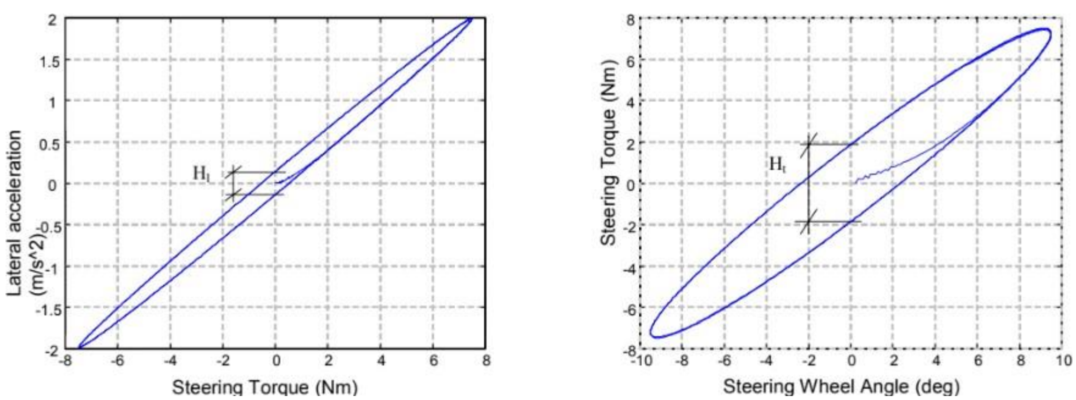
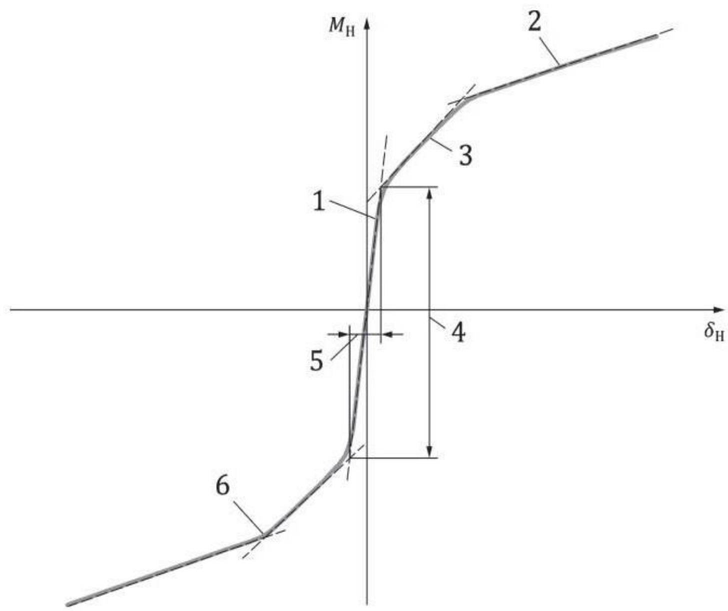


Figure 25. Lateral acceleration versus SWT and SWT versus SWA, from [41].

On center handling is concerned primarily with features that directly influence the driver's steering input, such as steering system and tire characteristics. Thus, test schedules for the evaluation of on-center handling seek to minimize other factors that influence wider aspects of straight line directional stability, such as disturbance inputs due to ambient winds and road irregularities.

One of the test methods theorized by the International Organization for Standardization (ISO) to quantify the on center handling characteristics of a vehicle is the so called Transition Test; an open-loop procedure and is conducted from an initial straight-line path. The vehicle is driven at a nominally constant longitudinal velocity. The standard test velocity is 100 km/h. Other longitudinal velocities may be used; these should be decremented or incremented by 20 km/h from the standard velocity. Commencing at time t_0, the steering input shall be applied for a minimum duration of 3 s, and at an angular velocity not exceeding 5º/s, until the lateral acceleration achieved by the vehicle reaches a minimum of 1,5 m/s^2.

When plotting the results of an ISO Transition Test, the SWT versus SWA plot can be used to evaluate six characteristics (Figure 26).



Key

1 steering stiffness
2 steering-wheel torque gradient – off-centre
3 steering-wheel torque gradient – on-centre
4 steering-wheel torque deadband
5 steering-wheel angle deadband
6 steering-wheel torque gradient breakpoint

Figure 26. SWT versus SWA in ISO Transition Test [36]

3.2.1.6 RSI Metrics

The Frequency Sweep Metrics, also sometimes referred to a "Random Steer Input" or "RSI" metrics, are useful to objectively study the transient handling behavior of vehicles, going beyond the study of steady state handling. The responses of the vehicle are measured with steering input frequency ranging from 0-4 Hz (although, only 0-2Hz is realistically encountered in real world driving), at varying levels of lateral acceleration and speed, and the results are expressed in terms of response gains and delay times of main relevant parameters (lateral acceleration, yaw rate, sideslip, roll, and steering torque), relative to steering wheel input and lateral acceleration.

An understanding of the interpretation of this data can help objectively define and study the way a vehicle responds, the behavior of the front and rear axles, the roll response characteristics, and also the steering characteristics, in transient conditions before a steady state is reached. These methods not only study the capability of the vehicle, but how the vehicle arrives at its ultimate capability, and also how it behaves in routine handling. The phenomenon known as "phase lag", or "how well is the front connected to the rear", can now be objectively studied using this method [45].

3.2.1.7 Ride

In [20], a study was conducted on the same dynamic driving simulator DiM-250; the goal was to evaluate ride and handling with different damper settings, determining the sensitivity of the simulator to such changes, and developing procedures for subjective evaluation methods. Using as reference another study [46], just the low-damping region of the dampers characteristics was altered, because it is the more impactful one for the ride and handling performance of a vehicle. One of the ride events that was used in the simulations was the Cleat Test; a method established by Fiat to measure the impact harshness. It consists in driving on a 25 mm high by 100 mm long cleat [45]. Sinasac[20] used this test with the intent to obtain feedback from drivers on secondary ride, encompassing motions in the frequency range of 5 to 20 Hz. The OMs more tightly linked to the driver's feedback were:

- Peak to peak (P2P) Sprung mass vertical acceleration
- P2P Sprung mass vertical displacement
- P2P Unsprung mass vertical displacement

CHAPTER 4

Methodology

For this research, two vehicle development teams were involved: one representing Europe, one representing North America. For each team, two engineers performed a subjective assessment test on the DiM 250 and their feedback was compared.

The subjective assessment test included eight different maneuvers, with the intent of targeting a wide range on SA items. A big part of the questionnaire was dedicated to open questions, in which the driver expressed their feedback in some detail (i.e. beyond a numeric rating).

For each maneuver, a Jeep Renegade and two variants were used in the assessment. The Jeep Renegade was chosen because it represents the intersection between European and North American vehicle markets, being a vehicle developed in Italy but with which both areas are familiar. The Jeep Renegade is a crossover SUV, therefore designed for more extreme conditions than the regular urban driving operations. The original concept of the Jeep itself was of a light, capable and durable vehicle that could be used for reconnaissance operations by the US army in the Second World War [47]. The acronym SUV stands for "Sport Utility Vehicle"; a class of automobiles that combines elements of road going passenger cars with features from off-road vehicles [48].

To have a better outlook on the driver's opinions and preferences, two variants of the car were created for each maneuver which react differently to a targeted behaviour. For example, if the driver is asked to run a constant radius cornering test and assess the understeering behaviour of the car, two variants were created: one which understeers less than the baseline, one that understeers more than the baseline.

The aim of these alterations was to obtain a wide range of OM configurations, in order to force the driver to compare variations of the vehicle model to bring out more observations and suggestions, to investigate driver subjectivity and to recognize key factors affecting SA.

4.1 Maneuvers

As anticipated in the introduction of this chapter, two couples of professional drivers from Europe and North America were involved in this project. They both underwent an extensive testing procedure comprised of 8 maneuvers run on the dynamic driving simulator, followed by a questionnaire and some open questions.

When choosing maneuvers for the subjective assessment test, the company's quality profile was used as guide to select a list of vehicle behaviours to assess, which will be referred to as "items". Maneuvers were selected to make it easier for the driver to assess an item, until all items on the list were complete.

Prior to choosing maneuvers, the list of items was rearranged in the following three groups:

1) Steering feel: the objective metrics (OMs) of these assessments always involve steering wheel torque and angle (SWT and SWA)
2) Handling: the OMs related to these assessments always involve the steering wheel angle input and vehicle yaw/ roll behaviour
3) Bounce and pitch motion.

Every maneuver allows the assessment of more than one SA item, but in this case the starting point was picking a small group of items to assess, and then decide which maneuver would highlight the behaviour in study.

Another criterion to pick the maneuvers was trying to include both open loop and closed loop as well as maneuvers at different levels of lateral acceleration. The final list is given in Table 3.

Table 3. Maneuvers list and the targeted vehicle behaviour.

Maneuver	Focus
Slalom	Lateral stability in highly transient conditions
Constant Radius Cornering- with acceleration and braking	Cornering behaviour
Fishhook Test	Roll stability limit
Straight and Braking	Behaviour in braking
On Centre Weave Test	Straight ahead stability
Frequency Sweep	Steering feel
Cleat Test	Ride

4.2 Choice of Vehicle Variants

When constructing the vehicle variant models for drivers to assess alongside the baseline model of the Jeep for each maneuver, these three steps were followed:

1) Selection of the OMs more tightly linked to the driver's feedback on a SA item
2) Targeting one or more of the design features that impacts more OMs
3) Parameter(s) tuning until there is a noticeable change in behaviour among the variant and the baseline

To summarize the process, the following example is provided. One of the questions given to the driver is "Evaluate the understeering behaviour of the car". One OM that can provide the designer with more meaningful information about this behaviour is the time history of the steering wheel angle in a constant radius cornering maneuver at increasing longitudinal speed. This scenario can be reproduced on a virtual simulation on the software VI- CarRealTime, and the graph SWA vs Time (or vs Longitudinal Speed) can be retrieved.

One factor that affects the attitude of a vehicle (understeering/oversteering) is the relative axle roll stiffness. If the front axle is stiffer than the rear, this can lead to an understeering behaviour, while on the other end, a stiffer rear axle causes the car to oversteer. The reason is that when cornering, a larger fraction of the weight transfer will be borne by the stiffer axle which, in turn, loses grip compared to the softer axle upon reaching saturation.

In order to change the relative axle roll stiffness, the parameters that can be tuned are the stiffness of the anti-roll bar on the front and rear. By iteratively adjusting the anti-roll stiffness, the results of the virtual simulations reveal the changing attitude of the vehicle and the magnitude of the change.

Figure 27 illustrates the variants' response to tuning of the brake pressure distribution to achieve a variant that pitches less upon braking and one that pitches more, as compared to the baseline.

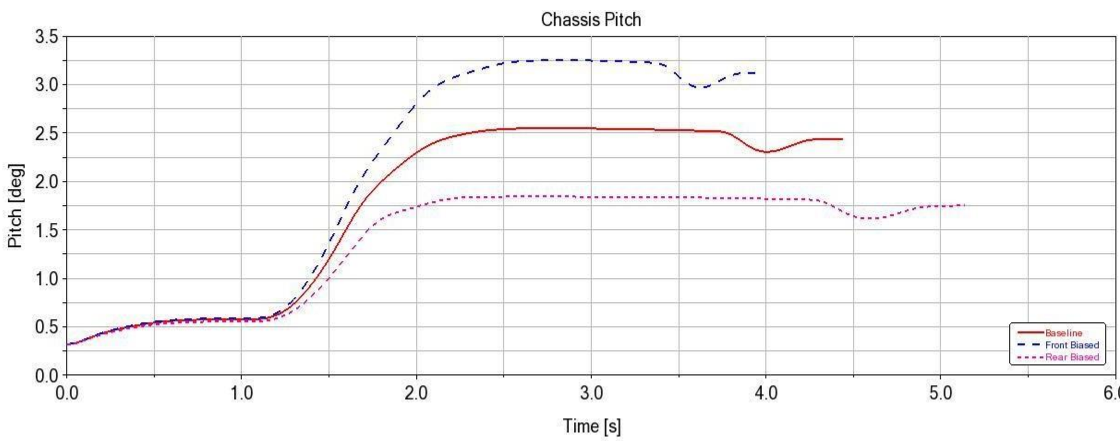


Figure 27. Time history of pitch angle in a straight and braking maneuver

To know which OMs to focus on when developing the variants, the results of experiments aimed at finding the correlation between SA and OM were used as a reference. What follows is the detailed description of each maneuver, the variants modelled and the offline simulations run prior the test on the driving simulator.

4.3 Slalom

A slalom consists in driving in a winding path trying to avoid obstacles (cones, in this case). The idea for this maneuver came from the Performance Engineer's Handbook [45], a guide meant for FCA test drivers which lists maneuvers that could be used to test a vehicle physical prototype along with suggestions on what the driver should focus on during each test. This maneuver is meant to take place on the Chrysler Proving Grounds (CGP), in Arizona, Michigan and Florida [49]. The database of the company has a virtual reproduction of these locations, which is loaded on the simulator, projected around it and used as a scenario for development and validation testing of new vehicles.

The purpose of a slalom maneuver is to assess the vehicle handling and lateral stability in a highly transient condition, gauging the combination of roll, yaw and steering feel as the vehicle approaches the limit. For this test, the driver enters at 70 kph the slalom through the "gate" which consists of three cones. Then, the vehicle is driven at nearly constant speed through a set of cones aligned in a straight path. The driver should attempt to repeat the maneuver at higher longitudinal speeds. The spacing between the cones is constant and the vehicle speed is increased after each successful run. The slalom is marked by 7 cones that are spaced 30.5 meters apart. When starting at 70 kph, the vehicle is still below its limit. The aim of the driver in the following attempts is to reach the limit.

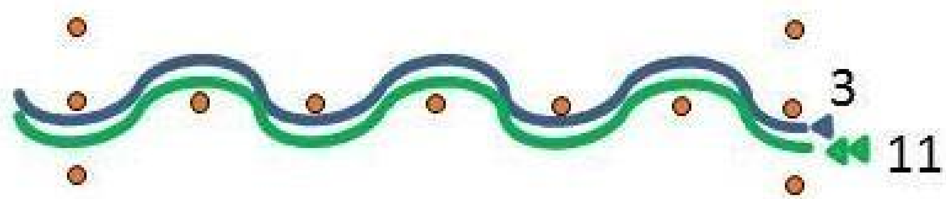


Figure 28. Representation of the slalom maneuver, taken from [45].

In [45] the driver is suggested to pay attention to how linear the steering feels and the presence of compliant yaw or "rear steer" sensation along with linearity, rate and magnitude of body roll.

As far as the questionnaire for this project is concerned, the focus is on yaw and roll response, as well as steering sensitivity. The behaviours that test drivers were requested to assess are the following:

- The vehicle sensitivity to the steering input
- The promptness of the vehicle
- The rolling behaviour of the vehicle
- The response lag between front and rear axle

As mentioned in the Literature Review, many efforts have been made to link objective metrics and subjective assessment. The main objective metrics that were used as a reference during the offline simulations when creating the variants to the baseline were chosen based on [39], [38], [25]. Despite the trajectory of the vehicle in a slalom is curvy (Figure 28), the plot of the steering wheel angle in time is more of a zig-zag line. In such a maneuver, it is important for the driver to precisely follow a trajectory without hitting the cones, and that the vehicle is stable and promptly responds when counter steering. In this test, precision, promptness and stability are the focus. The OMs that were deemed more significant to interpret the behaviour of the car via offline simulations are the yaw rate response, the roll gradient and roll angle.

4.3.1 Offline Simulation

When tuning the variants of the baseline to propose to the drivers for the slalom, the maneuver chosen as a reference for the offline simulations was the Impulse Steering Test; this kind of test evaluates the transient response of a vehicle during cornering at a constant speed set at approximately 70% of the maximum speed. In performing the test, a Gaussian pulse steering angle is applied to the steering wheel and, upon reaching an angle of 30 degrees, the wheel is returned quickly to the origin and then held still as the vehicle continues straight running in the forward direction. For the offline simulation, the duration of the impulse is set at 1 second. Figure 29 represents the trajectory taken by a vehicle when a Gaussian pulse steering angle is applied.

Figure 29.The trajectory of a vehicle subjected to an impulse steering wheel angle input [38].

4.3.2 Variants

When trying different variants for this test, the main parameter on which to base the final decision was the Roll Gradient. In Figure 30, the rotational displacement around the longitudinal was plotted against the lateral acceleration measured at the body center of mass. Numerically, the results do not change compared to plotting the roll angle of the chassis and the lateral acceleration. The points in which the Roll Gradient (given by the ratio of roll angle and lateral acceleration) was measured is the one at the peak of lateral acceleration. In Figure 30, the points used as a reference are circled.

In Table 4, the value of roll gradient at peak acceleration for the baseline and variants are reported.

