POLITECNICO DI TORINO

Master Thesis

Development of a New Methodology for Objective Assessment of Advanced Driver Assistance System

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"It's important to remember what made the moonshot the moonshot, a moonshot challenge requires a clear, measurable objective that captures the imagination of the nation and fundamentally changes how we view what's possible... when we do that, we chart a course for a future that is safer, healthier and stronger." [Bill Gates]

Per Aspera ad Astra

Abstract

The aim of this project is to explain the different conceptions of comfort inside a vehicle and to create a rating system that can consider people differences.
Until now, all the systems aim to create a controller with the ability to drive alone the vehicle. However, these new systems do not take into account the differences in how people feel comfortable inside the vehicle. At the end of the thesis, it is given a suggestion of improvement on how there could be introduced this differentiation.
However, the most important part is related to the implementation of software that aimed at the evaluation of common highway manoeuvres. Nowadays it is based on some fixed boundary conditions and the thesis wants to suggest how to uncouple the rating of the manoeuvres to this fixed constrains.
A new rating methodology is developed and explained in details. The study starts with the study of benchmark data and a detailed analysis of the functionalities and rating of AVL-DRIVE™ ADAS.
Five different common manoeuvres are investigated, explained, discussed and evaluated.

Acknowledgements

During your life you can meet essentially two different kinds of People: People you'll remember for life and people you'll forget after a while.
As far, I want to thank the entire AVL-ADAS group that coloured my days from everyday life to work.
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Per quanto una persona possa nascondere le sue paure, incertezze e difficoltà, nulla è facile ed un percorso lungo, come è giusto che sia, ha mille ostacoli nascosti, e solo chi li ha vissuti conosce. Questo percorso è iniziato con la volontà di lasciare l'università, poiché l'inglese era una barriera troppo ardua in quel momento da superare, ed è finito con un Erasmus in Austria, con una parlantina sviluppata anche in inglese e con la voglia di rimanere a lavorare all'estero.
La vita è fatta di barriere, ma siamo fatti di ragione e con questa ci sappiamo ingegnare superando ogni avversità.
Grazie. Grazie per non avermi fatto mollare e avermi fermata quando avrei voluto solo scappare via. Grazie per essermi stati vicini quando ho sbraitato e gridato contro tutti perché ero stressata, nervosa ed incasinata con gli esami e con la vita.

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Erika Santuccio
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1 Introduction

The present work aimed the development of a new rating methodology.
Several years ago, AVL patented a software with many features and the most important one is related to a methodology to rate some performed manoeuvres. AVL-DRIVE™ ADAS, the discussed software, utilizes some boundary and fixed constrains to rate these manoeuvres according to a conducted study of a cluster. Taking into account the average answer of the studied cluster, the boundary parameters were realized.
However, since the new vehicle implementations address to a full autonomous vehicle, car makers should consider all the differences among the people and not only the average. Having a full autonomous vehicle means an important change of the Figure of the driver: from a completely active Figure to a passive one. It changes the concept of comfort and it involves also the many psychological and physical differences among people. It is the basis assumptions of this work.
The thesis is divided in 6 sections. The first section describes the State of Art and it defines all the faces that compromise the comfort inside the vehicle. It explains the co-relation among acceptance, driving style and physical aspects, which affect the motion sickness sensibility, to the overall perceived comfort.
The second chapter describes the characteristics of AVL-DRIVE™ ADAS and it shows the detection and the rating of the studied manoeuvres. All of them are explained in details.
The following chapter explains the functionalities of the used controller to develop this study. To uncoupled the software from fixed constrains, a controller is introduced. Using this controller, the manoeuvres are performed in a simulation environment. The idea is that the controller is adjustable and can complain all the differences among people. It will generate a manoeuvre differently just changing some parameters. The result channels are considered as references. The environment and the general working principles are discussed. Some implementations are introduced to increase the performance of it and a suggestion for a future implementation is analysed.
The fourth chapter is named 'Evaluation' and it is the core of the project. All the developed criteria are explained and shown with the used rating system and the new methodology is so deployed. The entire next chapter shows the results for all the studied manoeuvres performed with four different calibrations, to get the feeling of the new rating methodology. Finally the conclusion is presented.
In the Appendix it is possible to find some parts of the Matlab® code.

1.1 Comfort

A state of physical ease and freedom from pain or constraint. The easing or alleviation of a person's feelings of grief or distress. (Oxford dictionary)
Whenever a person listens someone talks about comfort, he immediately thinks: "Is it comfortable for everyone or just for him?" and it is the right question because Comfort is a subjective feeling.
When engineers discuss comfort related to the vehicle environment is addressed to the interplay of many elements as smell, light, vibration, noise, climate and aesthetics.[4] Driving dynamics, with its subsections of longitudinal, lateral and vertical dynamics, significantly influences the occupant movements occurring in a vehicle, so the ride comfort includes all the mechanical and acoustic vibrations acting on the occupants. [4]
This thesis has the aim to answer to this main question: "if the comfort is a subjective feeling, are there some parameters that can be changed in order to be adaptable to the whole population?". The entire work is done starting from an already created controller that is

able to generate a trajectory according to the average feeling of comfort, and the purpose is to add some parameters that could be directly changed by the passengers inside the vehicle, and this controller is able also to change its characteristics in order to improve a more sport, or smooth, behaviour as well.
The general idea is to create something that everyone can feel as really suitable to their main characteristics so it will be adaptable on everyone as a dress that could be fit on everybody.
Since the realization of a highly and fully automated vehicles is drawing closer, the attention of all the engineers is shifting from the question of 'how to create an autonomous vehicle', that is already done, to a question more addressed to the acceptance of these new self-guided vehicles, how their driving style should be and the implementation of the comfort.[6] Due to the complexity of the theme, caused by the presence of the subjective analysis, it is divided into many parts in order to simplify the problem and the first chapter is focused on the explanation of how a highly automated vehicle should drive to ensure comfort, safety and chilly time to the new kind of passengers, also examining their psychological and physiological differences.
According to the Burkhard [16], changing the level of attention caused by the aim of the autonomous driving is ensure freedom to do all the activities that they want, i.e. reading, sleeping or working ..., the requirements and tasks for the driving dynamics of the vehicles have to change.
Different attempts need to be done as put limits in accelerations, lateral and longitudinal, or in time of manoeuvring and so on, in order to satisfy the occupant limits and less the vehicle ones. It implies an essential analysis of the commonly shared aspects of the majority of definitions of comfort that is affected by not only external factors but also internal ones and this opens the research fields also to the acceptance and biological aspects.[1]
It is highlighted that a strong relationship between the feeling of comfort and trust and, nevertheless, the acceptance of automated vehicles is another important investigation point. [19] Both trust and acceptance are necessary and essential to be analysed for this topic because they may be seen as a barrier to technology adoptions, this evaluates driving style preferences in automated driving important. [19]
So far, driving comfort is investigated in a context of manual driving, but it is essential to define the difference between 'drive' and 'being driven' in an automated vehicle because it addresses the feeling of control that is a possible reason for motion sickness, trustiness and factors influencing experiencing comfort.
Several pieces of research enhanced that studying driving styles is the most promising option for substantially affecting the experience of the driver in terms of comfort in highly or fully automated vehicles. [5] The research is linked to a change in terms of dynamical motion of the vehicle while passive safety systems of the vehicles, the seats and everything that is connected with what in automotive field is called 'comfort' that indicated the vertical dynamics of the vehicle, are not very likely to change substantially due to a higher automation level.
Considering the existing relationship presented in many references [1] [4] [5] [6] [7] and introduced above between user, comfort, acceptance, trust and likeliness of usage, it is important to identify a most comfortable driving style which is the basis of this work, but taking into account that the new passengers could change some parameters so it should be the right solution for everyone not just for a defined group. It means that the success of automated driving systems' is not only related to how much in terms of safety and correct dynamical parameters the vehicle is performing but also to the automated driving style.
From a technology-driven perspective, an endless number of automated driving styles present themselves.
Summarizing what it is presented upwards, the following chapter will be addressed to an analysis of the biological, physical and psychological problems of the passengers inside an

autonomous driving vehicle. It will be deployed paying attention to several psychological and medical issues: starting from the issued related to the acceptance of autonomous driving to the diversity style guides of people and finally analysing the subjective motion sickness problem.

1.2 General View of the Acceptance Problem

Nowadays everyone has already heard about autonomous driving, and several people had tried and commonly used some systems like the adaptive cruise control for instance, that help people to drive in safety conditions at high speed, on highway for example, and also a low speed as the parking sensors, however, it does not encourage people to trust in the use of full-autonomous vehicles.
It is the reason why users' perception and acceptance of autonomous technologies is highly discussed and investigated since it deeply affects the mobility context. [1]
Most of the users knows that driver assistance systems could really support the drivers security during the common routine giving a connection between infrastructures and the other traffic participants, trying to avoid collision as much as possible thanks to this connection, intervening during critical situation since it has a more open view that could analyse all the several possibilities quickly. [1]
Autonomous driving points out two important and sensible aspects: the lack of driving experience, so actually the driver should trust in the capability of the car to make the right decisions and the connectivity of the cars and drivers. Both of them are strictly related to shared data among vehicles, that means going towards a wide range of privacy and data security issues. Therefore the first one involves also the emotional value of driving, the high flexibility and the independence that just the drive feeling gives as also the fact that the driver loses the control giving it to the car. At least in the Western World, driving is perceived as part of the social life, think that when someone arises the age to take the driving license, he/she immediately wants to take it without waste time: it is perceived as a social worth. [1]
The problem is in such a way strictly related to how to break with tradition.
Nowadays the population is divided into two big catEgories: on one side people that have already a real experience with autonomous vehicles or with other assistant systems on the other side people that think that is still a theoretical construct for consumers. This huge distinction is underlined by a positive relationship between the acceptance of Autonomous Driving and previous experience with driving assistance systems, i.e. adaptive cruise control (ACC), automatic parking, lane-keeping assistant (LKA),..., whereas driving experience without the usage of that has a negative one.[4]
As every introduction of new product on the market, consumers show diverse adoption reactions to innovations: from 'early adopters', people that are much more willing to adopt a novelty, to 'laggards', who refuse the adoption of the innovation as long as possible, following the different shades of adoption willingness.[20]
Doing the market analysis, some researches [1] [19] found out that women and younger driver show a laggard behaviour towards advanced driver assistance systems (ADAS), while younger adults represent the more positive picture as the early adopters of the ADAS and the large-scale study focuses on how the acceptance varies at different possible automation levels. Regarding fully autonomous (i.e. driver-less) technology, the only group, that supports consistently it, is that one composed of younger adults.
Hence the different feelings captivated this technology may also derive from varying domain knowledge and experience with the old technology of the past: it is intuitive that someone

that has never tried some assistance systems. As a direct consequence of it, a generation comparison study showed how age negatively affects the perception of driverless technology and with the increasing of the age people deploy a lower interest to use it.[1] Therefore, beyond effects related to the knowledge and experience on the driver-less that are just explained, also age and gender are found to be potential factors in terms of autonomous technology confidence.[1]
One of the studies about the acceptance of the Autonomous Driving was conducted in the last year in the western part of Germany, and it was investigated how people perceived their role into a fully autonomous driving car (fifth level). As soon as they perceived and realized their role in the vehicle as passengers and not anymore as an active driver, they started to enjoy the reduction of the perceived stress and the possibility to use travel time for doing other things.[1]
However, 10% of interviewers disagreed with this general idea and only wanted to be able to gain back control at all times, always for the feeling of lost control. Moreover, at the end of the study, 60% interviewed participants said that they would not use an autonomous vehicle today with the actual knowledge of this such systems whereas the others would at least try but with someone else in the car.
The overall perception of 'caution' was enhanced just from an interview and not from a real trying.
The loss of control, loss of driving pleasure, giving away responsibility, distrust in technology and technological development create all the negative reasons that instigate people not to want to use this new technology.
Considering what it is presented until now, it is quite evident that people are not still ready to accept a fully autonomous driving, because they would like to have a possible intervention when they do not trust in the vehicle decisions. At the end of this short presentation of the problems affecting the trust of this new technology, a critical task of the car-makers, in order to enhance the adoption of ADAS systems, could be to work on the acceptance of the population.

1.2.1 Acceptance Study

Acceptance is depicted in general terms as 'agreeing, accepting, approving, acknowledge: to agree with someone or something'.[19]
As discussed above, acceptance must be brought into the discourse that is developed around autonomous driving in an early stage, even if the road traffic with fully automated vehicles is not still ready.[19] The introduction of this new technology will potentially change the entire sphere of mobility since it goes to attack all the society development but to do this, it is really necessary to break the thread that connects experiences related to the driving feeling to the acceptance of the new way to move to the fear of being controlled by a technology that all together give an overall bad feedback. Working on the acceptance problem is addressed to solve and manage the development of the new technology following it in all the phases: in simple words, it means that it is important to identify which factors are important to influence people and understand their dynamics in order to control the total acceptance feeling of the newly presented technology. This discussion involves every new product on the market, not only autonomous driving, and it is strictly addressed to marketers that should introduce the new product. [19] [20]
When in the automotive field it is referred to Acceptance, it is also essential to encompass a sense of "willingness for something" because, in this way, it is bestowed to it an active component on acceptance: it changes the problem drastically from the psychological point

of view because it creates a differentiation between simple acquiescence and the absence of opposition, but also it gives a distinction between just tolerance and acceptance. Many parameters involve this issue and they are strictly related to people, i.e. their attitudes, expectation, actions and values, to the environment where they live, but also on economic and political changes over time. [19]
At each stage of technology development, implementation and adoption, different factors and main characters are relevant to acceptance, so the stakeholders and stakeholder groups are various. [20]
Acceptance is a complex multi-layered construct that is not directly measurable since it is a psychological state of mind, and for which there are no calibrated measuring instruments as involve the human psyche.[19]
There are many different levels of acceptance that involves different aspects, and they can be described as:

- Attitudes: 'acceptance that can be surveyed include mindsets, values and judgements. Attitudes are significant for acceptance research, as it is assumed that they can be read as willingness and intent for concrete actions.' [19]
- Actions: 'observable behaviour, although acting in this sense may relate either to doing something or to refraining from it.'[19]
- Values: 'dimension of values comes into its own, however, when acceptance is visible on the level of actions, for instance in the use of a specific product.'[19]

Acceptance is always investigated compared to an already existing system composed of norms and values since it is a related feeling. Nevertheless it is really important to underline that acceptance takes place not only, as described, at various levels, but it is also a result of all the processes through the individual and the group of the evaluation and the nEgotiation. For a relatively new technology as Autonomous Driving it is so necessary to study all the different characters that give challenges to the technological and scientific progress, for instance social groups, organizations, institutions and also individual stakeholders. [19]

1.2.2 SAE Levels Explanation

According to the website [3], the following section is dedicated to the explanation of the SAE Level, and it is inserted in the acceptance sub-chapter since it is strictly connected to it: the acceptance problem is overcoming with a slow introduction of the new technology.
In order to analyse the differences among the several levels of automation, SAE has introduced the level definitions called driving mode with the meaning of a type of driving scenario with characteristic dynamic driving task requirements.
Research has forecast that the year 2025 will see eight million autonomous or semi-autonomous vehicles with SAE level 3,4 or 5.
From fully manual to fully autonomous capabilities, this is the distinction:

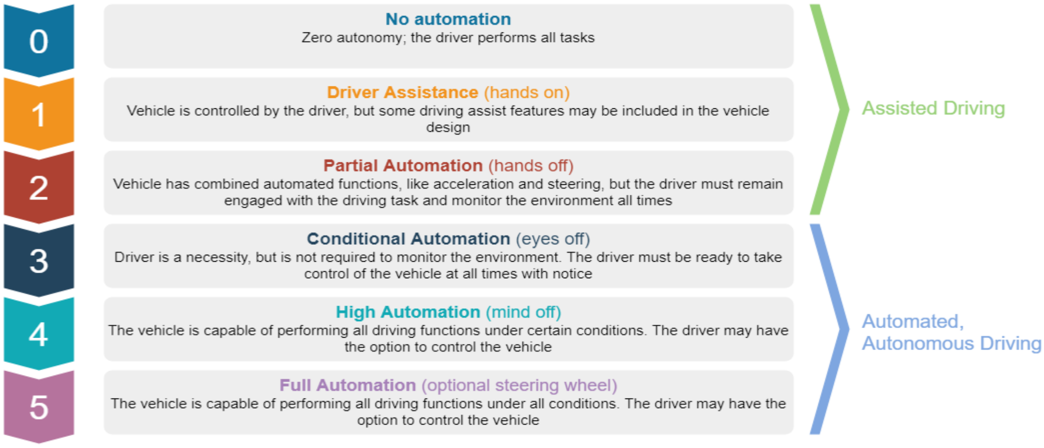


Figure 1: *Table with SAE Automation Levels*

Level 0 : **Fully manual vehicle**
All aspects of driving are fully human and manually controlled.

Level 1 : **One single automated aspect - hands on**
It is the lowest level of automation: substantially, the vehicle assists the driver during some manoeuvres as steering, speed/braking control.

Level 2 : **Automated steering and acceleration capabilities - hands off**
SAE level 2 is where the vehicle can control both the steering and acceleration. It allows the vehicle to automate certain parts of the driving experience, and the driver remains complete control of the vehicle at all time, i.e. the vehicle helps the lane-keeping and self-parking features.

Level 3 : **Environment detection - eyes off**
The vehicle can detect the environment around them. Thankful to it, it can make informed decisions for themselves, such as overtaking slower-moving vehicles. However, human interaction is still important: human override is required when the machine is unable to execute the task at hand or the system fails.

Level 4 : **No human interaction required - mind off**
The key difference with the previous level is that Level 4 vehicles can intervene themselves if something goes wrong or the system fails. The cars are left completely to their own devices without any human intervention in the vast majority of situations, although the option of manually override does remain in difficult or preferable circumstances.

Level 5 : **Human driving is completely eliminated - steering wheel optional**
SAE Level 5 does not require human attention.

According to this classification, up to now the development of the vehicle automation has arrived at the 3^{rd} Level also called Conditional Automation.

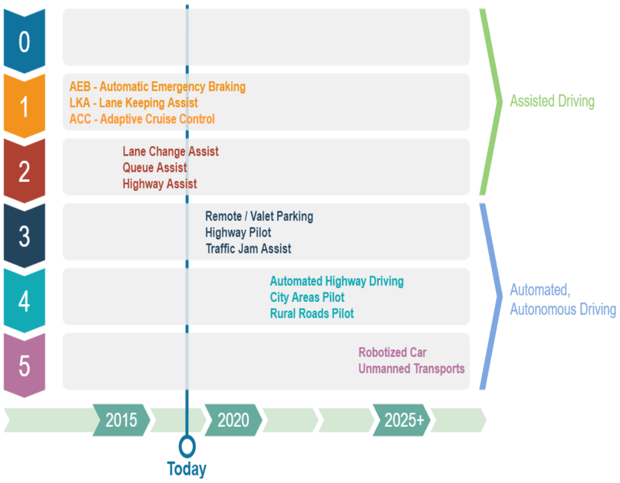


Figure 2: *Chart of our actual point*

As it was mentioned previously, the human driver is still required for some manoeuvres, but the aim of this level is possible to work on the highway without a human driver.
It should be available starts for the 2020.
A system with the capability to drive a vehicle on Highway alone, without human interventions, is already implemented by AVL and nowadays the issue is to create such as a controller that should be able to adapt the driving to the different kind of drivers and passengers in order to be more suitable with their personal physical and psychological characteristics.

1.3 Classification of People According to Multidimensional Driving Style Inventory (MDSI)

Observing the daily traffic, all the drivers behave differently, and this was at the basis of several pieces of research, whose went to analyse differences among drivers. They have confirmed the existence of individual dissimilarities between drivers. The distinct habits that characterize them outline their driving style.
At the beginning of these researches, the scientists wanted to construct a model that was able to conceptualize how habitually a driver behaves as a driving-specific factor, since they wanted to explain involvement in car crashes and why people make traffic violations both directly in a sphere more concerning socio-demographic and personality perspective.
For this reason, it was introduced a Multidimensional Driving Style Inventory, that in the following parts it will be indicated as MDSI, and it is a self-reported questionnaire that exploits the driving styles in order to analyse the differences dealing with the different driving behaviours.
For the first time the MDSI was published in 2014 in Israel, then it has been subjected of studies conducted around the world to study the drivers' behaviours to associate the MDSI factors with social-demographic and driving-related variables in the several studies, also small and limited ones.
Discussing driving skills and driving style is not the same:

- skill is related to the driver's performance capabilities, the ability to handle the vehicle and respond adaptively also in complex traffic scenarios, and it is expected to improve gradually with practice and training,

- style is related to how habitually the driver chooses to drive, i.e. including choice of driving velocity, and level of carefulness and assertiveness.

The driving velocity, the time to the collision to a preceding vehicle (distance in between the vehicle and the previous one), overtaking other vehicles and the frequency to break the traffic rules are the daily choices that a driver take and constitute the behavioural tendencies of he/she.
In order to analyse the driving style, other parameters, which should be correlated to the style, were studied as a youth. For instance, young drivers tend to report being more angry and hostile when driving than older ones; it has found a correlation between age and driving style.
Driver's experience that is the length of the time that the individual has had a driving license, which is closely related to age has also been found to be a relevant characteristic. It is correlated positively with the careful and patient style.
Also, there is a relevant significant gender difference, so that men use to have more reckless and angry driving style, whereas women have a more anxious and careful style.
Nevertheless, ethnicity is another important characteristic that affects the driving behaviour of the driver.
It highlights how is important to study the different behavioural driving style because everyone is different and that, psychologically speaking, we find more safety and comfortable to be driven in a kind of more similar way that we use to drive.

1.3.1 MDSI and ADAS

Advanced Driver Assistance Systems (ADAS) are developed with the purpose of the increased safety, efficiency and driver comfort and reducing driver's workload. To the extent

that the advice or assistance requires drivers to deviate from their typical behavioural patterns, acceptance of those systems may be jeopardized.
For instance if a speed advice system advises the driver to slow down or if a speed control system reduces the speed of the car without a clearly perceivable and obvious need, drivers who are used to drive at a higher speed may not adopt the advice or allow the vehicle to reduce the speed of the vehicle.
With the term driving style, it has indicated the choice of driving speed, headway, overtaking of other vehicles and the tendency of committing traffic violations.
It is important to study how people's driving style influences the compliance to ADAS.
Advanced Driver Assistance Systems have the potential to improve traffic safety and throughput when drivers comply with using these systems. The big issue is that if these systems do not meet drivers needs and expectations, drivers will refrain from using them.
Provided that different people are sensitive to different forms of persuasion, the notion of the drivers' profiles may help to identify common differences in characteristics between groups of drivers.
Substantially eight different factors that define driver's profiles could be identified as Dissociative driving, Anxious driving, Risky driving, Angry driving, High-velocity driving, Distress-reduction driving, Patient driving and Careful driving.
An easy explanation of the different profiles is the following:

- Dissociative Driving: People are easily distracted and dissociated during driving. They are characterised by inattentiveness; this may result in errors in gear shift or unawareness of still driving with lights on a full beam or abrupt braking.

- Anxious Driving: People show signs of anxiety and lack of confidence, that feel distressed and worried while driving. They tend to over-regulate driving, which can result in maladaptive responses.

- Risky Driving: People seek for sensation and more risky driving, they are characterised by speeding and excitement of dangerous driving. Some drivers drive at higher speed for the thrill and sensation as a part of their attitude towards taking risks.

- Angry Driving: People tend to be hostile and aggressive; they use to swear, make more use of the horn in the vehicle or beam to other road users. Their road rage is seen as a threat to driving, next to drinking and not using a seatbelt.

- High-velocity Driving: People tend to drive faster and are more time driven.

- Distress-reduction Driving: People engage in relaxing activities to reduce stress (i.e. listen to music)

- Patient Driving: People are polite to other users and have no pressure time.

- Careful Driving: People drive carefully and structured, maintaining a safe speed. They anticipate other road users' movements, traffic lights and speed limits.

Later, High-velocity driving behaviour was associated with the risky one as patient driving to the careful one, so actually, the most relevant profiles are six. Many researches define these different profiles starting from the analysis of the multiple-choice questionnaire (MDSI) and the study of the achieved score considering that the factor loadings are adjusted to take account of the initial correlations between items, because otherwise there is not a diversification between the different profiles and most drivers are identified as Careful drivers. It may be due either to respondents giving socially desirable answers or to the fact that people

try to avoid accidents.
Driving style is defined as an attitude, orientation and way of thinking for daily driving. Many components affect the driving style such as confidence in driving skill, hesitation for driving, impatience in driving, methodical driving, preparatory manoeuvres at traffic signals, the importance of automobile for self-expression, moodiness in driving and anxiety about traffic accidents.
The catEgorisation of people's driving style can help in understanding how to incorporate certain aspects of behaviours in ADAS to enhance compliance towards these systems. For example, drivers who are catEgorized as Risky drivers may prefer a smaller headway compared to Careful drivers. This aspect might be incorporated into an ADAS to enhance compliance. There is no a priori reason to assume that driving style is a one-dimensional construct, so if it is considered as a multidimensional construct it might be more appropriate to talk about driver profiles, and someone might be said to be both a careful and attentive driver.
In the end, 21 different profiles consisting of one or two driving styles were found.

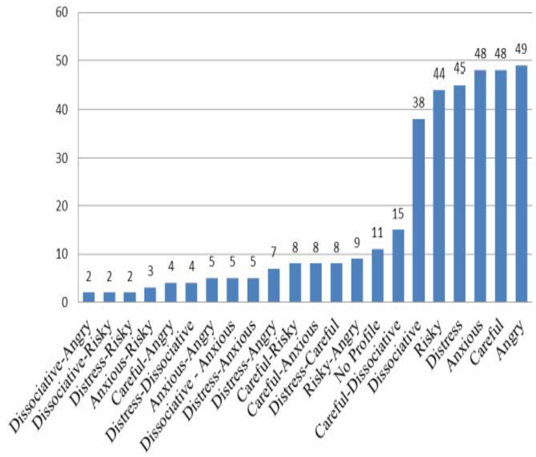


Figure 3: *Different Driving Style*

It shows how using only a single dominant driving style is too simple to understand the different behaviours of the different drivers.
Nevertheless, many factors may influence driver's behaviour, such as the driving environment, traffic conditions, the driver's condition and personal characteristics (i.e. gender, age, driving experience,...).
Although driver behaviour is not necessarily static but evolves over time and in context, depends on the ability of the drive and the driving performance of a particular person in a specific environment and under specific circumstances.
It can enhance the understanding of driving styles and the relation to specific behaviours and help to decide which direction to take when investigating how persuasive systems can be used to influence the compliance towards ADAS.
It is not only a theoretical study thankful to many researchers that studied if the MDSI questionnaire was a description of driver's behaviour in terms of speeding, braking, steering, lateral positioning and maintaining distance to a preceding vehicle. The result was that several types of research support the use of MDSI as a diagnostic tool for screening participants with different driving styles for simulator studies.

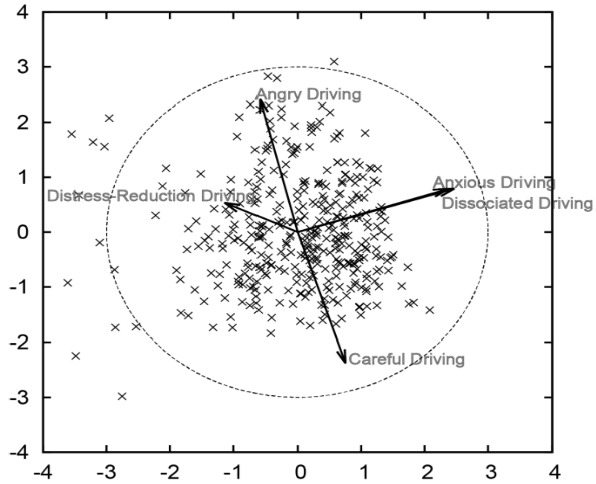


Figure 4: *Two Dimensional description of driving behaviour*

1.3.2 Simulator Studies

Collecting data from a self-report driving style questionnaire should be an excellent way to evaluate the driving behaviour of a driver? To answer these questions, several tests in simulators took place, therefore in this thesis is shown one of them to highlight the relationship between the driving style and the MDSI questionnaire.
For instance, in real-life situations, the concerned drivers should be identified preferably from behavioural indices, for testing the effectiveness of the interventions in the laboratory, participants representing particular driving style may be recruited through a questionnaire. Several self-report measures of driving behaviour, style and cognition have been constructed and validated.
The study involved two tasks: filling in the MDSI questionnaire and driving in the driving simulator. The questionnaire was filled beforehand at home, and then participants had to drive in the simulator into the Eindhoven University of Technology for half an hour.
The simulator consisted of a car seat, a Ford steering wheel, indicators, ignition key, pedals, a gear lever and a handbrake. The simulator logged Speed, lane position, deceleration, acceleration and braking at 50 Hz .
In this way, the simulation was done, and the data were collected.
For each participants the speed on different road segments [in km/h], speed variation when driving on straight segments [in km/h], the average jerk [m/s^3], average deceleration [in m/s^2], lateral position and distance to preceding vehicles were taking into account [in m].
A careful driver may decelerate more smoothly compared to a more risky driver by just releasing the gas pedal and letting the vehicle roll, and pressing the brake pedal gently to come to a standstill, while, at the same time, a risky driver is expected to continue driving at high speed so that she/he has to brake harshly at the end and therefore exhibits a stronger deceleration for a shorter moment of time.
As a result of this study, the older drivers tend to have higher scores for Careful driving and lower for Anxious, Dissociative and Distress-reduction driving. Therefore, male drivers tend to have higher scores for Angry and Risky driving than women, which tend to be positive at Anxious and Dissociative driving behaviours. Overall older people tend to have a lower average speed and less variation of their position within the lane. Moreover, men tend to have lower variation in their speed and decelerate faster.
So the results highlight that:

- Careful driving style: They had a lower average speed on roads, they drove more towards the centre of the lane and showed less variation in their lateral position. Besides, they maintained a long distance to preceding vehicles on the highway.

- Angry driving style: They had significant correlations with the standard deviation of speed driven on the highway and the distance to preceding vehicles on the highway and also with gender and age.

- Risky driving style: They are more correlated with a significant variation in their speed when driving on the highway and a variation in lateral position.

- Anxious driving style: There is a significant correlation with age and gender, but there is not a correlation with the distance to a preceding vehicle as well as speed variability.

- Dissociative driving style: they had a higher variation in their speed when driving.

- Distress-Reduction driving style: they do not present any particular associations.

So, this supports the idea that the outcomes of the Multidimensional Driving Style Inventory (MDSI) have a predictive value of driving behaviour in a simulator.
Most important is the correlation with age, and average speed, an increase in age is associated with a decrease in average speed as measured from behaviour and with a higher score for self-reported careful driving. Also, male behaviour shows steeper deceleration, while female behaviour shows more variation in speed, which is compatible with the finding that women score higher for anxious driving in the self-report questionnaire.
However, it is important to underline that the simulation was done inside a driving simulator that could in such a way be different from actual driving behaviour on the road. Driving inside a simulator was experienced as less realistic in some respects compared to driving on the road. The problem in the simulator is the lack of the perception of feedback of acceleration, deceleration and lateral movement that makes the experience less realistic.
The overall result of the mentioned test put in evidence the significant correlations between the driving style scores retrieved from the MDSI questionnaire and several behavioural scores derived from driving behaviour in the driving simulator. This study is put in this thesis to support the hypothesis that strategies for persuading people to accept and comply with advice and actions of an automated driving system can be made more effective if they are tuned to the driving styles of individual people. In real contexts, the driving style of people needs to be inferred from actual driving behaviour. In order to evaluate our hypothesis, we began by conducting studies with a driving simulator. For such studies, people's driving style is usually determined based on their response to a driving style questionnaire. Because there is a good correspondence among the two, the practice of using a questionnaire to identify people's driving style is justified.

1.4 Motion Sickness

Carsickness decreases the comfort of humans in a vehicle, so it is necessary to clarify its mechanism and to develop a reduction method. The prediction of motion sickness or ride comfort of vehicles is important to create a comfortable vehicle motion. For estimating the severity of motion sickness, many studies revealed the motion sickness sensitivity by using the frequency and the magnitude of acceleration.
Many different theories changed in the last fifty years in terms of identifying the physiological mechanisms underlying the motion sickness response and we still do not have a definitive explanation for this syndrome because there is no single explanation.
Since the beginning of the motion sickness study, the vestibular system was investigated ad implicated in the aetiology of motion sickness. In 1942, McEachern had written: 'It can scarcely be denied that visual, kinesthetic and psychologic factors play a part in the development of sickness, although the primary disturbance may lie in the vestibular apparatus or some other mechanism.'

1.4.1 Vestibular Apparatus

The vestibular sense is our ability to sense body movement combined with our ability to maintain balance. The human body has a remarkable ability to sense and determine the direction and speed in which it is moving and maintain the postural equilibrium. Maintaining postural equilibrium, sensing movement and maintaining an awareness of the relative location of our body parts requires the precise integration of several of the body's sensory and response systems including visual, vestibular, somatosensory (i.e. touch and pressure) and auditory.
The vestibular apparatus is located inside the ear. The ear is made up of several smaller structures that can be organized into these distinct anatomical regions: an outer ear which extends from outside the body through the ear canal to the tympanic membrane (eardrum), a middle ear, an air-filled cavity containing three tiny bones (ossicles) that transmit and amplify sound between the eardrum and the cochlea, where the sense of hearing is located, and the inner ear, composed of the cochlea and the vestibular system.

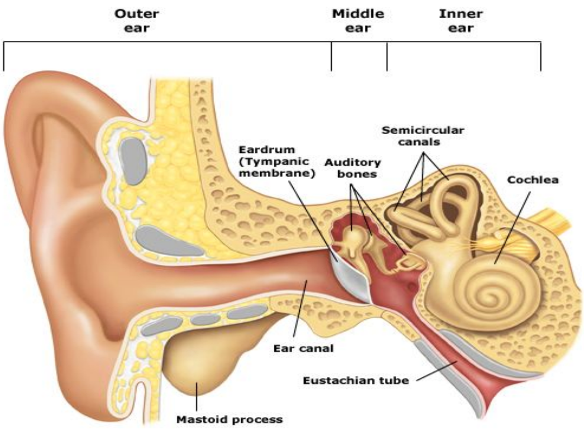


Figure 5: *Ear picture and Vestibular System Position*

The vestibular system, which is the key to our sense of balance, motion and body position, is comprised of three semicircular canals connected to two membranous sacs called the

saccule and utricle, they create the otolith organs. The otolith organs allow us to sense the direction of the linear acceleration and the position (tilt) of the head while the semicircular canals allow us to sense the direction and speed of angular acceleration. The semicircular canals are oriented along three planes of movement with each plane at right angles to the other two.
Since any vehicle operating in three-dimensional space can accelerate in three planes of rotation and often along more than one plane at the same time, the otolith organs and semicircular canals enable to sense these linear and angular accelerations.
So the vestibular system is a kind of image stabilizer because it takes over the image stabilization process.
The semicircular canals are a set of three membranous tubes embedded within a bony structure of the same shape. The central cavity of each canal is filled with a fluid called endolymph. Each endolymph-filled canal has an enlarged area near its bade called an ampulla.

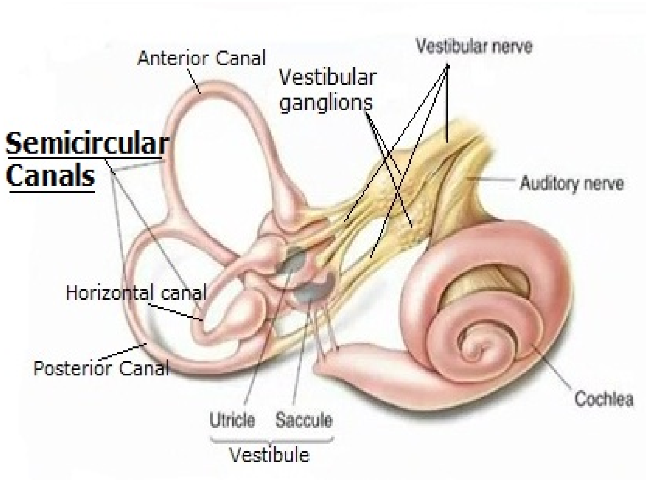


Figure 6: Vestibular System: Semicircular Canals and Utricle and Saccule

The mechanics of how the semicircular canals function to sense angular acceleration may be more easily understood by reviewing the physics of inertia: a body at rest remain at rest unless acted upon by an unbalanced force. The angular acceleration and deceleration primarily affect the semicircular canals and entirely depend on the relative movement of endolymph concerning the cupula. The endolymph tends to remain at rest due to inertia. Sometimes due to friction and the drag it induces, the fluid begins to move at the same speed as the components within which it is contained, and when it occurs, the acceleration is not sensed, and the person incorrectly perceives that he/she is stationary. Precisely the contrary could happen if the fluid has momentum and so it continues to move until friction and drag bring it to a stop.
For what concern the otolith organs they sense linear acceleration and are affected by gravity, and they also provide the information concerning a change in head position (tilt).

According to their position in the vestibular apparatus, the saccule is more sensitive to vertical acceleration and the utricle to horizontal acceleration. Both the saccule and the utricle contain a thickened patch of specialized cells called a macula that consists of sensory hair cells interspersed with supporting cells. These hair cells are embedded in a gelatinous otolithic membrane which supports small piles of calcium carbonate crystals on its surface, and altogether these crystals are called otoliths. When the head is tilted to the left or right, forward or back, the otoliths tend to move along the gravity gradient (downwards). Even

a slight movement of the otolithic membrane is enough to bend hair cells and send sensory information to the brain.
Both systems depend upon inertia and the mechanical deflection of hair cells to initiate nerve impulses that are sent to the brain and interpreted as body movement. The brain reflexively initiates appropriate corrective actions within the nervous, visual and muscular systems to ensure that situational awareness and balance are maintained.
Analysing a rapidly acceleration straight ahead in a car, inertia causes the utricle's otolithic membrane and its associated otoliths to lag behind the portion of the utricle that is firmly attached to the head and this backward deflection stimulates sensory nerves to fire and this provides the brain with information on the direction and speed of acceleration.
When there is no visual input as is everyday in-vehicle situations, we rely more heavily on our vestibular sense for this informations.
After this overview of the vestibular sense, many different theories are elaborated in order to find out what gives us a sense of motion sickness.

1.4.2 Motion Sickness theory

Until now there is not a precise explanation on which particular centres and pathways within the central nervous system are involved in either the cause of the various motion sickness responses or the process of adaptation to provocative motion. Several researchers consider the vestibular apparatus and its projection in the cerebellum, area of the brain that controls coordination and balance, are necessary to be investigated for the development of the theory of motion sickness.
Wang and Borison have a 'vomiting centre' in the brain stem that received inputs from various sources, both central and peripheral, such as the diencephalon, the posterior part of the forebrain, containing the epithalamus, thalamus, hypothalamus, and the gut.
There are many theses about the motion sickness that are formulated during the last years but the two main essential pieces of research: Sensory Conflict Theory and Neural Mismatch Hypothesis.
The oldest one is the vestibular over-stimulation theory, but this not a reasonable explanation for the aetiology of motion sickness. As soon as this first theory was overcome, it has been replaced by the sensory conflict theory.
This hypothesis has proposed that the physiological component was not merely a single vestibular event, but a combination of some body's response to inharmonious sensory information reaching the comparator presents in the brain. The eyes and the vestibular apparatus mainly detect provocative motion stimuli. Passive provocative stimuli are caused by the body being moved by some form of vehicular motion. An active component may be caused by bodily movements, such as moving the head, which also affects the vestibular apparatus. The restriction of head movement can prevent motion sickness.
Later on, in 1978, Reason proposed a change to the sensory conflict theory with a Neural Mismatch Hypothesis. The reason has suggested that the concept that a direct comparison in which inputs from eyes and ears took place somewhere in the central nervous system was not acceptable. So he rearranged the old theorists explaining that before a person has become adapted to the new situation, there was a state of conflict between the total arrangement of sensory input and that which has been expected based on that individual's experience.
There was the introduction of the comparison of the sensory inputs with an engram based on previous experience. This means that a neural centre within the central nervous system works as a comparator of both the afferent signals from the internal model and if any

sustained difference or mismatch between this actual information and that which had been expected has enough intensity, it both modify the internal model and caused the neuro-vegetative responses that we recognise as motion sickness.
What precisely happens inside a vehicle is a visual/inertial mismatch, the motion inputs from the eyes and vestibular or non-vestibular proprioceptors are contradictory, it is amplified when reading a hand-held book in an auto. In this situation, either active or passive movement of the head, ad indicated by the vestibular apparatus, alters the visual picture in an unexpected way.
There is also the canal/Otolith mismatch, but it is not the relevant in-vehicle environment. There is finally the third catEgory of neural mismatch that is the vestibular/Proprioceptor Mismatch. Quite naturally, the human body is designed for the acts of walking, running or jumping on the surface of the Earth.
Consequently, during the performance of these natural manoeuvres, the main acceleration frequencies reaching the head lie somewhere between 0.5 Hz and 8 Hz, a linear oscillation at 1 Hz does not produce motion sickness.
On the other hand, oscillation at 0.2 Hz is highly provocative, and this is probably due to the nature of the engram, based on canal/otolithic activity that has been established during these locomotor activities on the Earth.
For example, the engram associated with approaching an escalator is based on the corrective movements necessary to step onto a stairway, which is usually motion, hence the tendency to stumble when it is not. This response is not related to the peripheral visual stimulus that causes section; it is based upon expected signals from previous experiences of an environment that usually is moving. Brief mismatches cause an immediate corrective muscular response; sustained mismatch signals reprogramme the internal model in the comparator by adaptation. The time delay varies significantly with both the individual and particular provocative environment.
In the meantime, the rearrangement that has been created triggers the bodily responses that it is known as motion sickness.

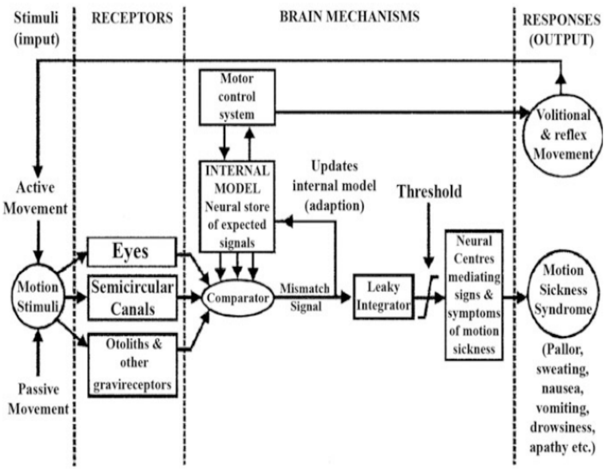


Figure 7: *Benson's Psychological Model of Motion Sickness*

Other several theories improve and summaries the two theories previously explained. The subjective of the motion sickness allows giving many different explanations that can describe for the majority percentage of the people that specific kind of phenomena but always remaining an experimental result.

1.4.3 Motion Sickness Affected by Ethnicity and Gender

In order to have a product that could satisfy the majority of people in the world, it is imperative to take care of the differences that affected people. Gender and Ethnicity origins influence the susceptibility of the motion sickness.
Nausea and Vomiting tolerance is lower in women than in men, and comparing races; it is lower in Asian subjects compared with Caucasians and Africans.
For the gender differences, the intolerance is attributed to the menstrual period, and the several pieces of research proofed that this distinction is linked to cyclic variations in reproductive hormones which have been shown to moderate autonomic and cardiovascular reactivity, gastrointestinal mobility and visceral perception. They prove how the motion sickness is a function of the phase of the menstrual cycle, highlighted how the different levels of progesterone and estradiol affected it.
The main finding concerning this topic underlines that women that do not take the pill as an oral contraceptive, and so are subjected to the cyclic change of hormones, are profoundly affected by Motion Sickness. It could be a result of the women tendency, when they have a peak of estrogen, to experience increased sensitivity in auditory, olfactory and visual, increasing also any possible mismatches between visual and vestibular perception.
About the Asian hyper-susceptibility is given by conflicting sensory inputs from the vestibular and other sensory systems. This difference compared to all the other people on the world is a result of genetic polymorphism of the α_2 adrenergic receptor, that genetic differences in central catecholamine release may predispose an individual to motion sickness. Nevertheless, this distinction affects Asians also for the variety of drugs that inhibits their central and autonomic nervous systems. Moreover, they differ in pharmacokinetic and in haloperidol concentration that creates a considerable difference in drug sensitivity.
It is reported this disequality in drug assumption because the sensory mismatch is sufficiently similar to disturbances in sensory input or motor control produced by the ingestion of toxins that one experiences nausea and vomiting. Asian people may have inherited a lower threshold for the responses of one or more of physiological systems, such as osmolality, stress hormones, or blood pressure that regulate vasopressin secretion.

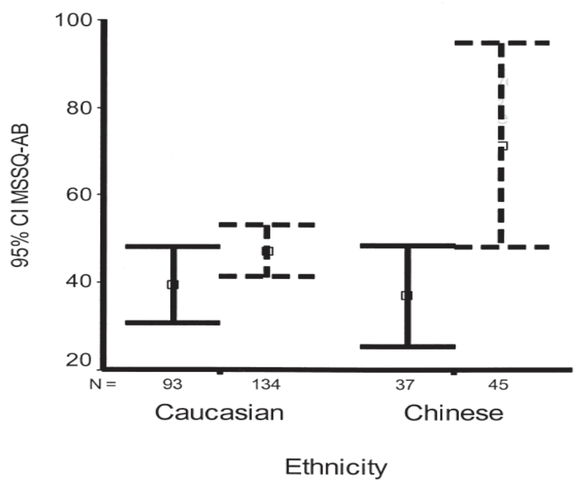


Figure 8: *Caucasian (male and female) vs Chinese (male and female)*

This table clearly is shown what it as previously described.
It may indicate that Asians are in general, less aware of their susceptibility to motion and, therefore, underestimate its consequences. It may also be that they experience less nausea-evoking symptoms in their everyday life. In a questionnaire that it is typically given before

and after every experiment, Asians reported that they have never subjected to potential neurogenic situations compared to Caucasians, but it could also be for cultural and social reasons.

1.4.4 A Mathematical Approach for the Study of Motion Sickness

As already said, Carsickness decreases the comfort of humans in a vehicle; for this reason, research has studied the driver's perceptual and cognitive characteristics to analyse ride comfort. The prediction of motion sickness is quite essential to create comfortable vehicle motion. Since nowadays the aim of the car-makers in the production of an automated car, it is one of the most important studies. For this reason, it is proposed by Kamiji a model of 6DOF that can estimate the motion sickness incidence in 6 DOF motion.

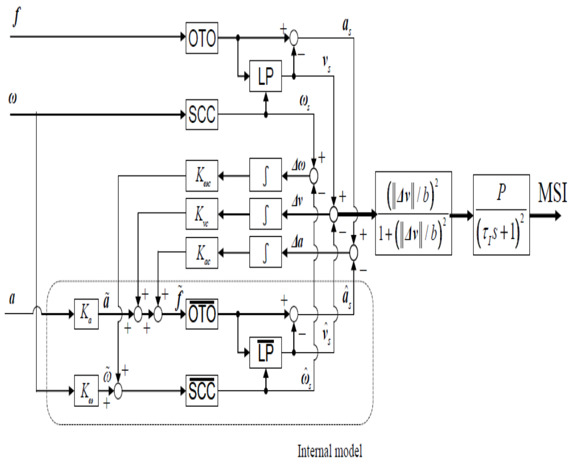


Figure 9: *Motion Sickness controller*

As recognized by the average driver, being a driver or being a passenger has a different impact on the comfort feeling. It was investigated why it happens and it is because the driver appropriately controls his/her posture of the head and the body tilting his/her head to the direction of the curve turns while the head of the passenger is subjected to a passive reaction and this implies that his/her head is tilted in the opposite direction.
Lots of experiments are done analysing driver's and passenger's heads:

- mild conditions results:

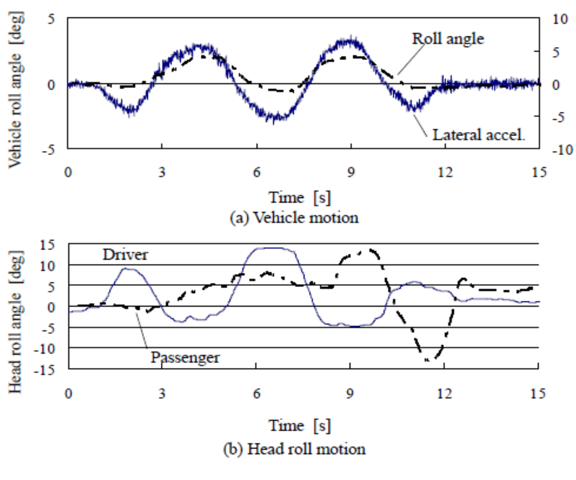


Figure 10: *Mild Condition Head Roll Motion*

- hard conditions results:

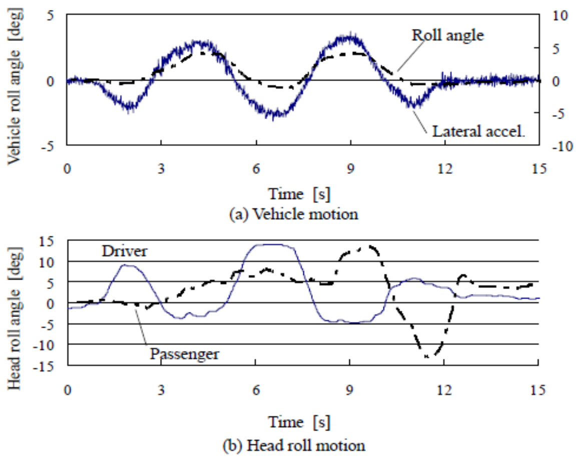


Figure 11: *Hard Condition Head Roll Motion*

It was found that the driver's head movement was in the opposite direction to the vehicle roll while the passenger's head roll followed the vehicle roll or was in the opposite direction but with a considerable time lag to the driver's head in a passive manner, and not in proper synchronization with the vehicle motion.
So the drivers tilted their head toward the centripetal direction which is the opposite tendency of the passengers.
In several pieces of research, they proofed the authenticity of the model before shown allowed the study in detail of the motion sickness.

1.4.5 Active Counteract of Motion Sickness

Several pieces of research wanted to investigate if an active head tilt could decrease the severity of Carsickness.
In order to support and develop this thesis, many experimental studies on human exposure to whole-body vibration were studied investigating the susceptibility of humans to motion sickness at many frequencies and amplitudes and they revealed that motion sickness is most acute for linear vibrations of around $0.1 - 0.3$ Hz in the vertical, fore-aft and lateral directions but the severity of the motion sickness increases with the increasing of the magnitude of vibrations. In the vehicle environments, vibrations in the vertical direction are outside the motion sickness range, while sharp hard braking could cause motion sickness.
The severity of the carsickness is correlated with the fore-aft and lateral accelerations of the head motion. Therefore it was deduced by some researches that the severity of it could sharply increase if the participants could not see the upcoming road through the front window of the vehicle.

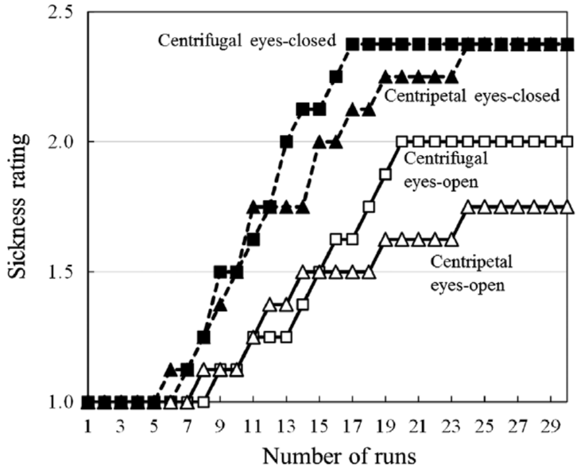


Figure 12: *Effect on Motion Sickness with eyes Open and Close*

So these researches highlighted a significant decrease in the sickness rating due to the centripetal head tilt, compared to the centrifugal head tilt, taking into account the influences of open or closed eyes. It is a significant result because it is demonstrated how a passenger could be reduced their carsickness just tilting their head, thus imitating the driver's head. Of course, comparing the results with open and closed eyes the difference is large enough, so the significant decrease in the sickness rating in the eyes-open condition, compared to the close one, has to be taken into account for the subsequent studies. It suggests that going versus full automated vehicle means that a remarkable improvement has to be done in this direction.

The different factors that contribute to the motion sickness when riding a car are not the only head movement, but also controllability, perceived control, visual information, predictability and activity. Perceived control or sense of control is a subjective psychological state by which the person can determine his or her behaviour, and it plays a significant role.

Because of carsickness sharply decreases Comfort of humans in a vehicle, some researchers introduce a system that could be able to reduce it acting on the control of the posture of the occupant. This control device is supposed to make passengers to tilt their head like average drivers. In that research, the device only intervenes when the lateral acceleration by the curve is significant. It consists of air packs expanded by compressed air, an air tank, a pressure regulator, control valves, a flow meter, a rotary potentiometer measuring steering wheel angle and a laptop.

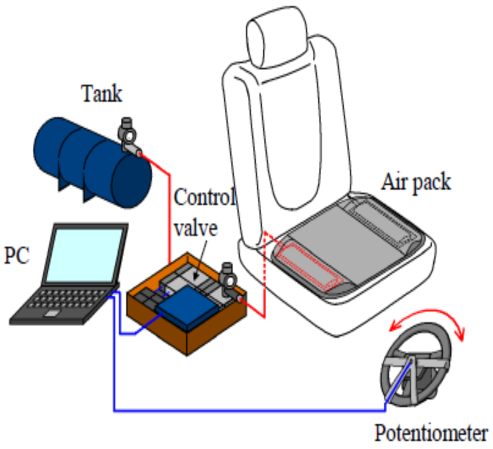


Figure 13: Image of the used device

As results by using this device, more than half of the participants' head roll angles with the device were smaller than without it. It means that it supports the body of passengers to the lateral acceleration helping to a reduction of carsickness.

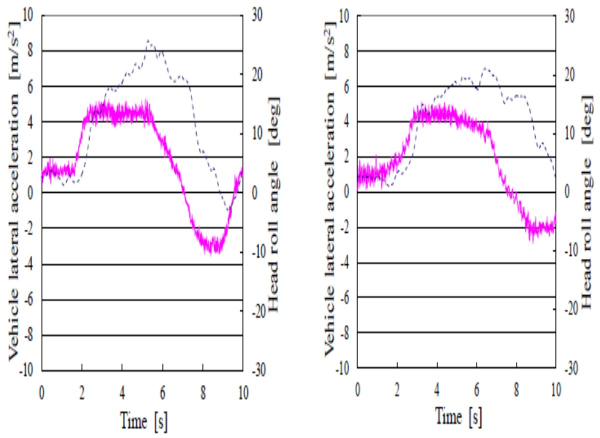


Figure 14: *Head Motion without (left) and with (right) device*

The pressure and the volume of these air packs should be related to the lateral acceleration, which these participants were subjected. A device as a postural control should be another significant development for the next vehicle generation.

Another critical point of discussion is that in the future, people would like also watching a movie inside in the car, as in a train, but the incidence of sickness was higher when watching an internal view than an external one.
This problem was already studied with the introduction of such rear-seat displays because they might induce carsickness in some passengers who watch the display while a vehicle is moving. This happens due to the discrepant information causes sensory conflict and induces carsickness. It is reasoned therefore that carsickness might be reduced if the internal view contained information about the external environment.
The result of the study was that Carsickness caused by watching the in-vehicle display was reduced by pitch compensation of the displayed images and removal of relative motion using image collimation, calibration of the image. When inertial force is applied to the human

body, the person feels the direction of the resultant gravitation force. The forces act on the heads of passengers in an accelerated vehicle and signals form their otoliths are interpreted as "tilt your head". If it happens in combination with the vision sensors coming from the screen, the amount of sensory conflict between their vision and vestibular systems will be too much, and the result is well known, but if the image is collimated, carsickness should be reduced.
The absolute accuracy of the angle might be not so important in comparison of inputs from vision and vestibular systems. Reduction of head motion by suppressing vehicle motion or by increasing head and body restraint reduces stimuli to the vestibular system due to head motion in space and stimuli to the visual system due to relative motion between the eyes and the display, and finally, the initial sensory conflict can be reduced. Additionally, the provision of space stables image on a display screen can also reduce sensory conflict.
In a motion environment, people unconsciously try to keep their head horizontal by the action of their vestibulocollic reflex or to reduce head rotation relative to the upper trunk by the action of the stretch reflex of their neck muscles.

1.5 Driving Comfort

As the development of autonomous driving systems passed to be a distant goal to be present, also the occupant is becoming the focus of research and development increasingly. It is studied the changed level of attention and possibly new activities of the passengers. To develop this study, the first step is to insert some threshold according to the experience done inside a conventional car. The first step was to insert Then it is possible to evaluate different driving scenario considering this threshold.
To improve the Driving Comfort there are two different aspects to analyse: the movement of the vehicle and the movement of the occupants inside, but nowadays it should be done in combination and no longer alone.
As external parameters it is relevant the study of the environment: the weather, the number of the lanes in highway, the width of the lanes, the elevation and the radius, the traffic intensity, are all the parameters that strongly affect the perception of safety.
For what concerns the passenger, the subjective perception of his acceleration consists of his individual psychic experience and the particular physical stimuli appearing as triggers. Physical stimuli are perceived by the vestibular system and have a strong influence on the well-being of the occupants.
It is analysed two different kinds of behaviour inside the vehicle: some people tried to compensate for any vibration stimuli experience at the head while others followed just passively the vehicle induced movements. This difference depends on the subject's visual estimation of the radius and not on the strength of the centripetal forces. However inattentive occupants, distracted by other activities during autonomous driving, will move their body more than the attentive ones, who observe their environment.
Maybe in the future, to go forward the drivers' behaviour should be essential to detect the degree of attention in order to adapt the driving style continuously on the state of the occupant.
Studying the degree of attentiveness the results conducted in an experiment are following shown:

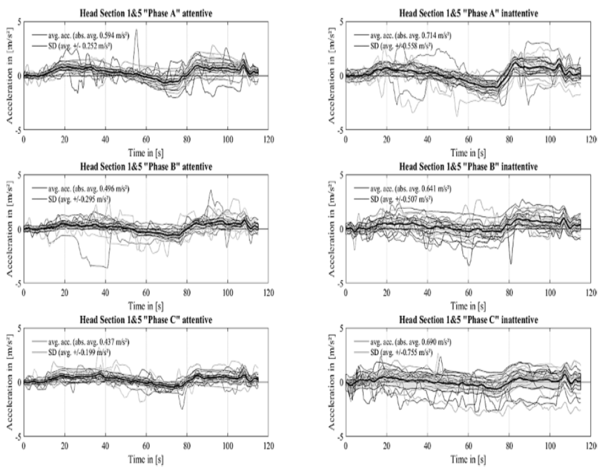


Figure 15: *Head Motion Comparison*

There are 3 phases:

A : A conventional chassis was examined; this created a roll angle of about 1 degree to the outside.

B : The centrifugal force acting on the occupant due to the centripetal acceleration was partially compensated. Here the vehicle rolled at an angle of about 3 degrees to the inside.

C : The centrifugal force acting on the passenger was almost completely compensated. The roll angle is about 4 degree.

It means that in the graph is shown the influence of the degree of attention and the acting centripetal force. It is clear that the inattentive is moving much more and it is the result of the limited perception of an occupant in a distracted state because of course, it is difficult for him to anticipate the vehicle initiated movements and therefore the resulting forces. It follows that he can only react to the perceived accelerations.
Moreover, attentive occupants seem to be moving more similar compared to inattentive ones, so the ability to compensate movements with the own body is easier in an attentive state, and it is more similar within the subjects. Nevertheless, the experience and expectation of occupants play an important role. It could be the reason why, since people do not have experience in autonomous driving, it might be more difficult for them to estimate movements during an inattentive drive correctly.
The results of these studies show that attentive occupants in autonomous driving care are significantly less susceptible to centripetal accelerations than inattentive ones. It is caused by the lack of awareness of the routing ahead for inattentive occupants. If it wants to make a comparison with a control system, the attentive driver possesses feedforward and feedback control, whereas the inattentive occupants solely rely on his feedback control. It is important to underline that these studies are conducted on highway driving situations at a constant speed and continuous but low dynamic accelerations.

2 AVL-DRIVE^{TM} ADAS

The second part of this thesis focusses on the implementation of the software AVL-DRIVE^{TM}. AVL developed this software with the aim of assessing and providing an objective evaluation of driveability.
"The AVL-DRIVE^{TM} solution package consists of comprehensive services like objective vehicle benchmarking and target setting, thorough vehicle analysis including presentation and reporting of modifications and improvement potential, the support of driveability development and calibration, the integration of OEM-specific criteria and assessment algorithms as well as system integration in the customer test field, as well as testing, validation and acceptance procedures[22]." Since this software can rate performed manoeuvres after they are made, it helps to understand which kind of improvements the driver should make.
AVL-DRIVE^{TM} is based on benchmark studies which have been conduced with different calibrations of a vehicle. At the end of the manoeuvre, a cluster of people was asked to fill out a questionnaire about comfort feelings of precise aspects, as minimum achieved acceleration. On the average of the answers, some constrains were fixed which allow the rating of manoeuvres. The issue is related to what is set as the most comfortable manoeuvre, based on the discussion in Chapter 1. Due to the fact that comfort is a subjective feeling, it cannot be evaluated on an average.
The new rating methodology overcomes this problem: instead of an average answer, the output of a controller is taken as model. Since the output is changeable, the rating could consider the diversity of people. The benchmark data will be compared to the new signals coming from the controller.

2.1 Driver's Perception

AVL-DRIVE^{TM} project started with some studies made on different calibrations of a vehicle. The entire system based its rating scheme on how people experienced different manoeuvres made with the different calibrations and scenarios, for example of Active Cruise Control.
People filled out subjective assessment questionnaires after the performed manoeuvres and rated them on a scale from 0-58, and 26 is assumed to be the best rating.
Various parameters were evaluated to get a complete overview of the feeling from the maximum achieved acceleration to the time delay of the start/finish manoeuvres and so on. The study highlighted and gave a general overview of all the parameters that affected the comfort of the occupants in terms of time reaction of the vehicle, time gap, time to collision, minimum achieved acceleration during braking, maximum achieved acceleration during traction, response delay and Jerk Evaluation.
The evaluation of all these parameters is subjective and the scale was designed as a 'bell shape' to evaluate how well the manoeuvre is performed and in which direction the performance exceeds.
The AVL-DRIVE^{TM} gave a rating out of ten, and every rating has a precise meaning (see Figure 16)

DR	Evaluation	Description
9 - 10	excellent	The vehicle exceeds all customer's expectations
8 - 9	good	The vehicle meets all customer's expectations
7 - 8	satisfying	The vehicle meets most customer's expectations
6 - 7	acceptable	Vehicle at basic level only, does not meet most customer's expectations
5 - 6	poor	Some customers complain about the vehicle
4 - 5	unacceptable	Most customers complain about the vehicle
3 - 4	defective	All customers complain driving the vehicle
2 - 3	unsafe operation	Only limited or unsafe vehicle operation possible
1 - 2	no operation	Vehicle not operational

Figure 16: *AVL-DRIVE^{TM} Rating System [23]*

A new implementation of AVL-DRIVE^{TM} includes a distinction between general considerations named as 'Host-Lane' and 'Perceived Safety' that takes care about parameters that affect the perception of safety inside the vehicle.
Finally, the further implementation made in the latest version also gives suggestions concerning all the adopted criteria to increase the rating of the performed manoeuvre.

2.2 Choice of the Most Relevant Manoeuvres

In AVL-DRIVE^{TM} the different manoeuvres are set and studied using precise boundary conditions or 'triggers', that occur in normal driving conditions.
Five different manoeuvres are investigated. The choice is not made randomly: they are chosen in order to observe among them all the different aspects that can characterize a manoeuvre, i.e. longitudinal acceleration and deceleration, time gap and time to collision evaluations,... .
This section provides a general overview of the considered manoeuvres.
For simplicity, the two actors of the different scenarios are called Ego, the principal vehicle, and 'Target Object Front' (TOF), the second participant of these studies.
The first scenario is called 'TOF-Approach' and it is the case when Ego is going at a higher speed compared to TOF, on the same lane and it has to approach TOF decreasing its speed.
The second scenario is named 'Follow Vehicle Stop': TOF is decelerating till it achieves standstill. Ego has to follow the deceleration.
The third scenario is 'Follow Drive Away': TOF and Ego are at standstill. TOF start to drive and Ego should follow it.
The last two scenarios are 'TOF free-lane Cut-In' and 'TOF free-lane Cut-Out' and with these scenarios, also the interaction with a vehicle that can change lane is studied. TOF free-lane Cut-Out: Ego and TOF are driving at constant speed. TOF changes lane. Ego can drive on a free-lane. TOF free-lane Cut-In: TOF and Ego are driving on different lanes. TOF changes lane and occupies Ego's lane. Ego has to decelerate.

2.2.1 TOF-Approach

The so-called TOF-Approach scenario is a scenario where there are two main characters: Ego, the studied vehicle, and TOF, Target Object Front, that is driving at a constant speed much lower than Ego. Since Ego is faster than TOF and the scenario does not allow to overcome TOF, Ego has to decelerate correctly.

To give a clear comprehension of the TOF-Approach scenario, the following image (Figure 17) is introduced.

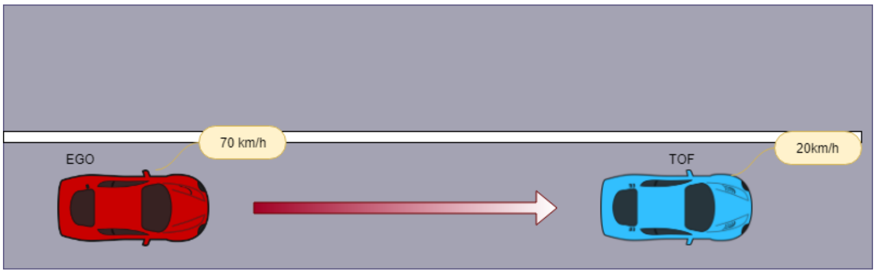


Figure 17: *TOF-Approach*

The research started with the study of the single scenario from an analysis of the benchmark data.
This part is dedicated to the understanding of the different parameters that characterize the setting scenario, i.e. Ego and TOF speed at the beginning and the end of the manoeuvre.
This scenario has two different settings: at low and high speed.
In order to understand how AVL-DRIVE^{TM} works, the first scenario comparison is made between the real and AVL-DRIVE^{TM} rating.
The questionnaire was arranged to illustrate the rating according to the following parameters: Delay Response, Braking Harmony, Control Response, maximum deceleration in terms of when it occurs and how strong it is.(see Table 1)

Table 1: *People's Answers about TOF-Approach 70-20 km/h Table*

Man.	Response Delay	Harmony	Barycenter Dist	Control Resp.	Acceleration	Overall
1	2.09[s]/8.1	7.6	43%/8.8	4.87[m]/8.2	-4.00[m/s^2]/8.6	7.0
2	2.64[s]/5.9	7.0	46%/7.2	0.47[m]/7.3	-4.67[m/s^2]/7.5	5.9
3	0.52[s]/9.6	8.4	49%/9.7	1.81[m]/8.1	-1.78[m/s^2]/9.8	8.4
4	0.52[s]/9.7	8.4	39%/9.7	0.09[m]/8.3	-2.19[m/s^2]/9.8	8.6

The table is structured to show the found values and the relative rates and since the manoeuvres are different and the answer is always subjected to several aspects, even if some values are equal sometimes the average rating is a little bit different.
AVL-DRIVE^{TM} gives a rating for TOF-approach according to many criteria: First reaction, acceleration, smoothness of the deceleration and time to collision (TTC) (see Table 2).

Table 2: *AVL-DRIVE^{TM} TOF-Approach 70-20 km/h Table*

Man.	First reaction	Acceleration	Smoothness	TTC	Overall
1	-3.39[s]/6.3	-4.00[m/s^2]/7.9	8.0	-2.61[s]/6.8	6.7
2	-3.10[s]/5.2	-4.67[m/s^2]/6.6	7.7	-2.20[s]/6.6	5.8
3	-6.11[s]/9.5	-1.77[m/s^2]/9.8	7.4	-3.40[s]/7.4	7.6
4	-5.31[s]/9.8	-2.19[m/s^2]/9.8	8.5	-4.12[s]/7.8	8.1

Observing the overall rates of the different tables, it is clear that the DRIVE rating is more severe than the previous one. It is because it considers many variables that are not shown in the table and in a more analytic way. Nevertheless, the rates are close.

Comparing the two tables, Braking Harmony is the equivalent of smoothness of the manoeuvre in mathematical meaning, as Response Delay and the Control Response are evaluated as the First Reaction of the vehicle. Therefore AVL-DRIVE^{TM} studies also the time to collision that it is given by the ratio between distance and the difference of speed between TOF and Ego(ΔV), it proves a safety behaviour of the vehicle.

After this evaluation, the following step was to carry out the several parameters that allow the creation of the controller scenario:

- Ego initial speed
- Ego final speed
- Ego maximum acceptable acceleration in terms of Comfort
- TOF initial speed
- TOF final speed
- Distance between Ego and TOF at first reaction

As imentioned above, the TOF-Approach was used with two different settings, one at the low speed [from 70 km/h to 20 km/h (see Table 2)] and the second one at high speed [from 150 km/h to 80 km/h].
It is essential to underline that particular triggers, determined in DRIVE, recognize the entire manoeuvre thanks to an analysis of the deceleration of Ego compared to the speed and the distance of TOF.

2.2.2 Follow Vehicle Stop

Follow Vehicle Stop scenario is quite similar to the TOF-Approach since it describes a vehicle, Ego, that follows the vehicle in front of it, TOF, that is decelerating till it stops.
Figure 18 represents this scenario.

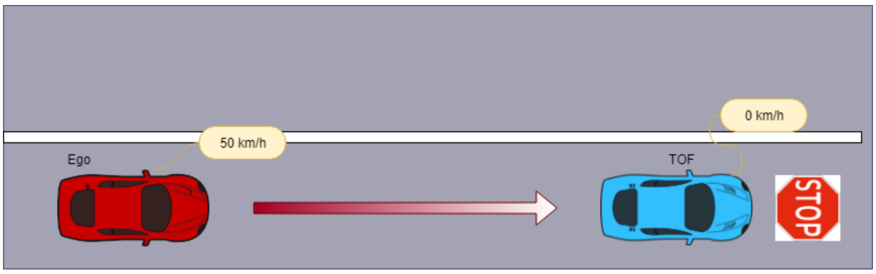


Figure 18: *Follow Vehicle Stop*

The study starts with the observation of the detected manoeuvres of the benchmark data in AVL-DRIVE, giving the fundamental parameters to build the scene in the virtual environment.
It is immediately clear that even if the manoeuvre is always the same, AVL-DRIVE^{TM} recognises it differently according to its triggers.
In this part of the study, the data are just reported in the following table (Table 3) to give a general overview, but in the 4^{th} chapter new triggers will be introduced to consider the total manoeuvre.

Table 3: *AVL-DRIVE™ Vehicle Stop Table*

Man.	StoppingDistance	StoppingBumps	TimeToStandstill	Smoothness	Overall
1	5.98[m]/7.7	7.3	8.9	6.7	7.1
2	1.21[m]/7.7	9.5	8.7	8.8	8.0
3	0.84[m]/6.5	9.8	5.3	8.6	5.9
4	3.57[m]/9.3	9.7	8.4	8.8	8.6

Table 3 serves to illustrate which parameters are used by AVL-DRIVE™ to rating this manoeuvre.
A quick explanation of the different parameters is now presented:

- Stopping Distance is the distance between Ego and TOF at the end of the manoeuvre.
- Stopping Bumps is an evaluation related to the end of the acceleration that highlights oscillation behaviour.
- Time To Standstill is the needed time during the manoeuvre to achieve the standstill.
- Smoothness is related to the analysis of the smoothness of the acceleration.

Therefore, the scenario parameters are set according to the observation of these different manoeuvres and the scenario:

- Ego initial speed
- Ego maximum acceptable acceleration in terms of Comfort
- TOF initial speed

2.2.3 Follow Drive Away

Follow Drive Away is a scenario where there are two characters: Ego and TOF at a standstill. Later on, TOF accelerates and Ego follows it, accelerating until they achieve the target speed. Figure 19 represents the scenario at hand.

Figure 19: *Follow Drive Away*

In the benchmark data of AVL, there were four different manoeuvres of the Follow Drive Away. They are analysed to obtain the fundamental parameters to build the scene in the virtual environment.
The manoeuvres are studied using AVL-DRIVE™ and in Table 4 the analysed criteria are shown.

Table 4: *AVL-DRIVE^{TM}: Follow Drive Away Results*

Man.	FallbackDistance	ResponseDelay	Smoothness	Overall
1	42.7[m]/4.7	4.43[s]/4.5	8.2	4.8
2	33.3[m]/6.8	1.56[s]/6.6	9.1	6.8
3	20.0[m]/9.7	1.20[s]/7.5	8.0	7.7
4	20.4[m]/9.7	1.30[s]/7.2	8.8	7.5

All the manoeuvres have a target speed of 70[km/h].
It is essential to underline the meaning of the response delay in this kind of manoeuvre: it is detected considering TOF. When TOF is accelerating, the time is counting till Ego starts to move, as well. It is highlighted how the response delay is calculated since in the present thesis the same name is used to indicate the response delay time from the reference signal.
The fallback distance means the maximum distance in between Ego and TOF during the entire manoeuvre.
Finally, the Smoothness indicates if the acceleration detected signal fits with a fixed chosen polynomial equation.
Moreover, according to the presentation of this scenario, the most important parameters are:

- TOF starting distance from Ego
- Target Speed
- TOF final distance
- TOF Acceleration

During the designing process of this scenario, many efforts were dedicated to re-creating the acceleration of TOF also in the simulation environment. During this manoeuvre, the Ego reaction at TOF acceleration is the central topic. A comparison can be done only if TOF reacts in the same way.

2.2.4 TOF free-lane Cut-Out

TOF free-lane Cut-Out is a scenario where Ego and TOF are on the highway and they are driving in the same lane. Later on, TOF is going to change lane and Ego will be the freedom to accelerate till the target speed. Free-lane is introduced since the characters of this scenario are just Ego and TOF.
Figure 20 represents the scenario at hand.

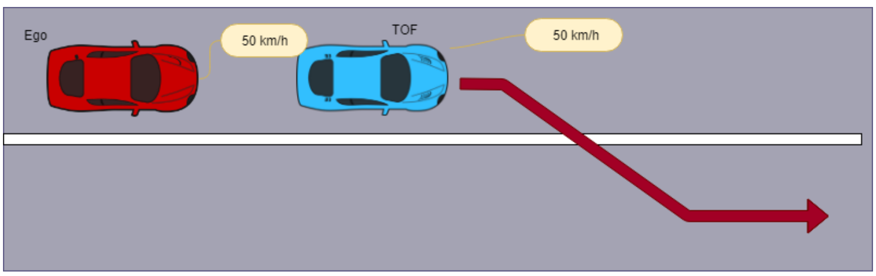


Figure 20: *TOF free-lane Cut-Out*

In the benchmark data of AVL, there were eight different manoeuvres of the TOF free-lane Cut-Out: four at low speed and four at high. They are studied to get the general parameters to build the scene in the virtual environment.