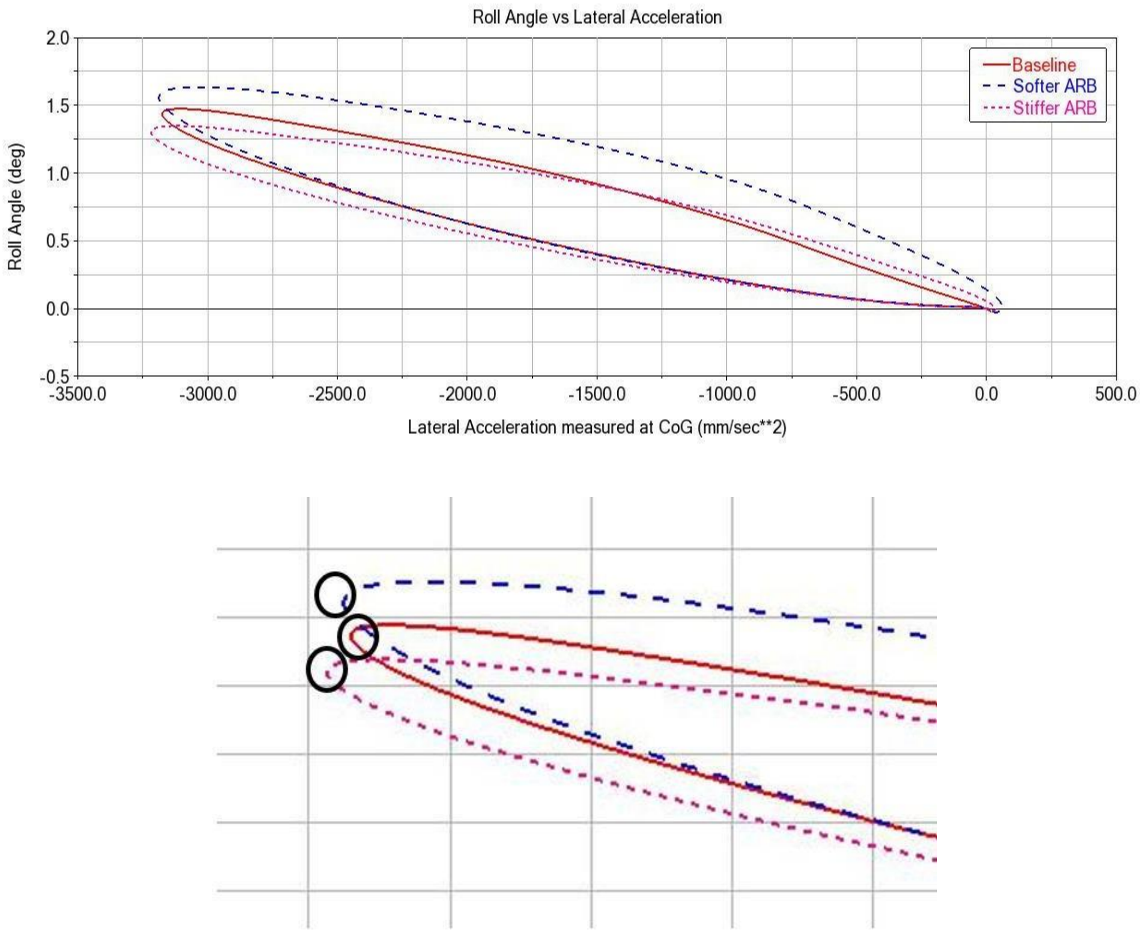


Figure 30. Roll Gradient in an Impulse Steering maneuver

Table 4. Roll Gradient at peak acceleration for the baseline vehicle and variants.

Model	Roll Gradient @ Peak lateral acceleration [deg s^2 m^{-1}]
Baseline	-4430
Variant 1 – Softer ARB	-4800
Variant 2 – Stiffer ARB	-3990

A different roll gradient was achieved between the baseline and the variants by tuning the stiffness of the anti-roll bar (ARB). That is done by modifying the suspension subsystem of the Jeep Renegade model on CarRealTime in the section “Auxiliary Anti Roll Forces”. Auxiliary anti roll forces are used in VI-CarRealTime to introduce the effect of elastic elements connecting left and right paired wheels (typically ARBs). Depending on the conceptual suspension model the force is projected at the wheels as a pair of opposite vertical forces acting between the wheel (unsprung mass) and the body chassis. In the baseline model, the anti-roll force at wheel was modelled with a dual table. In order to make the variants, a Rate method was used to make tuning easier.

With reference to Figure 30:

- The variant named “Softer ARB” has a rate of 17000 N/m in both front and rear axle
- The variant named “Stiffer ARB” has a rate of 27000 N/m in both front and rear axle

Tuning the ARB stiffness also implies that a different peak roll angle is reached. As shown in Figure 31, the Softer ARB variant is the one that rolls more, while the Stiffer ARB variant rolls less.

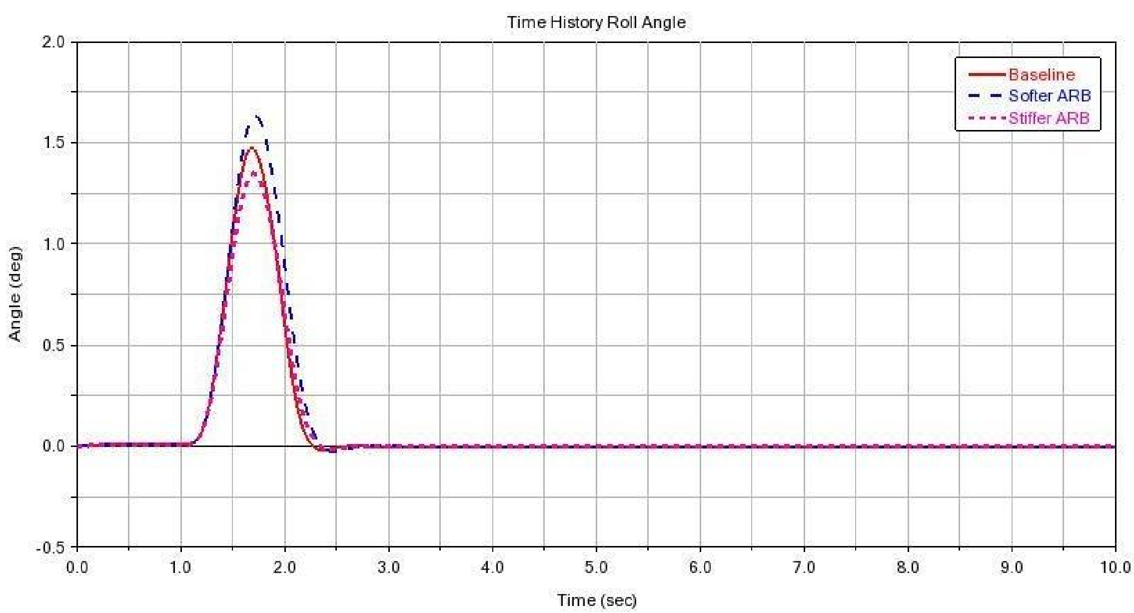


Figure 31. Time history of roll angle in an impulse steer test

4.4 Constant Radius Cornering (CRC) Test

The CRC test is an experimental method to compute the understeering gradient of a vehicle, defined by SAE as "The quantity obtained by subtracting the Ackerman steer angle gradient from the ratio of the steering wheel angle gradient to the overall steering ratio" [50]. Understeer is a steady state property of the vehicle. The CRC test consists in driving around a constant radius turn and observing how the steering wheel angle changes with the lateral acceleration, when slowly increasing the longitudinal speed (typically 0.1g increments of the lateral acceleration) [51].

For this study, a variation of the CRC test was used so that a common driving situation such as entering and exiting a highway from a ramp is reproduced. In [45] a similar test is described in which the driver is required to experiment different values of throttle, brake and steer while maintaining the circular path in the 300 feet diameter circle painted on the asphalt in the company proving grounds. The aim is to assess oversteer or understeer behavior while approaching a limit condition.

For the CRC maneuver in this study, the 300 feet circle in the proving ground was still employed, but a more precise description of the operations to follow was provided to the driver: they should approach the circle at a speed of 80 kph, lift throttle upon reaching the circle and brake until a speed of 40 kph is achieved, while attempting to maintain a straight path along the circle, then accelerating until the initial speed is reached again. Both braking and acceleration are in closed loop. The time taken to perform the maneuver is to be recorded and compared among the baseline and the variants; it can be an indicator of the stability of the vehicle during acceleration/ braking in cornering and of the easiness and confidence of the driver when negotiating the maneuver.

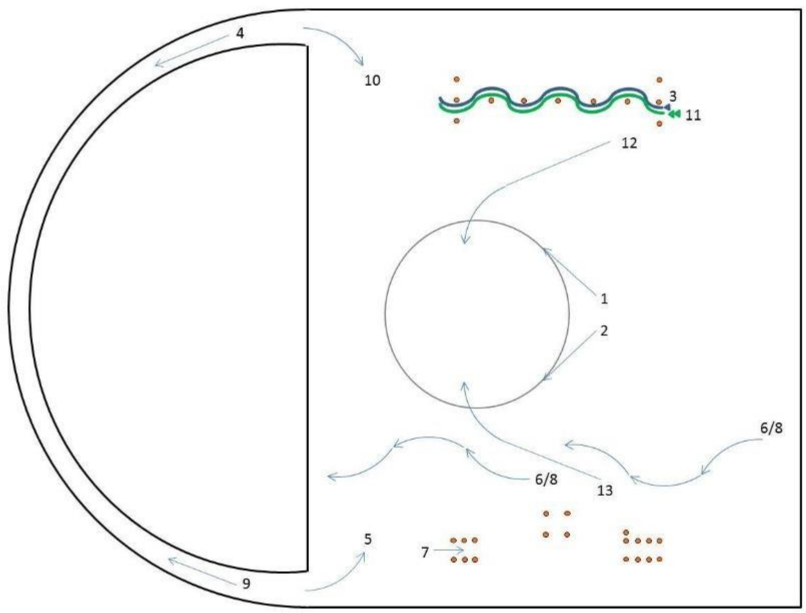


Figure 32. Map of the CPG

The items to assess for this maneuver are the following:

- The understeering attitude of the vehicle
- The easiness in maintaining the trajectory when cornering
- The predictability of the steering progression when cornering
- The rolling behavior of the vehicle

4.4.1 Variants

A simple CRC test was run as an offline simulation when tuning the variants for this test. In 4.2, it was explained as an example how to achieve an understeering/oversteering behaviour tuning the relative axle stiffness. The way in which this was done was through the ARB stiffness, as described in Section 4.3.2.

- The variant named “CRC Variant 1” has a rate of 60000 N/m at the front axle and a rate of 2000 N/m at the rear axle
- The variant named “CRC Variant 2” has a rate of 15000 N/m at the front axle and a rate of 40000 N/m at the rear axle

Figure 33 shows how Variant 2, with a stiffer rear ARB, has a remarkably oversteering behaviour compared to the baseline which is consistent throughout the maneuver, while Variant 1, with a stiffer front ARB, is slightly more oversteering than the Jeep baseline at low speeds, and then transitions to a high understeering behavior, leading to instability (later verified on the simulator by test drivers). The deviation in behaviour of the variants from the baseline isn't symmetrical but changing the vehicle attitude is not a process as straightforward as it is for other vehicle behaviours (like pitching and rolling); acting on the relative axle stiffness achieves a change in attitude, but not in a linear fashion because ultimately that depends on the interaction of multiple design components. Furthermore, the baseline already displays an understeering behaviour.

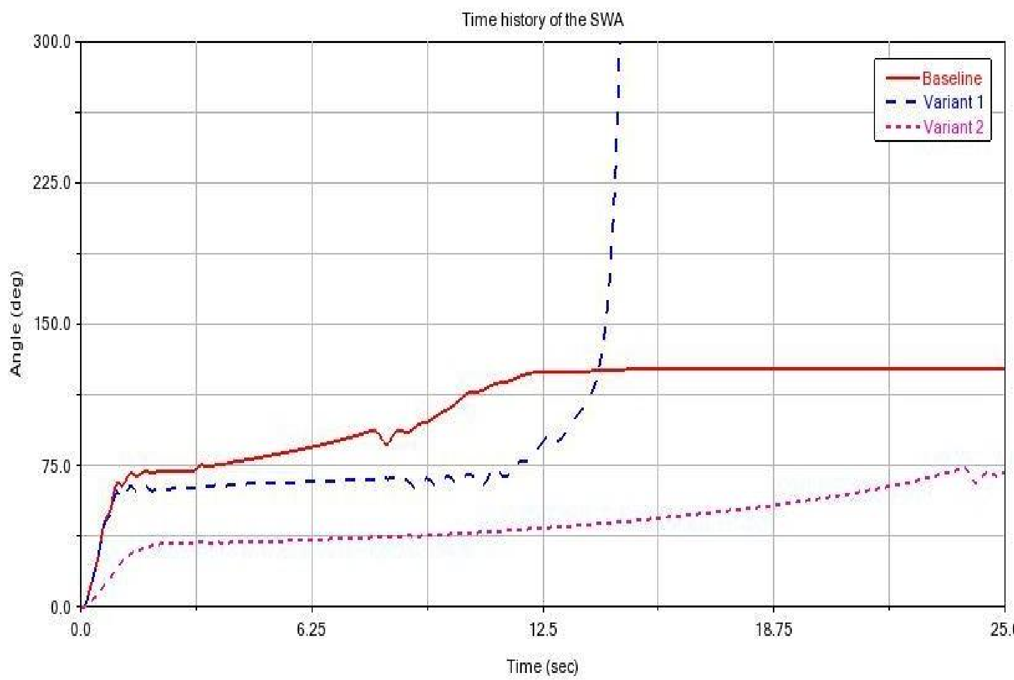


Figure 33.SWA versus time in a CRC test. Variant 1 has a stiffer rear ARB, while Variant 2 has a stiffer front ARB.

In Figure 34, the roll angle magnitude is plotted against the lateral acceleration in a CRC test.

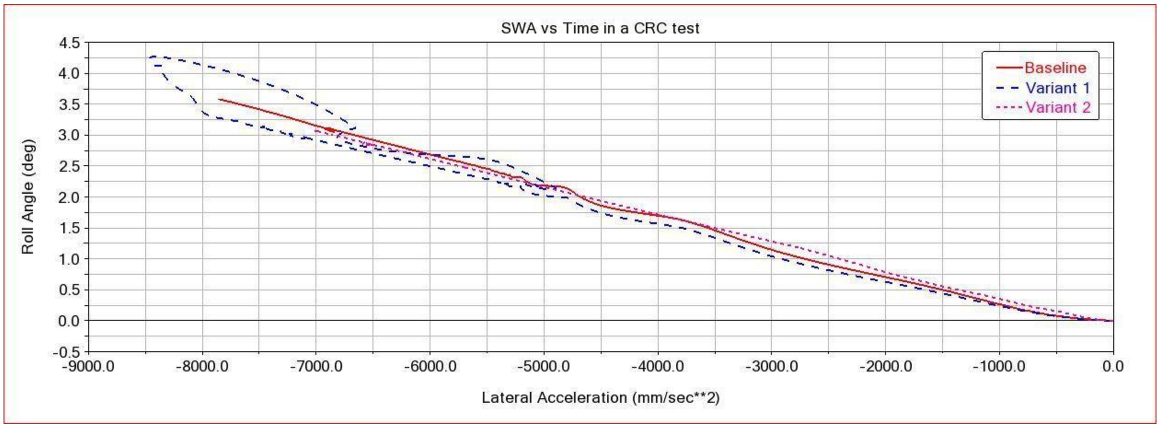


Figure 34. Roll angle versus Lateral Acceleration in a CRC test. Variant 1 has a stiffer rear ARB, while Variant 2 has a stiffer front ARB.

When measuring the roll gradient at peak lateral acceleration the same way it was done for the slalom test in 4.3, it was found that the variants differ from the baseline almost symmetrically (-4.47 deg/g for the Baseline, -4.88 deg/g for Variant 1, -4.29 deg/g for Variant 2).

After the canonic CRC test, also an open loop Acceleration-in-turn test was run offline. While the baseline and the less understeering variant manage to maintain the trajectory, the understeering variants struggles and goes out of track, as shown in Figure 35, where the x axis represents the longitudinal displacement while the y axis represents the lateral one.

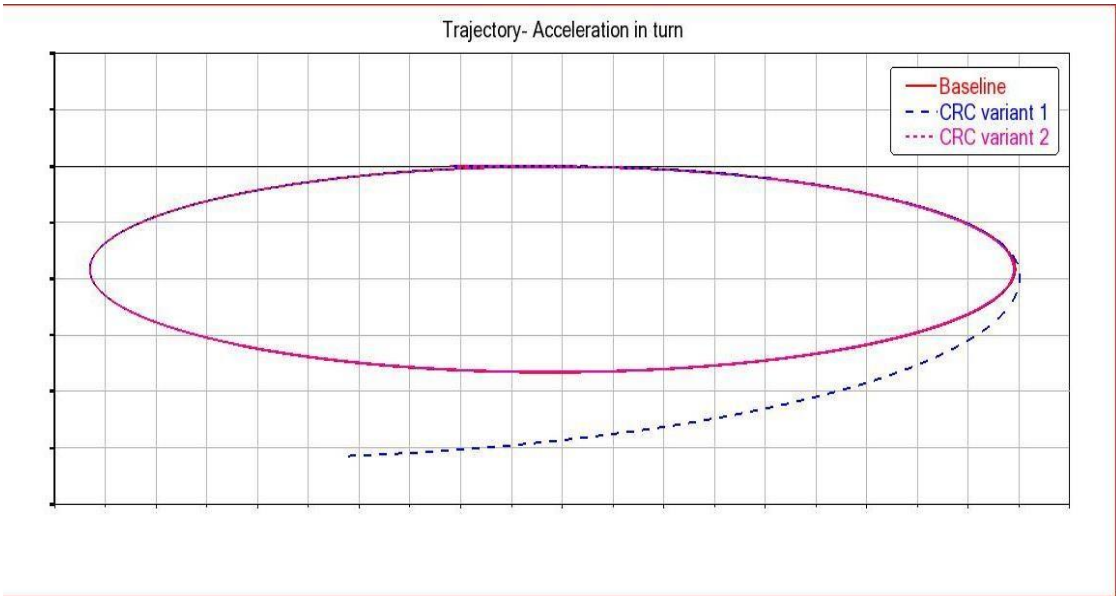


Figure 35. Trajectory during an acceleration in turn test. While the baseline and the less understeering variant manage to maintain the trajectory, the understeering variants struggles and goes out of track.

Another offline test was run featuring the baseline, Variant 1 and Variant 2; a closed loop brake in curve. The time history of the steering wheel torque shows how the aggressively understeering behaviour of Variant 1 causes the front tires to lose grip, with consequent drop of torque at the steering wheel (Figure 36).