The study of the scenario starts with the analysis of the benchmark data in AVL-DRIVE^{TM} and in Table 5 the results at low speed are shown.

Table 5: *AVL-DRIVE^{TM}: TOF free-lane Cut-Out low speed Results*

Man.	Max Acceleration	Response Delay	Smoothness	Overall
1	1.05[m/s^2]/9.5	1.29[s]/8.8	9.1	8.9
2	1.47[m/s^2]/9.6	1.14[s]/9.1	9.3	9.2
3	2.01[m/s^2]/9.3	2.43[s]/6.7	9.1	7.1
4	1.27[m/s^2]/9.8	1.99[s]/7.4	9.3	7.7

These manoeuvres have a target speed of 80[km/h].
In Table 6, the results of TOF free-lane Cut-Out at high speed are shown.

Table 6: *AVL-DRIVE^{TM}: TOF free-lane Cut-Out high speed Results*

Man.	Max Acceleration	Response Delay	Smoothness	Overall
1	0.98[m/s^2]/9.2	1.33[s]/8.7	9.1	8.9
2	1.40[m/s^2]/9.7	1.37[s]/8.7	8.7	8.7
3	1.73[m/s^2]/9.5	2.40[s]/6.8	9.2	7.1
4	1.15[m/s^2]/9.5	2.73[s]/6.4	9.3	6.7

These manoeuvres have a target speed of 150 [km/h].
According to how the scenario is performed, the most important parameters that were used to design the virtual scenario are:

- Ego and TOF initial speed
- Target speed

The most important parameter for this scenario is Ego reaction delay.

2.2.5 TOF free-lane Cut-In

The last studied manoeuvre is TOF free-lane Cut-In. The meaning of free-lane is related to the presence of just two involved characters: Ego and TOF.
This manoeuvre starts with Ego and TOF which are driving at constant speed on two different lanes: Ego is behind TOF, but slightly faster than it. Then, TOF performs the lane change and it occupies Ego's lane. Ego has to decelerate to avoid a crash and it should be positioned at a proper distance from TOF.
Figure 21 shows the manoeuvre.

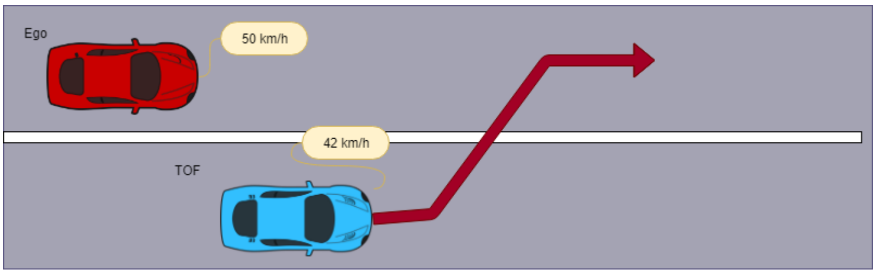


Figure 21: *TOF free-lane Cut-In*

Also for TOF free-lane Cut-In, the study of benchmark manoeuvres are evaluated with AVL-DRIVE^{TM}. The manoeuvres are detected and reported in the Table 7.

Table 7: *AVL-DRIVE^{TM}: TOF free-lane Cut-In Results*

Man.	Min Acceleration	Fallback distance	Response Delay	Smoothness	Overall
1	-0.77[m/s^2]/9.6	6.20[m]/9.1	0.17[s]/9.8	8.5	8.7
2	-1.25[m/s^2]/9.7	6.51[m]/9.8	0.10[s]/9.8	9.1	9.3
3	-2.43[m/s^2]/7.3	6.91[m]/9.7	0.10[s]/9.8	8.9	7.6
4	-3.58[m/s^2]/4.8	7.04[m]/9.7	0.14[s]/9.8	8.9	5.4

The initial conditions of all the manoeuvres are the same, however due to the difference of braking intensity the end conditions are different. For the first and the third manoeuvres the end speed of Ego is around 42[km/h] while in the second manoeuvre, Ego achieves an end speed 37[km/h] and in the last one 26[km/h]. The comparison could be made since during the entire duration of the manoeuvre, TOF is moving at constant speed of 42[km/h]. The used parameters for the construction of the virtual environment are:

- Ego initial speed
- TOF speed
- average distance among TOF and Ego during the cut-in

The most evident issue during this approach concerns the safety since Ego has to decelerate properly to avoid a collision and to safeguard the comfort inside the cockpit.

3 Controller Design and Simulation Environment

In previous research carried out by Astrid Rupp [2], a controller was created, which can simulate on highway, driving manoeuvres, e.g. double lane change.
The calculation of the global path to follow is performed thanks to motion planning of the Motorway Chauffeur, named also planning level since global and local decisions are made here.
Her thesis focusses on the implementation of the planning level, the 'intelligence' of the system: it can take global and local decisions, to predict the other participants (avoiding collision and detecting obstacles) and satisfy the different constraints as described in Chapter 2. All the data necessary are collected by the different systems: radar, camera and sensors.

3.1 Controller Logic

The controller used differs from the canonical ones. Its logic is close to a Model Predictive Control (MPC) logic. It studies the spatial detection of objects on its trajectory. Afterwards, it evaluates all the possible trajectories that it can follow according to a polynomial function. Then, it chooses the path to follow with a cost function. Finally, according to the chosen trajectory, it defines the main parameters like acceleration and yaw angle of the vehicle.
These operations are remade in the same order with a frequency of $100[Hz]$.
In Figure 22, the operational cycle is shown.

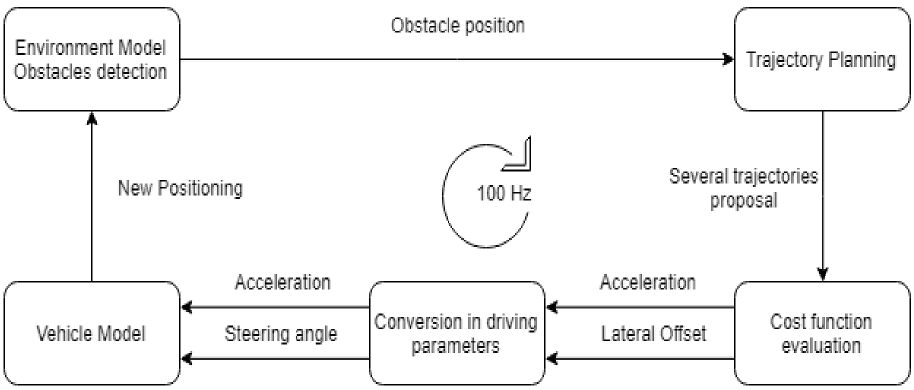


Figure 22: *Controller Logic*

The trajectories are estimated by the generation of polynomial functions in the lateral and longitudinal directions that are combined and investigated in spatial coordinates. The overall number of the generated trajectories is quite high, and the right one is found with a cost function that chooses the most comfortable one.
The polynomial functions govern the generation of the trajectories. The thesis written by Rupp [2] summarizes the research concerning this argument. The research found that the reduction of the jerk (the derivative of the acceleration $j = \dot{a} = \frac{\delta a}{\delta t}$) inside the vehicle improves the general comfort.
In terms of a mathematical equation, it is translated as:

$$min\ J = min \int_0^{t_f} \frac{1}{2} j^2(t) dt \tag{1}$$

In order to give a complete overview of how the controller works, the longitudinal formulation equations are introduced. They are completely studied and analysed in the afore mentioned PhD thesis [2].

The following equations are introduced to underline the relationship between jerk, acceleration, speed and space.

$$\dot{a_s} = j_s(t) \tag{2}$$
$$\dot{v_s} = a_s(t) \tag{3}$$
$$\dot{s} = v_s(t) \tag{4}$$

Starting and final conditions are decided a priori, as follows:

$$s(0) = s_0 \tag{5}$$
$$v_s(0) = v_{s0} \qquad a_s(0) = a_{s0} \tag{6}$$
$$v_s(t_f) = v_{sf} \qquad a_s(t_f) = a_{sf} \tag{7}$$

In equation 8, the Hamiltonian is considered. It represents the total energy of the system.

$$H = \frac{1}{2} j_s^2 + \lambda_{s2} a_s + \lambda_{s3} j_s \tag{8}$$

Under the previous assumptions, the result is:

$$\dot{\lambda}_{s2} = -\frac{\delta H}{\delta v_s} = 0 \rightarrow \lambda_{s2} = C_{s1} \tag{9}$$

$$\dot{\lambda}_{s3} = -\frac{\delta H}{\delta a_s} = -\lambda_{s2} \rightarrow \lambda_{s3} = -C_{s1} t + C_{s2} \tag{10}$$

$$0 = -\frac{\delta H}{\delta j_s} = j_s + \lambda_{s3} \rightarrow \lambda_{s3} = -j_s \tag{11}$$

Studying equations 10 and 11, jerk, acceleration, speed and space are computed as follows:

$$j_s = C_{s1} t - C_{s2} \tag{12}$$
$$a_s = C_{s1} \frac{t^2}{2} - C_{s2} t + C_{s3} \tag{13}$$
$$v_s = C_{s1} \frac{t^3}{6} - C_{s2} \frac{t^2}{2} + C_{s3} t + C_{s4} \tag{14}$$
$$s = C_{s1} \frac{t^4}{24} - C_{s2} \frac{t^3}{3} + C_{s3} \frac{t^2}{2} + C_{s4} t + C_{s5} \tag{15}$$

Using starting and final conditions, all the parameters are computed.

$$C_{s5} = s_0 \tag{16}$$
$$C_{s4} = v_{s0} \tag{17}$$
$$C_{s3} = a_{s0} \tag{18}$$
$$C_{s2} = \frac{(4a_{s0} + 2a_{sf}) t_f + 6(v_{s0} - v_{sf})}{t_f^2} \tag{19}$$
$$C_{s1} = \frac{6(a_{s0} + a_{sf}) t_f + 12(v_{s0} - v_{sf})}{t_f^3} \tag{20}$$

The lateral motion is studied in the same way (see [2]).
As mentioned above, the trajectory is then chosen according to a cost function composed of four different parameters that investigates collision avoidance, keeping constant velocity, lane maintenance and the acceleration. In Figure 23, the components of the cost function used are shown for five different trajectories.

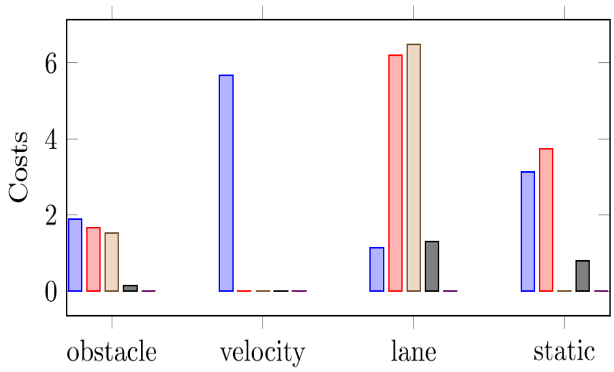


Figure 23: *Components of the Cost Function[2]*

Figure 24 shows an example of several calculated trajectories. The cost functions relative are shown in the upper part of the image, on the right, there are the cost functions relative to all the trajectories, while on the left the steering angle and the acceleration pedal of the simulated vehicle are illustrated.

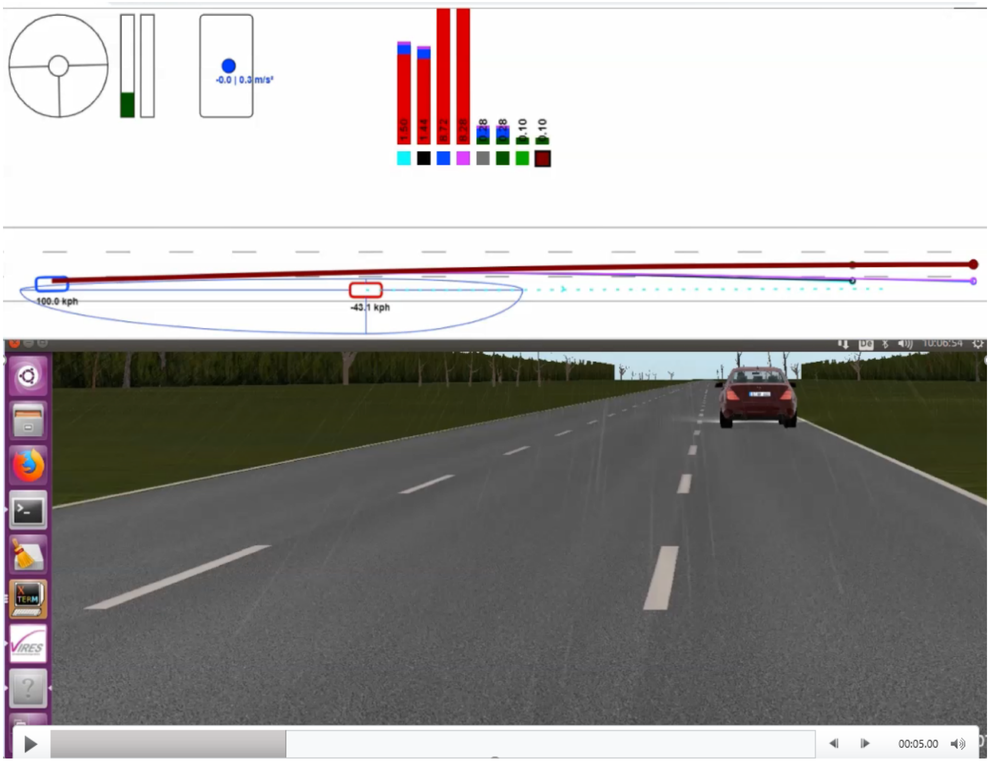


Figure 24: *Trajectories*

There is an ellipsis around TOF, which describes the area that Ego should avoid. The longitudinal extension is defined by internal adjustable parameters inside the controller: a minimum fixed distance, a term that depends on the speed of Ego called 'Look Ahead Time' and another term that depends on the difference in speed between Ego and TOF called 'Delta Speed time'. The lateral extension is fixed and depends on the European road code: on the right, the area is bigger than on the left since a vehicle is not allowed to overtake on the right.

3.2 Simulation Environment

The controller is created in Model.CONNECT^{TM}, "a neutral model integration and co-simulation platform connecting virtual and real components". [24]
The following section explains all the main components that cooperate with the main functions above discussed in Paragraph 3.1. Figure 25 shows the entire working scheme of the controller.

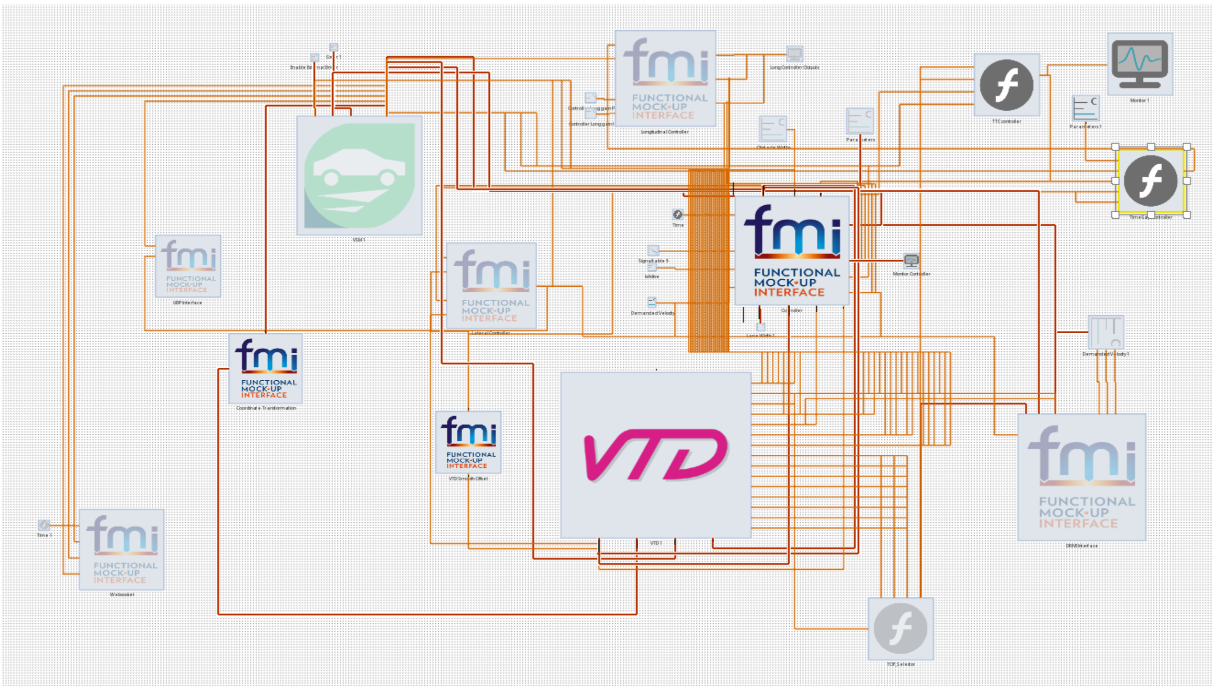
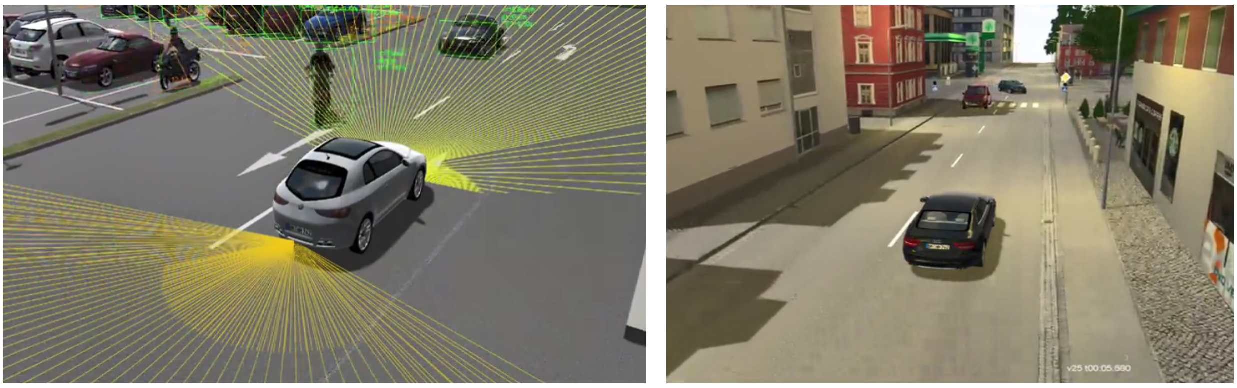


Figure 25: *Model.CONNECT^{TM} Overview*

One of the main components is AVL VSM 4^{TM}. It is a vehicle dynamic simulator. Inside this block, the main parameters of the vehicle are introduced in the software. Thus, it can predict the dynamics of the vehicle [25].
All the Functional Mock-Up (FMI) blocks represent the functions that govern the controller. Its core is the central one where all the arrows are connected.
Virtual Test Drive (VTD) is a platform developed by MSC-Software ®. It can generate a 3D environment where the creation of different scenarios is possible [26]. Two tools allow the reproduction of the environment: ROD and Scenario. ROD is used to build the environment, e.g. building a street and adding all the other elements such as traffic lights, while Scenario governs the characters of the scenario: in this case Ego and TOF. It allows also the introduction of internal settings and this function is used to move TOF and regulates to its behaviour.
Figure 26 shows VTD visualisation.



(a) *VTD and Sensors Visualisation* (b) *Street Visualisation*

Figure 26: *VTD Virtual Environment*

3.3 Controller Parametrization

Figure 27 shows the output of the controller.

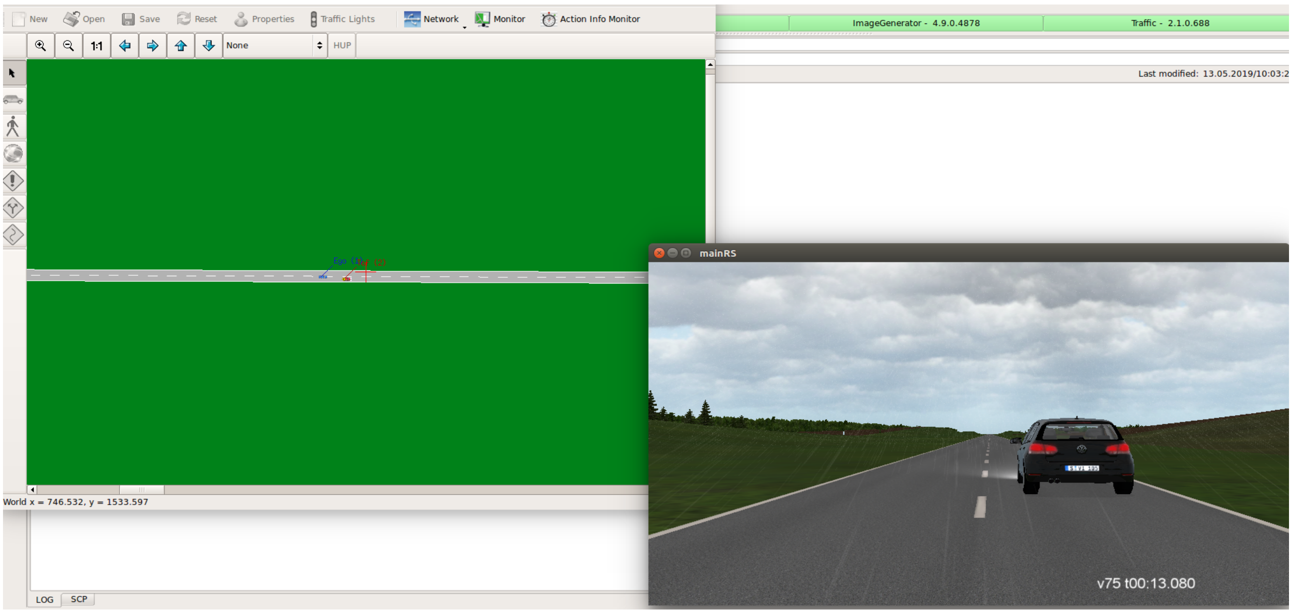


Figure 27: *Controller Working Scenario*

To reproduce the different scenarios, Ego and TOF are changed in the Scenario environment, and all the parameters of TOF are set there as speed variations, acceleration, target speed, lane change,... . Ego behaviour is regulated by the Model.CONNECT^{TM} interface according to the following parameters:

- Maximum acceleration: it regulates the maximum (and minimum) achievable acceleration during a manoeuvre
- Look ahead time (LAT): it defines the minimum distance that Ego can achieve at a precise speed from TOF. For instance, it is multiplied for Ego speed as follows:

$$distance_1 = speed_{Ego} \cdot LAT$$

- ΔV_{time}: it defines the minimum distance between Ego and TOF when they are travelling at different speed as follows:

$$distance_2 = (V_{TOF} - V_{Ego}) \cdot \Delta V_{time}$$

- Minimum distance: it is a safety fixed distance that does not change as the previous parameters

$$distance_3 = minimumdistance$$

- Cost function parameters.

In this study, for each manoeuvre, only one parametrization of the controller is chosen according to AVL-DRIVE™ Rating system (Figure 16) to obtain an acceptable result.

The building of the different scenarios is defined according to the general settings of the available benchmark data to have comparable data. The following is an example of a complex scenario: Follow Drive Away.
In this scenario, the behaviour of TOF in all the different manoeuvres should be closed otherwise the results are not comparable.
In Scenario, a set of different triggers is used to get the following result (Figure 28).

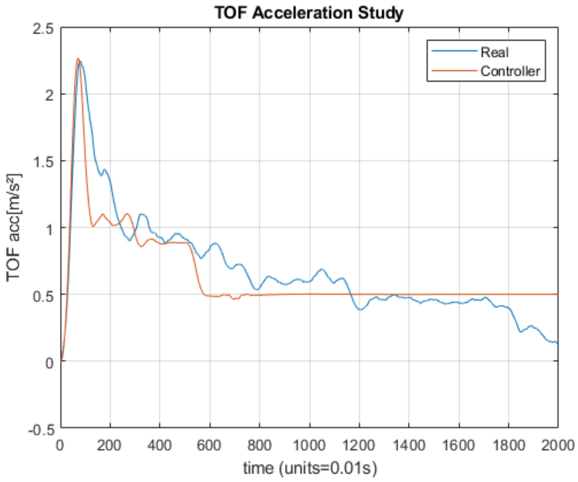


Figure 28: *TOF Acceleration - Comparison*

This is repeated for all the scenarios.

3.4 Implementations

Different implementations are made to the controller in order to adjust some uncorrected behaviour. A collision-avoidance system and an adaptive cruise control are integrated.

3.4.1 Collision Avoidance Implementation

The controller can work in safety conditions only during common scenarios without considering that sometimes there could be some unpredictable events and the vehicle might crash into the obstacles.
Since the controller has to be comparable with a real environment, it should be able to work also under unwanted conditions. A function is added that is able to maintain the wanted acceleration as the set one except for critical situations.
Since the main question is the recognition of a hazardous manoeuvre, an analysis of the time to collision (TTC) is made.
Observing the TTC of some benchmarks, it is reasonable to consider all the manoeuvres that have a TTC equal or higher than $-2[s]$ as risky. In these conditions, if the vehicle does not have an immediate strong deceleration or it cannot change lane, it will inexorably crash.

3.4.2 Function Implementation

In comfortable situations and at an automation level equal or up to 3 (Figure 1), the maximum average comfortable, desirable deceleration is around -2.1 $[m/s^2]$. Therefore, the maximum achievable strong deceleration by the tires is around -6 $[m/s^2]$. The following function is created according to these limits.

$$a_{x_{max}} = -0.35\ TTC^3 - 2.6\ TTC^2 - 4.35\ TTC + 3.9 \tag{21}$$

This function is implemented in the controller.
Firstly, the deceleration approach in normal conditions is observed, giving particular attention to the difference of speeds between Ego and TOF, and is indicated as

$$\Delta V = V_{TOF} - V_{Ego}$$

- $\Delta V > -50[km/h]$ the maximum deceleration is considered equal to what it is inserted in the controller. In this study it is equal to $-2.1[m/s^2]$.

$$a_x = a_{x_{ind}} \tag{22}$$

- $\Delta V < -50[km/h]$ and $\Delta V > -95[km/h]$ the maximum tolerable deceleration should decrease.

$$a_x = \frac{\Delta V}{50} - 1.1 \tag{23}$$

  These distinctions are important only if the occupants are active, for instance up to SAE 4 Level (Figure 1), otherwise the difference is made just by the intensity of the acceleration.

- Otherwise, it is just equal to:

$$a_x = a_{x_{ind}} - 1 \tag{24}$$

  where $a_{x_{ind}}$ is equal, as it is already explained, to $-2.1[m/s^2]$.

Secondly, the Time To Collision (TTC) is evaluated .
By definition:

$$TTC = \frac{distance}{\Delta V} \tag{25}$$

It is compared to $TTC_{comp} = -4$ $[s]$. It is an arbitrary value and was chosen after the observation of some different benchmark data. It is reasonable to use it as a threshold to avoid a strong deceleration. The purpose of the controller is to maintain comfort inside the cockpit.
The formulation is done as follows:

- When $TTC < TTC_{comp}$:

$$a_{x_{min}} = a_x \tag{26}$$

- While if $TTC > TTC_{comp}$ & $TTC < -1$:
  it is used equation 21.

- if the TTC is very smaller than -1 $[s]$:

$$a_{x_{min}} = -6\ [m/s^2] \tag{27}$$

The final formulation looks as follows:

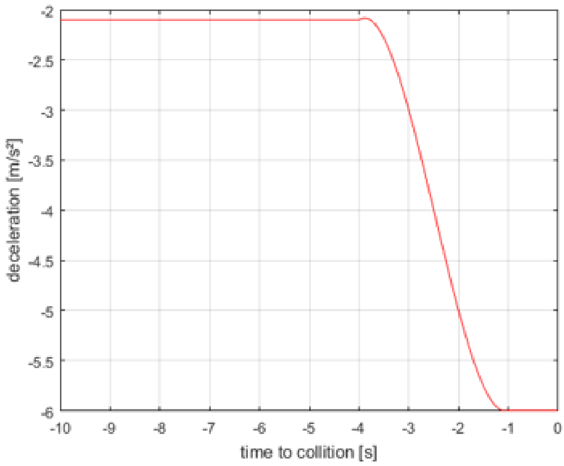


Figure 29: *Collision Avoidance Function*

3.4.3 Proof of the Benefits of the Function Implementation

The new adjustment was then studied at low and high speed to analyse and prove that it works as expected. It was also observed how the behaviour in the controller-environment changes.
A dangerous situation was arranged using the previous controller, Ego crashed against the TOF, while, thanks to the new implementation, it has a strong deceleration according to the TTC and ΔV as it is investigated in Paragraph 3.4.2.
Old and new acceleration and TTC signals with the same conditions are plotted on Figures 30 and 31.
When the old simulated vehicle crashed it is highlighted with a red rectangle. The new signal, the lowest acceleration and the highest TTC are highlighted in yellow.
In low and high speed, the reaction time of the vehicle is decreased. It describes when the deceleration of Ego starts and it is reduced to build an unwanted situation.
In Figure 30), it is shown the low speed case: Ego speed is 70 km/h and TOF speed is 20 km/h.

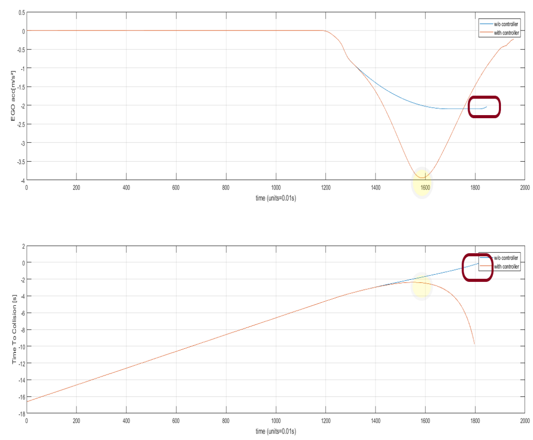


Figure 30: *Low Speed: Collision Avoidance Implemented Function*

In the following, the high speed case is shown: Ego speed is 150 km/h and TOF is 70 km/h.

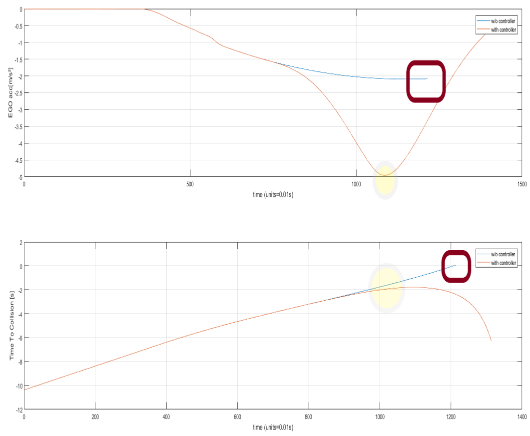


Figure 31: *High Speed: Collision Avoidance Implemented Function*

3.4.4 Time Gap Function Implementation

For two scenarios, Follow Drive Away and TOF free-lane Cut-In, a function that works as an adaptive cruise control is introduced in order to get comparable results.
The control logic, as it is explained in Paragraph 3.1, works by creating an area that Ego should avoid. However, it does not mean that if Ego is inside this area, it will go out. Due to the complexity of these scenarios, an introduction of time-gap function is necessary. Since the two functions cannot work together, for these two scenarios the original functions are turned off.
The definition of time gap (TG) is:

$$TG = \frac{distance}{V_{Ego}} \tag{28}$$

where distance means that one between Ego and TOF.
A reference time gap is required from the user of the software ($TG_{demanded}$).
The wanted distance is evaluated:

$$distance_{wanted} = TG_{demanded} \cdot V_{Ego} \tag{29}$$

Thus, whenever the TG is smaller than $TG_{demanded}$:

$$acc = \frac{d - d_{wanted}}{2} \quad if(d - d_{wanted}) > -5 \tag{30}$$

$$acc = -2.5 \quad if(d - d_{wanted}) \leq -5 \tag{31}$$

Conversely,

$$acc = 2.0 \quad if(d - d_{wanted}) > 150 \tag{32}$$

$$acc = \frac{d - d_{wanted}}{75} \quad if(d - d_{wanted}) \leq 150 \tag{33}$$

These new equations define the acceleration that governs the Ego motion performing the two different mentioned scenarios.

4 Evaluation

The definition of the controller and the different studied scenarios allow the building of a new rating methodology. The controller is considered as a reference and the comparison among the signals is made. It is considered the output signal of the simulator as a perfect reference signal and all the ratings are built according to it.
As it was mentioned above, the idea is to release the rating from some fixed constraint to something variable, since the output of the controller is variable it is related to it.
In the following sections, many criteria are created. Most of them are used for many manoeuvres, i.e. Minimum Acceleration, Jerk Evaluation and Acceleration Shape Comparison.

4.1 TOF-Approach Criteria

The first described manoeuvre is the TOF-Approach.
In the Virtual Environment, the manoeuvre was generated to obtain a good rating according to AVL-DRIVE™ ADAS setting, since it is not essential which shape the signals have according to the aim of this thesis. Therefore it is used as a reference.
The analysis starts with the detection of TOF-Approach manoeuvre in AVL-DRIVE™, and a function (DOMI-function) of the software, which allows to choose which are the most important signals to report in Matlab® for the study of the detected manoeuvre, is enable. Then they are investigated in Matlab®.
In the following section, seven different criteria are developed.

4.1.1 Criterion 1: Minimum Acceleration

The manoeuvres are detected in AVL-DRIVE, and then the signals are reported and studied in Matlab. Since the discomfort is mostly affected by the acceleration/deceleration of the vehicle, the analysis begins with the study of it.
In the following image (Figure 32), the blue signal is detected from benchmark data and the red signal is detected from the Virtual Environment by AVL-DRIVE.

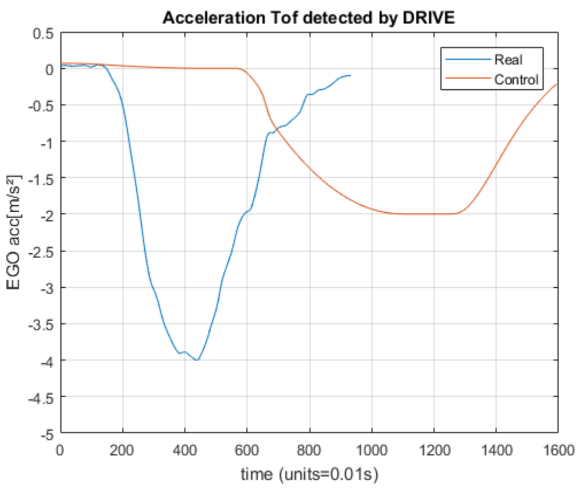


Figure 32: *Ego Acceleration of TOF-Approach Manoeuvre detected by AVL-DRIVE™*

The two signals are not aligned, so as first operation they are positioned according to the 0-point, the point where the deceleration of the vehicles starts.
This positioning is not perfectly right from the physical point of view. In that case, the positioning of the two signals according to the distance from TOF will give a major contribution

since they allow to feel the deceleration regarding the distance, but from an analytic point of view, this visualisation helps the first analysis.(Figure 33)

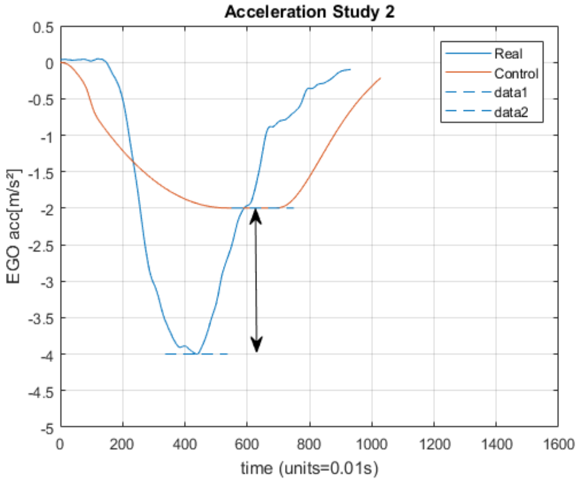


Figure 33: *Ego Acceleration of TOF-Approach Manoeuvre: Minimum Acceleration Study*

In Figure 33 the minimum acceleration achieved by the vehicles is also highlighted. It is an interesting aspect since the maximum deceleration, as well as the maximum acceleration, achieved in a vehicle can really stress the occupants.
The first rating is evaluated: first, the percentage is calculated and after it is rated in the following way:
If $acc_{min_c} > acc_{min}$

$$\%acc = \frac{acc_{min}}{acc_{min_c}} \tag{34}$$

Otherwise

$$\%acc = \frac{acc_{min_c}}{acc_{min}} \tag{35}$$

%acc indicates the percentage of the acceleration that could be calculated as the ratio between the two minimum acceleration, the biggest one is chosen to be at the denominator.
Then according to the AVL-DRIVE^{TM} Rating Scale (Figure 16), the rating is given as follows:

$$DRIVE\_Rating1 = 7 \cdot \%acc + 3 \tag{36}$$

Figure 34 shows the rating approach:

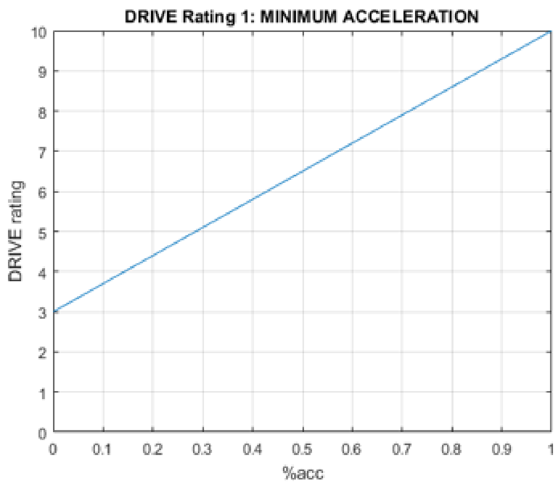


Figure 34: *Visualisation of DRIVE Rating 1 in TOF-Approach*

4.1.2 Criterion 2: Jerk Evaluation

Comfort is highly affected by jerk, the derivative of the acceleration: when a controller is designed, the major consideration is related to the jerk observation, which is always desired to be as small as possible.
The effect determined by the jerk influences the passengers: since the jerk is the derivative of the acceleration, it evaluates how often the acceleration changes (bumps) and its gradient (the roughness of the manoeuvre) perceived inside the cockpit.
For this issue, particular attention is paid to the Jerk Evaluation, which is divided into two parts: the first one has the aim to understand how often the controller accelerates or decelerates (changing its acceleration it creates bumps inside the vehicle), the second one is addressed to an absolute evaluation of the maximum jerk achieved, to study its gradient (the gradient highlights if the manoeuvre is performed smoothly).
The imperfection of the manoeuvre is also visible in Figure 32, where some irregularities in the acceleration signal of the benchmark data can be seen. This analysis allows to determine how those imperfections affect comfort.
The jerk is computed in Matlab, and it is shown in Figure 35. According to the mathematical definition of the derivative, to analyse how often the acceleration achieves some local maxima and minima, the jerk has to be computed and then evaluated. A particular spot is reserved to find the "zeros" in the function.
In Figure 35 the zeros are circled.

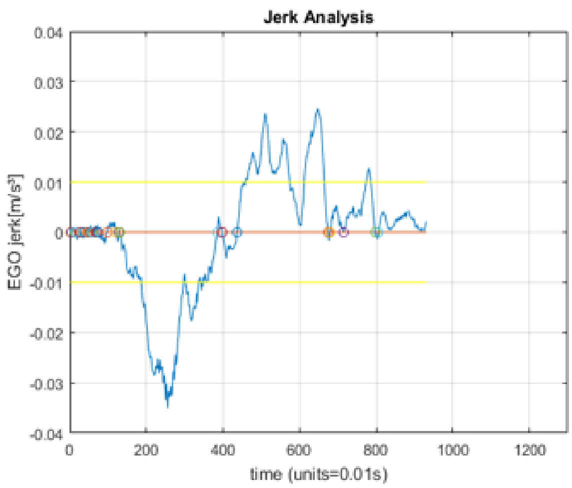


Figure 35: *Ego jerk in TOF-Approach Manoeuvre: Jerk Study*

Observing Figure 35 , most of the zeros do not highlight a strong variation of the acceleration, and sometimes there is only an oscillation of the function.
For instance, a trigger is built to evaluate when the oscillation is important enough to be considered. The introduction of a threshold $[-0.01, 0.01]$ helps this selection. The values are arbitrary, and they are chosen after the observation of many jerk functions. Since the threshold is arbitrary, if the tolerance is too strict, it could be easily adjustable.
As it was mentioned above, two different aspects of the jerk evaluation are studied: Smoothness analysis and Gradient analysis.

Jerk Evaluation: Smoothness Analysis

In Figure 36, the "zero" points are reported on the acceleration:

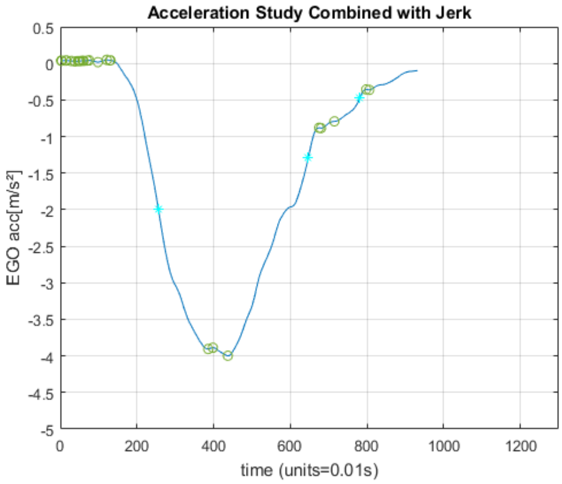


Figure 36: *Ego Jerk in TOF-Approach Manoeuvre. Jerk Study: Smoothness Analysis*

Some circled points represent all the "zeros" found in the jerk function, and some of them coloured in cyan due to the high value of the jerk.
The aim of this analysis is to highlight if the acceleration is smooth, so it has to recognise if in the cockpit the passengers can feel bumps, that cause high discomfort.
The discomfort is affected by the *difference in amplitude* of the acceleration around this point, by the *time* in between of two high values, that we will call "peaks" for simplicity and by the *number* of them.
The first step is related to how to analyse the change in amplitude of the acceleration around the peak points in the jerk function (it is called 'Ampl' in the function below). This evaluation underlines the bump feeling inside the vehicle, and the rating is created as follows:

$$rate_{Ampl} = \frac{10}{e^{\frac{max(Ampl)}{-min(Acc_C)}}} \tag{37}$$

For the rating, the maximum difference of the amplitude is normalised with the maximum deceleration achieved by the controller, it is considered as the most comfortable one.
Even if normally all the rating is considering from 3 to 10 according to the DRIVE Rating (Figure 16), in this case, a high amplitude will generate motion sickness as a minimum collateral effect. It is the reason why in this precise case the rating is considering from 0 to 10.
The second step is the evaluation of the time between the peaks of the jerk function. Afterwards, the time rating is developed in the following equation:

$$rate_{time} = \frac{7}{1 + e^{-1.2P(min(time_{peak}-1)}} + 3 \tag{38}$$

For a clear understanding, $time_{peak}$ is the time in between two successive significant peaks, P is an arbitrarily chosen parameters that determines the tolerance range of the discomfort and, in this study, it is equal to 3. In the analysis, just the minimum time gets this partial rating since it affects the comfort severely. In the equation, the minimum achievable rating is 3, according to the DRIVE Scale (Figure 16).
Figure 37 shows the visualisation of the partial ratings above discussed above.

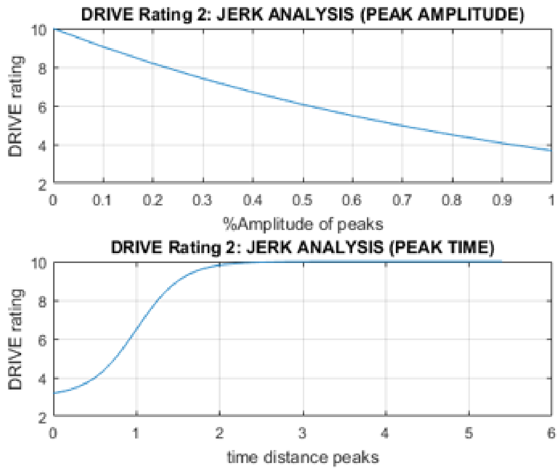


Figure 37: *Visualisation of partial DRIVE Rating 2 in TOF-Approach: Amplitude and Time*

Finally the overall rating of this criterion is given as follows:

$$DRIVE\_Rating2 = (0.3min(rate_{Amp}) + 0.7min(rate_{time})) \cdot \frac{-0.01(\frac{num_{peaks}}{500})^2 + 10}{10} \tag{39}$$

It is a weighted average between the two partial ratings discussed above and then it is multiplied for a correction factor that considers also the number of the peaks.

Jerk Evaluation: Gradient Analysis

In the following section, the gradient of the acceleration, it is rated.
Figure 38 gives an idea of the focus of this study:

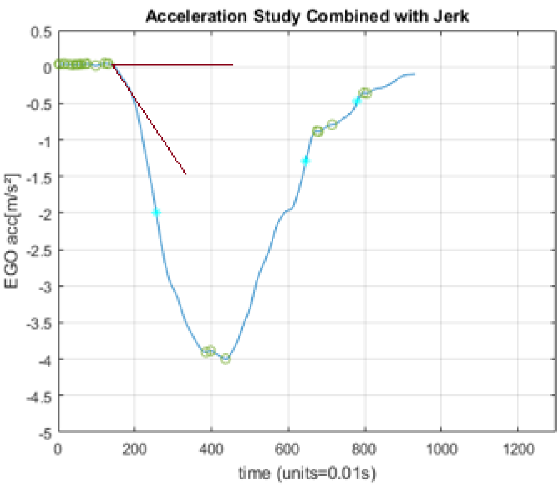


Figure 38: *Ego jerk in TOF-Approach Manoeuvre. Jerk Study: Gradient Analysis*

The analysis focuses on finding the maximum jerk in the jerk function to give a feeling if the manoeuvre is aggressive.
The rating is calculated:

$$DRIVE\_Rating2a = (1 - 5max(|peaks|))7 + 3 \tag{40}$$

where peaks are minima and maxima of the function and are evaluated in absolute terms.
In Figure 39, there is the visualisation of DRIVE Rating 2a.

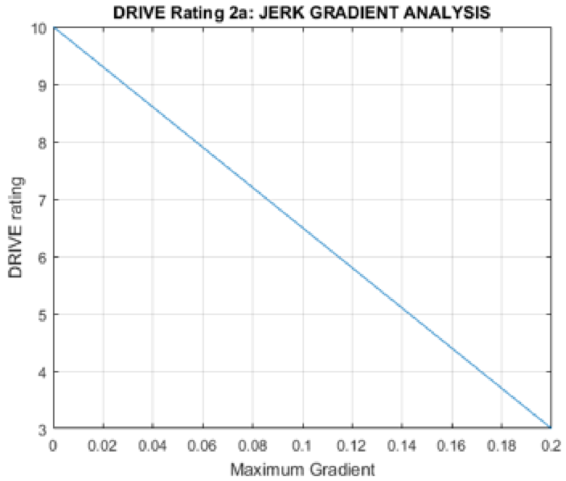


Figure 39: *Visualisation of DRIVE Rating 2a in TOF-Approach*

4.1.3 Criterion 3: Distance Study from TOF at first reaction

The study of the distance at first reaction is investigated.
This study is vital for the understanding of the time reaction of the vehicle since it estimates the rating of safety feeling that an active passenger perceived.
The deceleration starting point is assumed when the deceleration achieves -0.3 $[m/s^2]$. The distance is estimated according to the time distance in between the two vehicles to have always a genuine feeling of the distance, since the amount of it should always be related to the different speeds of two participants and the initial speed of Ego. Figure 40 shows the methodology approach used.

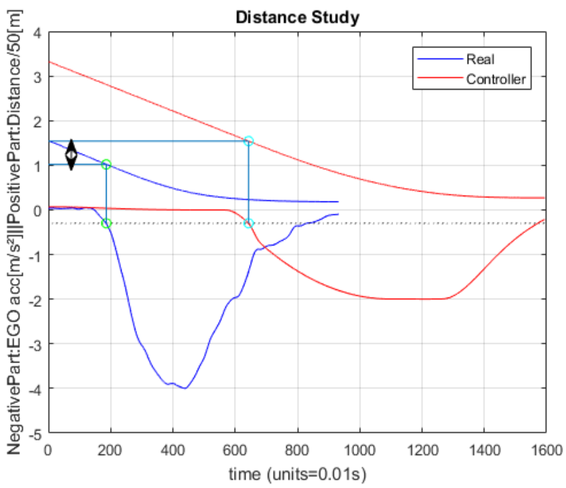


Figure 40: *Distance Study at first reaction in TOF-Approach*

In Figure 40, the distance is shown in the positive part of the chart with a scale factor of $\frac{1}{50}$, while the acceleration plot is represented in the negative part. Here the dotted line showed the position of the threshold mentioned above. The last one can be changed by the driver, according to the sensitivity of the car maker. The plot has the aim to shown which is the contemplated distance according to the acceleration threshold.
In both environments, the time-distances between Ego and TOF are evaluated as follows:

$$time_{dist} = \frac{distance_{@startdec}}{V_{@startdec} - V_{TOF_{@startdec}}} \tag{41}$$

Then the % distance is computed to create the new rating way:

$$\%distance = \frac{time_{dist} - time_{dist_c}}{time_{dist_c}} \tag{42}$$

where $time_{dist}$ is referred to the computation [41] according to the real environment and to the controller one, marked with a subscript 'c'.
If the distance is smaller than the controller, the situation could be even dangerous, so the rating is adapted to the two situations: if the distance of the controller is smaller than the real benchmark ($time_{dist} > time_{dist_c}$)

$$DRIVE\_Rating3 = 7\sqrt{1 - \%dist^2} + 3 \tag{43}$$

Conversely,

$$DRIVE\_Rating3 = 10 \cdot (1 - |\%dist|) \tag{44}$$

In the following Figure (Figure 41), the rating approach is shown:

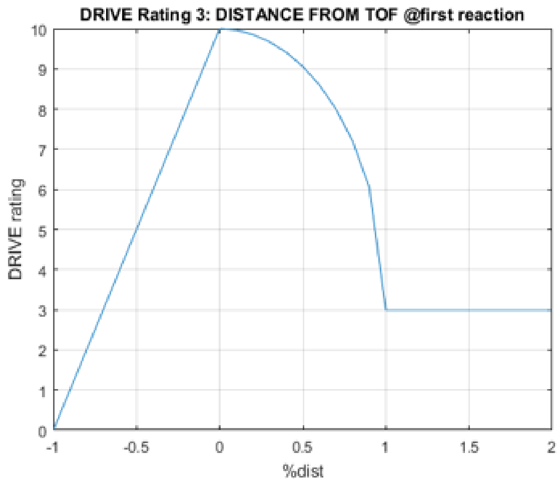


Figure 41: *Visualisation of DRIVE Rating 3 in TOF-Approach*

As already mentioned above, the rating is divided according to the DR Rating (Figure 16), if the distance of the starting manoeuvre from TOF is equal to 0, it means that a collision occurs: this is the reason why the rating in this case is equal to 0. While if the vehicle reacts at the double distance of the controller, the manoeuvre is too early and the passengers can feel the difference. However, the entire action is safe: this is the reason why a rating equal to 3 is appropriate.

4.1.4 Criterion 4: Acceleration Shape Comparison

In this paragraph, the acceleration shape of the benchmark data is compared with the virtual ones.
The general idea behind the study is related to the comparison between a signal that should be the best-performed manoeuvre and a performed one. Since the generation of the signal is variable depending on the people, the comparison of the shape of the signal makes sense. Instead, if the generated signal has a fixed shape, this evaluation makes no sense: so it should be used only if the controller works as discussed.
To get a reasonable result, the two signals have to be aligned according to the starting distance, so the same starting distance is evaluated (it is considering the ones of the controller,

and it is clear in the following image (Figure 42).
This evaluation is performed, considering how far the two curves are:

$$distance_{shape} = \sqrt{[Acc(i) - Acc_c(i)]^2} \tag{45}$$

where (i) means that the evaluation is done at each gap of $0.01[s]$.
In Figure 42) there are the two acceleration signal and a blue area which represents the distance between the two signals:

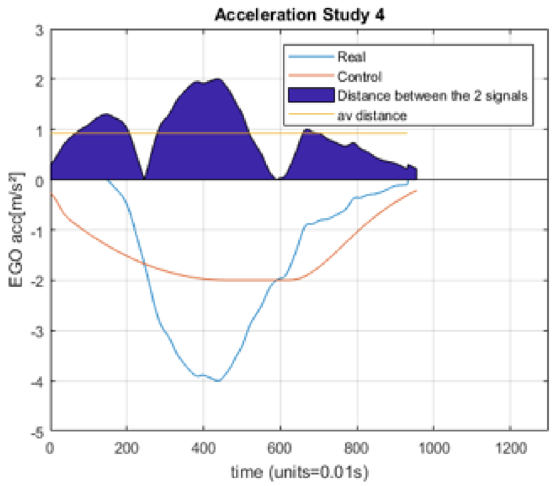


Figure 42: *Acceleration Shape Study in TOF-Approach*

Therefore the average distance is evaluated:

$$average_{dist} = \frac{\int distance_{shape} dt}{T} \tag{46}$$

Where T indicates the duration of the manoeuvre.
Later, the rating is elaborated, taking into account the DRIVE Rating (Figure 16) as follows:

$$DRIVE\_Rating4 = 7\frac{average_{dist}}{acc_{min_c}} + 3 \tag{47}$$

In Figure Figure 43, it is shown how the rating is given:

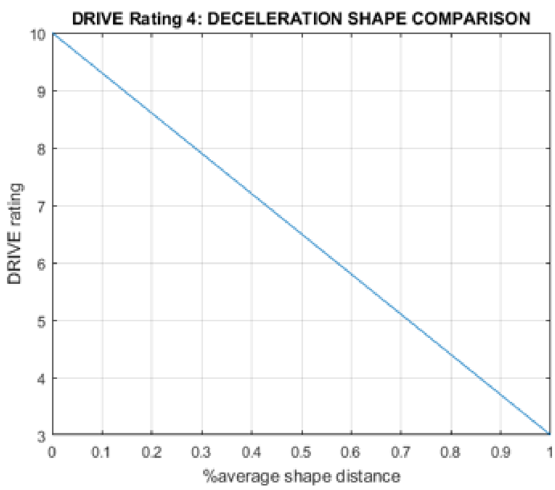


Figure 43: *Visualisation of DRIVE Rating 4 in TOF-Approach*

4.1.5 Criterion 5: Position of the Minimum Acceleration

In this paragraph, the aim is to study the position of the minimum point of the acceleration. This is a weak point in the evaluation due to the fact that it changes the feeling inside the vehicle. An anxious driver prefers an early reaction compared to the average, while a sport one is interesting in feeling the aggressive behaviour of his/her vehicle, so a more squared shape or a retarded increment of deceleration is preferable.
This study is divided into two different sections: the first one is the relative position of the minimum acceleration compared the reference shape of the acceleration while the other is the absolute one.
In the following sections, they are explained in detail.

Relative Position of the Minimum Acceleration

The evaluation is addressed to find the position of the minimum compared to the total length of the deceleration (Period).
The Figure 44 shows the analysis.

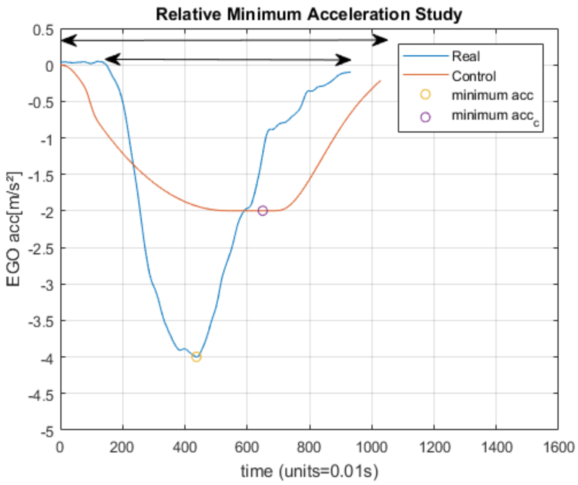


Figure 44: *Relative Position of the Minimum Acceleration Study in TOF-Approach*

In Figure 44, the total length of the deceleration during the TOF-Approach and the minimum acceleration are highlighted: in the real signal the minimum acceleration is coloured in red, while in the simulated one is in yellow.
The shown points are from both environments since the two deceleration are then compared to give a rating.
With the following formulation, the percentage of the position of the minimum acceleration is determined:

$$\%pos = \frac{pos_{acc_{min}}}{Deceleration\ Period} \tag{48}$$

The rating is elaborated as follows:

$$DRIVE\_Rating5 = 7(1 - |\%pos_c - \%pos|) + 3 \tag{49}$$

where the c underlines the difference between a controller and the real environment.
In Figure 45, the rating approach is shown:

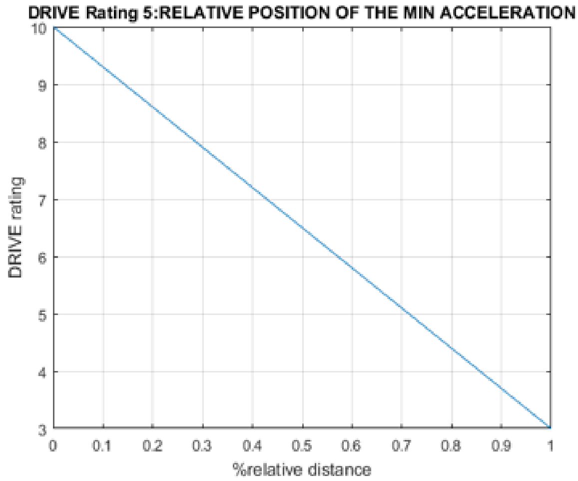


Figure 45: *Visualisation of DRIVE Rating 5 in TOF-Approach*

Absolute Position of the Minimum Acceleration

This evaluation aims to identify when the real data have the minimum acceleration in terms of distance compares to the ideal controller.
This analysis underlines the importance of the distance between the two vehicles because it gives to the driver a feeling of safety.
In the following image (Figure 46), the study is presented:

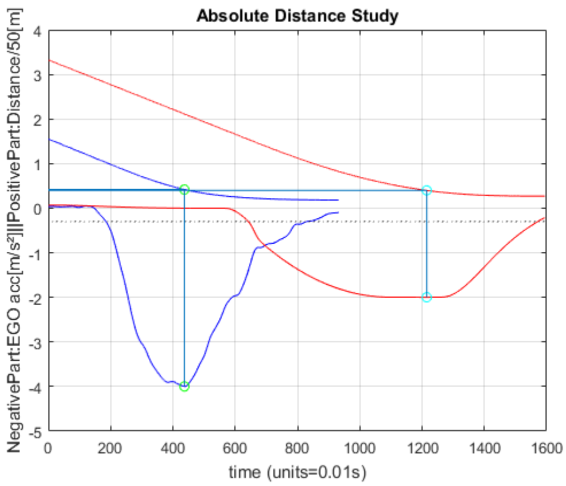


Figure 46: *Absolute Position of the Minimum Acceleration Study in TOF-Approach*

In order to show on the same graph the distance and the acceleration, the distance is scaled of 1:50 factor and it is drawn in the positive part of the graph, while the deceleration is in the negative part.
Since the rating is given considering the distance difference among the two manoeuvres, the percentage distance is evaluated:

$$\%dist_{acc_{min}} = \frac{dist_{acc_m} - dist_{acc_{m_c}}}{dist_{acc_{m_c}}} \tag{50}$$

The rating is studied in a different way if the $\%dist_{acc_{min}}$ is positive or negative.
If it is positive, the situation is better than the negative one from a safety point of view:

$$DRIVE\_Rating5a = 7\sqrt{1 - \%dist^2_{acc_{min}}} + 3 \tag{51}$$

Otherwise:

$$DRIVE\_Rating5a = 7(1 + \%dist_{acc_{min}}) + 3 \tag{52}$$

In the following image (Figure 47), it is explained how the DRIVE Rating 5a is given.

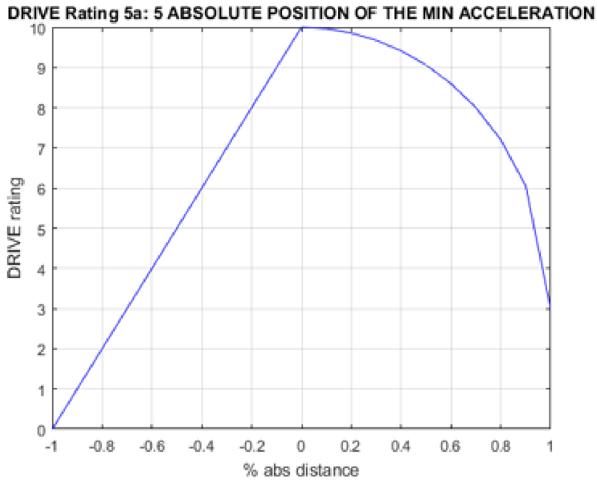


Figure 47: *Visualisation of DRIVE Rating 5a in TOF-Approach*

4.1.6 Criterion 6: End-Velocity Analysis

This criterion is used to conduct the velocity analysis.
The acceleration is the derivative of the velocity, and the only meaningful analysis should be addressed to the shape of it since all the previous criteria well investigated the acceleration. In this particular analysis, the end part of the velocity is observed because there could be a wanted or unwanted overshoot.
In the following image (Figure 48), the two different curves represent the two-speed profiles of the benchmark data (blue line) and the controller data (red line).

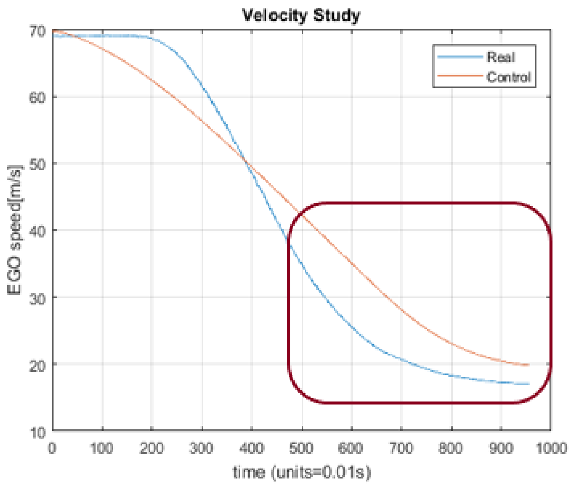


Figure 48: *End-Part Velocity Study in TOF-Approach*

The rating only serves to underline the presence of an overshoot, so it is computed as follows:

$$\%overshoot = \frac{\frac{V_{min}}{V_{end}}}{\frac{V_{min_c}}{V_{end_c}}} \tag{53}$$

If %overshoot is bigger than 1, then %overshoot is equal to the inverse of the Eq.53.
Then the rating is elaborated:

$$DRIVE\_Rating6 = 7 \cdot \%overshoot + 3 \tag{54}$$

As in the previous criteria, also in this evaluation it is shown how the rating is given with the following figure(Figure 49)

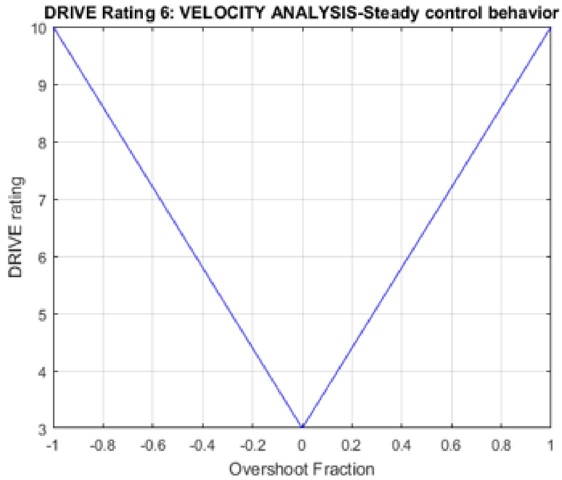


Figure 49: *Visualisation of DRIVE Rating 6 in TOF-Approach*

4.1.7 Criterion 7: Time To Collision (TTC) Analysis

During the TOF-Approach manoeuvre, if the occupants are active (look outside of the vehicle), it is important to maintain a TTC quite high to give a safe feeling to them. That is the reason why the Time To Collision is studied.
The time to collision (TTC) is:

$$TTC = \frac{distance}{\Delta V} \tag{55}$$

where the distance is that between the two vehicles while ΔV is the difference between TOF and Ego speeds.
In the following image (Figure 50), the TTC of the two manoeuvres are shown:

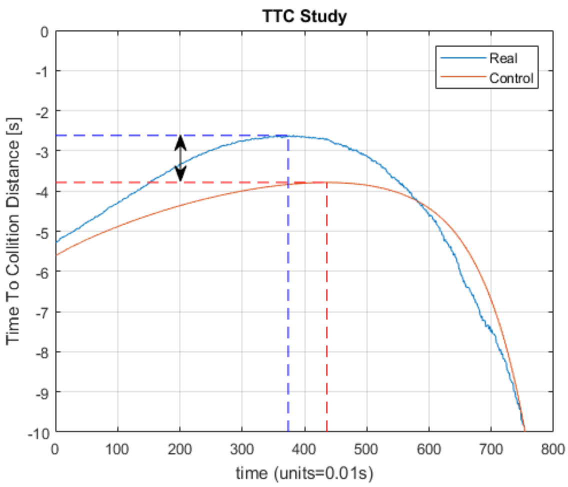


Figure 50: *Time to Collision (TTC) Study in TOF-Approach*

The critical point is the highest TTC because from the formulation it is clear to see that it represents when the difference in speed of the two vehicles is too high and the distance is too small.
The $\%TTC_{crit}$ is estimated:

$$\%TTC_{crit} = \frac{TTC_{max_c} - TTC_{max}}{TTC_{max_c}} \tag{56}$$

The result is evaluated to consider also the sign (negative or positive) of the calculation since it represents if TTC is higher in the simulation or the benchmark. This analysis is strictly related to the safety of the manoeuvre and the safe feeling, which is why it is important to give a different rating depending on which side the real manoeuvre is different. If the $\%TTC_{crit}$ is smaller than 0, it is the most critical situation:

$$DRIVE\_Rating7 = 10 \cdot (1 - |TTC|) \tag{57}$$

Otherwise the rating is as follows:

$$DRIVE\_Rating7 = 7 \cdot \sqrt{1 - \%TTC^2} + 3 \tag{58}$$

In the next Figure (Figure 51), the rating method is illustrated:

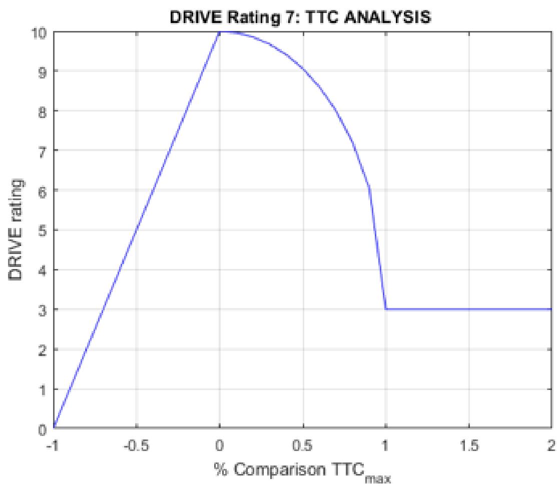


Figure 51: *Visualisation of DRIVE Rating 7 in TOF-Approach*

4.1.8 Overall Rating

Considering the importance of the different contributions, the car maker can choose which parameters are most important using a scale from 1 to 5 according to AVL-DRIVE^{TM} (indicated as w_i in the formula).
Before performing the overall rating, the criteria are divided in two categories: Comfort and Safety.
Criterion 1, Criterion 2 and 2a, Criterion 4 and Criterion 6 belong to the comfort class rating. All the other criteria belong to the safety class rating as it is shown in the following equations:

$$COMFORT = \frac{w_1 Rate1 + w_2 Rate2 + w_{2a} Rate2a + w_4 Rate4 + w_6 Rate6}{\sum w_i} \tag{59}$$

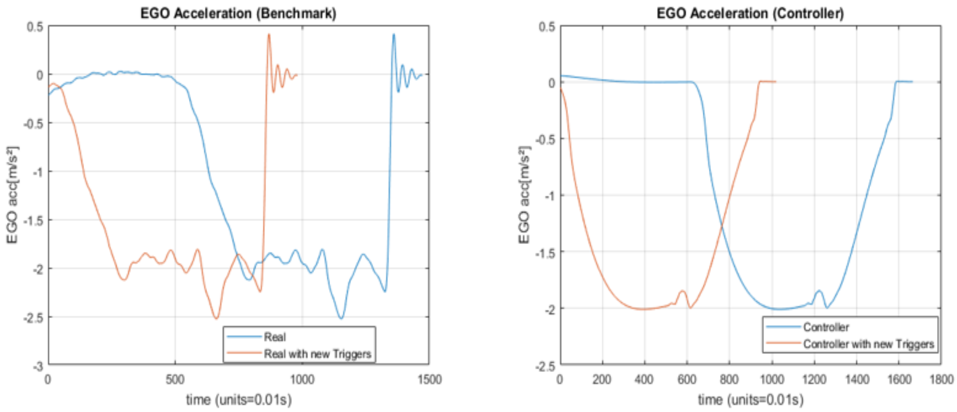
$$SAFETY = \frac{w_3 Rate3 + w_5 Rate5 + w_{5a} Rate5a + w_7 Rate7}{\sum w_i} \tag{60}$$

The total rating is then calculated:

$$TOTAL\_Rate = \frac{COMFORT + SAFETY}{2} \tag{61}$$

4.2 Follow Vehicle Stop Criteria

The manoeuvre was explained in paragraph 2.2.2.
Using AVL-DRIVE^{TM}, some manoeuvres are studied just in the end part. To create a clear and complete analysis, the deceleration is studied completely and then some triggers are added to focus on the main interesting points.
In the following picture (Figure 52), there is a representation of how the original manoeuvre (blue signal) is cut to get out the interesting part (red signal):



(a) *Real Ego deceleration* (b) *Control Ego deceleration*

Figure 52: *Setting triggers of Follow Vehicle Stop Manoeuvres*

The manoeuvre is classified as follow vehicle stop if TOF is decelerating till stop, Ego is following TOF and decelerates instead of performing a cut-out and its deceleration is lower than $-0.3[m/s^2]$.
All the studied manoeuvres are cut as it is shown in Figure 52. So far, the signals are adjusted and the evaluation criteria are realized. In this section, seven different criteria are discussed.

4.2.1 Criterion 1: Minimum Acceleration

Due to the fact the criterion is equal to the one developed in TOF-Approach, the reader is reminded to the Paragrapher 4.1.1.
To facilitate the reading, Figure53 describes the minimum acceleration rating approach.

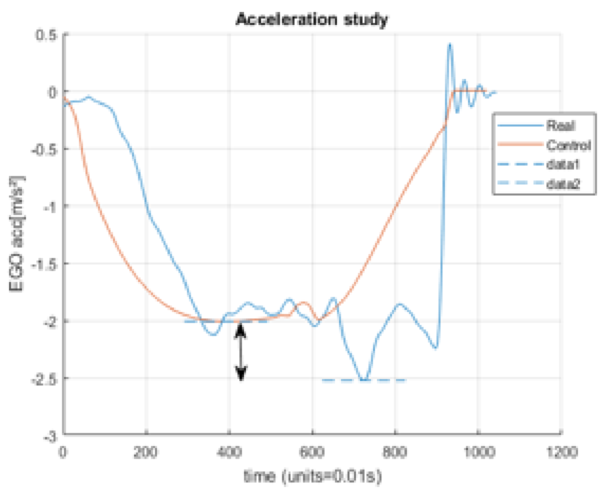
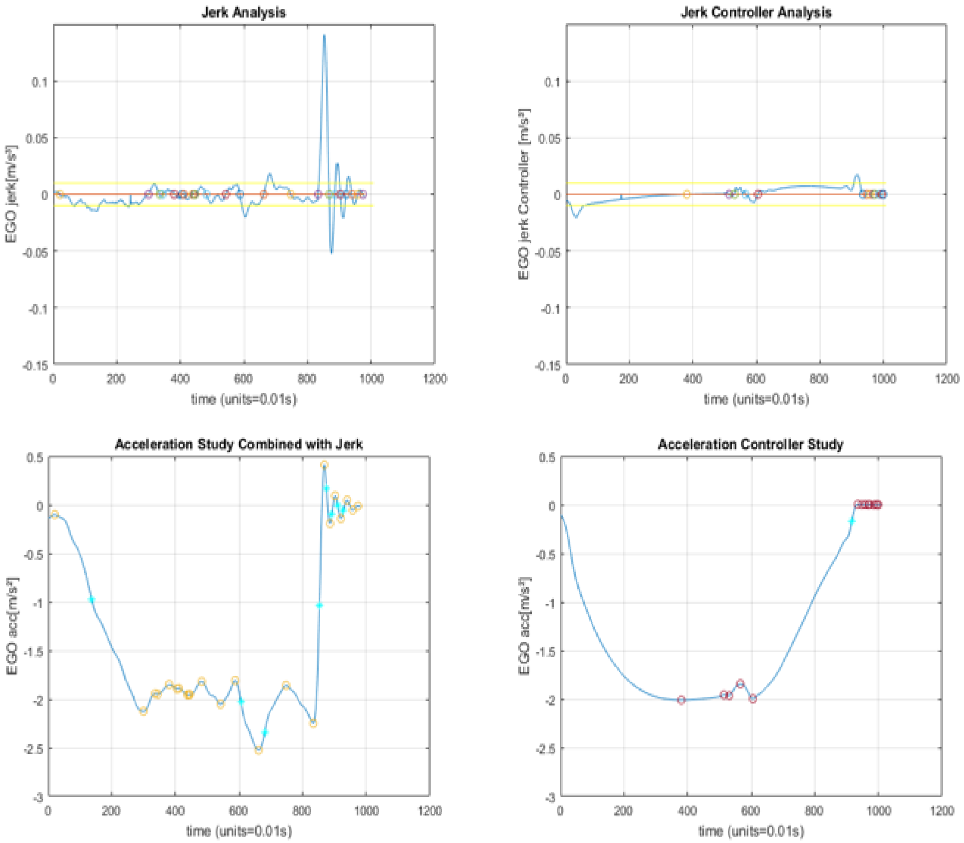


Figure 53: *Ego Acceleration of Follow Vehicle Stop Manoeuvre: Minimum Acceleration Study*

4.2.2 Criterion 2: Jerk Evaluation

The following criterion is the same developed for TOF-Approach manoeuvre (see Paragraph 4.1.2).
However, during this study it became apparent that also the controller is affected by jerk variations, for instance the study involves also the controller and then a comparison among controller and benchmark data is made to get a proper rating.
Figure 54 shows a real manoeuvre and the controller manoeuvre in order to highlight the differences:



(c) *Jerk and Acceleration of a real manoeuvre*

(d) *Jerk and Acceleration of a simulated manoeuvre*

Figure 54: *Jerk Evaluation of Follow Vehicle Stop Manoeuvre*

The entire manoeuvre follows the already mentioned criterion, but the overall rating of this criterion is finally given as follows:

$$DRIVE\_Rating2 = 10\frac{Rate2\_RealEnvironment}{Rate2\_ContrEnvironment} \tag{62}$$

This approach is used for both the Jerk Evaluation: Smoothness and Gradient.