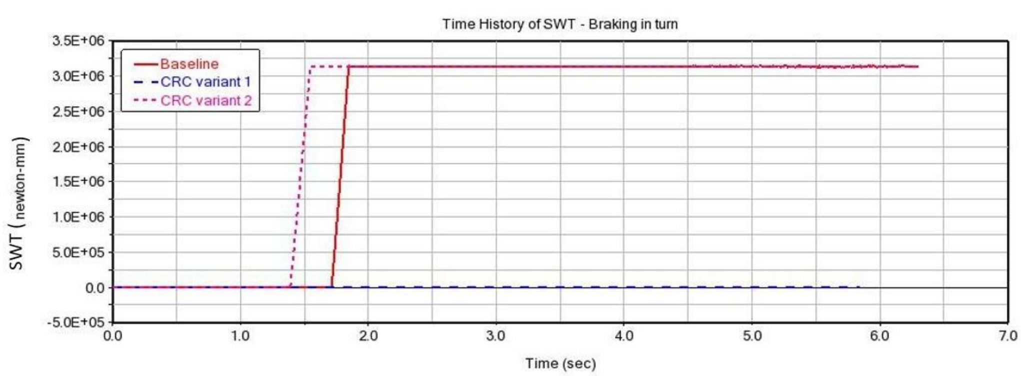


Figure 36. SWT versus time in a brake- in- turn simulation. Variant 1 has a stiffer rear ARB, while Variant 2 has a stiffer front ARB.

Comparing the trajectory of the baseline and the variants in the same maneuver in Figure 37, it's clear how Variant 1 struggles to keep a trajectory when cornering.

While Variant 1 is very likely to have a degraded performance compared to the baseline due to its aggressive understeering attitude, Variant 2 is not too far from the reference Jeep Renegade. It was considered useful for the purpose of this study to see how the drivers would judge the degraded performance of Variant 1 and which suggestions they would give, and how they would assess instead the variant whose behaviour is close to the baseline.

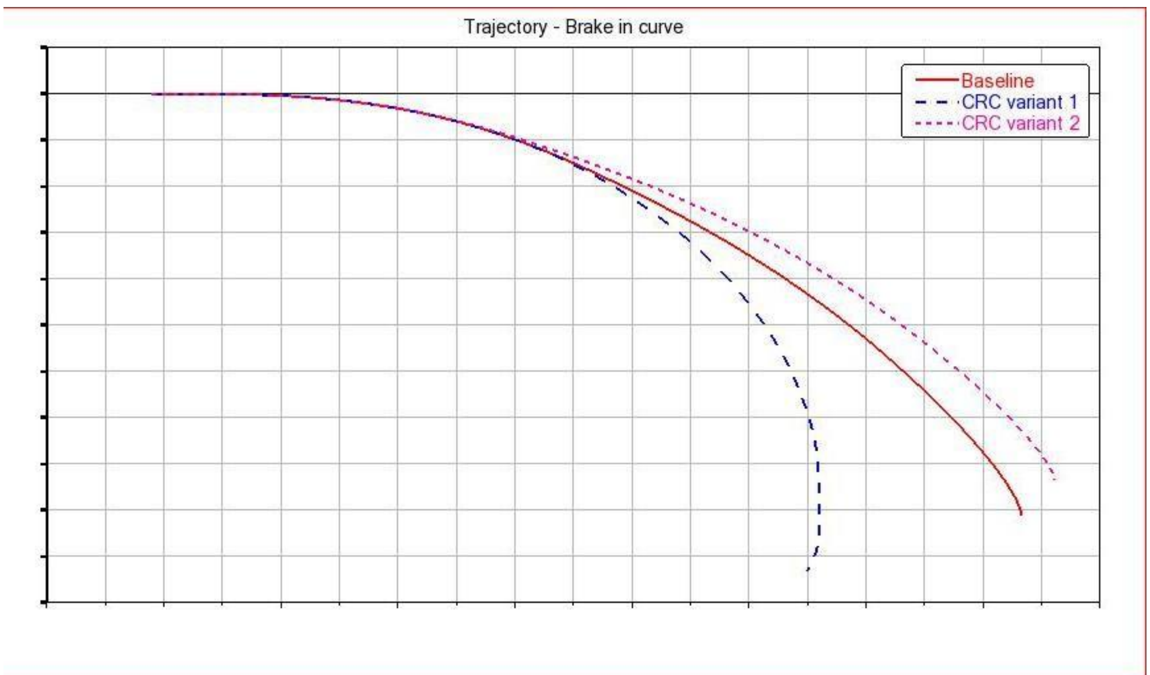


Figure 37. Trajectory in a brake-in-turn maneuver. Variant 1 has a stiffer rear ARB, while Variant 2 has a stiffer front ARB.

4.5 Fishhook Test

The Fishhook test is used for comprehensive evaluating dynamic anti-rollover propensity. It reflects the ability of chasing trail, avoiding obstacle in emergency and detecting roll stability of the vehicle, being one of the worst driving conditions [52]. This test was developed by the

National Highway Traffic Safety Administration to ensure that vehicles sold in the USA would not rollover when subjected to an avoidance maneuver. It is a steer and countersteer maneuver that aims to reproduce the reaction of a panicked driver avoiding an obstacle in the road. Maximum severity is achieved by triggering the countersteer when the maximum roll angle is approached following the initial steer input. The maneuver is named after the shape assumed by the trajectory during this test.

Here are the steps to follow for this maneuver provided to the drivers:

- Drive straight at 80 kph
- Apply a steering input of 30 degrees and hold it for 0.25 seconds
- Apply a steering input of -240 degrees and hold it for 3 seconds
- Come back to a steering input of 0

The value of the initial steering input, called "calibration angle" [45] was found via offline simulations and it is the steady state steering angle for which a lateral acceleration of 0.3g is achieved when driving at 80 kph.

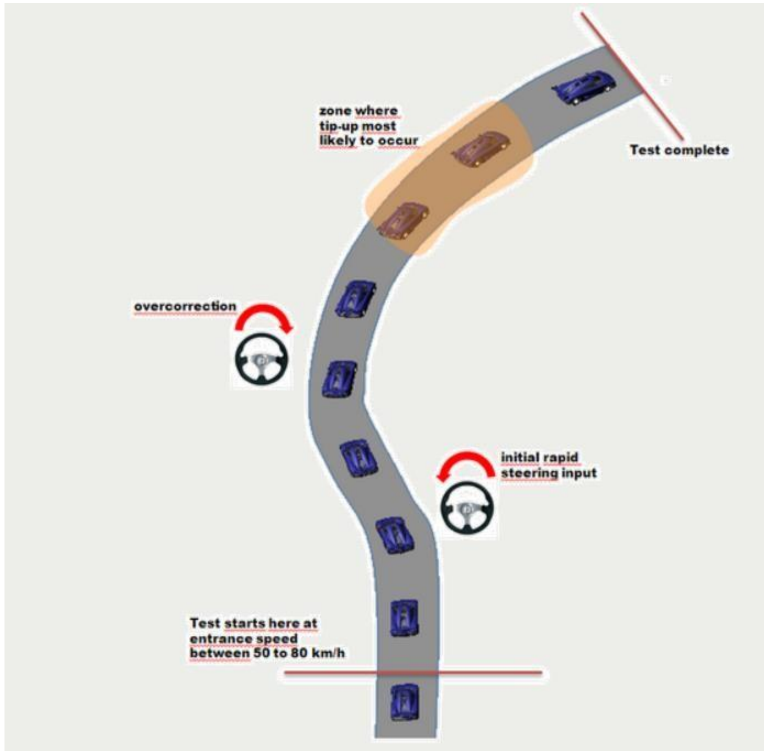


Figure 38. Fishhook test, picture taken from [53].

The items to assess for this maneuver are the following:

- The rolling behaviour of the vehicle
- The yawing behaviour of the vehicle
- The steering effort required for the maneuver

4.5.1 Variants

When creating the variants for this maneuver, the focus was on achieving a different rolling behaviour on the first place, since it's the focus of this maneuver. This was done by acting on the characteristic curve of the dampers. The slope of the curve was changed in the low-speed region, both on the front and rear dampers. Softer dampers were made by multiplying the slope of the baseline of a factor of 0.6, while the harder dampers were made by multiplying by a factor of 1.5.

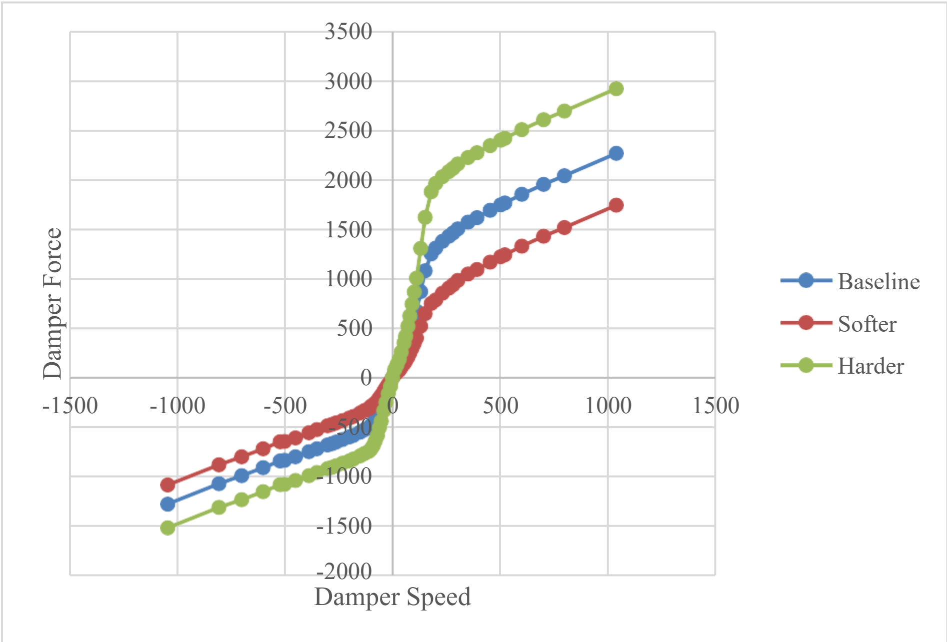


Figure 39. Front dampers characteristic curve.

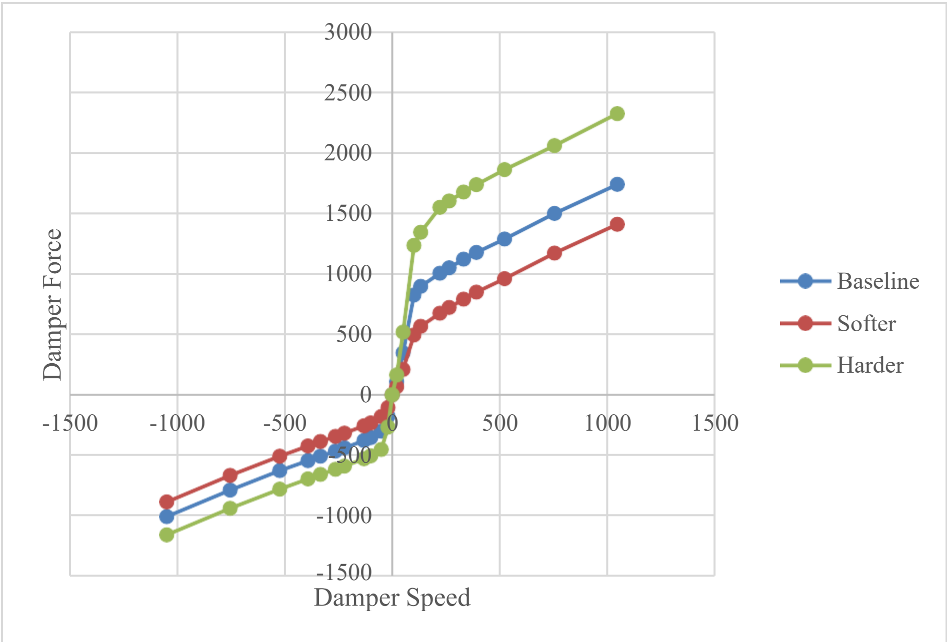


Figure 40. Rear dampers characteristic curve.

As can be noted in Figure 41, the magnitude of the roll angle is affected by this design change, alongside the roll gradient (Figure 42). The variant with harder dampers has a lower roll gradient, and consequently its trajectory has a larger cornering radius [25] (Figure 43). On the other end, the higher roll gradient in the variant with softer dampers might affect the responsiveness of the vehicle perceived by the driver.

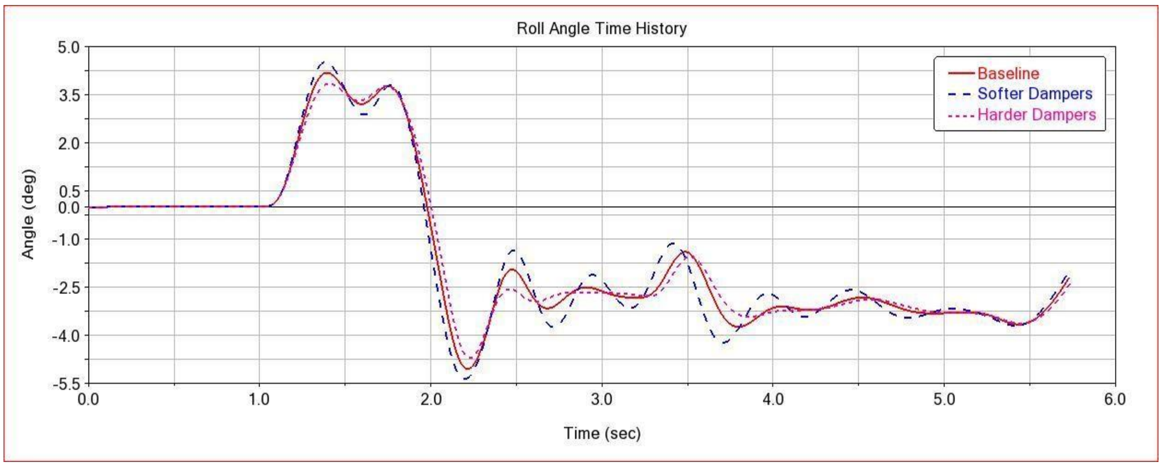


Figure 41. Roll Angle in a fishhook maneuver

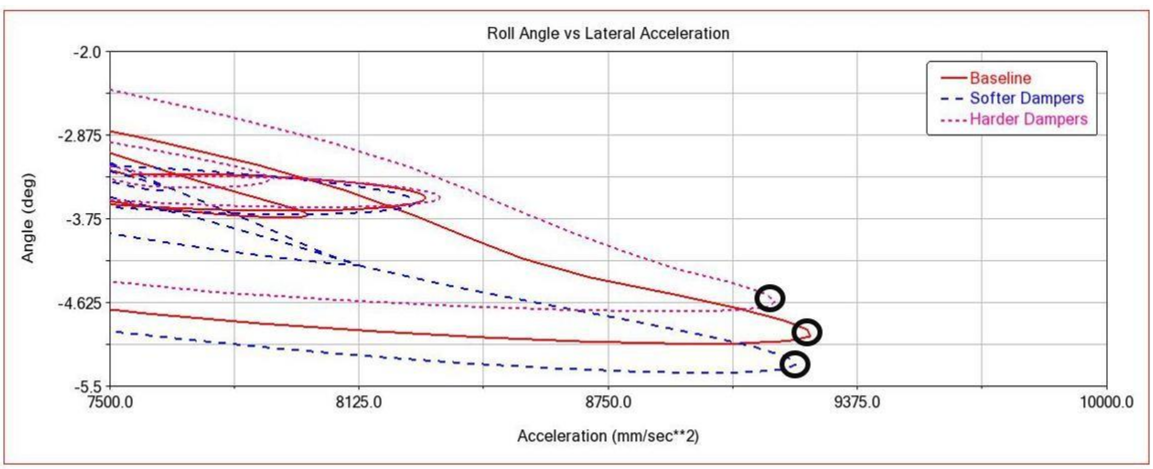


Figure 42. Roll angle versus lateral acceleration. The roll gradient is measured in the circled points (peak acceleration)

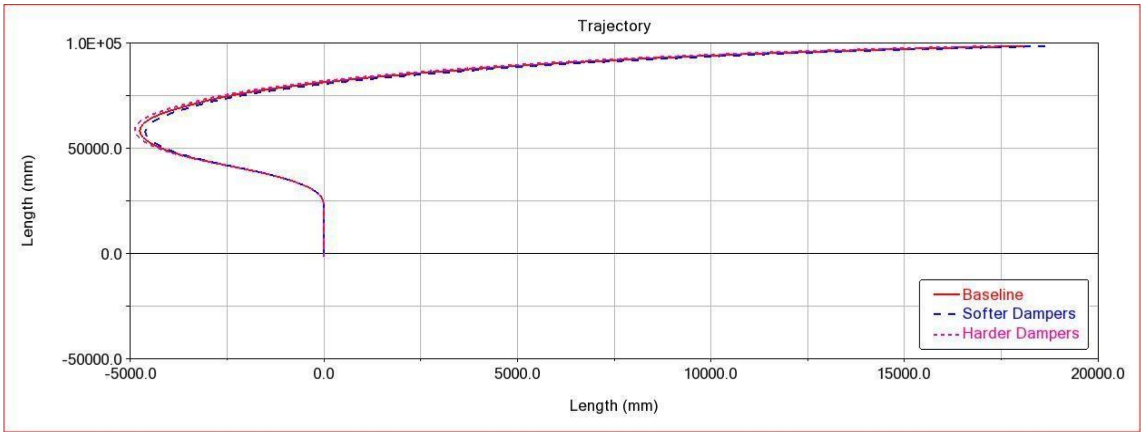


Figure 43. Trajectory in the fishhook test. The x-axis is the displacement in the longitudinal direction, the y-axis in the lateral one.

4.6 Straight and Braking Maneuver

The aim of this maneuver is to study the response of the vehicle during a braking operation and how it's perceived by the drivers.