4.2.3 Criterion 3: End-Distance Analysis

In Follow Vehicle Stop Approach is very important to analyse when the manoeuvre ends and for this reason, it is considered that the manoeuvre is finished when the acceleration is lower than $-0.1[m/s^2]$ and at that point the end distance is found.
In the following image (Figure 55), the distance between Ego and TOF are represented considering also how they are detected.

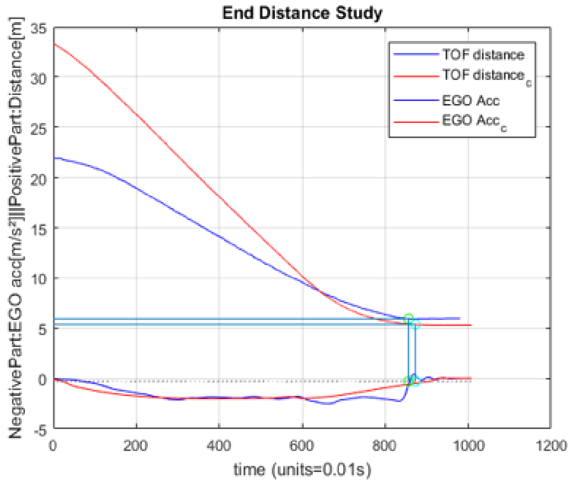


Figure 55: *End-Distance of Follow Vehicle Stop Manoeuvre*

From the rating point of view, also, in this case, the approach was the same as with the distance study from TOF at first reaction (Paragraph 4.1.3) explained previously in the analysis of TOF-Approach manoeuvre.
The difference with the rating approach is how the percentage distance is computed:

$$\%dist = \frac{TOF_{dist} - TOF_{dist_c}}{TOF_{dist_c}} \tag{63}$$

For the rating analysis, the reader is reminded of the equations 43 and 44.

4.2.4 Criterion 4: Duration Analysis

This is an analysis of the entire deceleration time of the manoeuvre starting from the minimum acceleration. If the manoeuvre takes longer, it is a more uncomfortable manoeuvre since it tried to go closer to the TOF many times. It is rated worst in this situation since it has creepy behaviour.
In Figure 56 some arrows give the idea of the analysed and compared interval time.

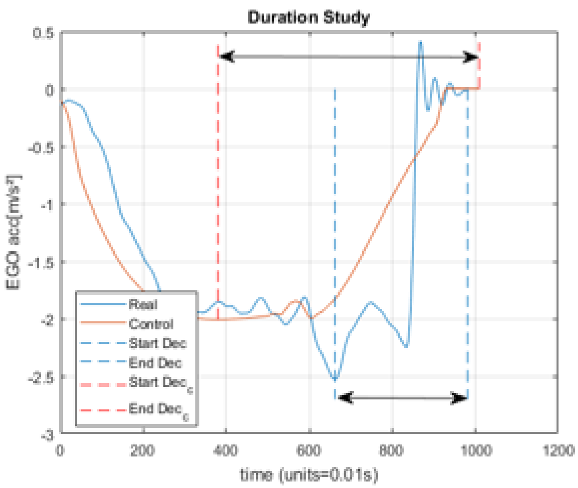


Figure 56: *Duration Analysis of Follow Vehicle Stop Manoeuvre*

If the time of the manoeuvre is longer in the controller environment

$$\%duration = \frac{End_{dec}}{End_{dec_c}} \tag{64}$$

Otherwise, the %duration is evaluated

$$\%duration = \frac{End_{dec_c}}{End_{dec}} \tag{65}$$

After that this percentage is computed, the rating is also calculated as follows:

$$DRIVE\_Rating4 = 10(1 - \%duration) \tag{66}$$

However, if the rating is lower than 3, then it will be equal to 3 according to the Figure 16 since it does not compromise the safety inside the vehicle.

4.2.5 Criterion 5: Acceleration Shape Comparison

This analysis is the same as that shown in Paragraph 4.1.4.
Figure 57 shows the methodology.

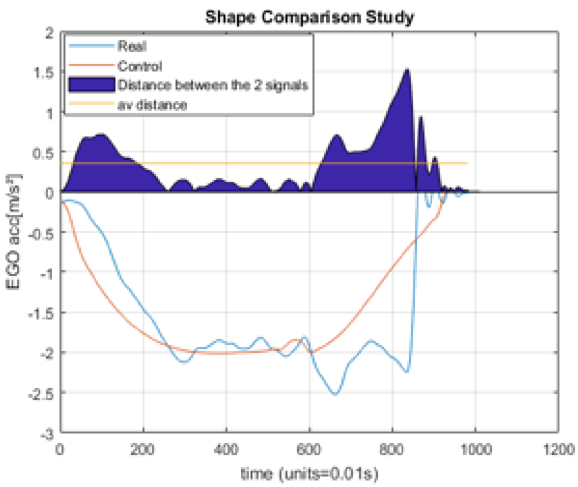


Figure 57: *Acceleration Shape Comparison of Follow Vehicle Stop Manoeuvre*

4.2.6 Criterion 6: End-Acceleration Analysis

As mentioned above, during this kind of manoeuvre creepy behaviour (Ego tries to go closer to TOF) might show up: it creates the basis to compute an analysis of this behaviour.
In this section, the aim is to analyse and evaluate the bumps that can be present at the end of the manoeuvre if the vehicle accelerates and decelerates continuously to achieve the standstill.
Figure 58 shows exactly the unwanted discussed behaviour. Three main characters influence the analysis: the number of oscillations, their amplitudes and frequencies.
The presented manoeuvre shows exactly a damped oscillation behaviour.

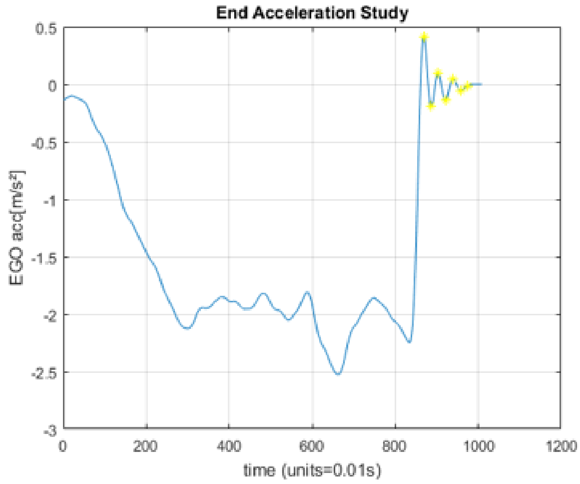


Figure 58: *End-Acceleration Analysis of Follow Vehicle Stop Manoeuvre*

A first step is the individuation of the points of maxima and minima acceleration at the end of the deceleration and the estimation of their amplitude,

$$amp = |acc_{i+1} - acc_i| \tag{67}$$

and of their frequency

$$freq = time_{i+1} - time_i \tag{68}$$

where i indicates maxima and minima acceleration of the function.

A rating of all these parameters is introduced as follows:

$$rate_{amp} = 7\left(1 - \frac{amp_{crit}}{acc_{min_c}}\right) + 3 \tag{69}$$

$$rate_{time} = 7\frac{e^{\frac{freq_{crit}}{T}}}{e} + 3 \tag{70}$$

$$rate_{num} = 10\left(\frac{num_{oscill}}{40} - 1\right)^2 \tag{71}$$

where amp_{crit} and $freq_{crit}$ stand for the maximum amplitude and minimum frequency and T is the period of the the entire manoeuvre.
The overall rating of this criterion is:

$$DRIVE\_Rating6 = 0.375rate_{amp} + 0.5rate_{time} + 0.125rate_{num} \tag{72}$$

4.2.7 Criterion 7: Position of the Minimum Acceleration

As described in Paragraph 4.1.5, the position of the minimum acceleration is evaluated according to Figure 59 and Figure 60.

Relative Position of the Minimum Acceleration

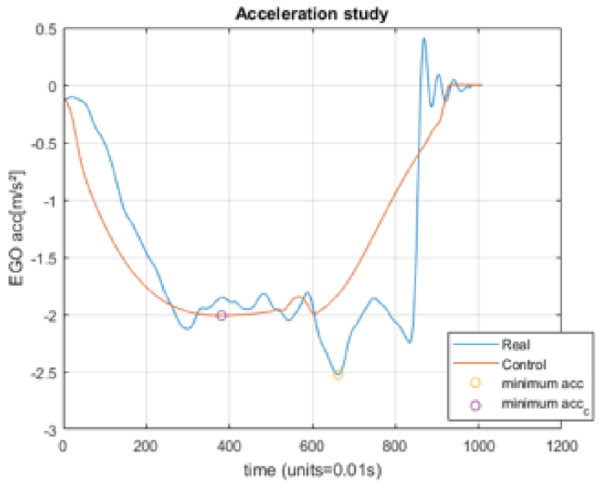


Figure 59: *Relative Position of the Minimum Acceleration of Follow Vehicle Stop Manoeuvre*

Absolute Position of the Minimum Acceleration

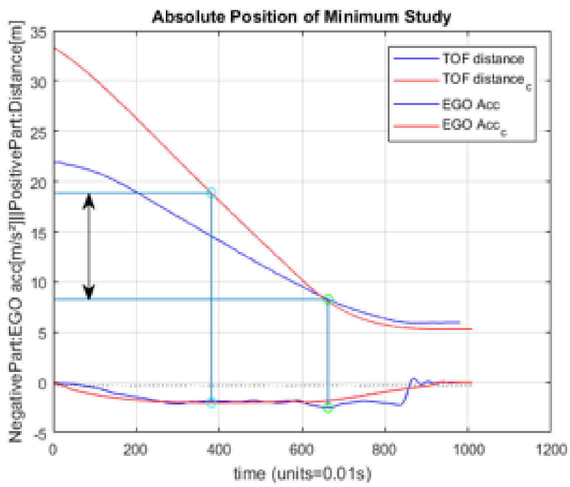


Figure 60: *Absolute Position of the Minimum Acceleration of Follow Vehicle Stop Manoeuvre*

4.2.8 Overall Rating

As was done for the TOF-Approach Overall Rating, the importance of the different contributions is given a weighting between 1 and 5.
A previous distinction is made between safety criteria and comfort criteria:

$$SAFETY = \frac{w_3 RATE(3) + w_7 RATE(7) + w_{7a} RATE(7a)}{\sum w_i} \tag{73}$$

$$COMFORT = \frac{w_1 RATE(1) + w_2 RATE(2) + w_{2a} RATE(2a)}{.} \dots$$
$$\dots \frac{+ w_4 RATE(4) + w_5 RATE(5) + w_6 RATE(6)}{\sum w_i} \tag{74}$$

The overall rating:

$$TOTAL\_Rate = \frac{SAFETY + COMFORT}{2} \tag{75}$$

4.3 Follow Drive Away Criteria

Previously, Follow Drive Away manoeuvre was presented in Paragraph 2.2.3.
This section provides the theoretical basis concerning how the criteria for the evaluation of this manoeuvre were built. Six criteria will be presented, some of which have already been discussed above.
Figure 61 shows the detected manoeuvre in AVL-DRIVE^{TM} in comparison with the controller manoeuvre.

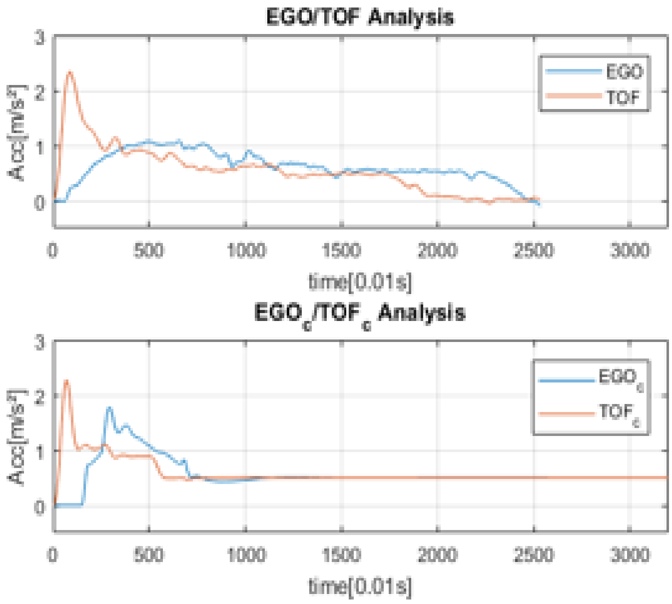


Figure 61: *Detection of Follow Drive Away*

The first plot shows a benchmark manoeuvre while in the second one the controller behaviour is shown to get an idea of the two manoeuvres.

4.3.1 Criterion 1: Maximum Acceleration

As described in Paragraph 4.1.1, the maximum acceleration is evaluated.
However, during the Follow Drive Away manoeuvre the vehicle is accelerating instead of decelerating as was the case in TOF-Approach. In this rating instead of evaluating the minimum acceleration, the comparison is made considering the maximum acceleration of EGO in the controlled environment and the real benchmark data.
Figure 62 gives a clear idea of the similarity between the evaluation of the minimum and maximum acceleration.

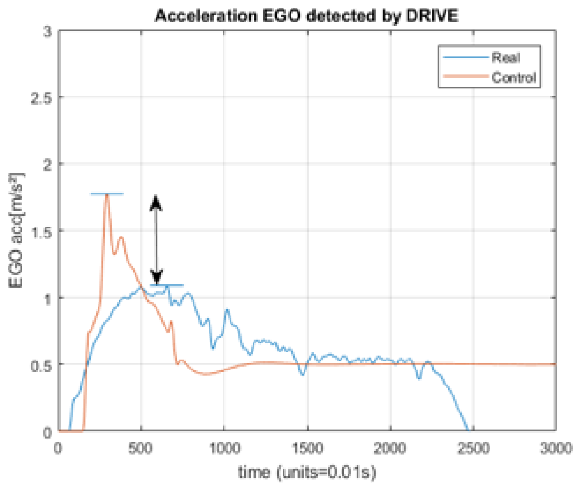


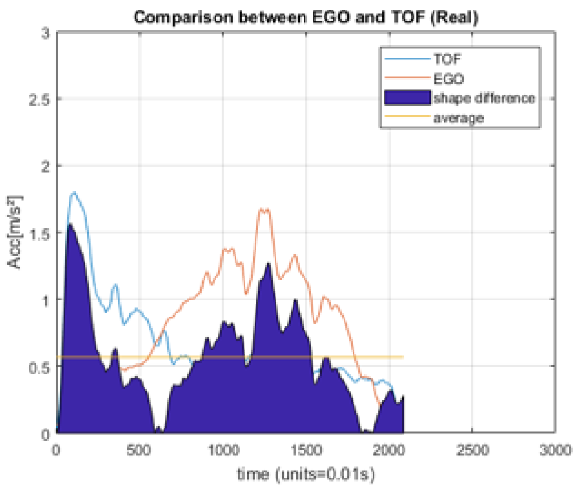
Figure 62: *Ego Acceleration in Follow Drive Away Manoeuvre: Maximum Acceleration Study*

4.3.2 Criterion 2: Acceleration Shape Comparison

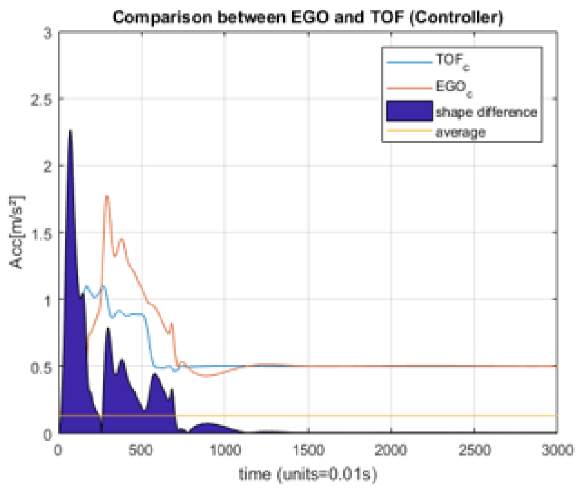
The Follow Drive Away manoeuvre is highly dependent on TOF, and in detail on its acceleration. Consequently, this section is devoted to an analysis of the relationship between TOF and Ego acceleration.
The methodology is the same as used in Paragraph 4.1.4. However, Ego and TOF signals coming from the same environment are compared instead Ego signals of the different environments. The study is divided into two sections: the first is related to an analysis of Ego acceleration against TOF acceleration, while the second one is aimed to find the position where the differences are.

2 Acceleration Shape Comparison: Ego versus TOF

The aim of this analysis is to find out the differences between Ego and TOF in both the studied scenarios, as shown in Figure 63.



(a) *Acceleration Shape Comparison - Real Environment*



(b) *Acceleration Shape Comparison - Simulation Environment*

Figure 63: *Follow Drive Away Manoeuvre: Acceleration Shape Comparison Ego vs TOF*

The evaluation aims to highlight the difference between the investigated signals and get a rating. The high dependency on TOF behaviour has reasonably motived a study of the

the difference between Ego and TOF signals. It is made distinctly for both the environments (see Figure 63).
As can be seen in Figure 64, the two founded differences between Ego and TOF have been overlapped to compare the two results previously obtained. Afterwards, the study follows the same methodology seen in TOF-Approach, Paragraph 4.1.4.

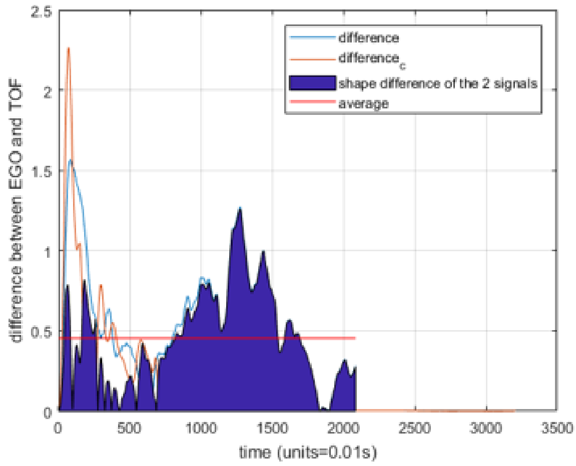


Figure 64: *Differences Analysis in Follow Drive Away Manoeuvre: Acceleration Shape Comparison*

2a Acceleration Shape Comparison: Major Differences Detected

The second analysis is directed to find out where the difference between the signals is bigger and which signal achieves the biggest differences.
In Figure 65, the difference is evaluated relatively and not absolutely, as was the case in the previous analysis.

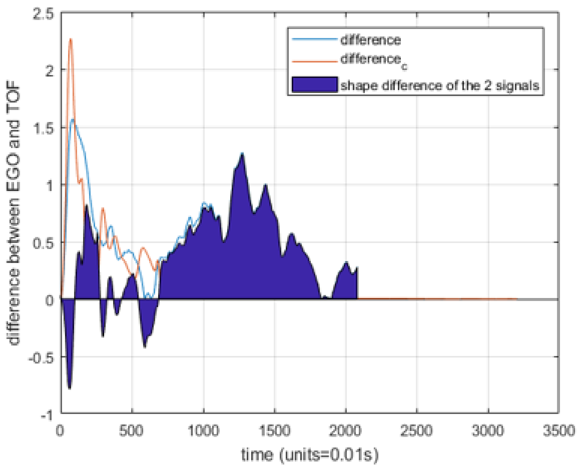


Figure 65: *Relative differences analysis in Follow Drive Away Manoeuvre: Acceleration Shape Comparison*

Ego has to follow TOF according to some general comfort rules. If the difference from the real environment is lower than the simulated one, it means that Ego does not follow TOF properly. Thus, the manoeuvre is not well performed.
To compute this evaluation, two thresholds are introduced:

- 0.5 < | difference | < 1: all the points that overcome this threshold receive a weight of 1.
- |difference| > 1: if a point exceeds this threshold, it receives a weight of 2.

Moreover, the difference curve is distinguished between the first and the second half depending on whether the signal from the controller is bigger than the benchmark one.
The worst situation happens when in the first half the controller signal is bigger than the real one, while in the second half it is other way round.
The analysis is carried out calling weak points if they belong to the worst situation as just discussed. Then, also the other points are counted.
Two counters are introduced: the first one called 'weak points', and the second one, 'points' where the points are just counted according to their weight.

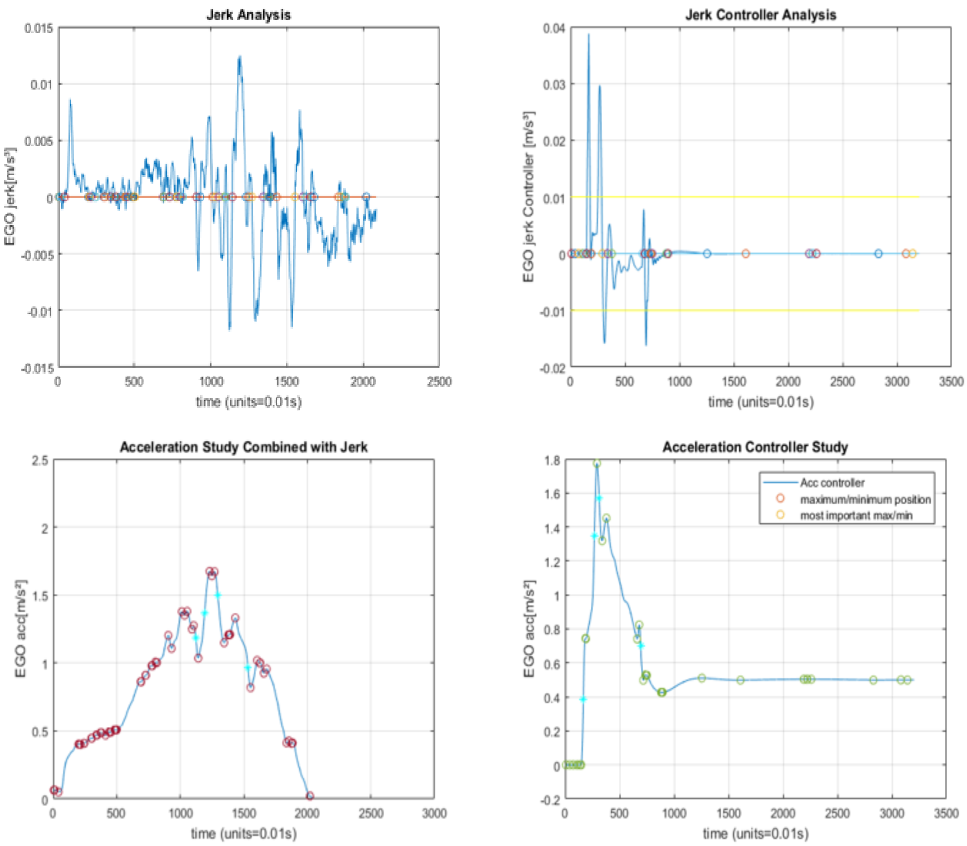
Finally, the rating is elaborated, as follows:

$$DRIVE\_Rating2a = 7\left(1 - \left(\frac{weakpoints}{T}0.6 + \frac{points}{T}0.4\right)\right) + 3 \tag{76}$$

where T indicates the period of the analysis.

4.3.3 Criterion 3: Jerk Evaluation

This analysis is the same as that shown in Paragraph 4.2.2.
Figure 66 illustrates the methodology.



(c) *Jerk and Acceleration of a real manoeuvre*

(d) *Jerk and Acceleration of a simulated manoeuvre*

Figure 66: *Jerk Evaluation of Follow Drive Away Manoeuvre*

4.3.4 Criterion 4: Minimum Time Gap

The study of the time gap is introduced to evaluate the minimum time gap since it is the most critical and in a well-performed manoeuvre it coincides with the final distance. The time gap is evaluated as:

$$TimeGap = \frac{distance}{V} \tag{77}$$

where distance is the effective distance in between Ego and TOF and V is the Ego speed. Figure 67 shows the time gap.

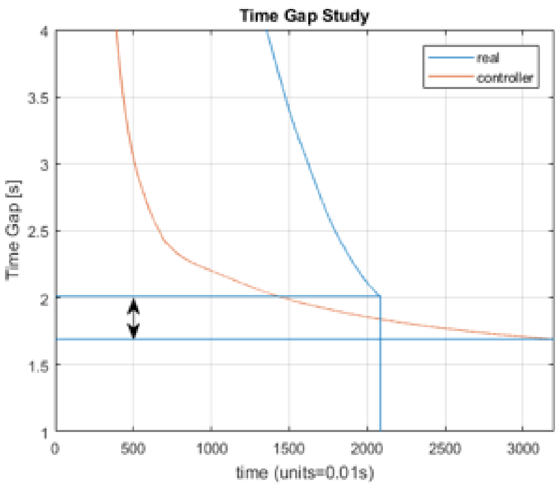


Figure 67: *Follow Drive Away Manoeuvre: Minimum Time Gap Comparison*

Here a distinction is made according to safety conditions: if the minimum time gap in the real manoeuvre is smaller than the simulated one, it can compromise not only the comfort inside the vehicle but also the safety. For this reason, two different rating analyses are introduced. If $min(timegap) > min(timegap_c)$

$$DRIVE\_Rating4 = 7\sqrt{1 - \left(\frac{min(timegap_c)}{min(timegap)} - 1\right)^2} + 3 \tag{78}$$

Otherwise

$$DRIVE\_Rating4 = 7\frac{min(timegap)}{min(timegap_c)} + 3 \tag{79}$$

4.3.5 Criterion 5: Response Delay Evaluation

Since the reaction of Ego is quite important for this kind of study, the time delay is investigated in this section. The manoeuvre starts when the acceleration is bigger than 0.1 $[m/s^2]$. Figure 68 shows the response delay: the upper part of the plot contains signals regarding the distance between Ego and TOF, while the lower part shows the acceleration with the delay of both the curves.

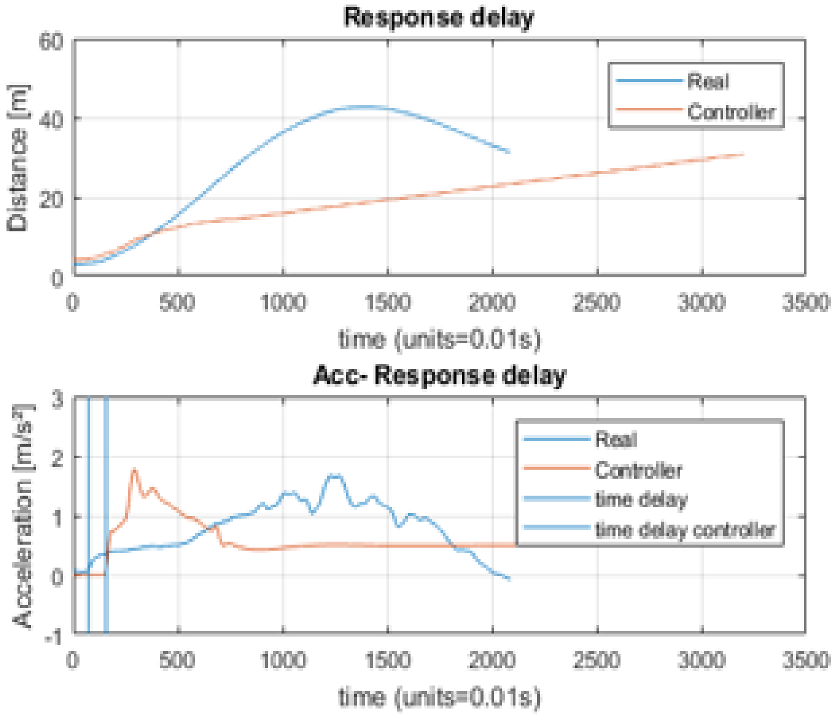


Figure 68: *Follow Drive Away Manoeuvre: Response Delay Analysis*

In this case, it is quite evident that if the delay is lower in the performed manoeuvre, the situation is not catastrophic. Also, in this case, the rating is divided into two parts.
If $delay > delay_c$

$$DRIVE\_Rating5 = 7\left(1 - \frac{delay_c}{delay}\right) + 3 \tag{80}$$

Conversely,

$$DRIVE\_Rating5 = 7\sqrt{1 - \left(1 - \frac{delay}{delay_c}\right)^2} + 3 \tag{81}$$

4.3.6 Criterion 6: Maximum Distance Evaluation

Processing the reaction of the Ego at TOF acceleration means studying all the aspects that can lead to comfort issues inside the cockpit. One of these is the maximum distance between the two characters. It underlines a negative reaction of Ego.
Figure 69 shows the maximum achieved distance of both Ego, and a narrow shows the distance between them.

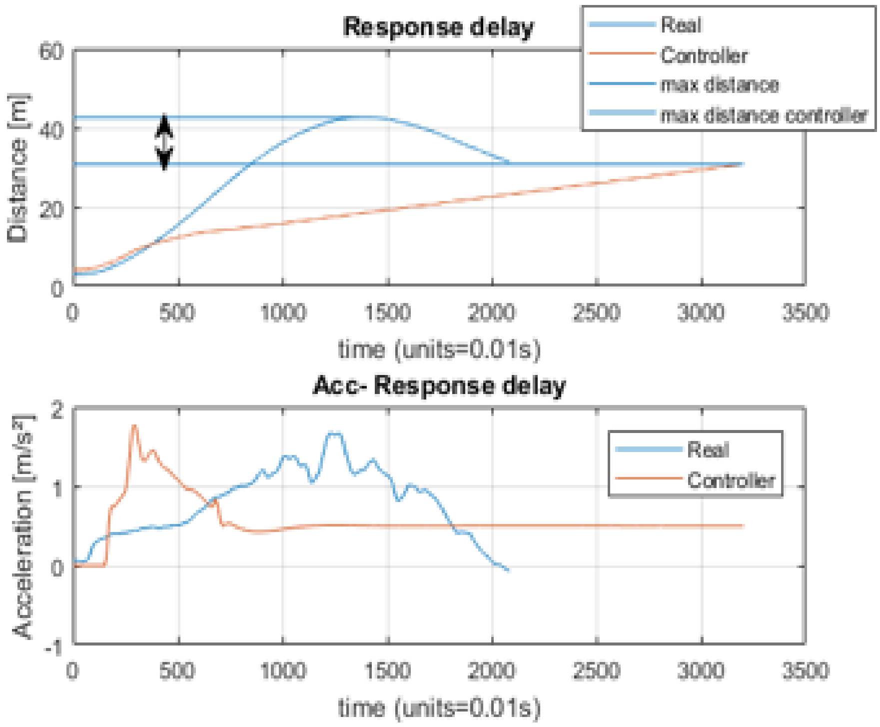


Figure 69: *Follow Drive Away Manoeuvre: Response Delay Analysis*

The rating is elaborated, as follows:

$$DRIVE\_Rating6 = 7\left(\frac{max(dist_1)}{max(dist_2)}\right) + 3 \tag{82}$$

4.3.7 Overall Rating

Also in this manoeuvre, the importance of the difference contributions is considered according to some "weights" between 1 and 5.
A previous distinction is made between Safety and Comfort criteria:

$$SAFETY = \frac{w_4 RATE(4)}{\sum w_i} \tag{83}$$

$$COMFORT = \frac{w_1 RATE(1) + w_2 RATE(2) + w_{2a} RATE(2a) + \ldots}{\ldots + w_3 RATE(3) + w_3 a RATE(3a) + w_5 RATE(5) + w_6 RATE(6)} \ldots \atop \sum w_i \tag{84}$$

The overall rate:

$$TOTAL\_Rate = \frac{SAFETY + COMFORT}{2} \tag{85}$$

4.4 TOF free-lane Cut-Out Criteria

In the following Paragraph, the manoeuvre being investigated is the TOF free-lane Cut-Out. This manoeuvre is rated according to four different criteria that analyse the maximum achieved acceleration, response delay, Jerk Evaluation to detect the smoothness and the maximum gradient of the acceleration, and differences between the shape of the acceleration signals. All these criteria have already been analysed in the previous studies. For this reason, the following sections will only include the relevant figures and a brief explanation in each case.

4.4.1 Criterion 1: Maximum Acceleration

The maximum acceleration (Figure 70) is evaluated as shown in Paragraph 4.1.1.

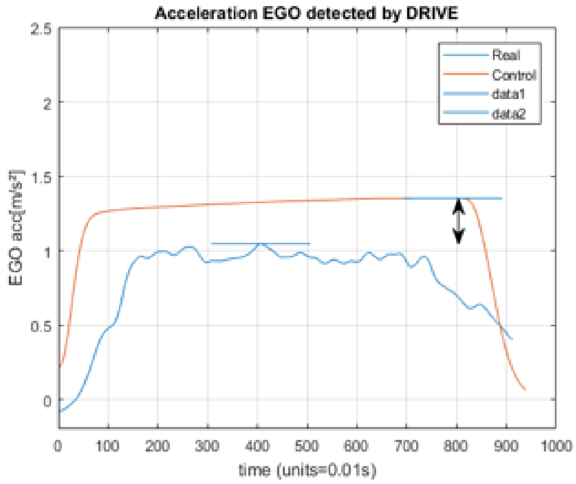


Figure 70: *TOF free-lane Cut-Out Manoeuvre: Maximum Acceleration*

4.4.2 Criterion 2: Response Delay Evaluation

For TOF free-lane Cut-Out manoeuvre, the reaction time is quite important since, as fast as TOF changes its lane, Ego should accelerate. It can highly increase the comfort inside the vehicle.
The vehicle is accelerating when the acceleration is bigger than 0.2 m/s^2.

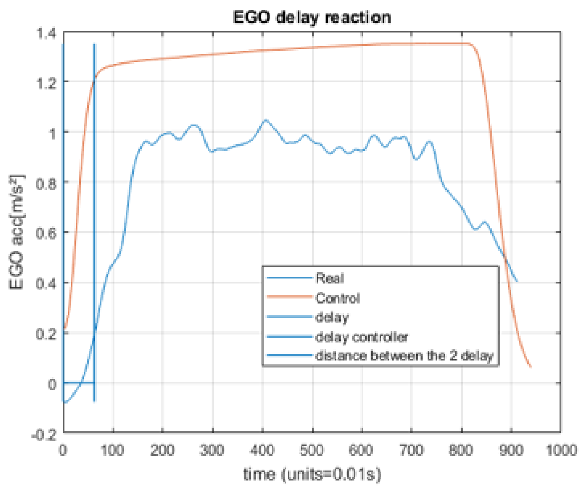


Figure 71: *TOF free-lane Cut-Out Manoeuvre: Response Delay*

In Figure 71, the delays are indicated with vertical lines.
Again, the signals are compared. For this scenario it is assumed that if the real Ego accelerates before the virtual one, the response delay can be considered as perfect.
For this reason, if the response delay is smaller than the response delay in the simulation environment:

$$DRIVE\_Rating2 = 10 \tag{86}$$

Otherwise, the rating is computed as follows

$$DRIVE\_Rating2 = 7\frac{delay_c}{delay} + 3 \tag{87}$$

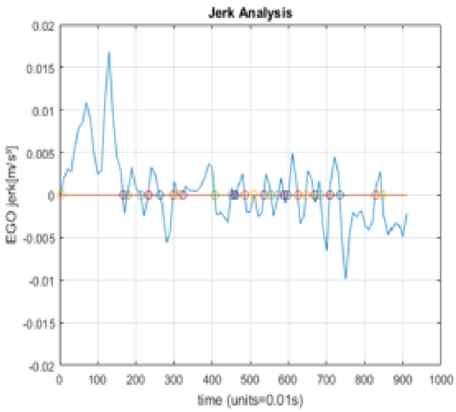
However, the controller might react immediately and the response delay in its environment, as in this specific case, is equal to 0. Thus, if the response delay of the controller is equal to 0, the rating is elaborated as follows:

$$DRIVE\_Rating2 = 10 - 5\ delay \tag{88}$$

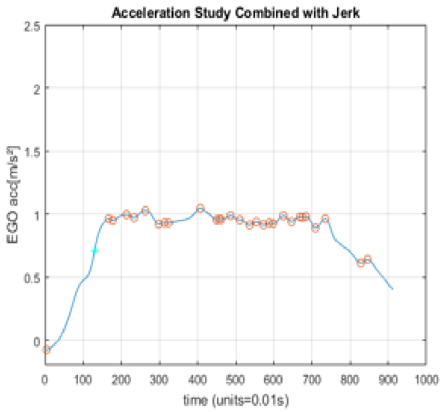
but if $DRIVE\_Rating2 < 3$ then its rating is equal to 3 according to Figure 16 since Ego does not make unsafe operations.

4.4.3 Criterion 3: Jerk Evaluation

The Jerk Evaluation (Figure 72) is computed as seen in Paragraph 4.2.2.



(a) *Jerk Evaluation*



(b) *Weak points and Acceleration Analysis*

Figure 72: *Jerk Evaluation of TOF free-lane Cut-Out Manoeuvre*

4.4.4 Criterion 4: Acceleration Shape Comparison

The evaluation is computed in two steps; the first of which is already discussed in Paragraph 4.1.4.
Figure 73 resumes the discussed Acceleration Shape Comparison.