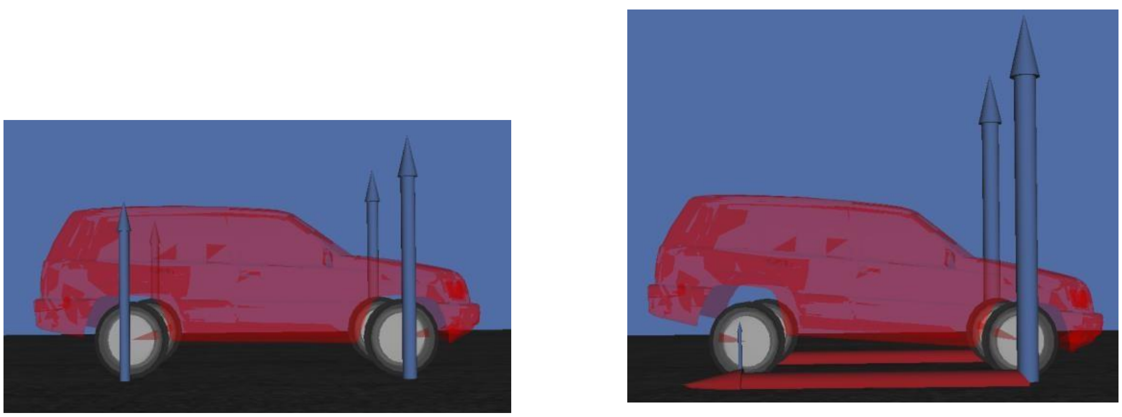


Figure 44. Straight and braking maneuver

For this maneuver, two scenarios are considered:

- An emergency braking operation, in which the driver is proceeding straight at 90 kph and then slams on the brakes
- A predictable braking operation, which reproduces a common scenario like stopping at an intersection or at the traffic lights in which the driver proceeds at 90 kph and is required to stop after a certain distance (within 100 meters)

In the first scenario, which consisted of an open loop maneuver (the input 100% brake is prescribed to the driver), the focus was on the stability and promptness of the car. In the second scenario, the driver could manage the brake pressure in the way it felt more natural to them, as long as the vehicle stopped before a cone placed 100 m further; this is a closed loop maneuver. The focus is on the comfort experienced during this operation.

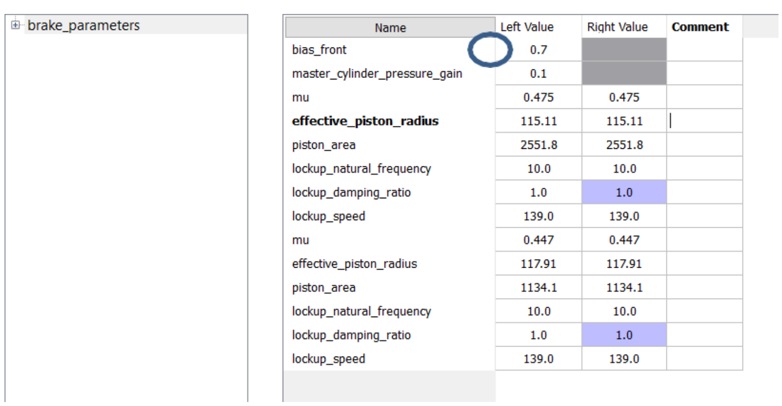
The distance of 100 meters chosen for the closed loop braking operation was defined based on the stopping distance in the open loop maneuver, extracted via offline virtual simulations, to which 20 meters were added to give the driver more freedom in the brake management.

The items that the drivers were asked to rate in these maneuvers are the following:

- The braking pitch of the vehicle
- The stability of the vehicle (i.e., if the vehicle tends to drift sideways during the brake operation)
- The longitudinal acceleration experienced

4.6.1 Variants

For this maneuver, the variants were made by changing the brake pressure distribution in the subsystem “brakes”. The parameter that was modified is called “bias_front”, in Figure 45. It ranges from 0 to 1 and represents the percentage of brake power delivered to the front axle. Two variants were made; one with a front to rear brake pressure distribution of 7/3, called “Front biased”, one with a distribution of 3/7, called “Rear Biased”.



Name	Left Value	Right Value	Comment
bias_front	0.7		
master_cylinder_pressure_gain	0.1		
mu	0.475	0.475	
effective_piston_radius	115.11	115.11	
piston_area	2551.8	2551.8	
lockup_natural_frequency	10.0	10.0	
lockup_damping_ratio	1.0	1.0	
lockup_speed	139.0	139.0	
mu	0.447	0.447	
effective_piston_radius	117.91	117.91	
piston_area	1134.1	1134.1	
lockup_natural_frequency	10.0	10.0	
lockup_damping_ratio	1.0	1.0	
lockup_speed	139.0	139.0	

Figure 45. Brake parameters on CarRealTime

The maneuver that was run offline when tuning the variants is an open loop braking. In Figure 46 it can be noted how the pitch angle for the Front Biased variant is higher compared to the baseline and the operation is completed in a short time. The opposite holds for the Rear Biased variant. The longitudinal acceleration at the center of mass of the car follows the same trend: higher and shorter in time for the Front Biased variant, lower and longer in time for the Rear Biased variant (Figure 47).

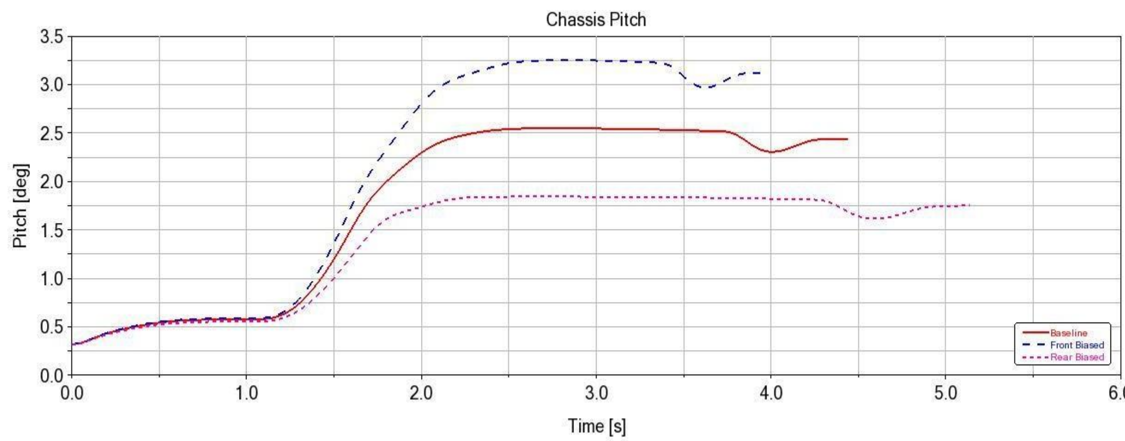


Figure 46. Pitching angle during open loop braking maneuver

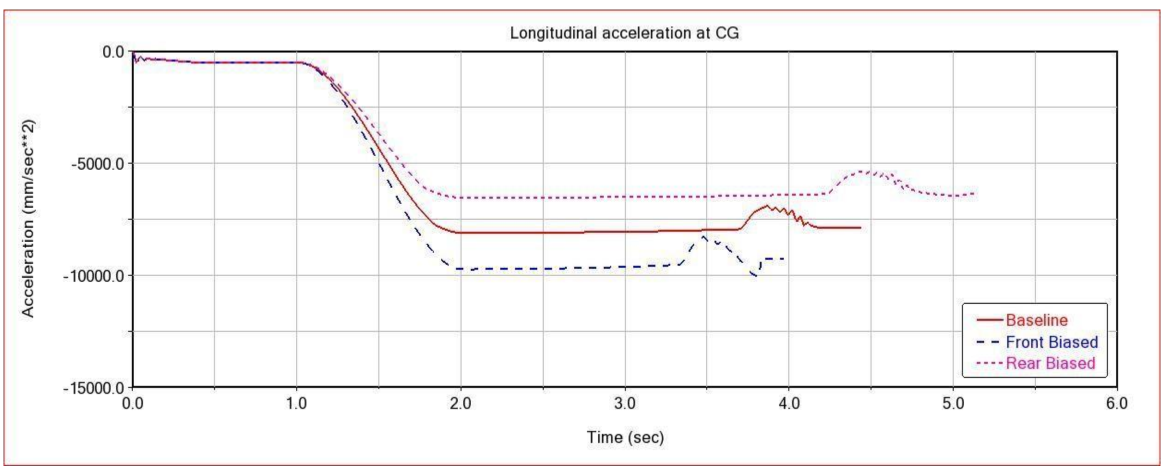


Figure 47. Longitudinal acceleration experienced at the vehicle CG during an open loop braking maneuver

According to the study conducted by [40], motion sickness caused by 0.2 Hz roll and pitch oscillation is dependent on the magnitude of the motion, with a trend for illness ratings to increase with increasing magnitude. The lowest magnitude of both roll and pitch oscillation caused the least sickness and the intermediate and higher magnitudes caused greater sickness. Using the Fast Fourier Transform (FFT) algorithm embedded in the post processing software Adams, the magnitude of pitch angle at different frequencies is plotted (Figure 48). At 0.2 Hz, the pitch angle magnitude of the Front Biased variant is higher than the one of the Baseline, that's higher than the Rear Biased variant.

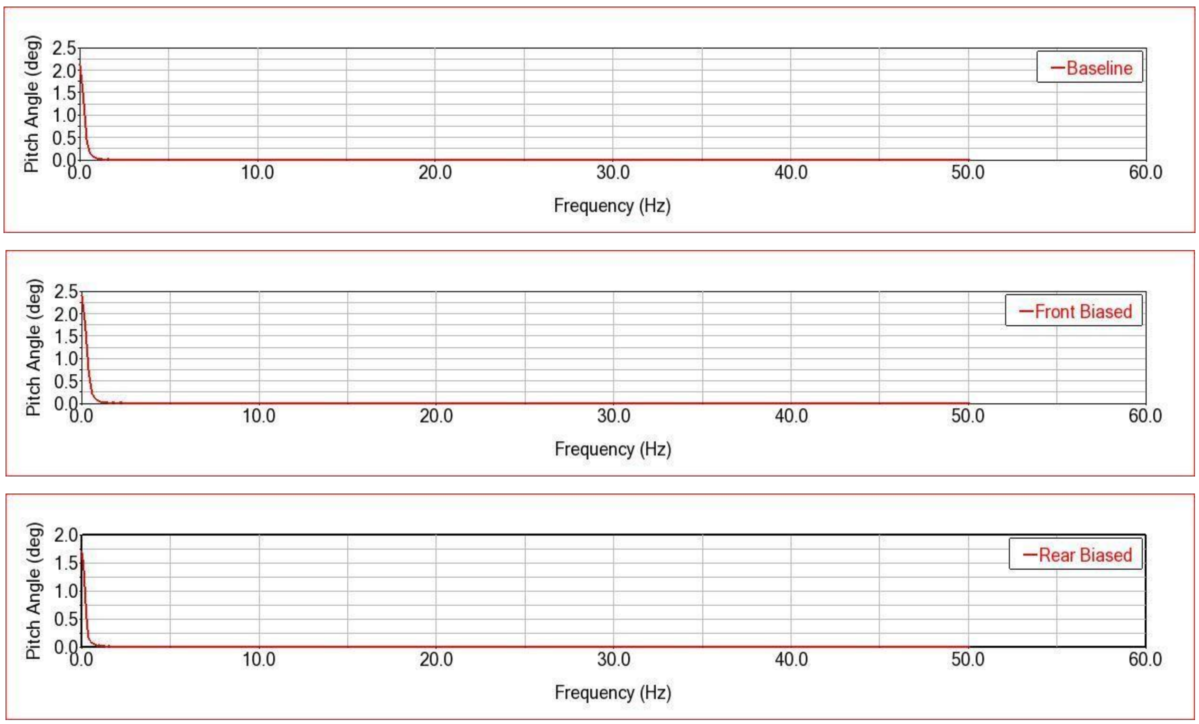


Figure 48.Pitch angle magnitude in the frequency domain

The Front Biased variant stops faster but is more likely to cause physical discomfort due to higher pitch angle. The Rear Biased variant, on the other end, pitches less and causes a lower longitudinal acceleration, more prolonged in time.

Another OM that was considered meaningful is the steering wheel torque. Looking at that provides information regarding the easiness in maintaining a straight trajectory when braking.

The oscillations in steering wheel torque reach higher peaks in the Front Biased variant than the baseline (Figure 49).

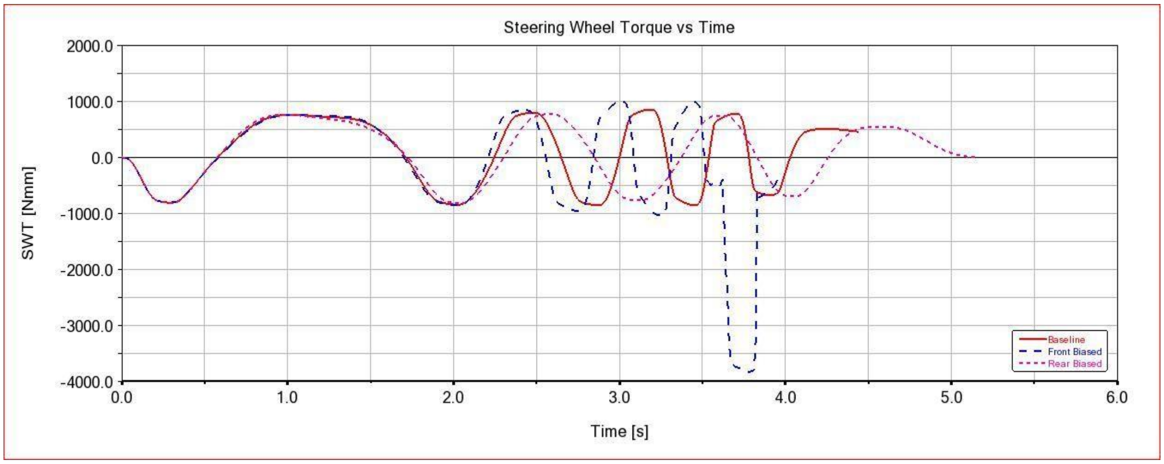


Figure 49. Time history of the SWT during an open brake maneuver. The Front Biased variant reaches higher peaks, which might make it harder for the driver to keep control of the car during the maneuver.

4.7 On-center Weave Test

In order to evaluate the behaviour of the vehicle when driving straight at high speed and low lateral acceleration (like in a highway), an On Center Weave Test was included in the simulation; this test consists in applying a sinusoidal steering input with a frequency of 0.2 Hz at a constant vehicle longitudinal speed of 100 kph. The steering wheel amplitude must be determined to produce a lateral acceleration of 2 m/s^2 [42].

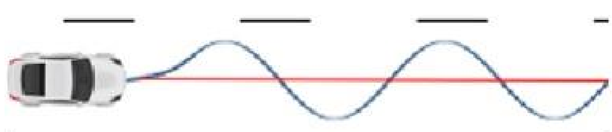


Figure 50.On Center Weave Test. Image courtesy of [54].

The items the drivers were required to rate are the following:

- The on-center feel (i.e. the responsiveness and feel of the steer when the wheel is approximately centered)
- The centering feel (i.e. if the reaction torque felt by the driver makes it easy to identify the 0° SWA position).

4.7.1 Variants

The OMs that have experimentally proved to be more tightly liked to the on center handling feel are the hysteresis in the Steering Wheel Torque versus Steering Wheel Angle and Lateral Acceleration versus Steering Wheel Torque. The first graph can be modified by acting on the steering stiffness; a characteristic that can be evaluated via an ISO Transition Test. Simulations were run offline and two variants were made tuning the torsion bar stiffness and the torsion bar twist limit.

In Figure 52 and Figure 53, the parameters chosen for the variants are shown and compared to the ones chosen for the baseline (Figure 51).

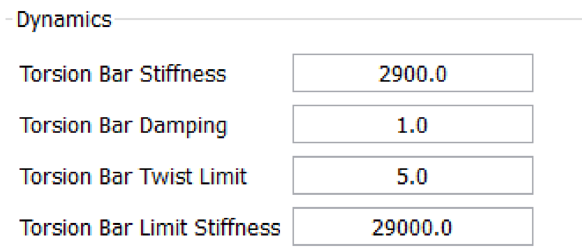


Figure 51. Torsion Bar parameters of the baseline on CarRealTime

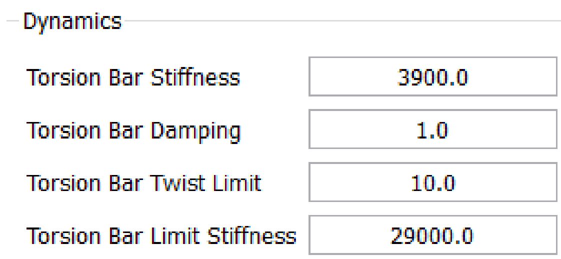


Figure 52. Torsion Bar parameters of Variant 1 on CarRealTime

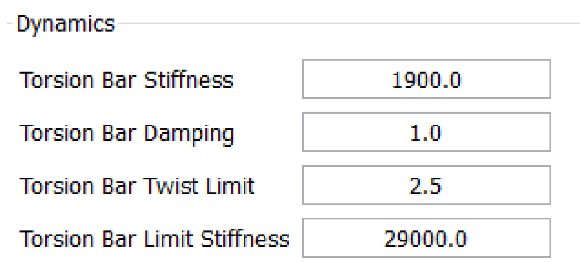


Figure 53. Torsion Bar parameters of Variant 2 on CarRealTime

In Figure 54, the SWT vs SWA characteristic is plotted. Both variants have lower steering stiffness compared to the baseline, and different on center torque gradient.

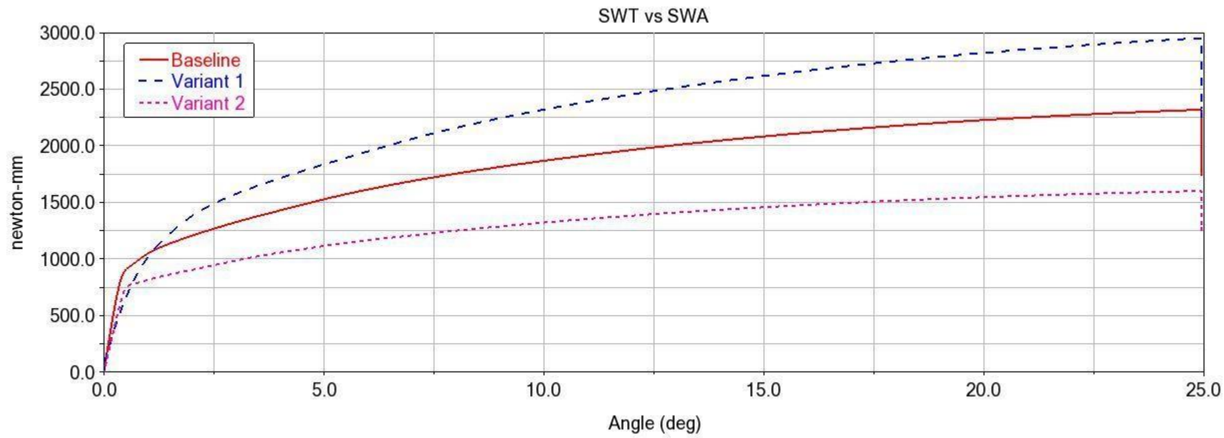


Figure 54.SWT vs SWA in a Transition Test. Variant 1 has a stiffer torsion bar compared to the Baseline, while Variant 2 has a softer one.

An On Center Weave Test was also run offline. In Figure 55, the difference in hysteresis width between the three models in the SWT versus SWA angle. This should lead to a different perception of the on center handling. However, as Figure 56 shows, there is no difference between the models in the hysteresis width in the Lateral Acceleration versus SWT graph.

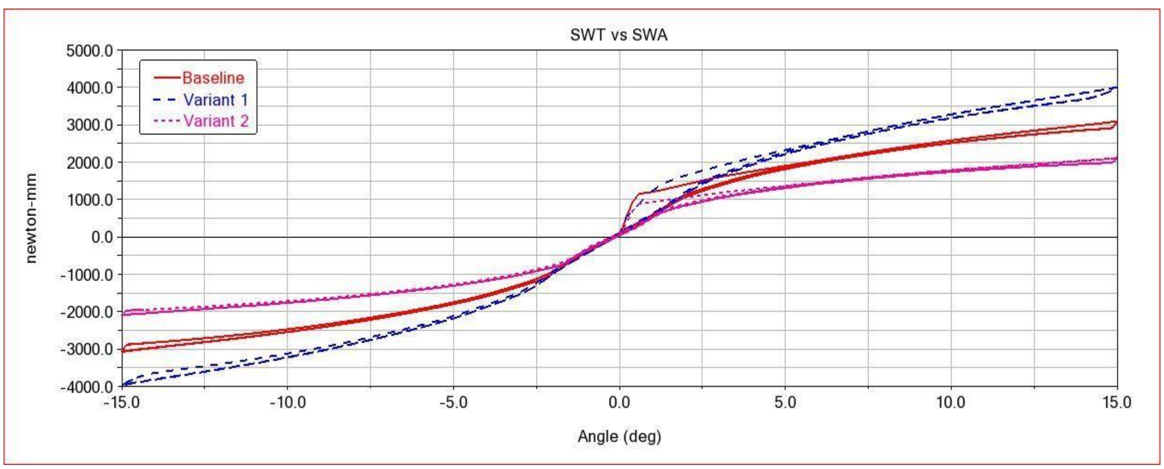


Figure 55. SWT versus SWA in an On Center Weave test. Variant 1 has a stiffer torsion bar compared to the Baseline, while Variant 2 has a softer one.

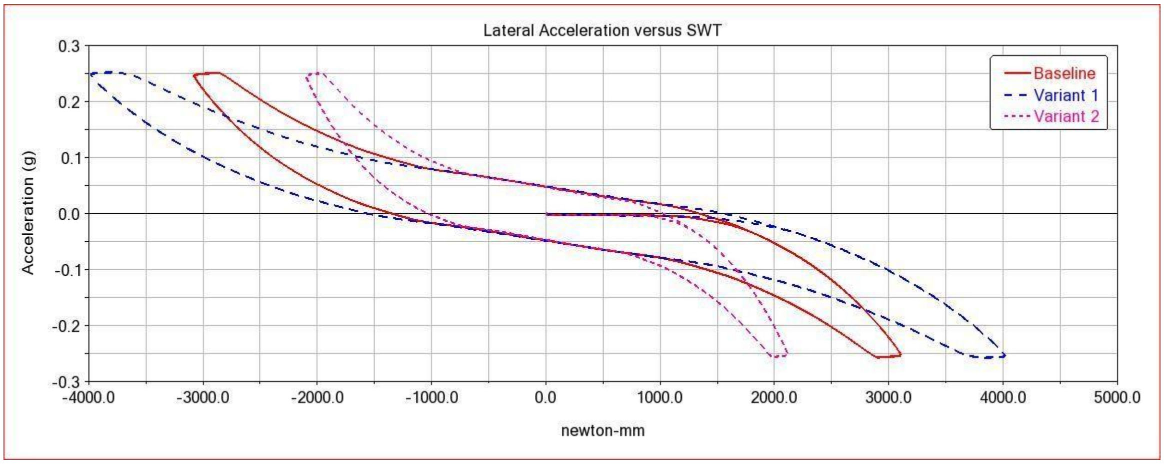


Figure 56.lateral Acceleration versus SWT in an On Center Weave test. Variant 1 has a stiffer torsion bar compared to the Baseline, while Variant 2 has a softer one.

4.8 Frequency Sweep

In order to have a more comprehensive assessment on the steering feel of the vehicle, a Frequency Sweep maneuver was included in the simulations. The drivers were informed of the aim of this maneuver and were given more freedom: they are required to apply a steering input of amplitude comprised between 30 and 45 degrees, at different longitudinal speeds, trying to remain within the 0-4 Hz range (as recommended in [45]). The aim was for them to assess the following items:

- Steering effort
- Torque change compared to the steering angle
- Centering feel

4.8.1 Variants

The variants for this maneuver were made by tuning the Torsion Bar Stiffness and Damping on Car Real Time.

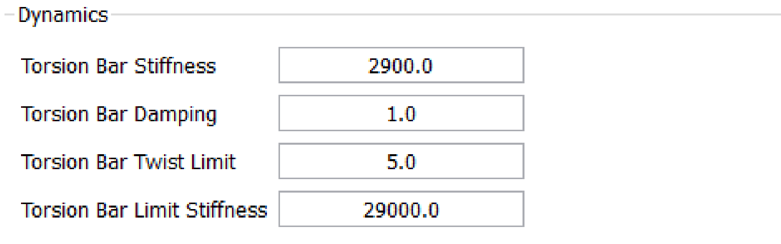


Figure 57. Torsion Bar parameters of the baseline on CarRealTime

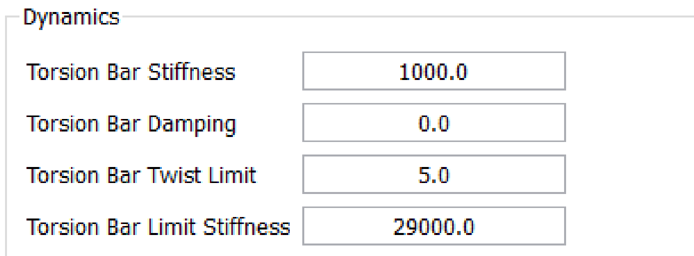


Figure 58.Torsion Bar parameters of Variant 1 on CarRealTime

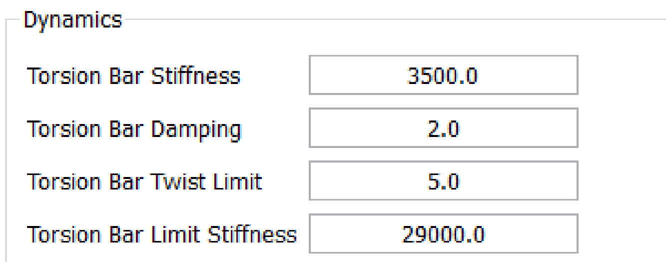


Figure 59. Torsion Bar parameters of Variant 2 on CarRealTime

As far as the offline simulations are concerned, three swept steer simulations with a sinusoidal steering input of 30 degrees and at a frequency increasing from 0 to 4 Hz at a rate of 1 Hz/s were run at three different speeds: 18 kph, 50 kph, 90 kph. The lateral accelerations achieved during this test range from 0.12 g to 0.37 g. The three vehicle models displayed a different behaviour in their Steering Wheel Torque versus Steering Wheel Angle and Lateral Acceleration versus Steering Wheel Torque characteristics (Figure 60 and Figure 61).

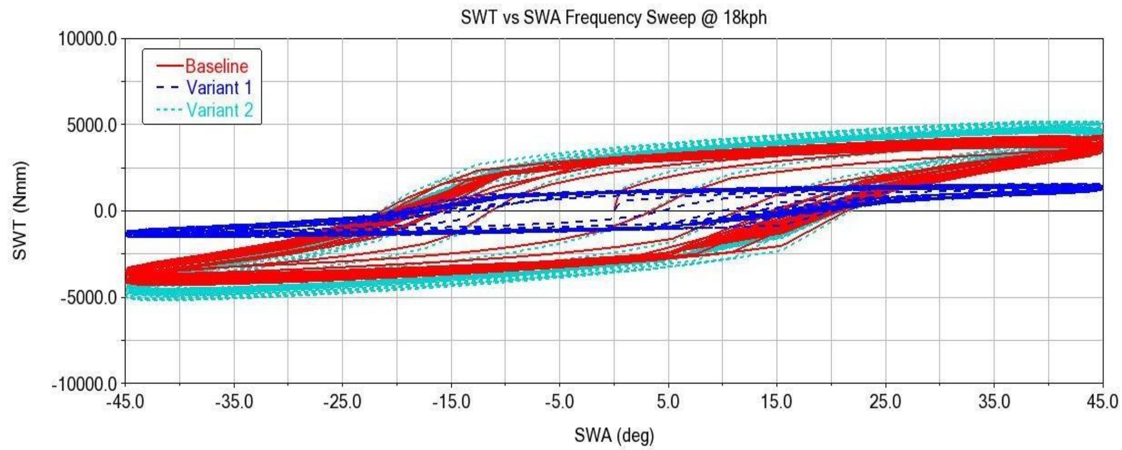


Figure 60. SWT vs SWA in a Frequency Sweep Test run at 18 kph.

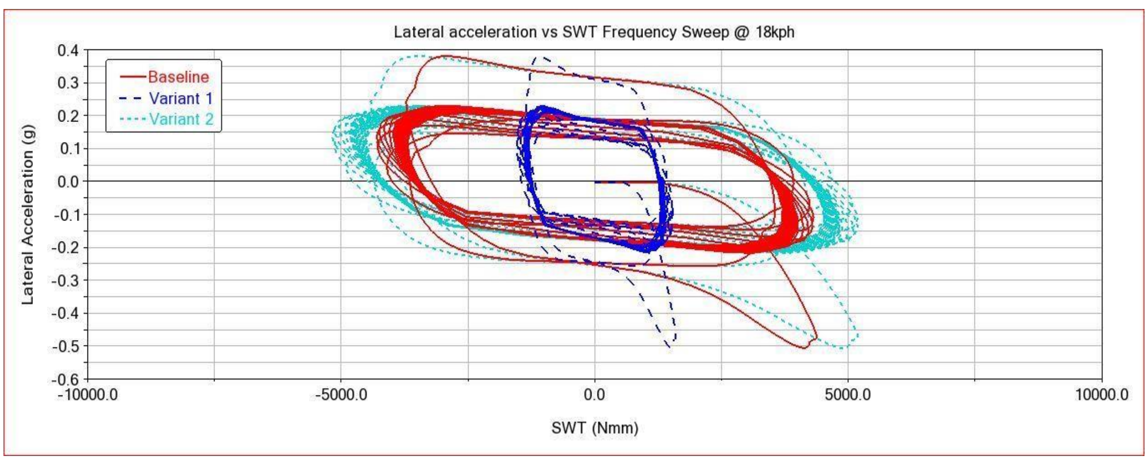


Figure 61. Lateral acceleration vs SWT in a Frequency Sweep Test run at 18 kph.

4.9 Cleat Test

A ride event was included in the simulations, targeting the secondary ride frequency range (from 5 to 20 Hz). The drivers were asked to drive over a cleat at 30 kph and evaluate the following items:

- The severity of the impact felt by the driver when the front suspension hits the cleat
- The severity of the impact when the rear suspension hits the cleat
- How quickly the vertical motion dissipates when hitting the cleat

The cleat was modelled by changing the road profile on one of the flat pads available in the company database. The cleat dimensions are 25 mm high and 100 mm long. This same test was included in a previous project featuring the use of the dynamic driving simulator DiM-250 with the goal of evaluating ride and handling with different damper settings, determining the sensitivity of the simulator to such changes, and developing procedures for subjective evaluation methods [20]. The cleat test method was established by Fiat to measure the impact harshness on a vehicle [45].

4.9.1 Variants

The variants used for this test are the same ones employed for the Fishhook test, called Softer Dampers and Harder Dampers (Figure 39and Figure 40). The secondary ride frequency involves motions of both sprung and unsprung mass, so it was reasonable to think that a change in the damper characteristics would affect the driver's vertical motion. However, this was double checked via an offline cleat test, analyzing the following OMs:

- Peak to peak vertical acceleration at body centre of gravity
- Peak to peak vertical displacement at body centre of gravity

As can be noted in Figure 62 and Figure 63, the change in behaviour among baseline and variant is noticeable.

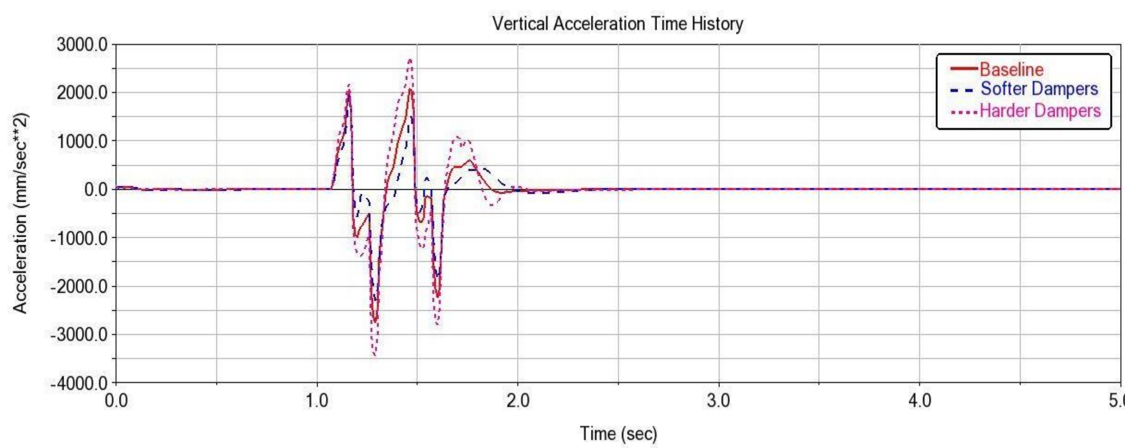


Figure 62. Vertical Acceleration at body CoG

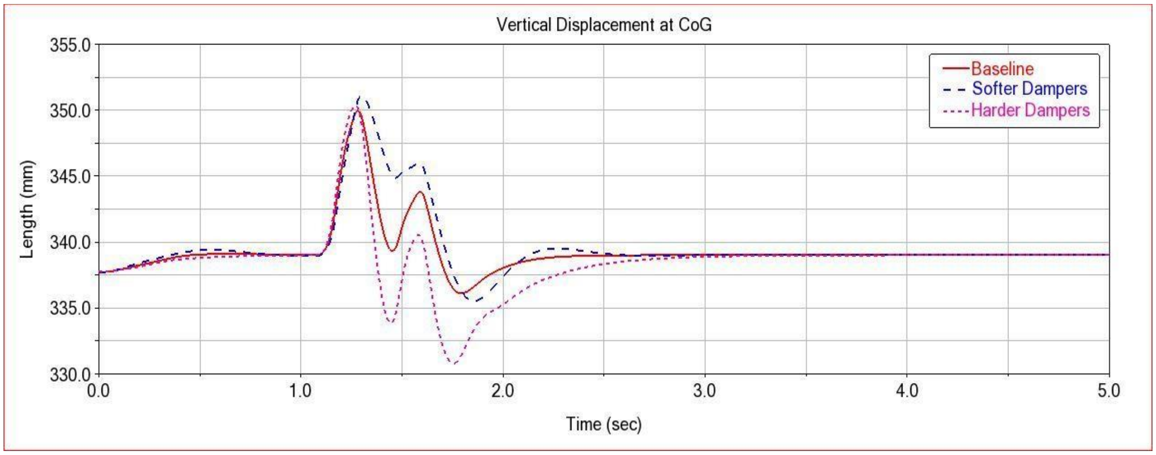


Figure 63. Vertical displacement at body CoG

4.10 SA questionnaire

The way in which the subjective assessment questionnaire given to expert drivers is structured is functional to not only know what their assessment of the Jeep Renegade and its variants is, but also their different outlook on what the optimal characteristics of a car should be when it comes to ride and handling.

Here are some reasons why the numerical rating among test drivers could differ:

- *Different interpretation of the question.* The influence of this factor should be minimized in this study since the items of the questionnaire that require a numerical rating are drawn by the company Quality Profile, on which test drivers from both regions are instructed
- *Different rating tendency or usage of the rating scale.* When a larger number of drivers is involved in this kind of testing, it's usually found that some drivers tend to give lower or higher scores than the average, and each driver spreads their scores in a different way; some exploiting a wider range of the rating scale than others
- *Different training.* Some test drivers might be educated to search for brand identity, others to seek for the car behaviour which would make it safer to handle by a non-professional driver
- *Different preferences and expectations towards the driving experience.* While the previous items of the list are inherent to the simulation context, this factor represents the

uttermost subjectivity of the driving experience. Ultimately, regardless of the training received, every driver has their own interpretation of what meeting the required target during a driving experience is. Professionals might be trained to minimize the bias when it comes to assess the handling characteristics of a vehicle, but the way the human body "feels" a certain motion is always different from one individual to the other.

In another study in which the subjective assessment test took place on physical prototypes [34], an interpretation was given to the unexpected high variance in rating displayed among drivers who had been working in the same vehicle dynamics department for several years. Such a difference could be due to the fact that only closed loop maneuvers were chosen for the test; the unconstrained evaluation method is a possible justification for the poor repeatability, leading drivers to provide ratings based on different assessment conditions. Among the maneuvers proposed to the drivers in this project, some of them are in closed loop, so that might also be a source of variance among their ratings. However, the driver's freedom in those situations isn't necessarily a negative thing; the focus of this work isn't assessing a specific set of vehicle configurations in order to decide which one is the best, but the main goal is to study the subjective assessment testing procedure itself and how the driver's subjectivity comes into play. In order to achieve that, the drivers have been encouraged to read the questionnaire, identify clearly what needs to be assessed and carry out the test according to that expectation. In the Frequency Sweep test, the most unconstrained among the proposed ones, the aim is to do an evaluation of the steering feel. The input commands applied by the drivers are recorded and they are also asked their opinion about what could be the best way to perform an evaluation of the steering feel.