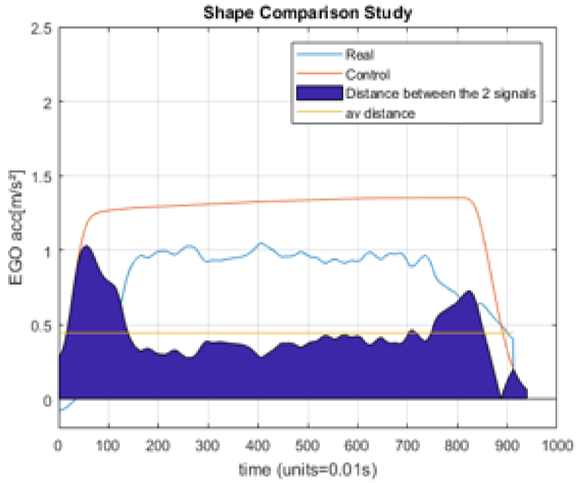


Figure 73: *TOF free-lane Cut-Out Manoeuvre: Acceleration Shape Comparison*

However, an indication of the shape of the acceleration signal is introduced to suggest the kind of acceleration. If the acceleration has a rectangular shape, its behaviour is more sporty whereas if it follows a triangular shape, the behaviour is more comfortable.
This sub-criterion is not added to the overall rating. Nevertheless, it is only a comment.
In Figure 74, the methodology approach is shown.

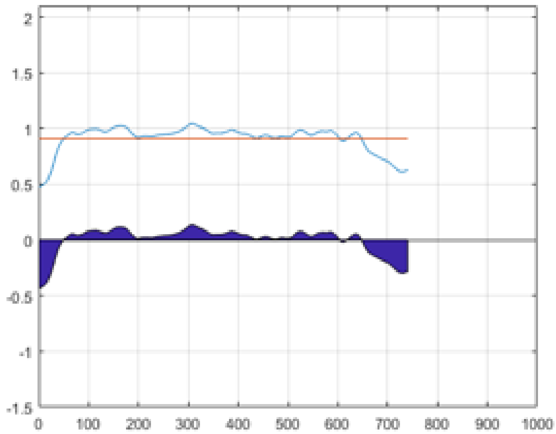


Figure 74: *TOF free-lane Cut-Out Manoeuvre: Acceleration Shape Comment*

The first step is to consider the acceleration range above $0.5[m/s^2]$. Then the average is computed. Afterwards, all the points belonging to the acceleration signal are compared with the average. These are counted in two different variables if they are upward or downward the average. Finally, the difference between these two variables is computed and according to a arbitrary threshold (chosen after an observation of the results) the estimation is made. The result in the code is distinguished in 0 and 1 indicating if the signal has a rectangular or triangular shape.

4.4.5 Overall Rating

All these criteria are related to comfort.
The total rating is thus given by a weighted average.

$$TOTAL\_Rate = \frac{w_1 RATE(1) + w_2 RATE(2) + w_3 RATE(3) + w_3 a RATE(3a) + w_4 RATE(4)}{\sum w_i} \tag{89}$$

4.5 TOF Free-Lane Cut-In Criteria

The last studied manoeuvre is the TOF free-lane Cut-In.
It differs significantly from TOF free-lane Cut-Out since it has also to consider some safety issues related to the manoeuvre. Eight different criteria are created for this manoeuvre. All of which have already been explained above.
In this section, they will merely be mentioned and only differences to the previous assumptions will be mentioned.

4.5.1 Criterion 1: Minimum Acceleration

Figure 75 shows the methodology approach as already seen in Paragraph 4.1.1.

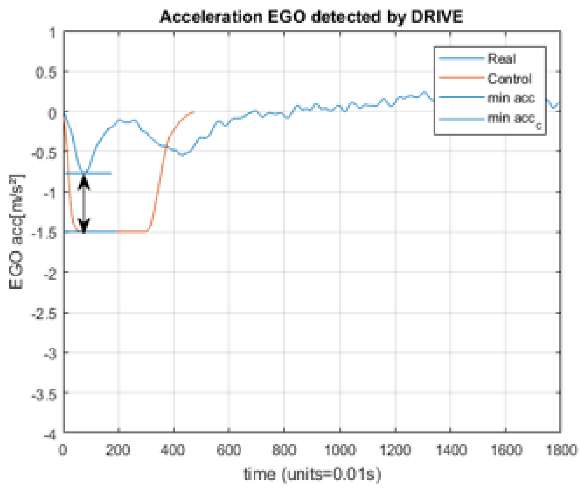


Figure 75: *TOF free-lane Cut-In Manoeuvre: Minimum Acceleration*

4.5.2 Criterion 2: Response Delay Evaluation

Figure 76 shows how the response delay is computed as previously shown in Paragraph 4.4.2.

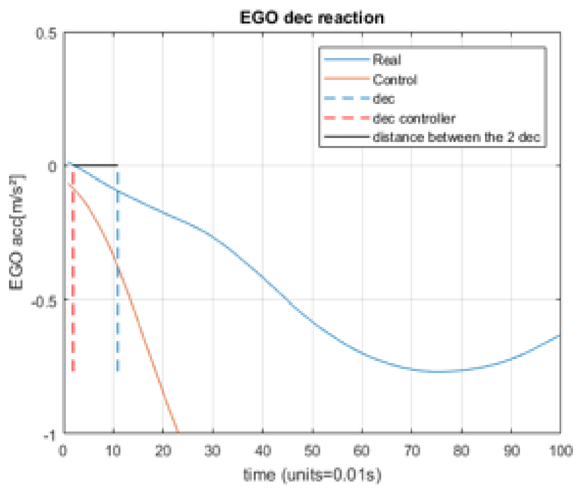


Figure 76: *TOF free-lane Cut-In Manoeuvre: Response Delay Evaluation*

4.5.3 Criterion 3: Jerk Evaluation

3 Jerk Evaluation: Smoothness Analysis

The jerk smoothness analysis (Figure 77) is evaluated as seen in Paragraph 4.2.2.

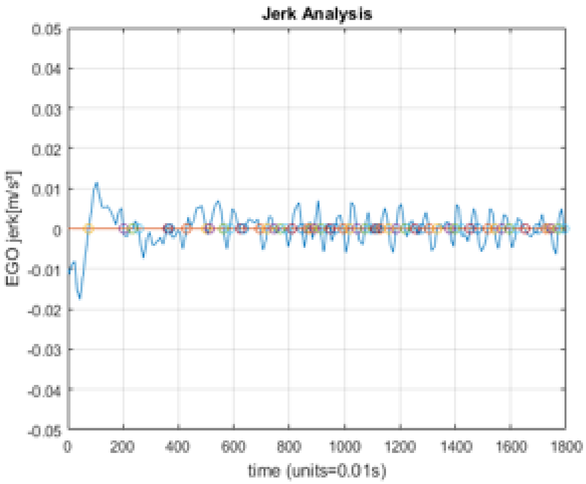


Figure 77: *TOF free-lane Cut-In Manoeuvre: Jerk Smoothness Evaluation*

3a Jerk Evaluation: Gradient Analysis

The second evaluation relates to the gradient analysis and it is computed slightly different. During the deceleration, the gradient analysis is divided into two parts. Figure 78 shows the deceleration and weak points.

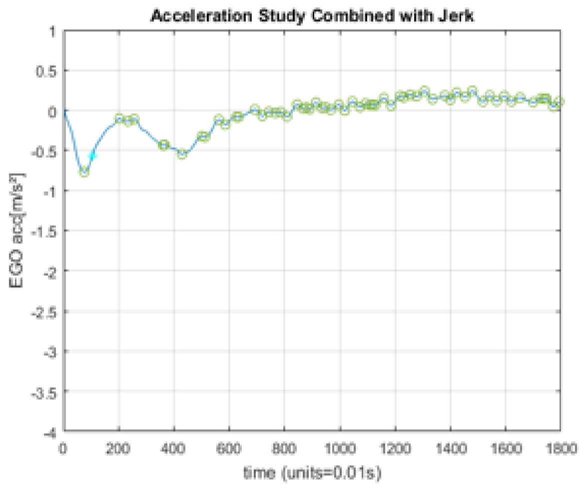


Figure 78: *TOF free-lane Cut-In Manoeuvre: Jerk Gradient Evaluation*

When the vehicle is decelerating, the first part is related to the braking phase while the second to the release of the brake. Since the vehicle is decelerating due to the sudden presence of another vehicle on its lane, the gradient is related to a safety reason more than comfort one. It means that a strong deceleration could be necessary (negative jerk). While during the release of the braking, a strong gradient is completely unwanted for comfort reasons.
Due to these considerations, the rating is given as in equation 40 but the final result is weighted as follows:

$$DRIVE\_Rating3a = 0.3 Rate\_Grad_{neg} + 0.7 Rate\_Grad_{pos} \tag{90}$$

4.5.4 Criterion 4: Acceleration Shape Comparison

In Figure 79, the Acceleration Shape Comparison discussed in Paragraph 4.1.4 is presented.

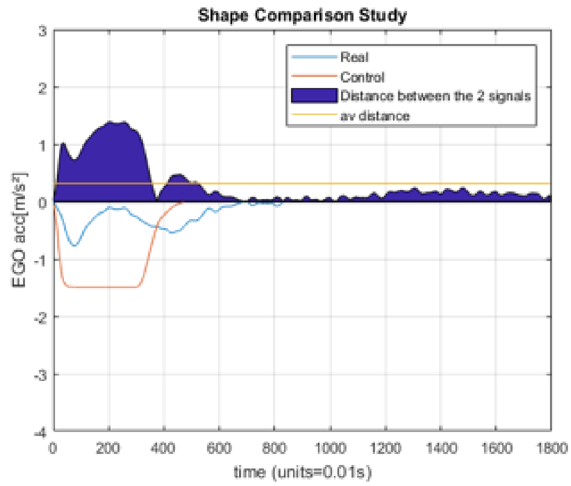


Figure 79: *TOF free-lane Cut-In Manoeuvre: Acceleration Shape Comparison*

4.5.5 Criterion 5: Duration Analysis

The duration analysis is already discussed in Paragraph 4.2.4. In this evaluation, the only difference is the threshold that studies starting and ending point of the deceleration which is set equal to $-0.1[m/s^2]$.
In Figure 80, the criterion is represented.

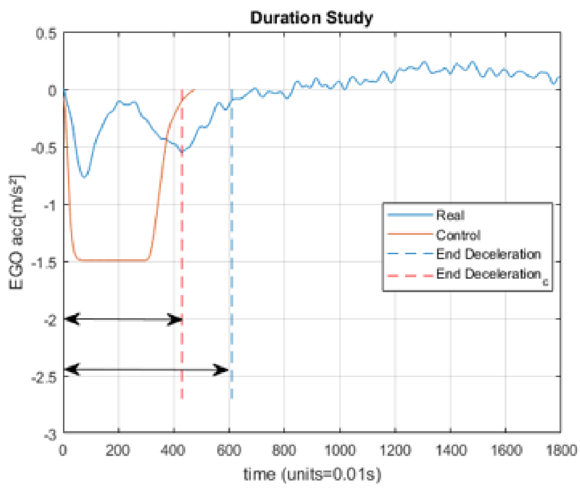


Figure 80: *TOF free-lane Cut-In Manoeuvre: Duration Analysis*

4.5.6 Criterion 6: Bumps in Acceleration Analysis

Bumps in acceleration analysis is similar to the analysis shown in Paragraph 4.2.6 under the name of 'End-Acceleration Analysis'. While the rating and the methodology are the same, the location where the evaluation is performed - in this case on the entire manoeuvre - is different.
In Figure 81, the approach is shown.

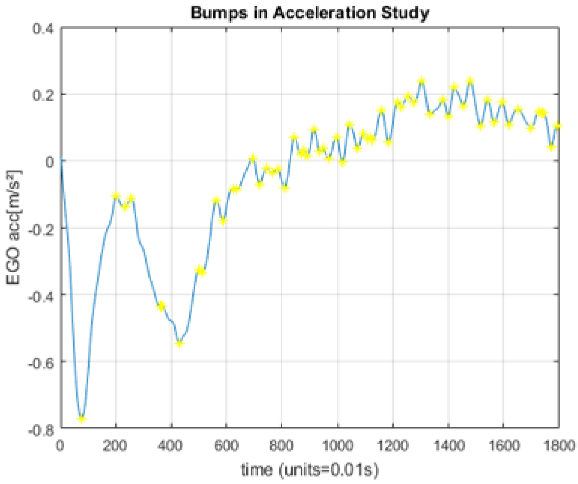


Figure 81: *TOF free-lane Cut-In Manoeuvre: Bumps in Acceleration Analysis*

4.5.7 Criterion 7: Position of the Minimum Acceleration

This analysis is the same as shown in Paragraph 4.1.5.

Relative Position of Minimum Acceleration

Figure 82 shows the relative position of minimum acceleration.

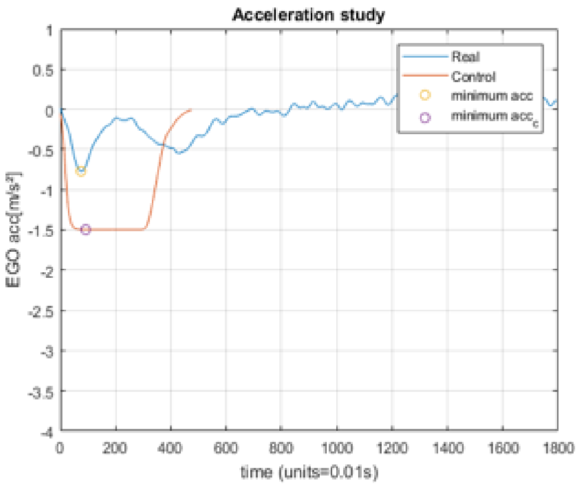


Figure 82: *TOF free-lane Cut-In Manoeuvre: Relative Position of the Minimum Acceleration Analysis*

Absolute Position of Minimum Acceleration

Figure 83 shows the absolute position of minimum acceleration.

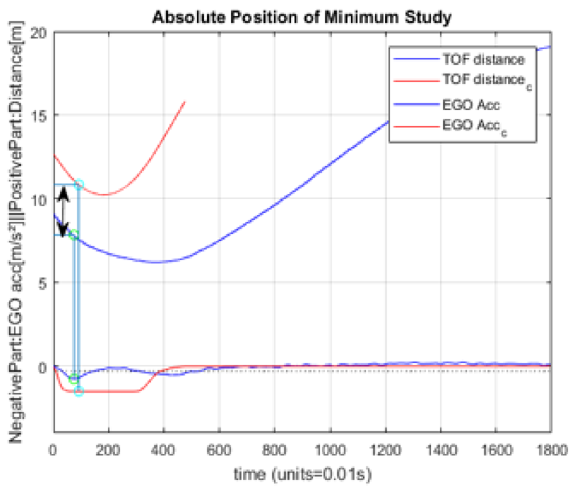


Figure 83: *TOF free-lane Cut-In Manoeuvre: Absolute Position of the Minimum Acceleration Analysis*

4.5.8 Criterion 8: End-Distance Analysis

In this paragraph, the End-Distance Analysis is introduced as the last criterion. It is already seen in Vehicle Stop Criteria, Paragraph 4.2.3.
This analysis considers the end distance at the end of the deceleration (Figure 84).

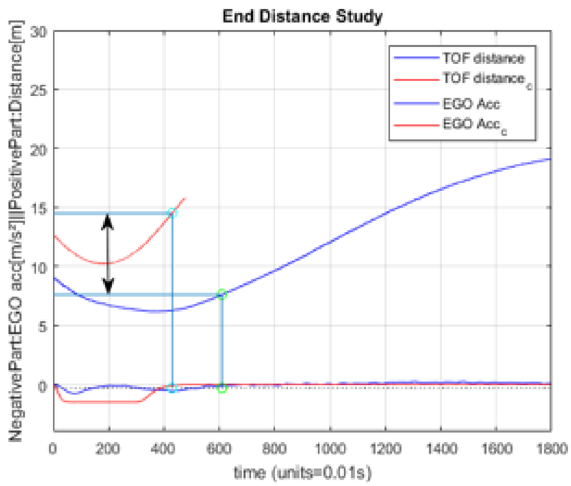


Figure 84: *TOF free-lane Cut-In Manoeuvre: End-Distance Analysis*

4.5.9 Overall Rating

At the end of the last manoeuvre, the overall rating is investigated. The criteria are divided in comfort and safety.

$$SAFETY = \frac{w_2 RATE(2) + w_8 RATE(8)}{\sum w_i} \tag{91}$$

$$\begin{aligned} COMFORT = & \frac{w_1 RATE(1) + w_3 RATE(3) + w_{3a} RATE(3a) + w_4 RATE(4)}{} + ... \\ & ... + \frac{w_5 RATE(5) + w_6 RATE(6) + w_7 RATE(7) + w_{7a} RATE(7a)}{\sum w_i} \end{aligned} \tag{92}$$

Finally, the overall rating is the average of comfort and safety.

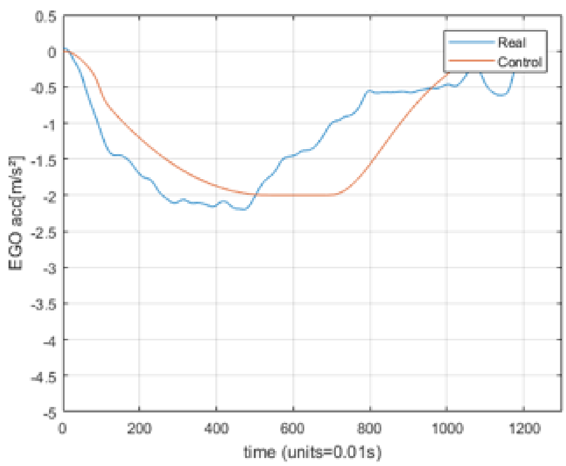
$$TOTAL\_Rating = \frac{SAFETY + COMFORT}{2} \tag{93}$$

5 Results

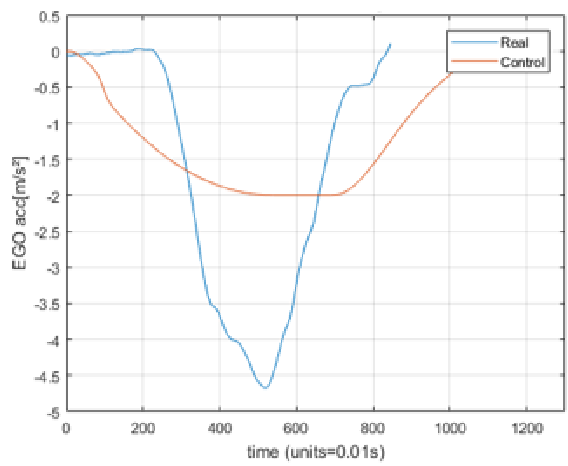
This section is reserved to show the different results of the investigated criteria to proof their validity. Different calibrations of the same manoeuvre will be compared to give the reader the feeling of how the study is conduced, analysing the results of each criterion. In Chapter 4, the evaluation criteria and the methodology were explained in details.
Here, there will be presented five different manoeuvres and for each of them four different calibrations are shown. For TOF-Approach and TOF free-lane Cut-Out, among the benchmark data there were also other calibrations. If the reader is interested on them, he/she is reminded to the Appendix.
The results are developed as the manoeuvres were explained in the previous chapters: TOF-Approach, Follow Vehicle Stop, Follow Drive Away, TOF free-lane Cut-Out and TOF free-lane Cut-In.

5.1 TOF-Approach: Low Speed

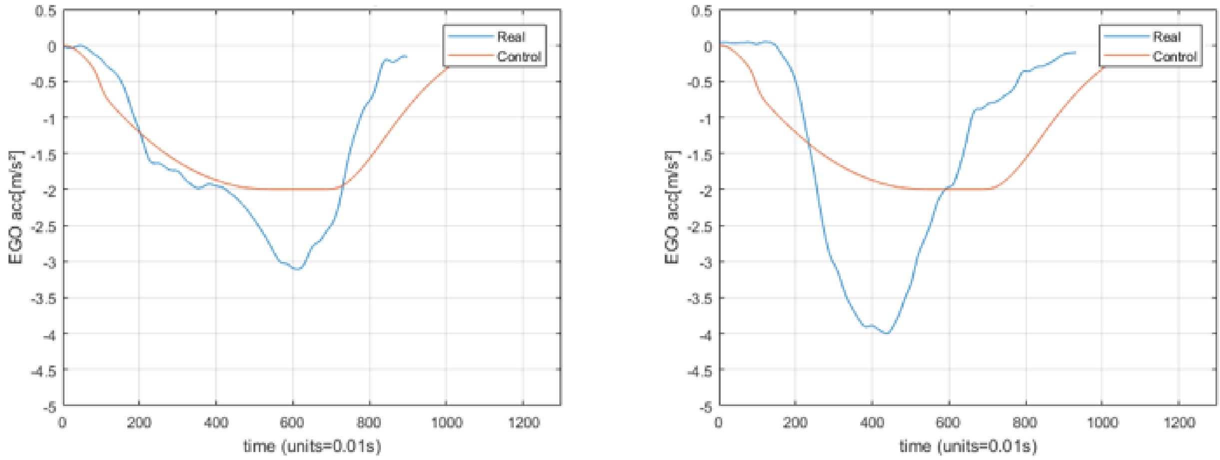
In Paragraph 2.2.1, the manoeuvre is explained: how it is performed and the obtained rating from AVL-DRIVE.
The boundary conditions should be equal. In this comparison, the initial speed of Ego is $70km/h$ and the final one is $20km/h$.
Figure 85 shows four calibrations and the controller behaviour.



(a) *Deceleration in TOF-Approach- Manoeuvre 1*



(b) *Deceleration in TOF-Approach- Manoeuvre 2*

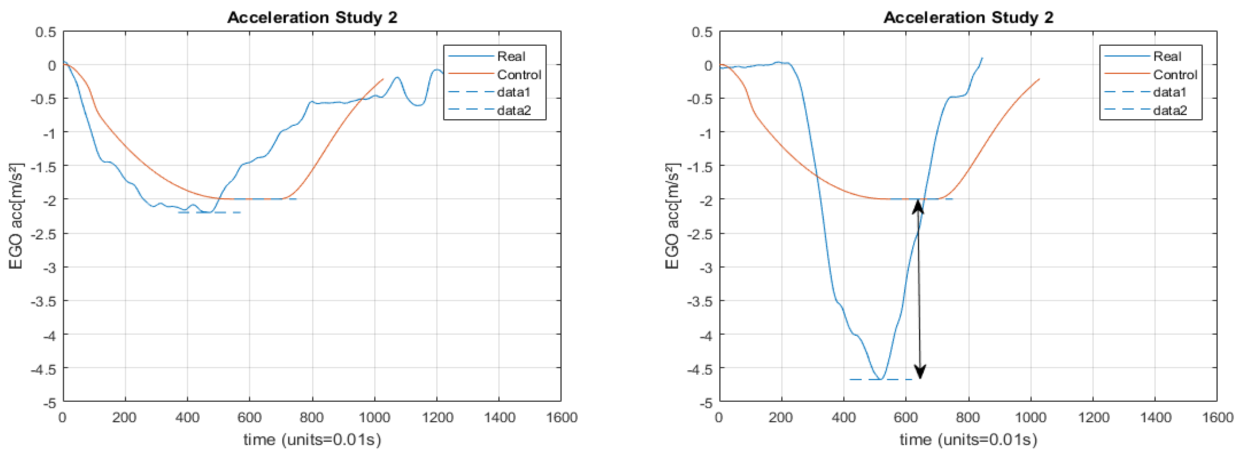


(c) *Deceleration in TOF-Approach- Manoeuvre 3*   (d) *Deceleration in TOF-Approach- Manoeuvre 4*

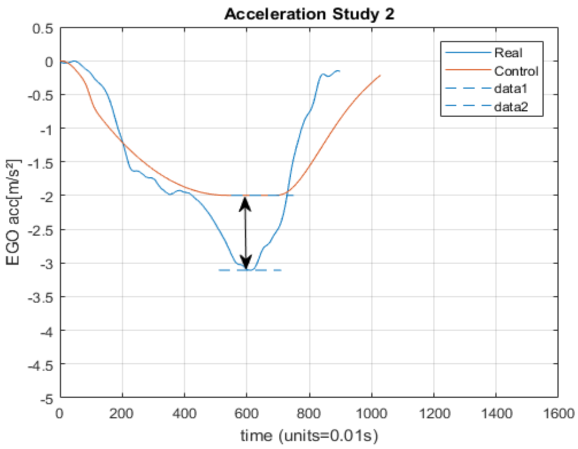
Figure 85: *TOF-Approach Low Speed: Four different calibrations*

5.1.1 Criterion 1: Minimum Acceleration

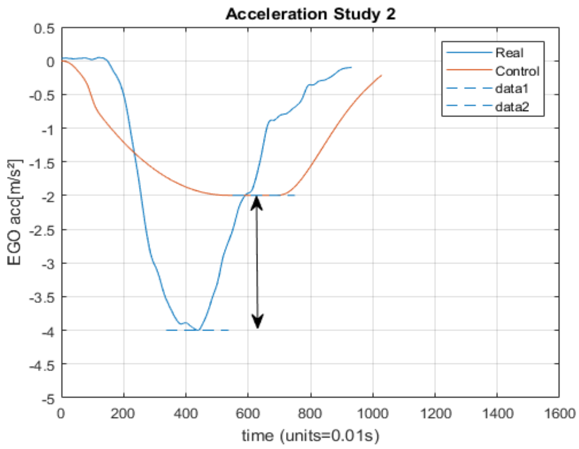
The first criterion is related to the evaluation of the minimum achieved acceleration.
In the following Figure (Figure 86), the four different calibrations are shown together in order to feel the difference among them.



(a) *Deceleration in TOF-Approach- Manoeuvre 1* $DRIVE\_Rating1 = 9.4$ (b) *Deceleration in TOF-Approach- Manoeuvre 2* $DRIVE\_Rating1 = 6.0$



(c) *Deceleration in TOF-Approach- Manoeuvre 3* $DRIVE\_Rating1 = 7.5$



(d) *Deceleration in TOF-Approach- Manoeuvre 4* $DRIVE\_Rating1 = 6.5$

Figure 86: *TOF-Approach Low Speed: Minimum Acceleration Comparison*

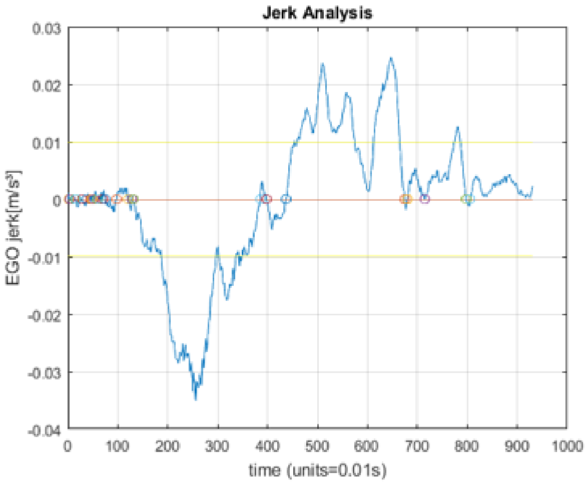
In the caption of the single figures, it is also inserted the rating that the code produced. The first calibration has the highest rate, since the minimum acceleration is quite similar, according to the analysis before discussed.

5.1.2 Criterion 2: Jerk Evaluation

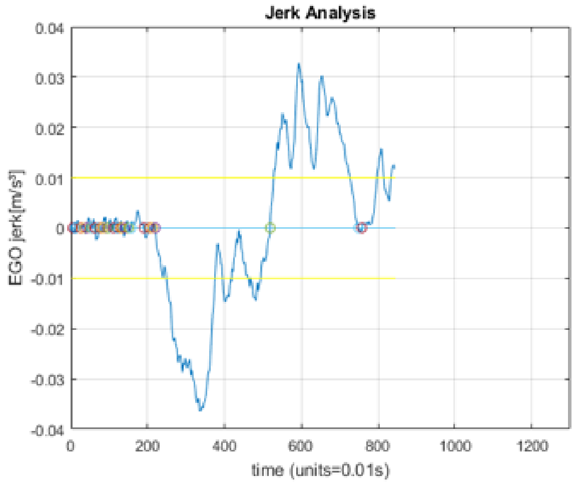
The second criteria were divided into two sections as discussed in Paragraph 4.1.2: Smoothness and Gradient analysis. In the following section, they are evaluated separately.

2 Jerk: Smoothness Analysis

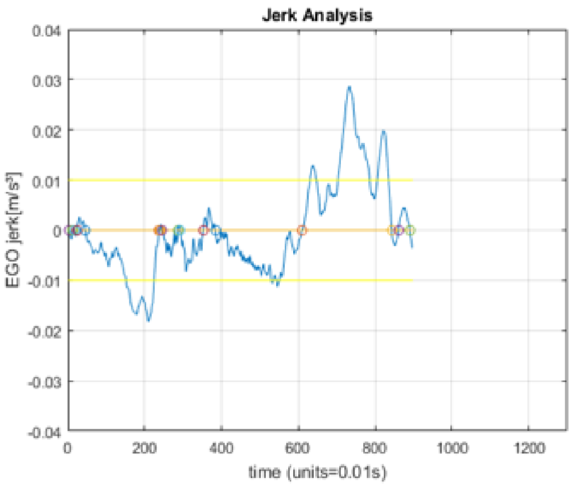
In the following images (Figure 87), the jerk of the four different calibrations is presented. The analysis aims to study how often the jerk changes its positivity.



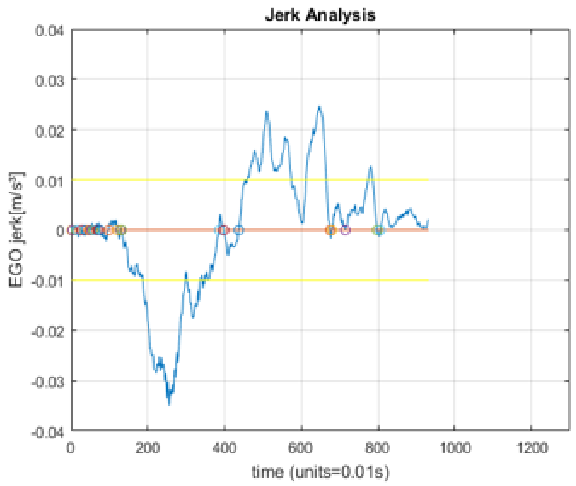
(a) *Smoothness Analysis (jerk)- Manoeuvre 1* $DRIVE\_Rating2 = 6.7$



(b) *Smoothness Analysis (jerk)- Manoeuvre 2* $DRIVE\_Rating2 = 9.9$



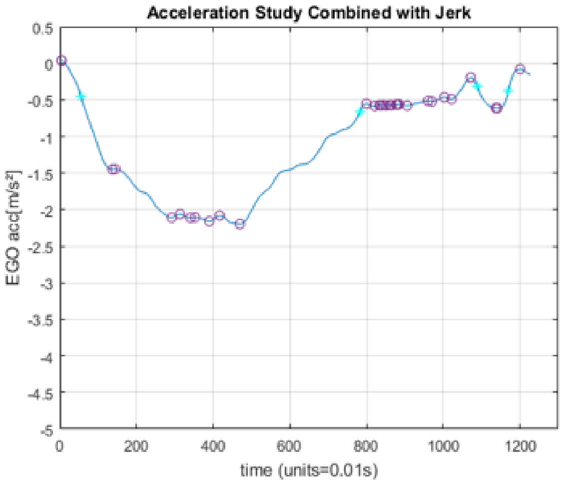
(c) *Smoothness Analysis (jerk)- Manoeuvre 3* $DRIVE\_Rating2 = 9.7$



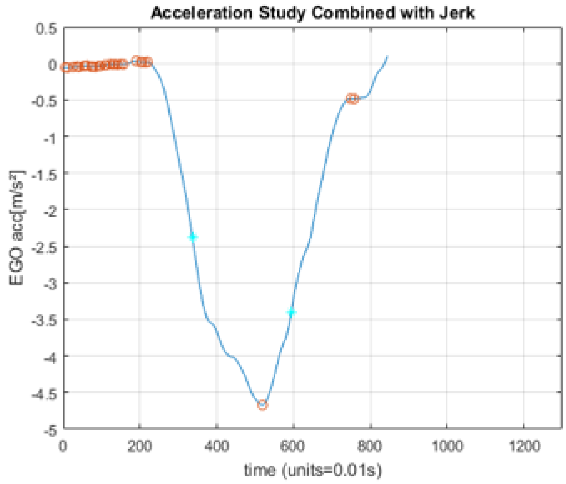
(d) *Smoothness Analysis (jerk)- Manoeuvre 4* $DRIVE\_Rating2 = 10$

Figure 87: *Smoothness - Jerk Comparison: TOF-Approach Low Speed*

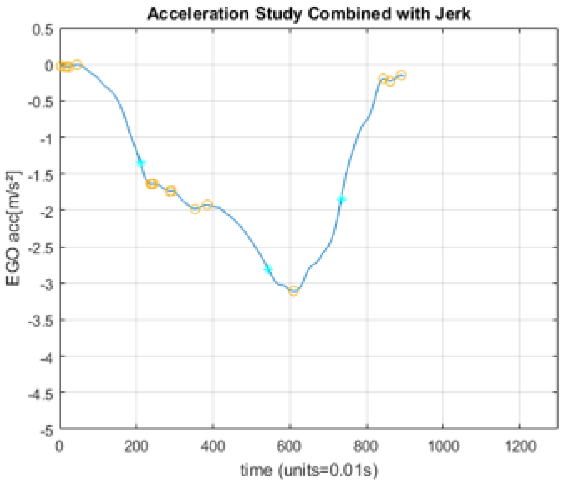
In the previous Chapter, it was explained how the jerk and the acceleration are connected, for this reason the following Figure (Figure 88) is introduced to get an idea of the weak points that affect the rate.



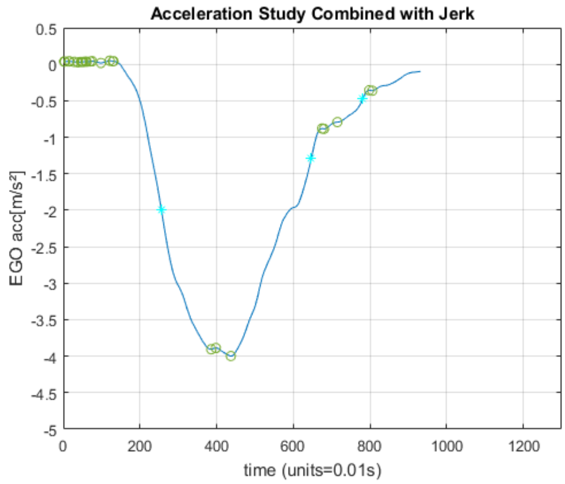
(a) *Smoothness Analysis (acceleration)- Manoeuvre 1*
$DRIVE\_Rating2 = 6.7$



(b) *Smoothness Analysis (acceleration)- Manoeuvre 2*
$DRIVE\_Rating2 = 9.9$



(c) *Smoothness Analysis (acceleration)- Manoeuvre 3*
$DRIVE\_Rating2 = 9.7$



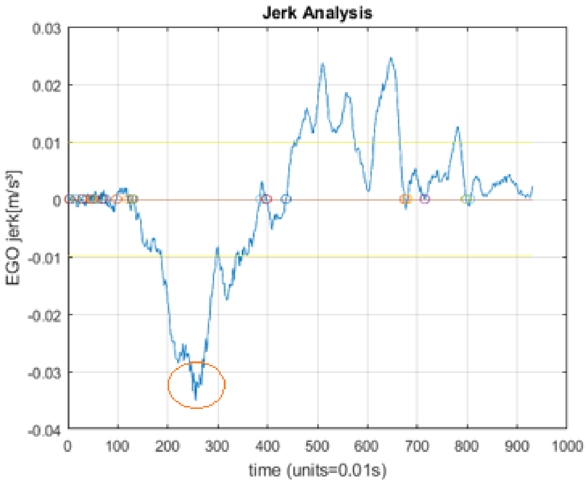
(d) *Smoothness Analysis (acceleration)- Manoeuvre 4*
$DRIVE\_Rating2 = 10$

Figure 88: *Smoothness - Acceleration Comparison: TOF-Approach Low Speed*

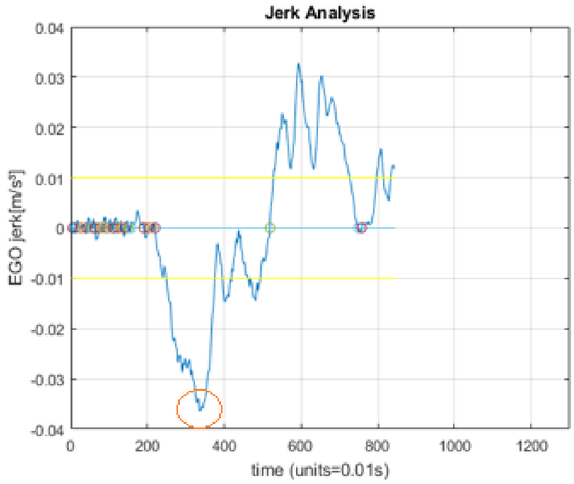
The only acceleration which presents sharp bumps is the first one; this justifies the lowest rating (6.7). The bumps are that kind of hills in the end part of the deceleration (a).