The SA questionnaire for this test (Appendix A) starts with a briefing on the driver's background and the type of cars usually tested. The reason of doing so is to identify if there are major differences in the drivers' training that might affect their assessment (for example: what if a driver is used to test sporty car, while the other is specialized in pickup trucks?).

The booklet presents a chapter for every maneuver with the following layout:

- A description of the maneuver to carry out

- The list of the items to assess, each one sided by a bipolar 10 points scale (a scale which ranges from one end of the spectrum to the other, in this case from "Intolerable" to "Excellent" behaviour), for each of the three variants tested
- A space to freely describe the behavior of each of the variants
- A space in which the drivers are asked which variant they preferred and why
- A space in which the drivers are asked to describe the optimal behavior a car like the Jeep Renegade should display in the maneuver just performed

The reason why it is important to ask the driver's feedback unconstrained by a numerical evaluation is to shift the focus on their interpretation of the test, their preferences and expectation towards the driving experience.

CHAPTER 5

Results and Discussion

A total of four drivers partook in these tests: two Italian test drivers working for Maserati in Modena, Italy, and two Canadian test drivers working at the Automotive Research and Development Center in Windsor, Ontario, Canada. Their background as test drivers reflects the differences between European and North American markets described in 1.1, even though the Italian team appears more oriented towards high performance and luxury vehicles which target a niche market. Another relevant difference is that the Italian team has more years of experience (6 to 8 years), including a lot of testing on physical prototypes, while the Canadian team was formed more recently (2-3 years) and trained almost exclusively on the dynamic driving simulator since the facility installation.

Table 5. Vehicles driven by the members of the two teams. If the symbol ◄ is present beside a vehicle model, it means the vehicle was not tested for work, but still owned and/or driven.

Canadian Team	Italian Team
• Dodge Charge • Dodge Challenger • Jeep Cherokee • Jeep prototypes • FIAT 124 Spider Sport◄ • Honda Civic Sedan◄ • Ford Escape SUV◄	• Alfa Romeo Giulia • Alfa Romeo Stelvio • Maserati MC20 • All Maserati models and benchmark competitors • Lifelive TN5 Demon Car (race vehicle) • Ferrari Road vehicles

The way in which the data were processed was as follows: for every test, any question which required a numerical answer was classified as an item. If there was four questions to answer after carrying out a maneuver, there was a total of twelve items: four for the baseline, and four for each of the two variants. In the whole test, there was a total of seventy-five items.

For every item, the score given by each driver was represented alongside with the average score of the team and the delta between the marks given by the two drivers of the same team (i.e., the difference between their scores). The results can be found in Appendices B and C.

The first remarkable difference between the feedback of the two teams is the variance displayed in the results. The Italians showed an average variance of 0.8, while the Canadians' variance was 1.44. Both teams carried out the tests at different times, not aware of the scores assigned by their teammate.

For each item, the average of each team was compared (Appendix D). The average difference between the scores given by each team was 0.96.

The items showing a difference in team score equal to or larger than 2 were investigated by comparing the observations made by the drivers in the open questions of the questionnaire. This choice is meant to account for the different rating tendencies that every driver inevitably displays, while still guaranteeing a good degree of agreement. The Guide to Rating provided to the driver in the Subjective Assessment Test Questionnaire (Appendix A) is reported in Figure 65: when the difference in score between two drivers is larger than two points, there is a higher chance that their opinions are qualitatively different (from Acceptable to Unacceptable, for example). There was a total of 13 items that were considered based on the larger score deviation.

Figure 64 represents the difference in score among the averages of each team. The difference was computed according to Eq. 19. Those items whose variation falls in the window (Figure 64) were not deemed to be object of disagreement among the teams, while the remaining ones led to further investigation.

$$V = C - I \tag{19}$$

Where V is the variation, C is the Canadian team average, and I is the Italian team average.

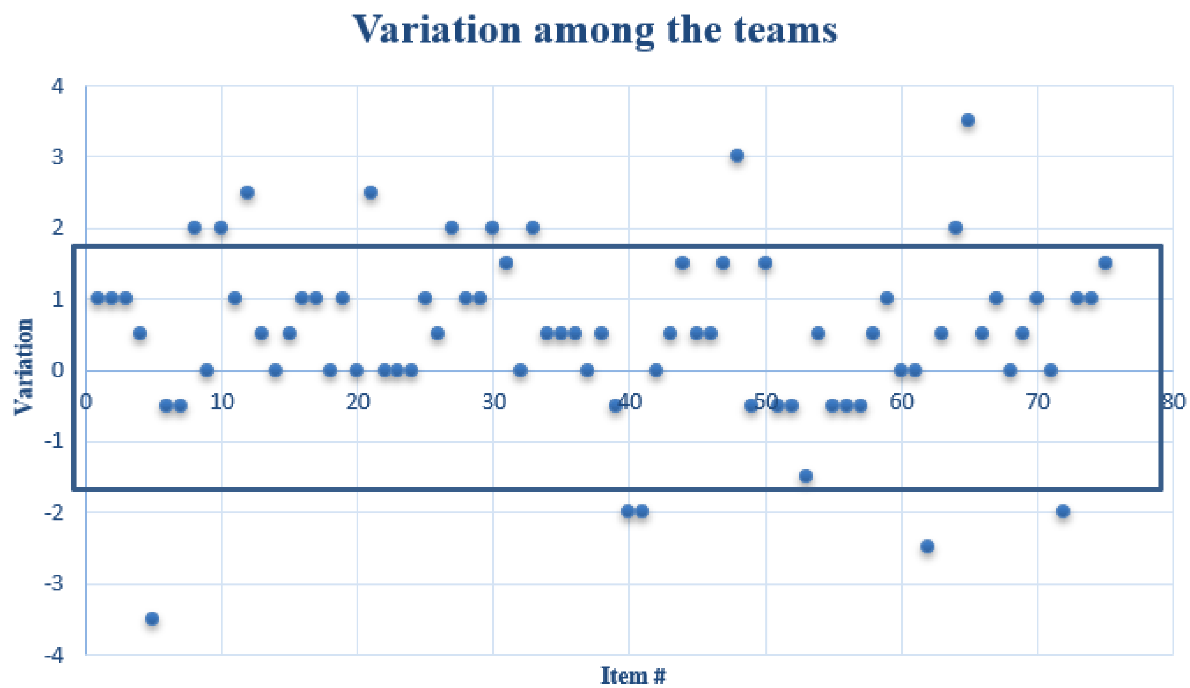


Figure 64. Difference in the average score of the teams for each of the 75 items, computed according to Eq. 19. The items out of the window represent object of disagreement.

Sections 5.1 to 5.7 describe the assessments performed for each maneuver.

5.1 Slalom

According to the numerical scores, the teams disagreed on the assessment of the first variant of the baseline provided for this test. They appeared to have different opinions regarding the vehicle sensitivity to steering input (score assigned: 8 and 4.5) and the response lag between front and rear axle (score assigned: 4 and 6). As far as the second variant is concerned, the teams' opinions on the vehicle promptness (score assigned: 6 and 8) and response lag between front and rear axle differ (score assigned: 5.5 and 8).

The first variant was made to have a higher roll gradient than the baseline, which was achieved by softening the antiroll bar. When asked to describe the handling behaviour of the vehicle, despite having given different scores, all four drivers agreed on the fact that this variant is more unstable than the baseline and that the excessive roll gradient makes it hard to control the rear axle during a slalom maneuver.

Comparing the descriptions given of the second variant with less roll gradient than the baseline, a major difference came across: in every team there is a driver whose assessment is based on what they know to be the best and safest vehicle for a non professional driver to handle, and another one who appears to prefer vehicles that provide a sporty feeling (i.e. a quicker response to the user input) when driven, even if that means sacrificing some stability during a maneuver which tends to push the car to the limit. Looking at the individual scores provided by each driver, it can be noted that there is some disagreement among team members when judging these two variants: the score of the Italian team differs on 2 points in two items related to the second variant, one item of the first variant and even one item of the baseline, while the difference in score among the members of the Canadian team reached values of 3 and 4 in three items related to the first variant, and of 2 in one item related to the second variant. Even if internal differences were encountered in both teams, the scores assigned by the Italians for the same item still fall within the Borderline- Acceptable category (Figure 65), while the Italians disagreed strongly on a couple items, one of them deeming the behavior acceptable (assigning a score of 8, which means "good") and the other considering it unacceptable (assigning a score of 4, which means "poor").

Guide to rating

Rating	Description	Observed by	Acceptability
①	Intolerable	All Observers	Unacceptable
②	Severe		
③	Very Poor	Most Observers	
④	Poor		
⑤	Marginal	Some Observers	Borderline
⑥	Barely Acceptable	Critical Observers	Acceptable
⑦	Fair		
⑧	Good	Trained Observers	
⑨	Very Good		
⑩	Excellent	Not Observed	

Figure 65. Guide to rating, from the questionnaire given to the drivers involved in this project (Appendix A).

5.2 Constant Radius Cornering

In this test, the scores assigned by the drivers were very close (average difference among the teams of 0.5 for both the baseline and the first variant) for every item except the understeering behavior of the second variant, the one made to be more understeering than the baseline. Every driver picked up on this difference, and they all agreed that this variant is better than the other one (much less understeering that the baseline), but that the baseline is the best without a doubt. It can therefore be concluded that despite the different numerical score, all drivers agree qualitatively.

5.3 Fishhook

Despite the fact that there were just two items on which the teams disagreed, more difference was displayed among the drivers in this test. First of all, it can be noted that two drivers experienced difficulty in replying to all the open questions or expressing their preference. When asked about what the ideal behavior of a car in an evasive maneuver such as the fishhook should be, all the drivers who replied had similar feedback: oversteering behaviors are not welcomed in this situation, the car must be responsive but still easy to control.

5.4 Straight and Braking

During this test, two major differences among the drivers were apparent:

- Even among professional test drivers with the same experience, sensitivity (i.e. the ability to pick up on the difference in behavior among different vehicles and identify what has been modified) changes
- Some drivers prioritize safety, even if that means sacrificing ride comfort or sport handling

When it comes to judge the longitudinal dynamics of the car in a longer maneuver such as a straight braking, the dynamic simulator was not the best tool because its physical constraints make it such that the acceleration experienced by the driver can't be accurate for the whole duration of the maneuver. The motion cueing reproduces the longitudinal acceleration experienced by the driver with a mix of tilting (Figure 66) and translation on the large linear longitudinal actuator. The length of the linear actuator is not enough to support long duration of longitudinal accelerations or decelerations.

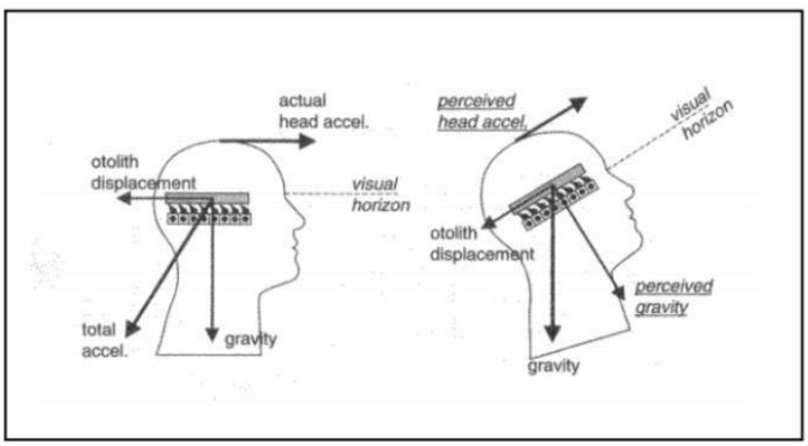


Figure 66. Tilt coordination technique, from [55].

One of the four drivers couldn't report any difference among the vehicles. The other three could tell the difference (the front biased variant has more braking potential, but it pitches more, leading to less comfort during braking operations), but not everyone agreed when expressing their preference.

Two drivers ranked the vehicle with more braking potential the highest (a Canadian and an Italian), while the other driver (Italian) preferred the baseline because it was more balanced, performing well in emergency braking operations while still displaying a progressive behaviour in slower braking. However, when assessing which behaviour would be preferred for a Jeep in this operation, both Italian drivers settled for the baseline or a mix of the two variants.

This difference in ranking leads to the following question: should vehicles be developed looking mostly at their behaviour in limit conditions, or according to how comfortable and stable they feel during normal operations?

The only Canadian driver able to assess the car models in the braking maneuver was accustomed to testing Jeep vehicles. They expressed a preference for the vehicle with more braking potential (which, according to [40], should be more uncomfortable because of increased pitching behaviour). They stated that this behaviour is what is to be expected by a vehicle like a Jeep. According to the description of the Jeep Renegade provided in Chapter 4, the driver's choice in this case respects the brand's identity and is consistent with it. The Italian drivers were completely aware of the difference between the baseline and the two variants, but decided to settle for an intermediate position, saying that the ideal behaviour was either the one displayed by the baseline, or a behaviour that switches from one variant to the other depending on how harsh the braking operation is going to be. Their stance reflects the type of car they are most familiar with: high performance cars that are mostly driven on city roads at medium-low speeds.

According to the Chief Driver Maserati and Test Driver Daniele Manca, an issue relevant to the braking maneuver is that many popular vehicle models in North America display larger body motions than the average European vehicle (attributed to the different calibrations of dampers, spring and bushings, which are softer in most North American cars in order to ensure more comfort and absorption of longitudinal impacts), so the larger pitching motion which characterizes the first variant might not be associated to a high discomfort by the Canadian test drivers the same way it is for the Italian drivers (personal communication, D. Manca, August 4, 2022).

5.5 On Center Weave

In this test, there was very little difference among the scores given by the teams and everyone's opinions and observations were aligned. The average difference between the scores of each team is 1.

5.6 Frequency Sweep Test

The overall perception of the drivers in this test is aligned (the average difference among the teams is of 1.17, the difference is equal or higher than 2 in just three out of nine items). Some of them displayed higher sensitivity to the torque progression and resonance at different frequencies. Three drivers out of four preferred the second variant, with higher stiffness and damping, recognizing that more steering effort was required but still deeming it more communicative, with a better torque build up and centering feel (how easy it is to identify the 0 degree steering wheel angle point). Just one driver considered the baseline the best choice but expressed the need for more torque at low steering wheel angle. Even though they didn't all agree on the final preference, given their previous responses, it is safe to say that if there was a way to get the torque build up and centering feel of the second variant but with some steering assist to diminish the effort required, they would all have settled for that option.

5.7 Cleat test

In this test, the teams were more like-minded, with an average difference in team score of 0.89 and just one item with a difference in score of 2. When required to express a preference, the team of Canadians didn't express any strong one while both Italians agreed to prefer the variant with harder dampers. This kind of event is probably not enough for the driver to formulate a more thoughtful opinion on the ride comfort of each vehicle, therefore it is suggested that in the future, if a more thorough subjective assessment testing needs to be done, this maneuver will be replaced with another event.

5.8 Discussion of Results

Since the limited number of test drivers involved in this project doesn't constitute a sample of statistical relevance, the nature of this investigation was mostly qualitative.

The reason why a team reported more similar results than the other might be due to incidental factors, such as carrying out the simulations on the same day and witnessing their team member's assessment, consequently being influenced by each other, or just the result of more years of working on the same team. However, it can't be excluded that there is actually a major alignment in perception and preferences among the two drivers of the Italian team. It was later confirmed by the Italian team members that the tests were carried out at two different times and drivers were not aware of the score given by their teammate, but the pair has worked together closely for four years and completed major development projects together.

Except for the Straight and Braking test, in which one of the possible interpretations of the results can be linked to the drivers operating in two different regions, no relevant difference could be noted that led us to think the major discriminant factor among the two teams was the region they work and trained in. However, it's not to be excluded that differences among the regions will be eventually displayed if more drivers are included in the assessment.

As far as this study is concerned, the first discriminating factor among the drivers appeared to be their sensitivity, or their ability to clearly identify the change in behaviour between two variants of the same vehicle. If the difference was identified, the next concern of the test driver seemed to be finding a balance between the brand identity research (i.e., which kind of customers are targeted and their expectations towards the driving experience) and the safety of the customer (understeering and more stable vehicles are easier to maneuver than reactive and sporty vehicles). Eventually, their individual preferences became evident; some people simply find a sporty driving more appealing while others prefer a vehicle that is stable, intuitive and designed with a focus on ride comfort. Overall, it can be concluded that further tests which involve more teams from both regions are needed to confirm regional versus personal preferences in the SAs.

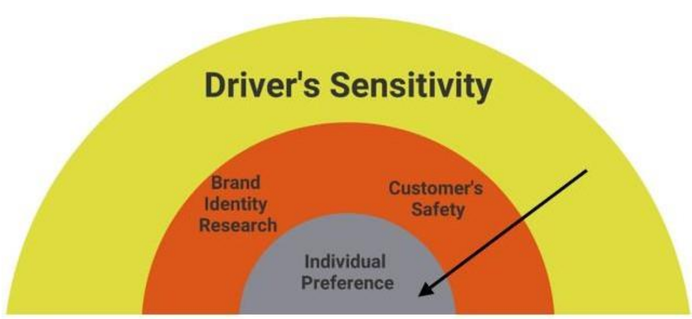


Figure 67.The elements that influence a driver's final feedback, from the most to the least influential.

In 2017, Daniele Manca and his team were asked to perform the ride and handling assessment of some competitor vehicles to determine if a different calibration was used in the models sold in North America compared to the ones sold in Europe. It was found that most European carmakers did not change vehicle parameters from those designed for the North American market. The only exception was one vehicle, which was sold in North America with the comfort package as the default, and the sport package as optional. In Europe, it was the opposite. The difference between the two packages was in the design of bushings, springs and dampers.

The choice made by the car manufacturer was consistent with the different topography of the two continents. Even when comparing the American and European proving grounds where performance engineers test new vehicles, it is found that American proving grounds mainly involve long straights and large radius curves, while the European proving grounds involve more elevation changes and smaller radius curves (the proving grounds used in this test on the simulator were all the same). According to Daniele and his team, the main concern of North American car makers is to focus on ride and road filtering, while Europeans focus on handling with a preference toward sport handling (personal communication, D. Manca, Chief Drivers Maserati, August 4, 2022).

CHAPTER 6

Conclusions and Recommendations

In order to precisely assess the extent and the way in which drivers' opinions about the ride and handling behavior of a car are affected by regional factors, it is necessary to extend the pool of test drivers involved in the investigation. The results of this research show that with a sample of four drivers the differences among them are attributed to personal factors, rather than regional. The first discriminant factor is their sensibility, followed by their concerns to respect the identity of the brand and guarantee that the product is intuitive to maneuver for the customer. Finally, their individual preference comes across: some prefer sport-like handling, other are more focussed on the quality of the ride comfort.

There are definitely differences in the way cars are designed and tested in order to accommodate the different needs of drivers in Europe and North America. This does not necessarily imply that the customer's preference when it comes to the driving experience is shaped after it: when buying a vehicle, the customer takes into consideration many factors related to their habits and necessities, not only the ride and handling characteristics of the product. It is suggested that in the future, the feedback of non-professional drivers is considered in inter-regional studies related to the ride and handling assessment in order to further expand the sample. In this chapter, the main recommendations for eventual future works related to this topic of research are outlined and further discussed.

6.1 Expand the pool of professional drivers

In view of developing a global vehicle (i.e., a vehicle destined to more than one market), the recommendation is that teams of test drivers from the regions targeted are assembled to test it and evaluate the marketability of it in their region. A good practice would be to discuss the target customers of the new car model prior to testing in order to ensure a more uniform approach to their assessments. They should be encouraged to include detailed qualitative comments in their assessments to facilitate identification of different calibrations of the vehicle that could fit better the needs and preferences of drivers in that region and make it more marketable.

Another consideration limited to the regions involved in this project, EMEA (Europe, Middle East, Africa) and NA (North America), is to adopt a more strategic analysis: the marketability of products developed in EMEA can be assessed by NA test drivers on ride-focused events, while products developed in NA can be assessed by EMEA drivers with events focused on handling and sporty driving.

6.2 Include non-professional drivers

Dynamic driving simulators were made available for car makers just in the past few years (the first Maserati model to be developed entirely virtually is the MC20, in 2019). There is a lot of potential in this technology that is still to be exploited. One of the possible future applications is the involvement of non-professional drivers in the development phase. As was evident among professional drivers, the driving experience is different for every individual. Satisfying customers is the end goal of a company; involving the targeted users in the development phase and getting their feedback might be beneficial in view of realizing customized packages with different calibrations, or even just to investigate how preferences and attitudes change among different categories of users when it comes to driving.

Non-professional drivers have always been excluded from highly technical tests like the ride and handling assessment, but are much more involved in comfort or behavioural studies. However, given that the dynamic driving simulator provides an environment in which to attempt different maneuvers without a real danger to get harmed, it is now more feasible to include them in the ride and handling testing. In this chapter, a list of recommendations for future studies on the matter is provided.

6.2.1 Improve the validity of the simulation

The lack of professional training is not the only limitation when performing a subjective assessment test of this kind. The simulator is just a reproduction of what the driving experience is; despite the motion cueing algorithms have been honed to provide the user with a realistic feel, authentically shrinking the motion of a vehicle on the road to a room is still impossible. Additionally, the visual and sound cues might throw a non-professional off, causing not only their assessment to be imprecise, but also physical discomfort in some cases. In the perspective of introducing non-professional drivers to these types of tests, all these factors must be accounted for (which, alongside the danger they might incur during a test on a physical prototype, is the reason for which the SA testing has always been carried out by trained professionals). However, studying the drivers’ feedback on their experience on the DiM250 might be of help to further improve the technology and all drivers’ experience in the simulation environment.

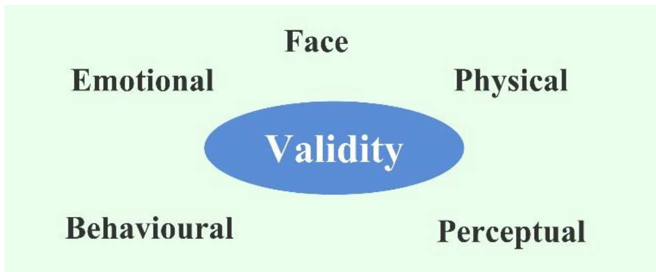


Figure 68. Five different aspects to account for when assessing the "validity" of a simulator, from [56].

Driver-centered validation studies conducted in the past [56] led to the identification of five main factors which affect the perception of the driver in the simulation environment (Figure 68). The following list doesn’t address exclusively dynamic simulators employed for ride and handling assessment but driving simulators in general.

- *Emotional validity.* To what extent does the simulated drive makes the driver feel involved?
- *Physical validity.* How does the motion and feedback of the simulator match that of the subject vehicle?
- *Face validity.* How is the simulator perceived in terms of looks and feel?
- *Perceptual validity.* Do drivers acquire the appropriate ocular, auditory and proprioceptive cues in order to make properly perceive distance, speed and acceleration?
- *Behavioural validity.* Does the driver’s perception of the environment lead to comparable vehicle control under both simulated and natural conditions?

The physical validity experienced by a driver in a simulator such as DiM-250 is expected to be very high given that it was designed with the purpose of reproducing the dynamic behavior of a real vehicle. However, it’s not uncommon for drivers to find the assessment hard to make and request to modify certain motion cueing algorithm parameters (this occurred during simulations performed during the current research). If a non-professional driver can precisely vocalize issues regarding imprecise dynamic behavior of the vehicle, the motion cueing algorithm can be modified accordingly. However, this might require some time depending on the clarity of communication between the driver and the engineers in charge of setting up the simulation and tuning the motion cueing parameters.

If regular drivers were to be included in this kind of test, a good practice aimed at improving the simulator technology would be to utilize a questionnaire in which they are asked to rank the five aspects of the validity of the simulation and provide suggestions on how to improve them.

6.2.2 Avoid physical discomfort

The physical discomfort experienced by some people in the simulator might influence their assessment. A method to assess the magnitude of this phenomenon is the Simulator Sickness Questionnaire (SSQ), in Figure 69, which identifies three main types of motion sickness symptoms: nausea (N), oculomotor (O), discomfort (D). Each symptom is assigned a score from 0 to 3, and then a final score is computed using the formula in Figure 69.

For many users, motion sickness is caused by a conflict between visual cues and the way in which brain combines what both eyes see. When a passenger is reading a book on a moving vehicle, their eyes are fixed on the text even when the road is bumpy but because their sense of gravity feels the bumpiness while they read, there is a mismatch in the cues of what they see and what they feel, thus creating the feeling of motion sickness. The graphics used on driving simulators are flat and this phenomenon might take place. Since the year 2015, the University of Stanford has been working on a new generation of virtual reality (VR) headsets that creates a more natural depth of field by letting the user's eyes focus on multiple images at once (building a type of hologram) [57].

TABLE 4
Computation of SSQ Scores

SSQ Symptom[a]	Weight N	O	D
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total[b]	[1]	[2]	[3]

Score
N = [1] × 9.54
O = [2] × 7.58
D = [3] × 13.92
TS[c] = [1] + [2] + [3] × 3.74

[a]Scored 0, 1, 2, 3. [b]Sum obtained by adding symptom scores. Omitted scores are zero. [c]Total Score.

Figure 69. Simulator Sickness Questionnaire (SSQ), from [58].

The application of VR headset technology to driving simulators is not uncommon; companies such as ARSOME Technology (specialized in developing augmented reality, virtual reality and mixed reality strategies for a wide variety of specific industries) developed a driving simulator which works with a VR set in order to offer driver education for new drivers and teens with a low-cost, compact, flexible, and manageable solution, but also to reproduce rapidly evolving and hazardous conditions that can't be easily duplicated or safely experienced in the real world [59]. Applying the VR technology to the dynamic driving simulator would be a way to improve the perceptual validity of it.

6.2.3 Re-adapt the simulation

During the SA of ride and handling qualities of a vehicle, professional drivers reply to very technical questions that would not be easily understood or properly answered by non-professional drivers. Their lack of technical background makes them unsuitable for a thorough analysis, but they can still express their opinions and preferences comparing different models in the same maneuver and give their overall impression. However, the items of the questionnaire must be rephrased and a briefing about the main body motions (roll, pitch and yaw) should be given to them in order to make the assessment possible. A non-professional driver lacks precision and training as compared to a professional driver, so it might be harder to precisely perform open loop maneuvers that require an accurate input. Closed loop maneuvers which recall common driving scenarios are expected to lead to better behavioural validity.

6.2.4 Investigate the drivers' sensitivity

Another aspect to account for with the view to include non-professionals in this type of testing is that they might lack sensitivity and not be able to pick up on the difference among different calibrations of the same vehicle. This happened even among professional test drivers who gathered many hours of experience and training, so it's safe to assume that non-professional drivers will display different levels of sensitivity. Collecting data about the sensitivity of average drivers could benefit development engineers. For example, consideration of two different types of dampers: one is less expensive but degrades the performance of the vehicle according to virtual simulations run offline. The team of expert drivers notices the change, but the difference in score between the two solutions is not high. A sample of non-professional drivers might be requested to try the two different damper configurations with some targeted maneuvers on the dynamic simulator and rate the vehicle behaviour. If most drivers don't seem to be affected by the change in dampers, the engineers might be able to justify selection of the less expensive damper technology.

REFERENCES

[1] T. Voelk, "Europe and the U.S. Share a Lot, Except When It Comes to Cars," 4 March 2020. [Online]. Available: https://www.nytimes.com/2020/03/04/automobiles/european-us-cars-automakers.html.

[2] "American Cars vs European Cars: What’s the Difference?," 15 October 2019. [Online]. Available: https://www.carsiceland.com/post/american-cars-vs-european-cars.

[3] H. Dia, "Difference Between American & European Cars," [Online]. Available: https://itstillruns.com/difference-between-american-european-cars-5959834.html.

[4] "What is Stellantis and what cars does it make?," 8 August 2021. [Online]. Available: https://www.briggsdodge.net/blog/what-is-stellantis-and-what-cars-does-it-make/.

[5] "Carsalesbase," 2021. [Online]. Available: https://carsalesbase.com/europe-dodge/.

[6] "Carsalesbase," 2021. [Online]. Available: https://carsalesbase.com/europe-chrysler/.

[7] C. B. V. H. M. P. S. M. D. R. M. E. Gemonet, "Drivers' Performances andf Their Subjective Feelings About Their Driving During a 40-min Test on a Circuit Versus a Dynamic Simulator," *Transportation Research Part F 78,* pp. 466-479, 2021.

[8] F. P. A. Kemeny, "Evaluating Perception in Driving Simulation Experiments," *TRENDS in Cognitive Sciences, Vol.7, No. 1,* January 2003.

[9] D. B. D. S. U. O. A. Capustiac, "Motion Cueing: From Design Until Implementation," *Proceedings of the Romanian Academy, Series A, Volume 12,* pp. 249-256, 2011.

[10] "DiM150 & DiM250 DYNAMIC Simulator," [Online]. Available: https://www.vi-grade.com/en/products/dim150_dim250_dynamic_simulator/.

[11] P. Seredynski, "FCA claims North America's most advanced driving simulator," 30 September 2019. [Online]. Available: https://www.sae.org/news/2019/09/fca-new-windsor-rd-simulator.

[12] "FCA Advanced Vehicle Driving Simulator," [Online]. Available: media.stellantisnorthamerica.com.

[13] B. P. Minaker, Fundamentals of Vehicle Dynamics and Modelling, Windsor: John Wiley

and Sons, Ltd, 2019.

[14] "Vehicle Dynamics Terminology," vol. SAE Recommended Practice J670f.

[15] *Road Vehicles - Vehicle dynamics and road-holding ability - Vocabulary,* ISO 8855, 1991.

[16] "Vehicle Model - Convention and References," VI Grade, [Online]. Available: file:///C:/Apps/VI-grade/VI-CarRealTime%2019/help/webhelp/index.html.

[17] "The Three Dimensions of Movement in a Car," [Online]. Available: https://www.gran-turismo.com/gb/gt7/apex/driving_technique/03.

[18] M. H. R. B. D. Schramm, Vehicle dynamics: modelinf and simulation, Berlin: Springer Berlin Hiedelberg, 2018.

[19] A. Tonoli, "Lateral dynamics," in *Automotive Engineering, Motor Vehicle Design*, Torino, Politecnico di Torino, 2019.

[20] Z. Sinasac, *Subjective Evaluation of Vehicle Semi-Active Suspension for Improved Ride and Handling.*

[21] VI-Grade, "VI-CarRealTime webhelp documentation - Vehicle Model," [Online].

[22] "Anti-roll bar," Wikipedia, 2022 May. [Online]. Available: https://en.wikipedia.org/wiki/Anti-roll_bar.

[23] M. Robinson, "How Do Anti-Roll Bars Actually Work?," CarThrottle, 2018. [Online]. Available: https://www.carthrottle.com/post/how-do-anti-roll-bars-actually-work/.

[24] E. Mason, "File: Alfetta front suspension antiroll.jpg," Wikimedia.

[25] T. D. Gillespie, "Fundamentals of Vehicle Dynamics," Society of Automotive Engineers, Inc., 1992, p. 323.

[26] T. D. Gillespie, "The steering system," in *Fundamentals of Vehicle Dynamics*, Society of Automotive Engineers, Inc., 1992, pp. 275-276.

[27] Jahobr, "Rack and Pinion," Wikimedia Commons, 2019.

[28] VI-Grade, "Steering Subsystem," in *VI-CarRealTime webhelp documentation*.

[29] VI-Grade, "Rack- Pinion Steering, Mechanical properties," in *VI-CarRealTime webhelp*

documentation.

[30] VI-Grade, "Torsion bar," in *VI-CarRealTime webhelp documentation*.

[31] A. Tonoli, "Suspensions," in *Automotive Engineering - Motor Vehicle Design*, Torino, Politecnico di Torino, 2019.

[32] KDS444, "Shock Absorbers Detail," Wikimedia Commons.

[33] VI-Grade, "Dampers," in *VI- CarRealTime webhelp documentation*.

[34] M. N. E. B. L. D. G. L. Gomez, "Findings from Subjective Evaluations and Driver Ratings of Vehicle Dynamics: Steering and Handling," *Vehicle System Dynamics, Vol. 53, ,* p. 1416–1438, 2015.

[35] D. C. D.C. Chen, "Subjective and Objective Measures of Vehicle Handling: Drivers & Experiments," in *Vehicle Systems Dynamics Supplement 28*, 1998, pp. 576-597.

[36] *ISO 13674-2 Road Vehicles - Test Method for the Quantification of On-Centre Handling; Part 2: Transition Test,* 2016.

[37] T. C. I. 108, *Mechanical vibration and shock - Human exposure - Vocabulary,* International Organization for Standardization ISO, 1997.

[38] M. T. H. Huang, "Vehicle Cornering Performance Evaluation and Enhancement Based on CAE and Experimental Analyses," *MDPI,* 2019.

[39] F. O. Jaksch, "Driver- Vehicle Interaction with Respect to Steering Controllability," *SAE Transactions, Vol. 88, Section 3,* pp. 2592-2629, 1979.

[40] G. M. Joseph J.A., "Motion Sickness: Effect of the Magnitude of Roll and Pitch Oscillation," *Aviat Space Environ Med,* 2008.

[41] P. S. G. A. Rohit Vaidya, "Study Of On-Center Handling Behaviour Of A Vehicle," Tata Technologies Limited , Pune.

[42] D. F., "A test method for quantification of on-center handling with respect to cross wind," *Proc Institution of Mechanical Engineers,* vol. Vol. 216, no. Part D, pp. 259-266, 2002.

[43] N. K.D., "Objective Evaluation of On-Center Handling Performance," *SAE Paper 840069.*

[44] F. D.G., "An Objective Measurement Technique for the Quantification of On-Centre

Handling Quality," *SAE Paper 930827.*

[45] F. H. H. P. S. K. Burns, *Performance Engineer's Handbook Version 6.1,* FCA, 2019.

[46] R. Agarwal and A. Adisesh, *Objective development of damper specification,* Gothenburg: Dept. Mechanics and Maritime Sciences, Chalmers University of Technology, 2018.

[47] "Learn all about the Jeep brand history," Ourisman Chrysler Dodge Jeep Ram of Bowie, 17 July 2021. [Online]. Available: https://ourismanchryslerdodgejeepramofbowieblog.com/2021/07/17/learn-all-about-the-jeep-brand-history/.

[48] "Sport Utility Vehicle," Wikipedia, 1 August 2022. [Online]. Available: https://en.wikipedia.org/wiki/Sport_utility_vehicle.

[49] "Chrysler Proving Grounds," Wikipedia, 30 January 2022. [Online]. Available: https://en.wikipedia.org/wiki/Chrysler_Proving_Grounds.

[50] "Vehicle Dynamics Terminology," *SAE J670e.*

[51] T. D. Gillespie, "Experimental Measurement of Understeer Gradient," in *Fundamentals of Vehicle Dynamics*, Society of Automotive Engineers, Inc., 1992, pp. 227-236.

[52] F. L. J. C. Y. Y. F. Xiong, "Investigation into Improvement for Anti-Rollover Propensity," *Chin. J. Mech. Eng. Vol 30,* p. 698–710, 2017.

[53] "Fishhook," VI-Grade, [Online]. Available: file:///C:/Apps/VI-grade/VI-CarRealTime%2019/help/webhelp/index.html.

[54] M. Becker, M. Höfer and P. E. Pfeffer, "Steering Feel of Lane Keeping Assist Systems," 2020.

[55] A. K. Z. Fang, "Motion Cueing Algorithms for a Real-time Automobile Driving SImulator," in *Driving SImulation Conference* , Paris, 2012.

[56] A. H. J. S. L. Jamson, "The validity of a low-cost simulator for the assessment," *Safety Science 48,* pp. 1477-1483, 2010.

[57] V. Ramachandran, "Stanford researchers unveil virtual reality headset that reduces eye fatigue, nausea," Stanford news, 3 August 2015. [Online]. Available: https://news.stanford.edu/news/2015/august/virtual-reality-headset-080315.html.