2a Jerk: Gradient Analysis

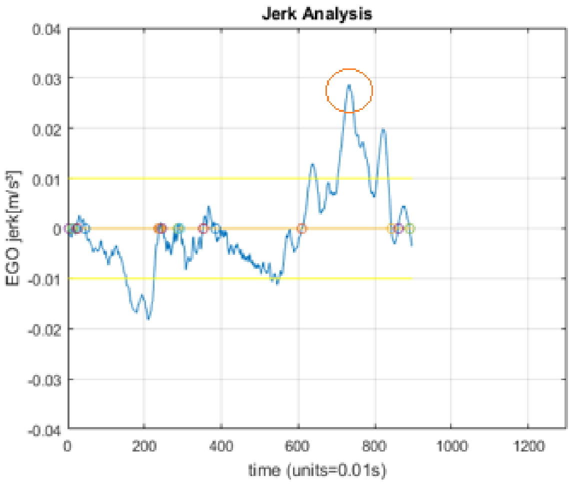
The study involves the highest achieved gradient in absolute terms. In image 89, the interested points are circled and the evaluation gives a rating to the four manoeuvres in terms of gradient analysis:



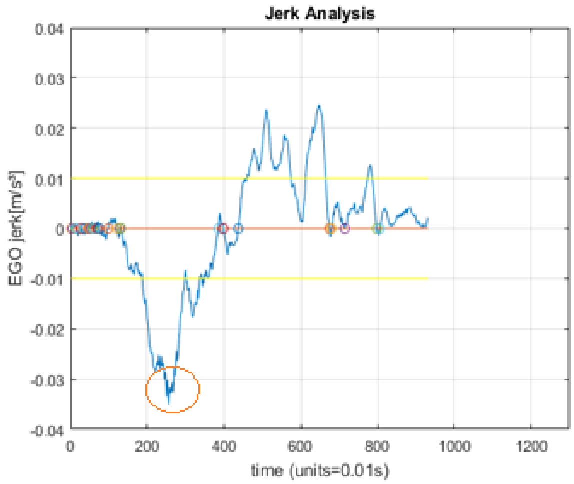
(a) *Gradient Analysis (jerk)- Manoeuvre 1*
$DRIVE\_Rating2a = 9.2$



(b) *Gradient Analysis (jerk)- Manoeuvre 2*
$DRIVE\_Rating2a = 8.7$



(c) *Gradient Analysis (jerk)- Manoeuvre 3*
$DRIVE\_Rating2a = 9.0$



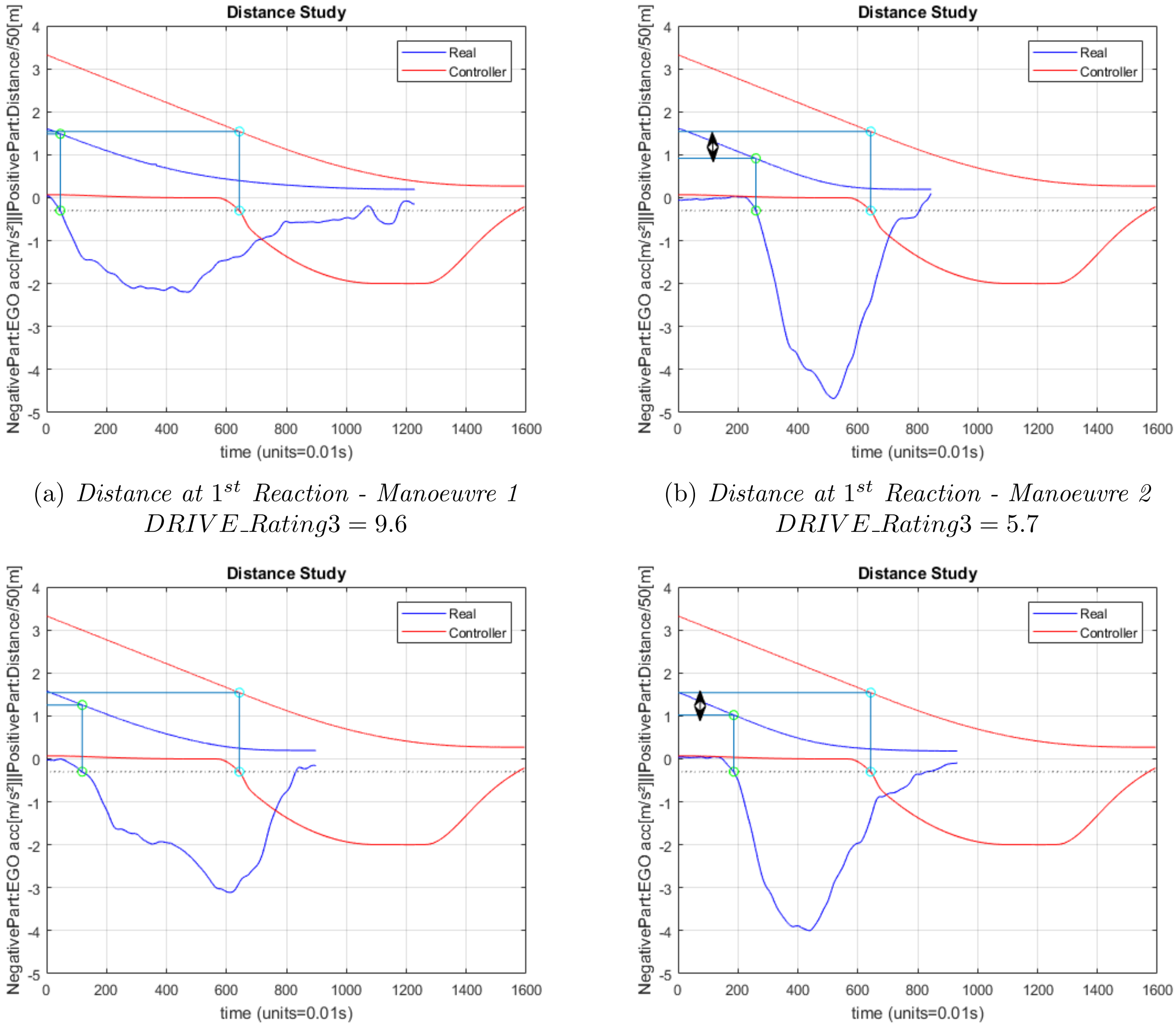
(d) *Gradient Analysis (jerk)- Manoeuvre 4*
$DRIVE\_Rating2a = 8.8$

Figure 89: *Gradient - Jerk Comparison: TOF-Approach Low Speed*

As it is evident in Figure 89, the weak points have quite the same jerk, that is the reason why the results are closed.
The reader could also have another look to the Figure 88 to have the meaning of what circled jerk values mean in terms of gradient analysis. As it was also mentioned in the paragrapher 4.1.2, it defines the roughness of the manoeuvre.

5.1.3 Criterion 3: Distance Study from TOF at first reaction

The third criterion aimed the study and the evaluation of the distance when the vehicle reacts, starting its manoeuvre.
The reader should take care about the used scale for the distance evaluation, it is divided by 50 in order to get a compact image, and also he/she should remember that the evaluation is relative to the distance although the attention has to be put to the y-axis.
The following plot (Figure 90) shows the evaluation of the distance study:



(a) *Distance at* 1^{st} *Reaction - Manoeuvre 1* $DRIVE\_Rating3 = 9.6$

(b) *Distance at* 1^{st} *Reaction - Manoeuvre 2* $DRIVE\_Rating3 = 5.7$

(c) *Distance at* 1^{st} *Reaction - Manoeuvre 3* $DRIVE\_Rating3 = 8.0$

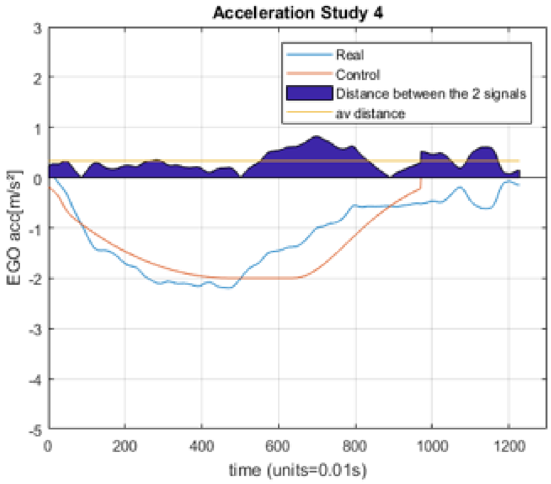
(d) *Distance at* 1^{st} *Reaction - Manoeuvre 4* $DRIVE\_Rating3 = 6.2$

Figure 90: *Gradient - Jerk Comparison: TOF-Approach Low Speed*

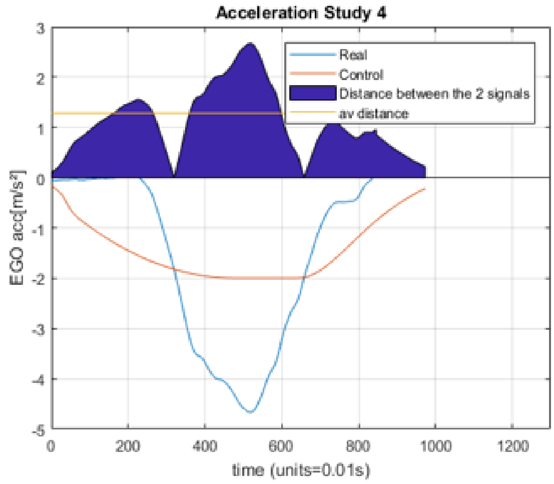
The first manoeuvre is the best one and it is quite clear from the image, looking to it the controller, and the real vehicle approximately react at the same distance; while it is also evident the worst case is case(b), the second manoeuvre, since the real vehicle reacts too late, at a distance of around $25[m]$.

5.1.4 Criterion 4: Acceleration Shape Comparison

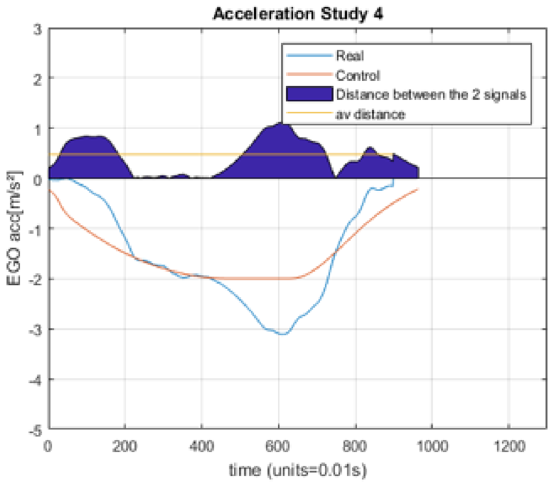
The following study presents the differences in the acceleration shapes between the virtual environment and the real one.
In Figure (Figure 91), the four manoeuvres with the relative rating are plotted.



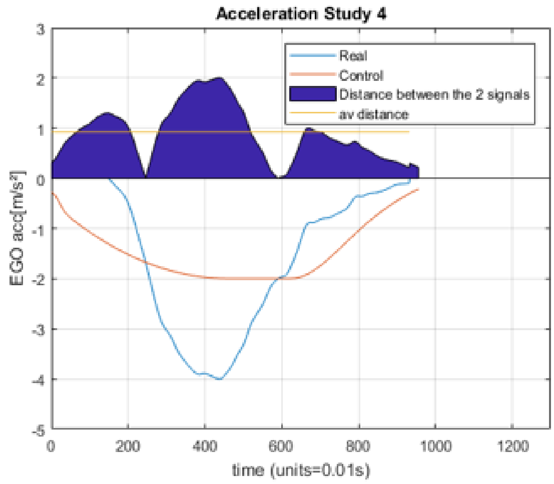
(a) *Acceleration Shape Evaluation - Manoeuvre 1* $DRIVE\_Rating4 = 8.8$



(b) *Acceleration Shape Evaluation - Manoeuvre 2* $DRIVE\_Rating4 = 5.5$



(c) *Acceleration Shape Evaluation - Manoeuvre 3* $DRIVE\_Rating4 = 8.3$



(d) *Acceleration Shape Evaluation - Manoeuvre 4* $DRIVE\_Rating4 = 6.8$

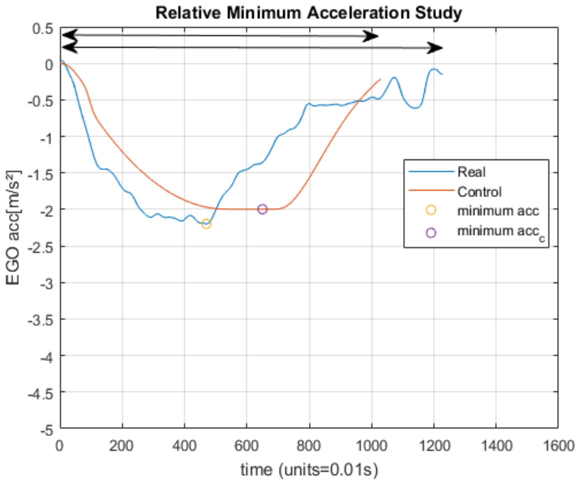
Figure 91: *Acceleration Shape Comparison: TOF-Approach Low Speed*

5.1.5 Criterion 5: Position of the Minimum Acceleration

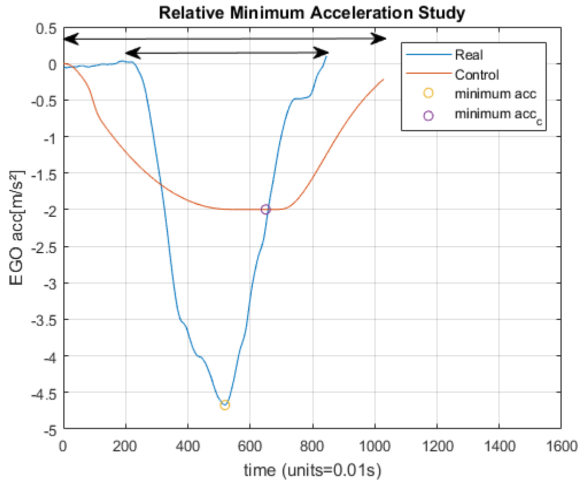
In the previous chapter (Paragraph 4.1.5), it is explained why the study is divided into two parts: relative and absolute position of the minimum acceleration.
However, it might be useful to recapitulate the distinction: the relative position study wants to highlight where the minimum acceleration occurs in the overall manoeuvre, if it is more close to the begin, middle or end part of the acceleration and make a comparison with the controller; the absolute position study defines the position of the minimum acceleration considering the distance from TOF.

Relative Position of the Minimum Acceleration

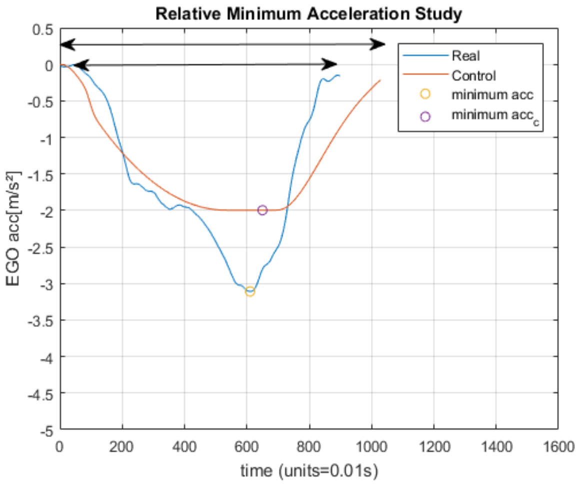
The relative position evaluation is shown in Figure 92:



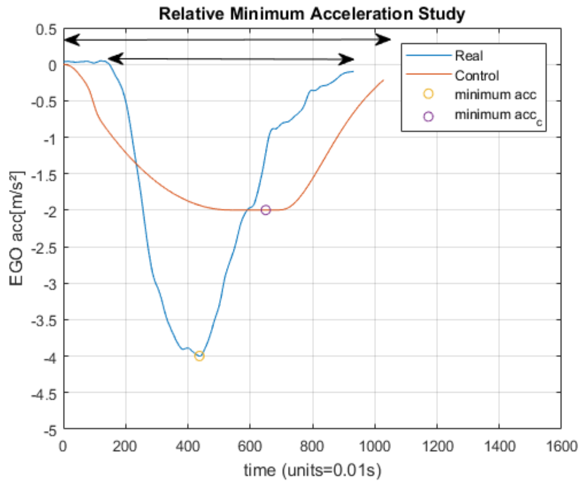
(a) *Relative Position of the Acc_{min} - Manoeuvre 1* $DRIVE\_Rating5 = 9.3$



(b) *Relative Position of the Acc_{min} - Manoeuvre 2* $DRIVE\_Rating5 = 9.5$



(c) *Relative Position of the Acc_{min} - Manoeuvre 3* $DRIVE\_Rating5 = 9.8$



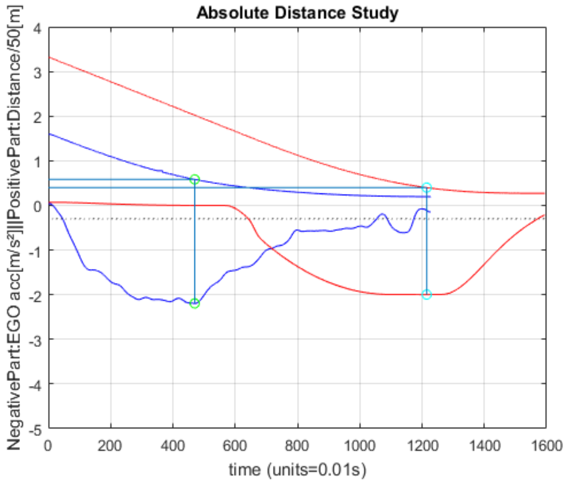
(d) *Relative Position of the Acc_{min} - Manoeuvre 4* $DRIVE\_Rating5 = 9.0$

Figure 92: *Relative Position of the Minimum Acceleration Analysis: TOF-Approach Low Speed*

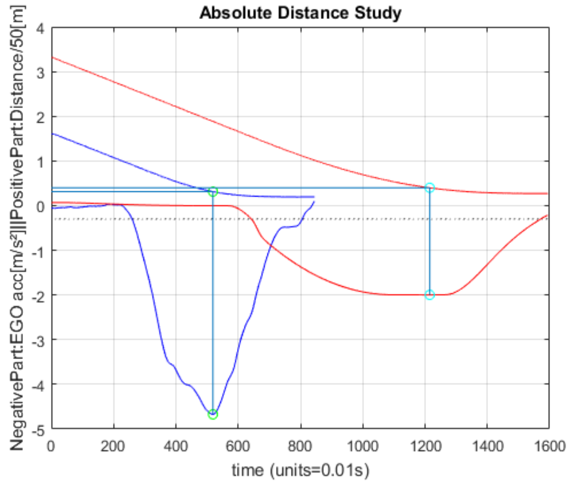
All the calibrations have a rating quite high because all of them have the minimum acceleration positioned in the nearby of the middle part of the deceleration curve.

Absolute Position of the Minimum Acceleration

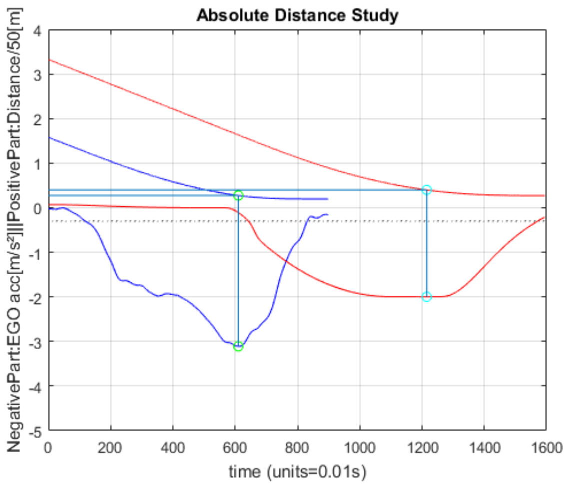
In the following Figure (Figure 93), the absolute position evaluation of the minimum acceleration is presented.
It is reminded to the reader the images are divided into two parts: in the positive part there is the distance of Ego from TOF scaled of 50 to give a more accessible view, while in the negative part the acceleration is represented.



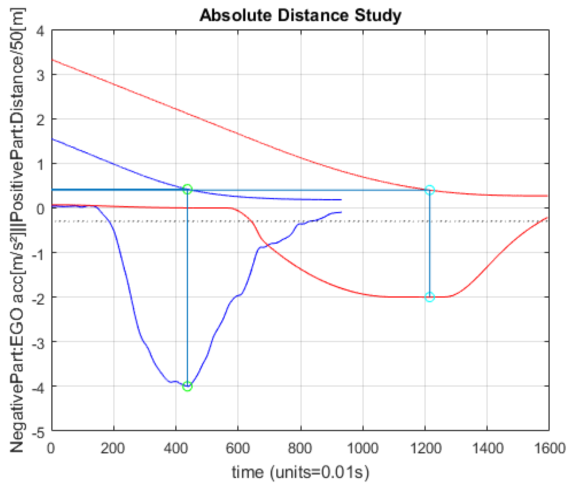
(a) *Absolute Position of the* Acc_{min} *- Manoeuvre 1* $DRIVE\_Rating5a = 9.2$



(b) *Absolute Position of the* Acc_{min} *- Manoeuvre 2* $DRIVE\_Rating5a = 7.9$



(c) *Absolute Position of the* Acc_{min} *- Manoeuvre 3* $DRIVE\_Rating5a = 6.9$



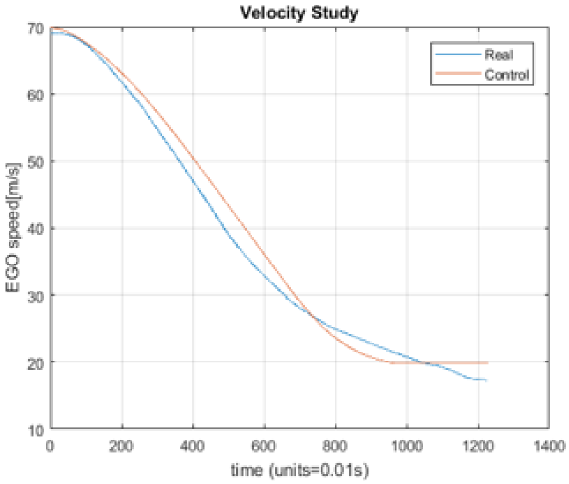
(d) *Absolute Position of the* Acc_{min} *- Manoeuvre 4* $DRIVE\_Rating5a = 10$

Figure 93: *Absolute Position of the Minimum Acceleration Analysis: TOF-Approach Low Speed*

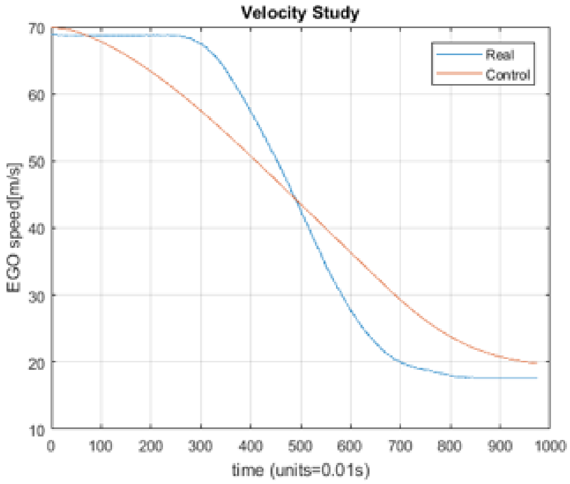
From the results, it is evident that the 4^{th} manoeuvre has the same starting deceleration distance of the compared computerized manoeuvre.

5.1.6 Criterion 6: End-Velocity Analysis

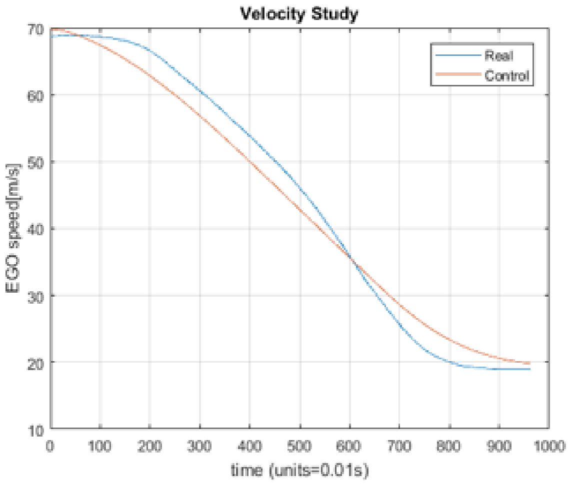
The following section studies the end part of the velocity shape signal during a manoeuvre, studying the presence of wanted and unwanted overshoots.
In Figure 94, the four manoeuvres are represented and rated:



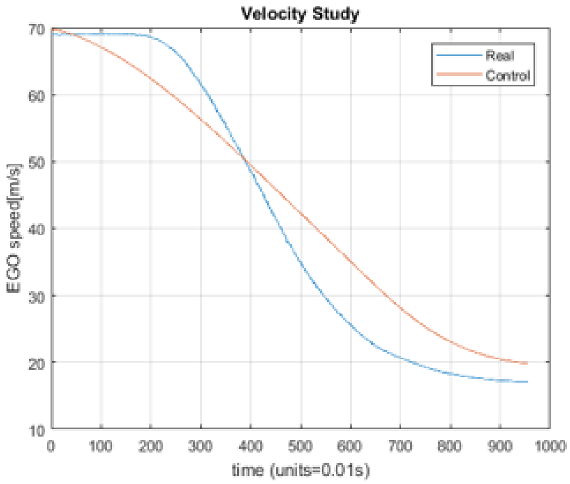
(a) *End-Velocity Analysis - Manoeuvre 1*
$DRIVE\_Rating6 = 10$



(b) *End-Velocity Analysis - Manoeuvre 2*
$DRIVE\_Rating6 = 10$



(c) *End-Velocity Analysis - Manoeuvre 3*
$DRIVE\_Rating6 = 10$

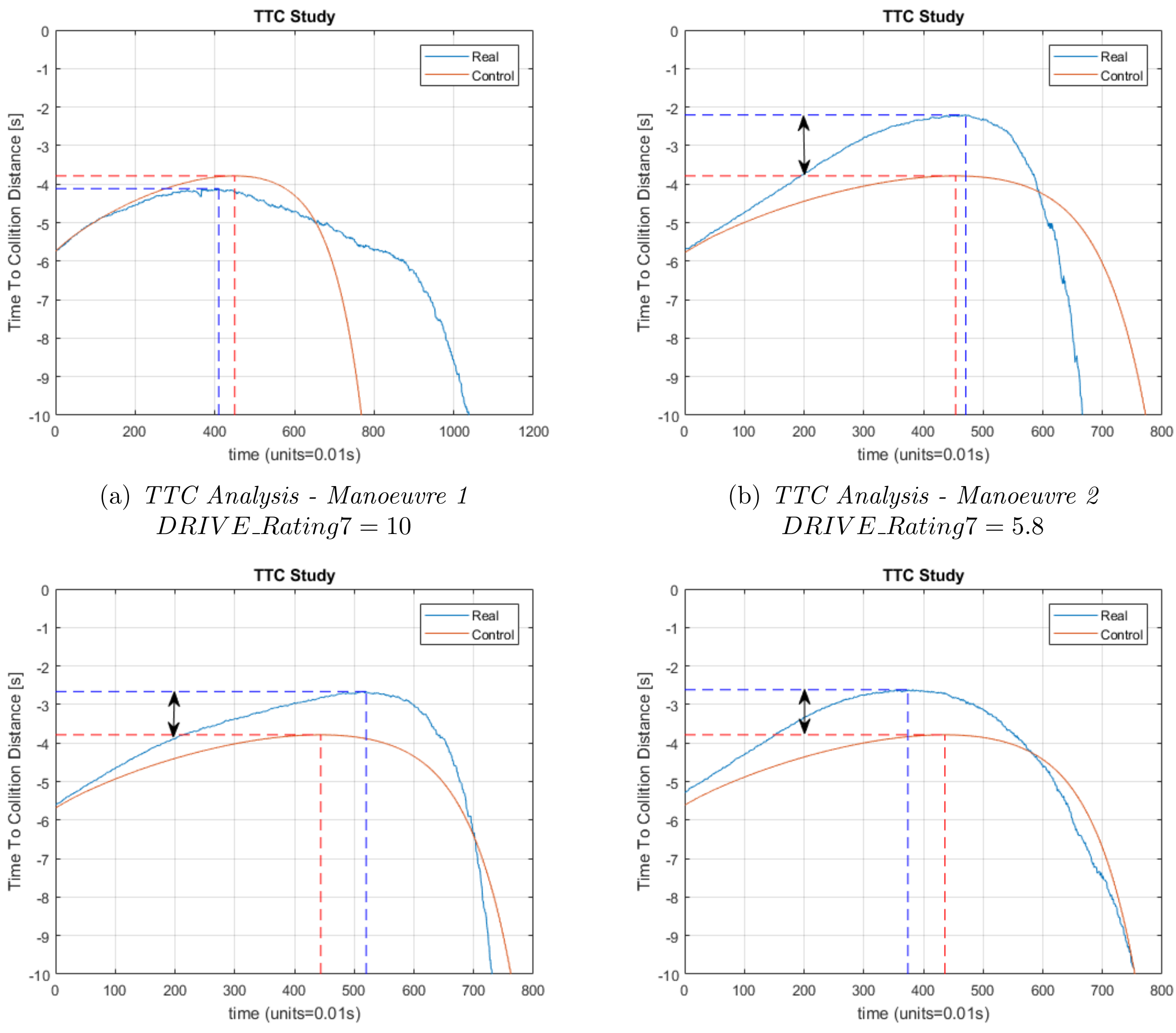


(d) *End-Velocity Analysis - Manoeuvre 4*
$DRIVE\_Rating6 = 10$

Figure 94: *End-Velocity Analysis: TOF-Approach Low Speed*

5.1.7 Criterion 7: Time To Collision Analysis

In the following section, the attention is given to the safety perception that an occupant has inside the vehicle.
The Figure 95 highlights the TTC of the four studied calibrations:



(a) *TTC Analysis - Manoeuvre 1* $DRIVE\_Rating7 = 10$

(b) *TTC Analysis - Manoeuvre 2* $DRIVE\_Rating7 = 5.8$

(c) *TTC Analysis - Manoeuvre 3* $DRIVE\_Rating7 = 7.0$

(d) *TTC Analysis - Manoeuvre 4* $DRIVE\_Rating7 = 6.9$

Figure 95: *Time To Collision Analysis: TOF-Approach Low Speed*

The 2^{nd} manoeuvre has the highest time to collision, and since it is close to $-2[s]$, it could be not only unwanted but also dangerous and this is the reason of a negative rating.

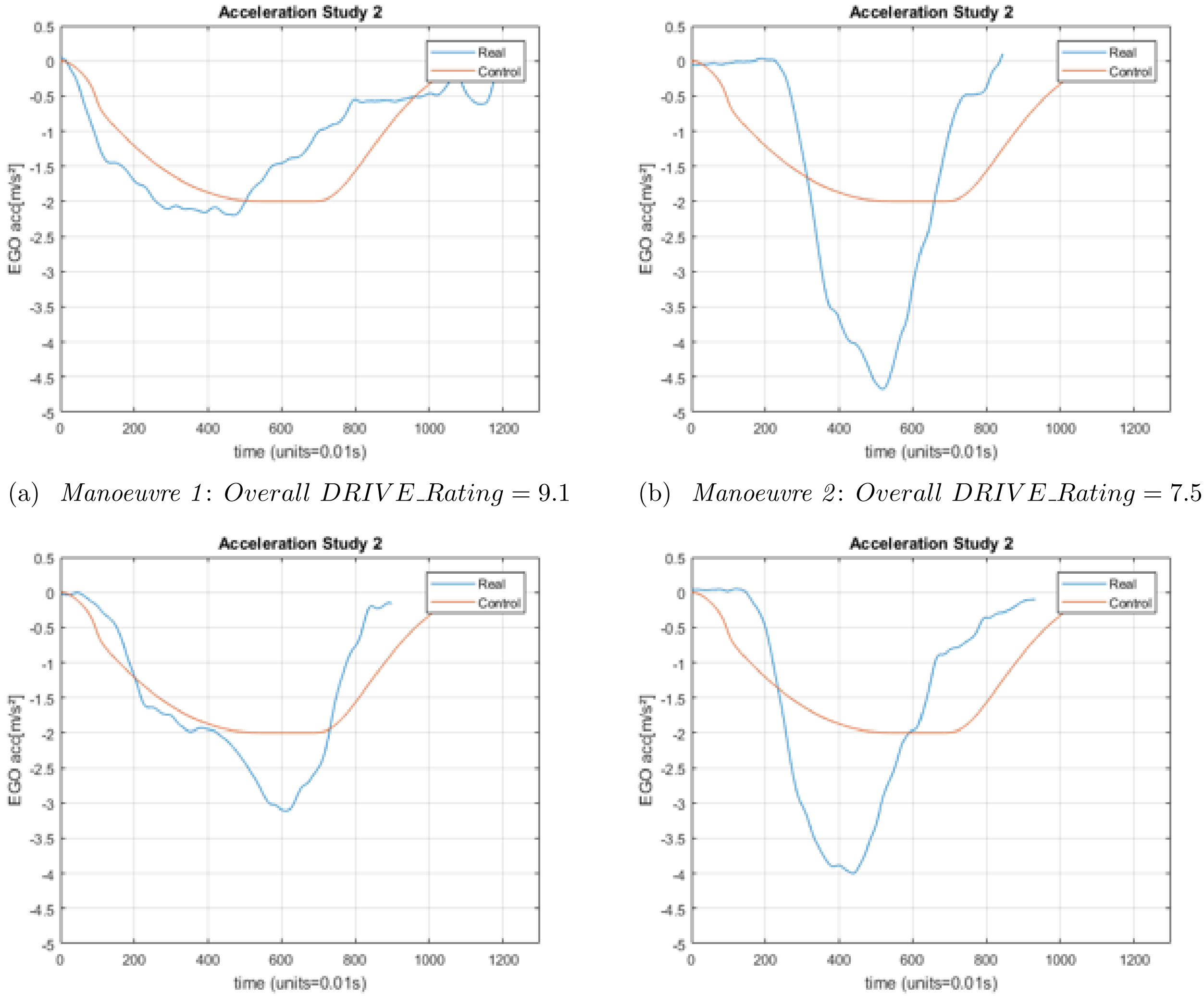
5.1.8 Overall Rating

Till now, all the criteria are observed and rated for all the four manoeuvres.
The general idea involves the choice of a third person, as a car-maker, to decide the important of the single criterion.
The adopted proposal in this work is:

$$COMFORT = \frac{3Rate(1) + 4Rate(2) + 4Rate(2a) + 1Rate(4) + 1Rate(6)}{13} \tag{94}$$

$$SAFETY = \frac{5Rate(3) + 3Rate(5) + 3Rate(5a) + 5Rate(7)}{16} \tag{95}$$

The overall rating is shown in this section, in the following image (Figure 96):



(a) *Manoeuvre 1: Overall DRIVE_Rating* = 9.1
(b) *Manoeuvre 2: Overall DRIVE_Rating* = 7.5
(c) *Manoeuvre 3: Overall DRIVE_Rating* = 8.3
(d) *Manoeuvre 4: Overall DRIVE_Rating* = 8.1

Figure 96: *Overall Rate: TOF-Approach Low Speed*

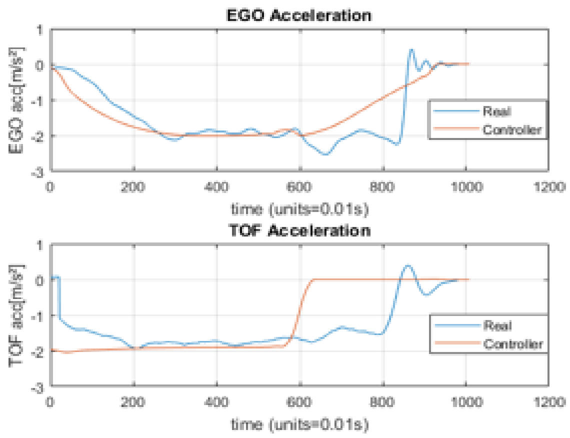
According to the chosen shape of the TOF-Approach Manoeuvre in the virtual environment, it is evident that the first manoeuvre is more similar to it and it has the highest result (9.1), while the second one makes the most different manoeuvre with a score of 7.5.

5.2 TOF-Approach: High Speed

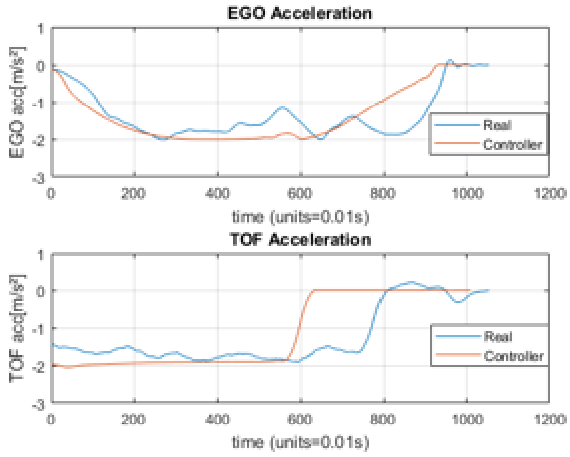
Thanks to the benchmark made in AVL, there were other data related to the TOF-Approach manoeuvre made at high speed (150[km/h] to 80[km/h]). In Appendix A, the TOF-Approach manoeuvre is attached to verify the efficiency and the validity of the new developed methodology.

5.3 Follow Vehicle Stop

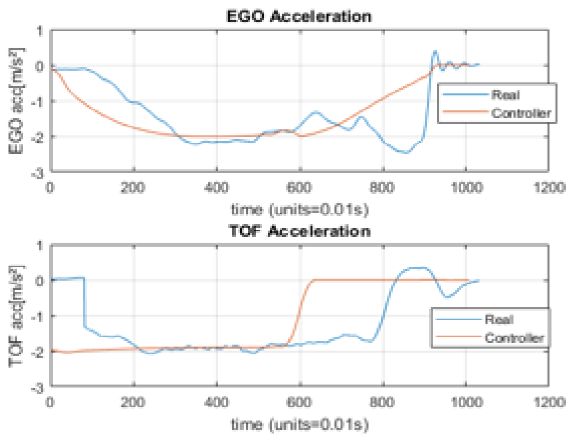
In this section, four different follow vehicle stop calibrations presented in Figure 97 are rated. The different criteria are developed and commented as shown in Paragraph 4.2.