[58] R. S. Kennedy, N. E. Lane, K. S. Berbaum and M. G. Lilienthal, "Simulator Sickness Questionnaire: an ENhanced Method for Quantifying SImulator Sickness," *The International Journal of Aviation Psychology,* vol. 3, pp. 203-220, 1993.

[59] "Virtual Reality Driving Training," ARSOME Technology, [Online]. Available: https://arsome.com/virtual-reality-driving-training.html.

APPENDICES

Appendix A – Subjective Assessment Questionnaire

University of Windsor

Politecnico di Torino

STELLANTIS

DIMD Manuela Maria Aleci
Subjective Assessment Test

This booklet is for the test drivers involved in the realization of my project.
Thank you for your availability.

Manuela

Briefing

____

(Name of the driver)

In which Country are you currently working?	
Have you been a test driver in other Countries before now? If yes, where?	
How many years of experience do you have?	
Which kind of cars do you usually test? List the models you have tested in the past, if possible	

Subjective Assessment Questionnaire

The test driver will run eight maneuvers and express their judgement on a list of subjective assessment items. After each questionnaire, there are some open questions. It is suggested that the test driver goes through all the items related to a maneuver before starting the test.

Guide to rating

Rating	Description	Observed by	Acceptability
①	Intolerable	All Observers	Unacceptable
②	Severe		
③	Very Poor	Most Observers	
④	Poor		
⑤	Marginal	Some Observers	Borderline
⑥	Barely Acceptable	Critical Observers	Acceptable
⑦	Fair		
⑧	Good	Trained Observers	
⑨	Very Good		
⑩	Excellent	Not Observed	

Potential scale refinement

1 point	Major Difference	Noticed by customers
0.5 point	Significant Difference	Noticed by some customers
0.25 point	Difference	Noticed only by critical observers
+ or -	Minor Difference	Used primarily to rank vehicles of similar performance

How to proceed?

For every maneuver, the driver will test the baseline and two variants. The variants are different for every maneuver, the baseline is always the same. The files are arranged in folders named after the maneuver. Here there is a list of the name of the maneuvers and the one of the variants.

Maneuver name	Name of variant #1	Name of variant #2
Slalom	*slalom_v1*	*slalom_v2*
CRC	*CRC_v1*	*CRC_v2*
Fishhook	*FH_v1*	*FH_v2*
Straight and Braking	*SB_v1*	*SB_v2*
On Center Weave	*OCW_v1*	*OCW_v2*
Frequency Sweep	*FS_v1*	*FS_v2*
Cleat Test	*CT_v1*	*CT_v2*

Slalom

Description

The vehicle is driven at nearly constant speed through a set of cones aligned in a straight path. The spacing between the cones is constant and the vehicle speed is increased after each successful run.

Seven cones x 30.5 m, 3 trials, start at 70 kph.

Vehicle 1

Item to Assess	Subjective Rating
1) Rate the vehicle sensitivity to the steering input	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the promptness of the vehicle *(Yaw response time and coherence)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
4) Evaluate the response lag between front and rear axle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1) Rate the vehicle sensitivity to the steering input	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the promptness of the vehicle *(Yaw response time and coherence)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
4) Evaluate the response lag between front and rear axle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1) Rate the vehicle sensitivity to the steering input	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the promptness of the vehicle *(Yaw response time and coherence)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
4) Evaluate the response lag between front and rear axle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Describe briefly the handling behavior of Variant 1

Describe briefly the handling behavior of Variant 2

Describe briefly the handling behavior of Variant 3

Which variant did you prefer, overall? Why?

Considering the vehicle model you tested (Jeep Renegade), what do you deem an optimal behavior for this test?

Constant Radius Cornering

Description

Approach tangentially the 300 feet circle at a speed of 80 kph, lift throttle upon reaching the circle and brake until a speed of 40 kph is reached, while attempting to maintain a path along the circle; then accelerate until the initial speed is reached again. Time how much it takes you to run this simulation with each variant

Vehicle 1

Item to Assess	Subjective Rating
1) Evaluate the understeering attitude of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the easiness in maintaining the trajectory when cornering	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the predictability of the steering progression when cornering	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
4) Evaluate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1) Evaluate the understeering attitude of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the easiness in maintaining the trajectory when cornering	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the predictability of the steering progression when cornering	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
4) Evaluate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1) Evaluate the understeering attitude of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the easiness in maintaining the trajectory when cornering	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the predictability of the steering progression when cornering	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
4) Evaluate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Describe briefly the handling behavior of Variant 1

Describe briefly the handling behavior of Variant 2

Describe briefly the handling behavior of Variant 3

Which variant did you prefer, overall? Why?

Considering the vehicle model you tested (Jeep Renegade), what do you deem an optimal behavior for this test?

Fishhook Test

Description

- Drive straight at 80 kph
- Apply a steering input of 30 degrees and hold it for 0.25 seconds
- Apply a steering input of -240 degrees and hold it for 3 seconds
- Come back to a steering input of 0

Vehicle 1

Item to Assess	Subjective Rating
1) Rate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the yawing behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the steering effort required for the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1) Rate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the yawing behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the steering effort required for the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1) Rate the rolling behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the yawing behavior of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the steering effort required for the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Describe briefly the handling behavior of Variant 1

Describe briefly the handling behavior of Variant 2

Describe briefly the handling behavior of Variant 3

Which variant did you prefer, overall? Why?

Considering the vehicle model you tested (Jeep Renegade), what do you deem an optimal behavior for this test?

Straight and Braking

In the next two maneuvers, you are going to assess the same three variants. It is up to you if to load a variant, run the open loop maneuver, answer and then do the same with the closed loop maneuver before switching to the next variant, or if to run the first test with three variants and then do the same for the second test. There is only one set of open questions for these two maneuvers. The suggestion is to look at it and then decide how you want to proceed.

Straight and Braking — Open Loop

Description

Reach the speed of 90 kph while driving straight, then full brakes.

Vehicle 1

Item to Assess	Subjective Rating
1) Rate the braking pitch of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the stability of the vehicle during the braking maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the longitudinal acceleration experienced during the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1) Rate the braking pitch of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the stability of the vehicle during the braking maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the longitudinal acceleration experienced during the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1) Rate the braking pitch of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the stability of the vehicle during the braking maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the longitudinal acceleration experienced during the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Straight and Braking —Closed Loop

Description

Reach the speed of 90 kph while driving straight until the first cone, then brake in order to stop before the second cone (placed 100 m further).

Vehicle 1

Item to Assess	Subjective Rating
1) Rate the braking pitch of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the stability of the vehicle during the braking maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the longitudinal acceleration experienced during the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1) Rate the braking pitch of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the stability of the vehicle during the braking maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the longitudinal acceleration experienced during the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1) Rate the braking pitch of the vehicle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Rate the stability of the vehicle during the braking maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Rate the longitudinal acceleration experienced during the maneuver	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Which variant made you feel safer during the emergency brake (open loop) test? Why?

Which variant was more comfortable in the slower brake (closed loop) test? Why?

Considering both situations (emergency brake and slower brake), how would you rank the variants overall? Why?

Considering the vehicle model you tested (Jeep Renegade), what do you deem an ideal behavior in a braking maneuver?

On center weave test

Description

Drive straight at the speed of 100 kph and apply a sinusoidal input steer of amplitude 10 deg and frequency of 0.2 Hz

Vehicle 1

Item to Assess	Subjective Rating
1)Evaluate the on center feel *(responsiveness and feel of the steer when the wheel is approximately centered)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the centering feel *(is it possible to feel the center position of the steering wheel according to the reaction torque?)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1)Evaluate the on center feel *(responsiveness and feel of the steer when the wheel is approximately centered)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the centering feel *(is it possible to feel the center position of the steering wheel according to the reaction torque?)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1)Evaluate the on center feel *(responsiveness and feel of the steer when the wheel is approximately centered)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the centering feel *(is it possible to feel the center position of the steering wheel according to the reaction torque?)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Describe briefly the steering feel of Variant 1

Describe briefly the steering feel of Variant 2

Describe briefly the steering feel of Variant 3

Which variant did you prefer, overall? Why?

Considering the vehicle model you tested (Jeep Renegade), what do you deem an optimal behavior for this test?

Frequency Sweep test

Description

You have more freedom in this test: apply a steering input of amplitude comprised between 30 and 45 degrees, try different longitudinal speeds and try to stay within the 0-4 Hz range. The purpose is to do a general evaluation of the steering feel. Make sure you record the steering wheel angle during this maneuver and send it alongside with the answers to this questionnaire.

Vehicle 1

Item to Assess	Subjective Rating
1)Evaluate the steering effort	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the torque change compared to the steering angle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Evaluate the centering feel *(is it possible to feel the center position of the steering wheel according to the reaction torque?)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1)Evaluate the steering effort	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the torque change compared to the steering angle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Evaluate the centering feel *(is it possible to feel the center position of the steering wheel according to the reaction torque?)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1)Evaluate the steering effort	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the torque change compared to the steering angle	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Evaluate the centering feel *(is it possible to feel the center position of the steering wheel according to the reaction torque?)*	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Describe briefly the steering feel of Variant 1

Describe briefly the steering feel of Variant 2

Describe briefly the steering feel of Variant 3

Which variant did you prefer, overall? Why? What is the best way to make an evaluation of the steering feel, according to you?

Considering the vehicle model you tested (Jeep Renegade), what do you deem an optimal behavior for this test?

Cleat Test

Description

Run over the cleat at a speed of 30 kph.

Vehicle 1

Item to Assess	Subjective Rating
1)Evaluate the severity of the impact felt by the driver when the front suspension hits the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the severity of the impact when the rear suspension hits the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Evaluate how quickly the vehicle vertical motion dissipates after hitting the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 2

Item to Assess	Subjective Rating
1)Evaluate the severity of the impact felt by the driver when the front suspension hits the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the severity of the impact when the rear suspension hits the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Evaluate how quickly the vehicle vertical motion dissipates after hitting the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Vehicle 3

Item to Assess	Subjective Rating
1)Evaluate the severity of the impact felt by the driver when the front suspension hits the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
2) Evaluate the severity of the impact when the rear suspension hits the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
3) Evaluate how quickly the vehicle vertical motion dissipates after hitting the cleat	① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩

Which variant did you prefer? Why?

Appendix B – Results SA testing Canadian team

Canada

		D1	D2	Average	Delta
Slalom	V1_1	7	8	7.5	1
	V1_2	7	8	7.5	1
	V1_3	7	8	7.5	1
	V1_4	7	8	7.5	1
	V2_1	4	5	4.5	1
	V2_2	5	8	6.5	3
	V2_3	4	8	6	4
	V2_4	4	8	6	4
	V3_1	8	6	7	2
	V3_2	8	8	8	0
	V3_3	8	8	8	0
	V3_4	8	8	8	0
CRC	V1_1	6	8	7	2
	V1_2	5	8	6.5	3
	V1_3	6	8	7	2
	V1_4	7	8	7.5	1
	V2_1	7	7	7	0
	V2_2	4	5	4.5	1
	V2_3	5	6	5.5	1
	V2_4	3	7	5	4
	V3_1	6	7	6.5	1
	V3_2	7	6	6.5	1
	V3_3	7	7	7	0
	V3_4	8	6	7	2
FH	V1_1	7	8	7.5	1
	V1_2	7	8	7.5	1
	V1_3	9	8	8.5	1
	V2_1	8	8	8	0
	V2_2	9	7	8	2
	V2_3	9	8	8.5	1
	V3_1	5	8	6.5	3
	V3_2	6	6	6	0
	V3_3	9	7	8	2
S&B-OL	V1_1	7	8	7.5	1
	V1_2	8	8	8	0
	V1_3	7	8	7.5	1
	V2_1	6	8	7	2
	V2_2	8	8	8	0
	V2_3	7	8	7.5	1
	V3_1	3	8	5.5	5
	V3_2	3	8	5.5	5
	V3_3	3	8	5.5	5
S&B-CL	V1_1	7	8	7.5	1
	V1_2	10	8	9	2
	V1_3	7	8	7.5	1
	V2_1	8	8	8	0
	V2_2	10	8	9	2
	V2_3	9	8	8.5	1
	V3_1	6	8	7	2
	V3_2	10	8	9	2
	V3_3	7	8	7.5	1
OCW	V1_1	7	5	6	2
	V1_2	5	6	5.5	1
	V2_1	7	8	7.5	1
	V2_2	7	8	7.5	1
	V3_1	6	7	6.5	1
	V3_2	4	7	5.5	3
F-SW	V1_1	7	7	7	0
	V1_2	7	7	7	0
	V1_3	6	6	6	0
	V2_1	3	6	4.5	3
	V2_2	3	4	3.5	1
	V2_3	3	6	4.5	3
	V3_1	6	8	7	2
	V3_2	8	8	8	0
	V3_3	7	8	7.5	1
Cleat	V1_1	7	7	7	0
	V1_2	7	7	7	0
	V1_3	7	8	7.5	1
	V2_1	5	7	6	2
	V2_2	5	7	6	2
	V2_3	4	8	6	4
	V3_1	8	8	8	0
	V3_2	8	8	8	0
	V3_3	7	8	7.5	1
				Average Delta:	1.44

Appendix C – Results SA testing Italian team

Italians

		D1	D2	Average	Delta
Slalom	V1_1	7	6	6.5	1
	V1_2	6	7	6.5	1
	V1_3	6	7	6.5	1
	V1_4	6	8	7	2
	V2_1	8	8	8	0
	V2_2	6	8	7	2
	V2_3	6	7	6.5	1
	V2_4	4	4	4	0
	V3_1	7	7	7	0
	V3_2	5	7	6	2
	V3_3	6	8	7	2
	V3_4	5	6	5.5	1
CRC	V1_1	6	7	6.5	1
	V1_2	6	7	6.5	1
	V1_3	6	7	6.5	1
	V1_4	6	7	6.5	1
	V2_1	4	8	6	4
	V2_2	4	5	4.5	1
	V2_3	5	4	4.5	1
	V2_4	6	4	5	2
	V3_1	5	3	4	2
	V3_2	6	7	6.5	1
	V3_3	6	8	7	2
	V3_4	7	7	7	0
FH	V1_1	6	7	6.5	1
	V1_2	6	8	7	2
	V1_3	6	7	6.5	1
	V2_1	6	8	7	2
	V2_2	6	8	7	2
	V2_3	6	7	6.5	1
	V3_1	4	6	5	2
	V3_2	5	7	6	2
	V3_3	6	6	6	0
S&B-OL	V1_1	7	7	7	0
	V1_2	7	8	7.5	1
	V1_3	7	7	7	0
	V2_1	7	7	7	0
	V2_2	7	8	7.5	1
	V2_3	8	8	8	0
	V3_1	7	8	7.5	1
	V3_2	7	8	7.5	1
	V3_3	6	5	5.5	1
S&B-CL	V1_1	7	7	7	0
	V1_2	7	8	7.5	1
	V1_3	7	7	7	0
	V2_1	7	8	7.5	1
	V2_2	7	8	7.5	1
	V2_3	6	5	5.5	1
	V3_1	7	8	7.5	1
	V3_2	7	8	7.5	1
	V3_3	8	8	8	0
OCW	V1_1	7	6	6.5	1
	V1_2	7	7	7	0
	V2_1	7	7	7	0
	V2_2	8	8	8	0
	V3_1	7	7	7	0
	V3_2	6	6	6	0
F-SW	V1_1	6	7	6.5	1
	V1_2	6	6	6	0
	V1_3	6	6	6	0
	V2_1	4	5	4.5	1
	V2_2	5	7	6	2
	V2_3	4	4	4	0
	V3_1	5	5	5	0
	V3_2	5	4	4.5	1
	V3_3	7	7	7	0
Cleat	V1_1	6	6	6	0
	V1_2	7	7	7	0
	V1_3	7	7	7	0
	V2_1	5	5	5	0
	V2_2	6	6	6	0
	V2_3	8	8	8	0
	V3_1	7	7	7	0
	V3_2	7	7	7	0
	V3_3	6	6	6	0
				Average Delta:	0.8

Item #	Average Comparison Italy	Canada	Delta
1	6.5	7.5	1
2	6.5	7.5	1
3	6.5	7.5	1
4	7	7.5	0.5
5	8	4.5	-3.5
6	7	6.5	-0.5
7	6.5	6	-0.5
8	4	6	2
9	7	7	0
10	6	8	2
11	7	8	1
12	5.5	8	2.5
13	6.5	7	0.5
14	6.5	6.5	0
15	6.5	7	0.5
16	6.5	7.5	1
17	6	7	1
18	4.5	4.5	0
19	4.5	5.5	1
20	5	5	0
21	4	6.5	2.5
22	6.5	6.5	0
23	7	7	0
24	7	7	0
25	6.5	7.5	1
26	7	7.5	0.5
27	6.5	8.5	2
28	7	8	1
29	7	8	1
30	6.5	8.5	2
31	5	6.5	1.5
32	6	6	0
33	6	8	2
34	7	7.5	0.5
35	7.5	8	0.5
36	7	7.5	0.5
37	7	7	0
38	7.5	8	0.5
39	8	7.5	-0.5
40	7.5	5.5	-2
41	7.5	5.5	-2
42	5.5	5.5	0
43	7	7.5	0.5
44	7.5	9	1.5
45	7	7.5	0.5
46	7.5	8	0.5
47	7.5	9	1.5
48	5.5	8.5	3
49	7.5	7	-0.5
50	7.5	9	1.5
51	8	7.5	-0.5
52	6.5	6	-0.5
53	7	5.5	-1.5
54	7	7.5	0.5
55	8	7.5	-0.5
56	7	6.5	-0.5
57	6	5.5	-0.5
58	6.5	7	0.5
59	6	7	1
60	6	6	0
61	4.5	4.5	0
62	6	3.5	-2.5
63	4	4.5	0.5
64	5	7	2
65	4.5	8	3.5
66	7	7.5	0.5
67	6	7	1
68	7	7	0
69	7	7.5	0.5
70	5	6	1
71	6	6	0
72	8	6	-2
73	7	8	1
74	7	8	1
75	6	7.5	1.5

Average Delta (abs. value): 0.96

Appendix D – Teams comparison