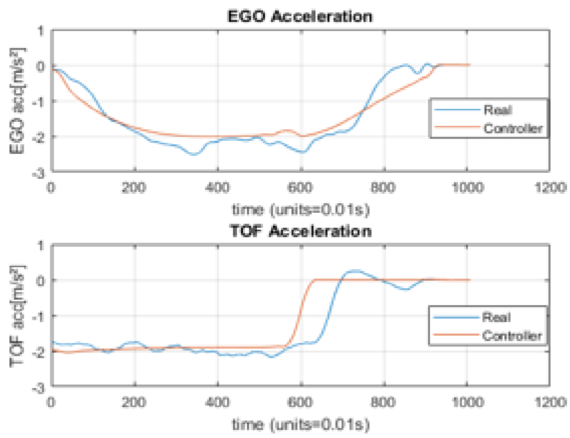
(a) *Follow Vehicle Stop - Manoeuvre 1*



(b) *Follow Vehicle Stop - Manoeuvre 2*



(c) *Follow Vehicle Stop - Manoeuvre 3*

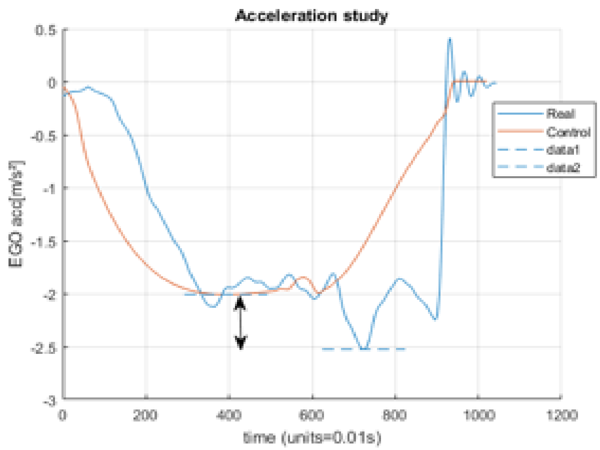


(d) *Follow Vehicle Stop - Manoeuvre 4*

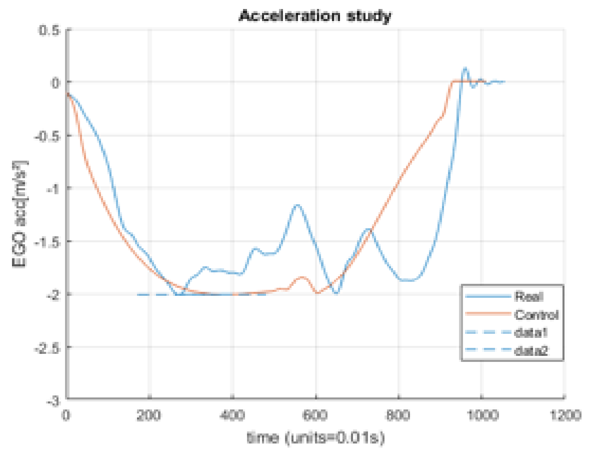
Figure 97: *Follow Vehicle Stop: Four different calibrations*

5.3.1 Criterion 1: Minimum Acceleration

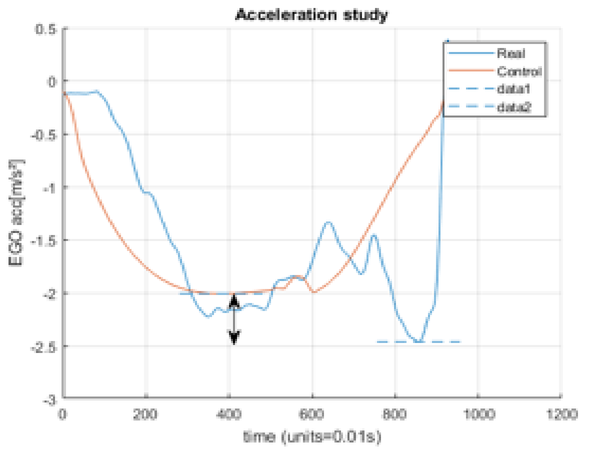
The following Figure (Figure 98) shows the minimum acceleration criterion of the follow vehicle stop manoeuvre.



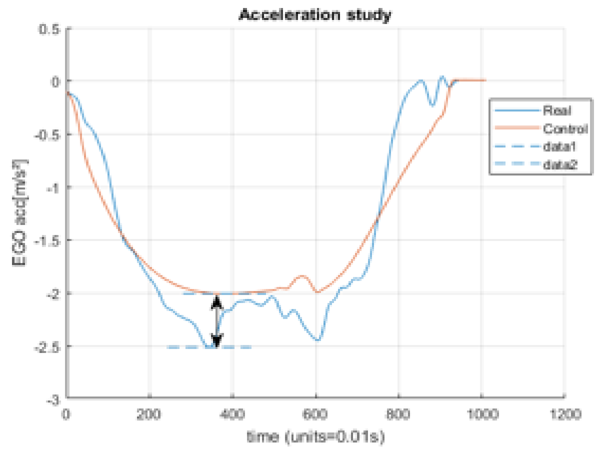
(a) *Acceleration Follow Vehicle Stop - Manoeuvre 1* $DRIVE\_Rating1 = 8.6$



(b) *Acceleration Follow Vehicle Stop - Manoeuvre 2* $DRIVE\_Rating1 = 10$



(c) *Acceleration Follow Vehicle Stop - Manoeuvre 3* $DRIVE\_Rating1 = 8.7$



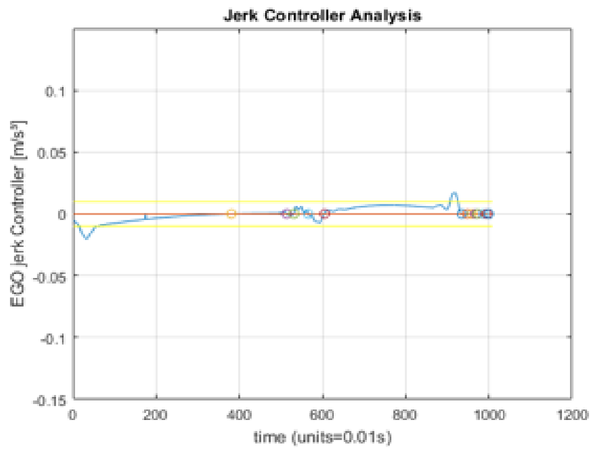
(d) *Acceleration Follow Vehicle Stop - Manoeuvre 4* $DRIVE\_Rating1 = 8.6$

Figure 98: *Minimum Acceleration Comparison: Acceleration Follow Vehicle Stop*

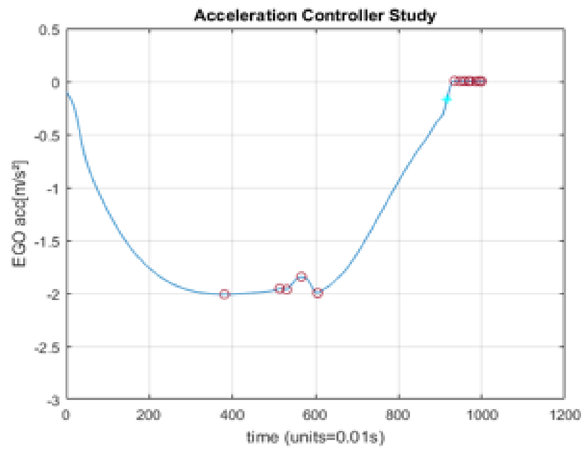
The second manoeuvre has a rating equal to 10 since the minimum achieved acceleration is equal to the one computed by the controller.

5.3.2 Criterion 2: Jerk Evaluation

In this section, the jerk evaluation is computed taking care about the distinction between Smoothness and Gradient evaluation, explained above in Paragraph 4.2.2 .
The entire analysis is made referring to the controller's one, in the Figure 99 jerk and acceleration with the weak points are shown.



(a) *Jerk Follow Vehicle Stop - controller*

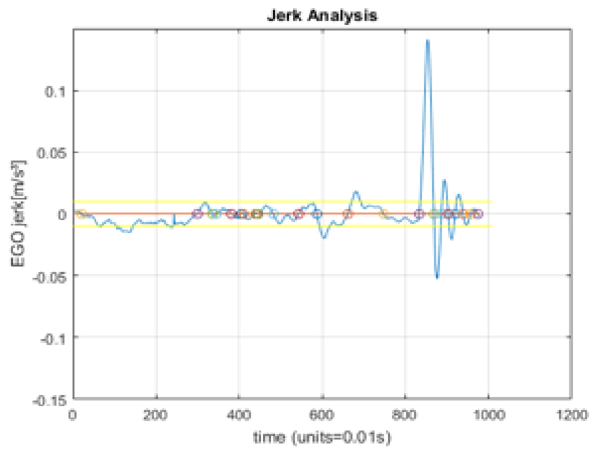


(b) *Acceleration(jerk) Follow Vehicle Stop - controller*

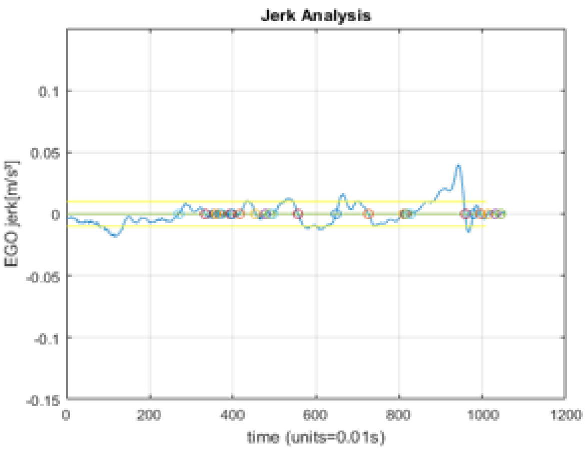
Figure 99: *controller Jerk Evaluation: Follow Vehicle Stop*

2 Jerk Evaluation: Smoothness Analysis

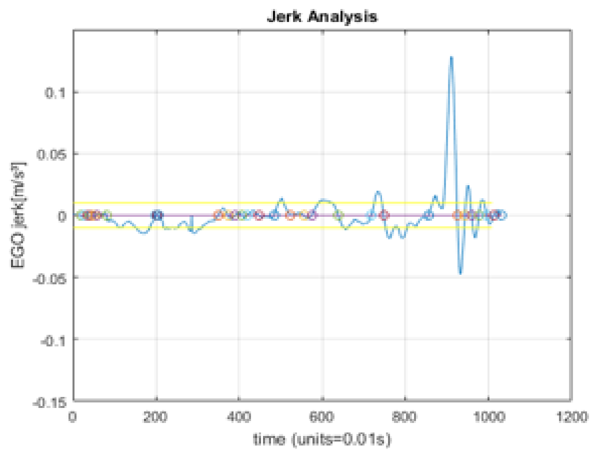
In the following figure(Figure 100) the Jerk Smoothness analysis is presented:



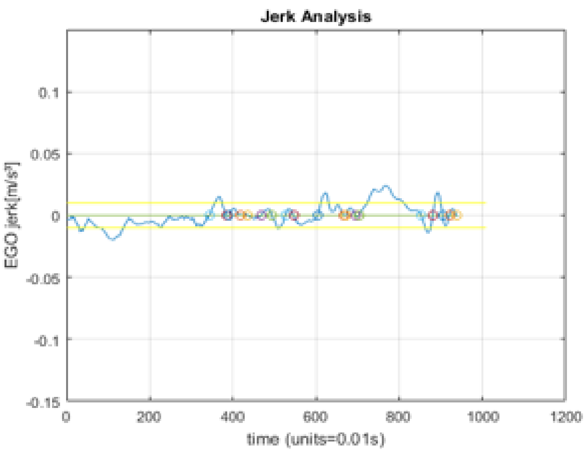
(a) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 1* $DRIVE\_Rating2 = 5.1$



(b) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 2* $DRIVE\_Rating2 = 5.3$



(c) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 3* $DRIVE\_Rating2 = 5.1$

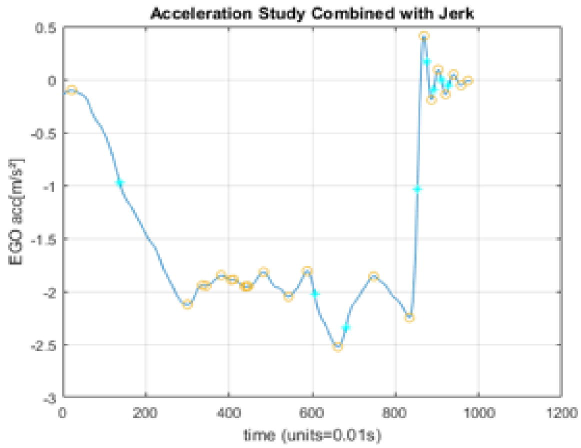


(d) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 4* $DRIVE\_Rating2 = 5.3$

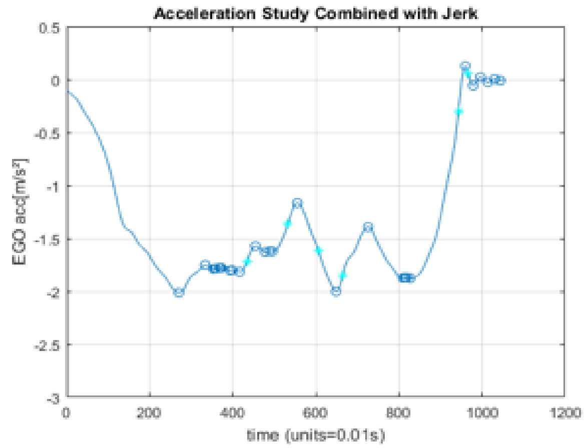
Figure 100: *Smoothness - Jerk Comparison: Follow Vehicle Stop*

Observing the controller, it behaves in a smooth way with a low jerk, that is the reason why, making a comparison among the manoeuvres and the controller, the results are negative.

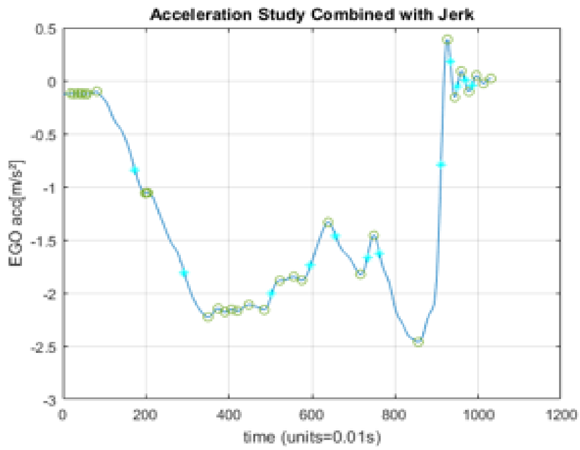
To better have a clear overview, in Figure 101 the acceleration with the weak points of the manoeuvres are presented.



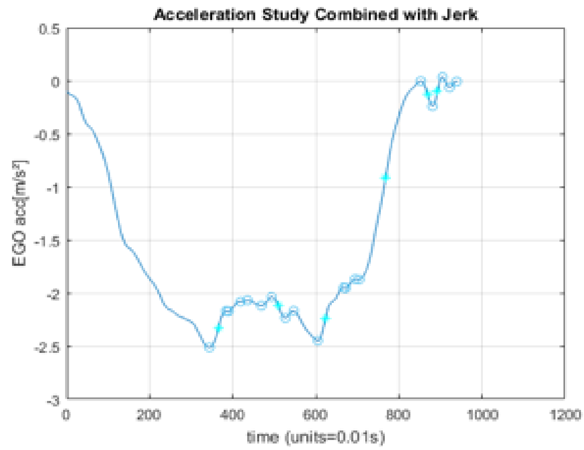
(a) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 1* $DRIVE\_Rating2 = 5.1$



(b) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 2* $DRIVE\_Rating2 = 5.3$



(c) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 3* $DRIVE\_Rating2 = 5.1$



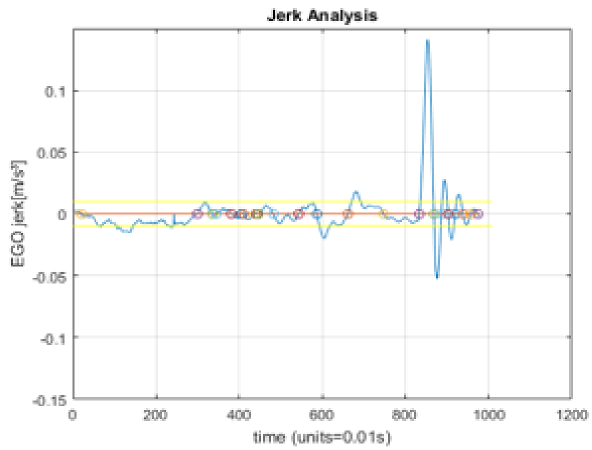
(d) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 4* $DRIVE\_Rating2 = 5.3$

Figure 101: *Smoothness - Acceleration Comparison: Acceleration Follow Vehicle Stop*

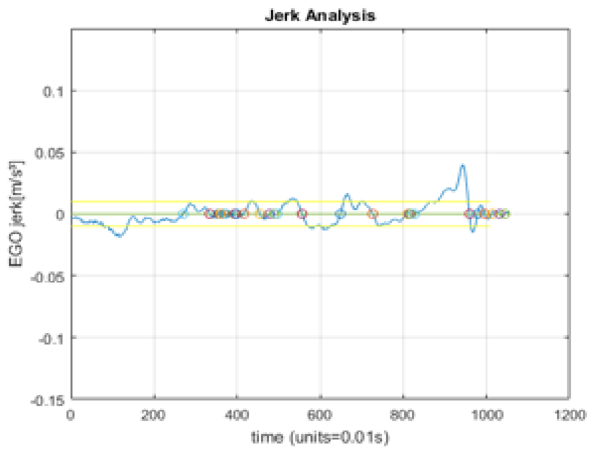
Figure 101 highlights the weak points, with high jerk, of the acceleration during the manoeuvre. It is also evident that the presented manoeuvres are not smoothie according with the obtained results.

2a Jerk: Gradient Analysis

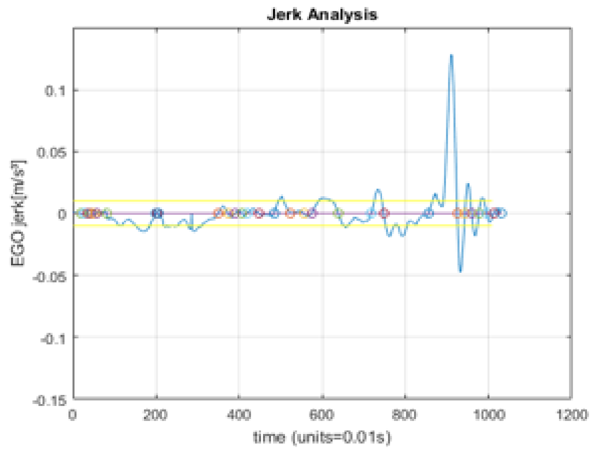
The gradient analysis aims the analysis of the presence of strong deceleration/acceleration in a manoeuvre.
In the following figure(Figure 102) the Jerk Gradient analysis is evaluated:



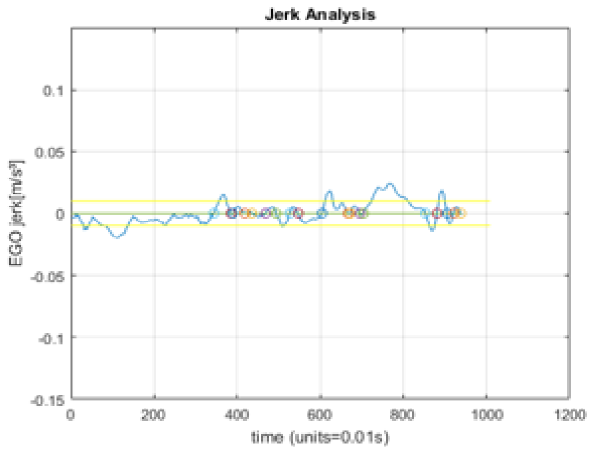
(a) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 1* $DRIVE\_Rating2a = 5.1$



(b) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 2* $DRIVE\_Rating2a = 9.3$



(c) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 3* $DRIVE\_Rating2a = 5.9$



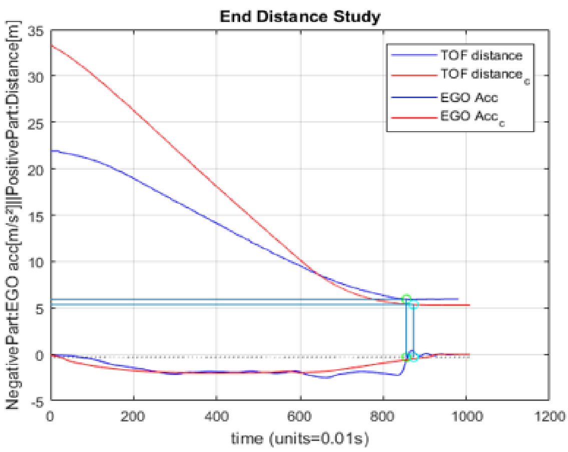
(d) *Jerk Evaluation Follow Vehicle Stop - Manoeuvre 4* $DRIVE\_Rating2a = 9.9$

Figure 102: *Gradient - Jerk Comparison: Follow Vehicle Stop*

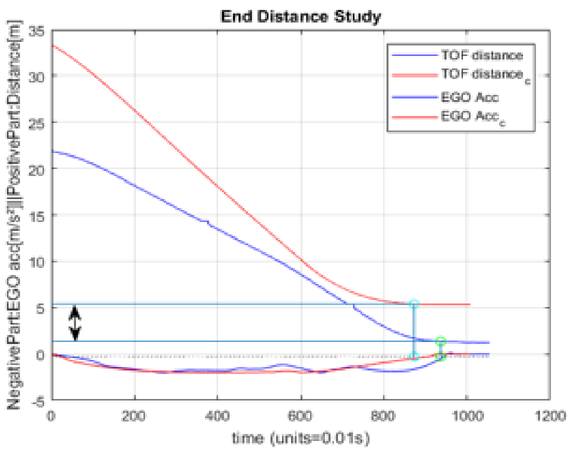
It is clear that in the fourth manoeuvre the jerk is not strong as in the previous ones. It allows to get a better rating.
The observation of Figure 101 could help the understanding of the presence of strong gradients.

5.3.3 Criterion 3: End-Distance Analysis

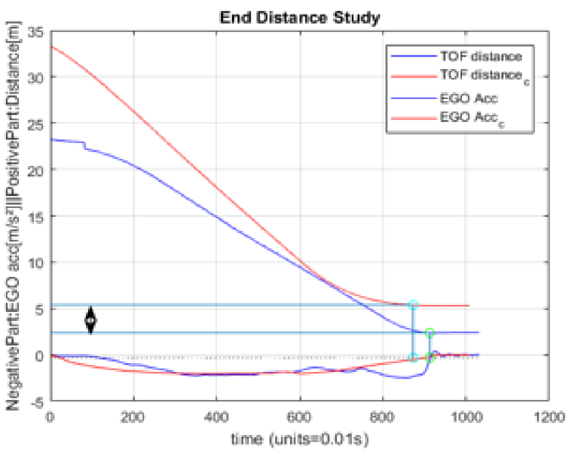
In the follow vehicle stop, the end distance is one of the most important aspect to determine if the manoeuvre is well computed. The Figure 103 shows the comparison between the end-distance achieved by the controller and by the benchmark manoeuvres.



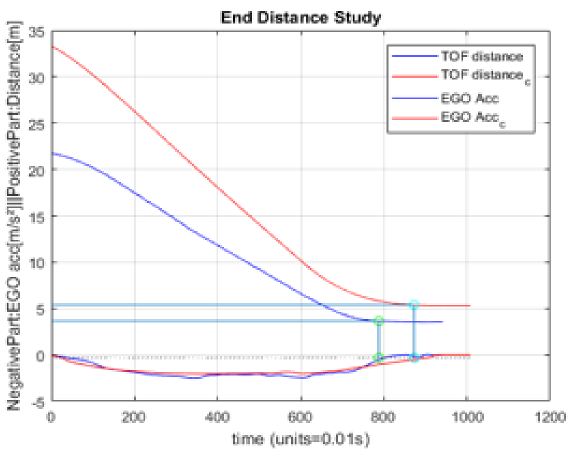
(a) *End-Distance Follow Vehicle Stop - Manoeuvre 1* $DRIVE\_Rating3 = 9.3$



(b) *End-Distance Follow Vehicle Stop - Manoeuvre 2* $DRIVE\_Rating3 = 7.6$



(c) *End-Distance Follow Vehicle Stop - Manoeuvre 3* $DRIVE\_Rating3 = 8.8$



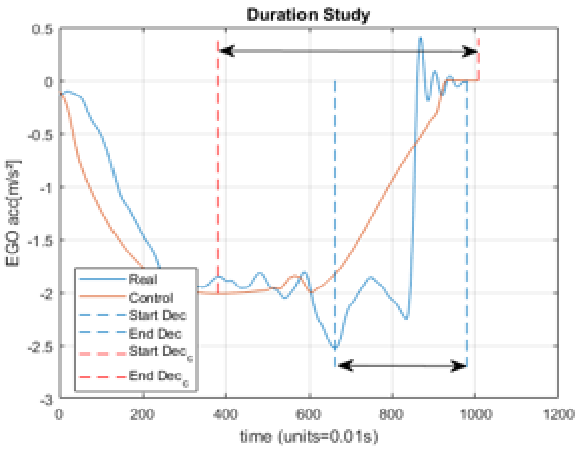
(d) *End-Distance Follow Vehicle Stop - Manoeuvre 4* $DRIVE\_Rating3 = 9.6$

Figure 103: *End-Distance Comparison: Follow Vehicle Stop*

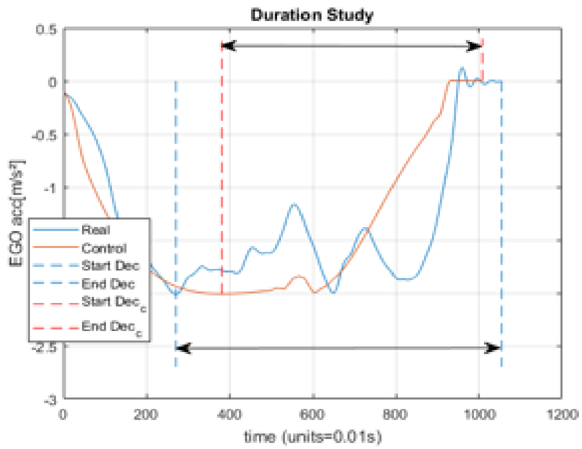
All the manoeuvres are well performed, however the reader should complain the difference between achieved a nearer or a farther distance from TOF, since the first situation could be more dramatical. In that case, the manoeuvre is judged in a more critical way according to Paragraph 4.2.3.

5.3.4 Criterion 4: Duration Analysis

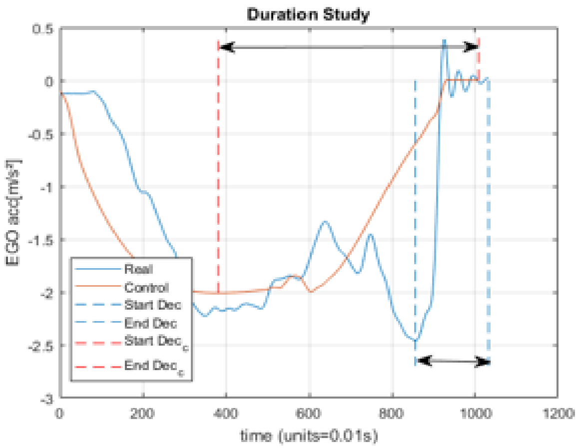
The aim of this study is the analysis of the duration of the manoeuvre from the minimum acceleration. The results are shown in Figure 104 and the presence of the narrows should help the reading of the results.



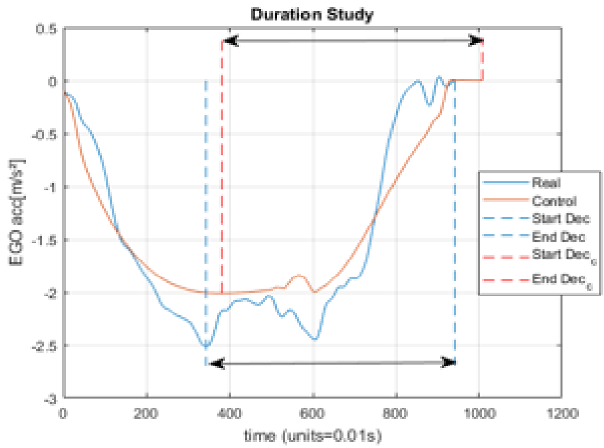
(a) *Duration Analysis Follow Vehicle Stop-Manoeuvre 1* $DRIVE\_Rating4 = 6.6$



(b) *Duration Analysis Follow Vehicle Stop-Manoeuvre 2* $DRIVE\_Rating4 = 8.6$



(c) *Duration Analysis Follow Vehicle Stop-Manoeuvre 3* $DRIVE\_Rating4 = 5.0$



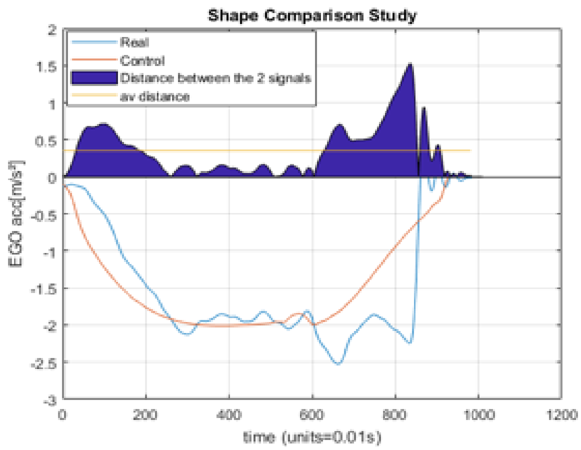
(d) *Duration Analysis Follow Vehicle Stop-Manoeuvre 4* $DRIVE\_Rating4 = 9.7$

Figure 104: *Duration Analysis Comparison: Follow Vehicle Stop*

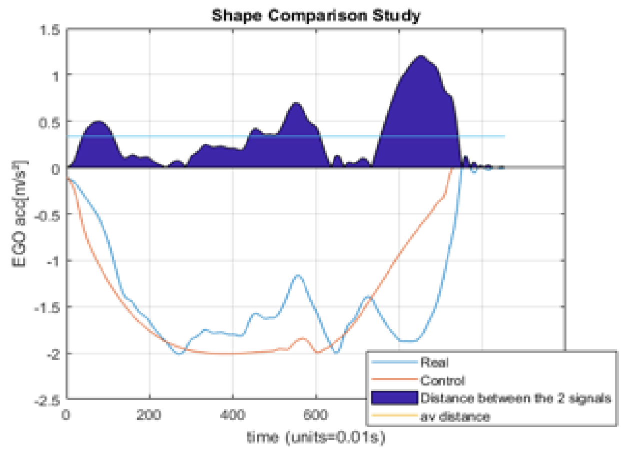
The fourth manoeuvre is the one that performed a manoeuvre closer to the controller.

5.3.5 Criterion 5: Acceleration Shape Comparison

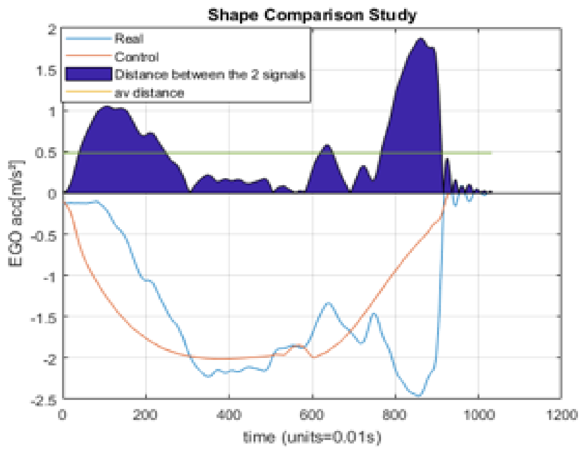
This analysis gives a rating to the different shapes of the acceleration during the manoeuvre. The four manoeuvres are rated as follows in Figure 105:



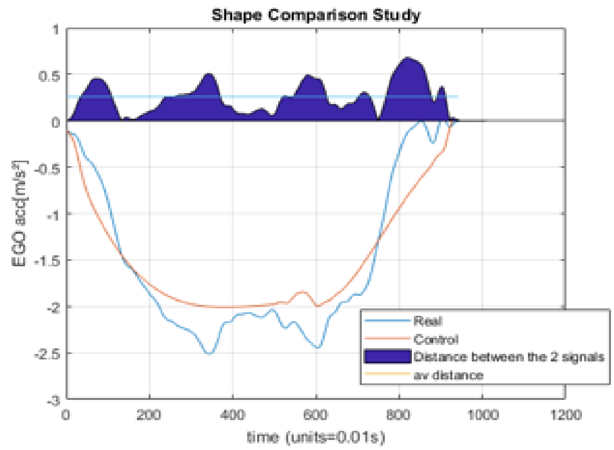
(a) *Shape Analysis Follow Vehicle Stop-Manoeuvre 1* $DRIVE\_Rating5 = 8.8$



(b) *Shape Analysis Follow Vehicle Stop-Manoeuvre 2* $DRIVE\_Rating5 = 8.8$



(c) *Shape Analysis Follow Vehicle Stop-Manoeuvre 3* $DRIVE\_Rating5 = 8.3$



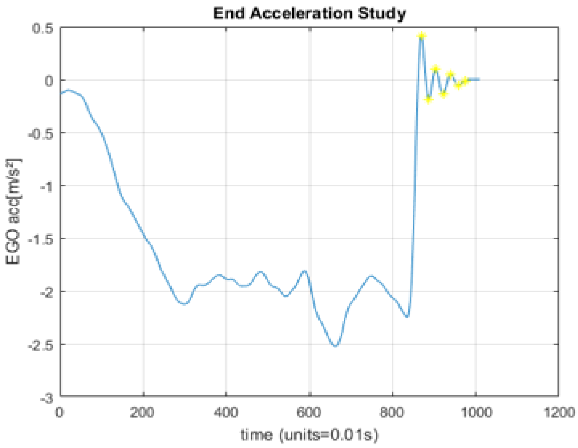
(d) *Shape Analysis Follow Vehicle Stop-Manoeuvre 4* $DRIVE\_Rating5 = 9.1$

Figure 105: *Shape Analysis Comparison: Follow Vehicle Stop*

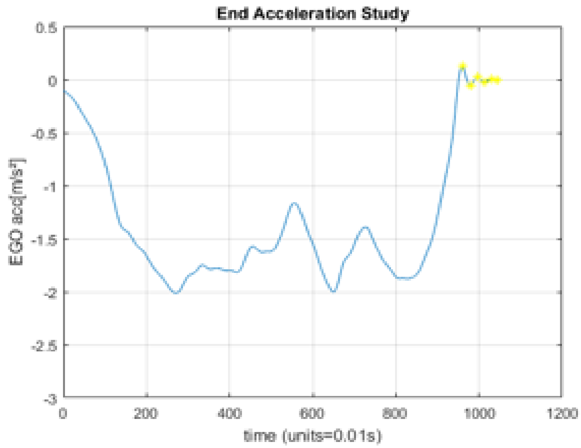
In this case, all the manoeuvres got good results, however, it is tangible that the fourth manoeuvre is quite closer to the reference one than the others. Thus, it is reasonable the highest result.

5.3.6 Criterion 6: End-Acceleration Analysis

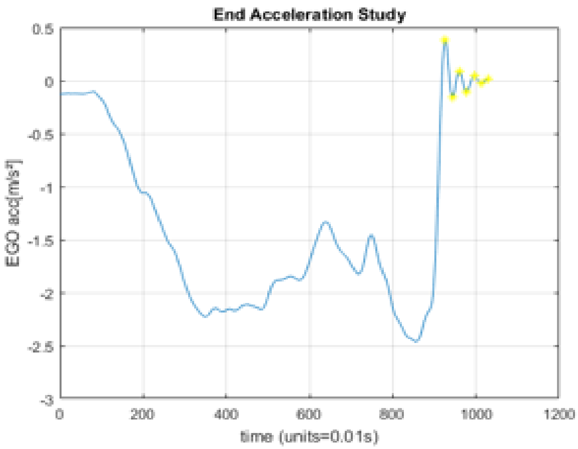
During Follow Vehicle Stop manoeuvre, it is quite common to have a bumping behaviour due to the willingness of the vehicle to get closer to TOF.
However, it is unwanted and it is rated for the four examined calibrations (in Figure 106) as follows:



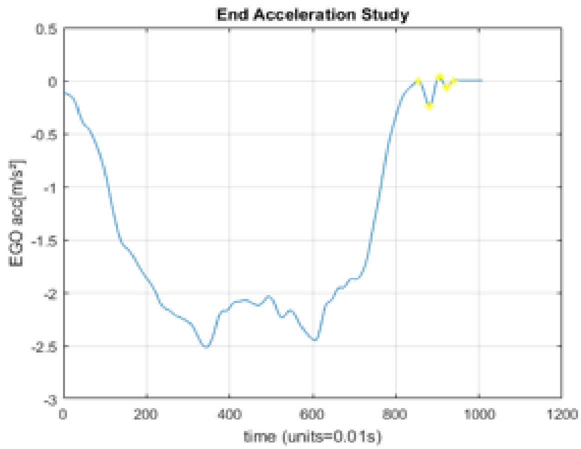
(a) *End-Acc Analysis Follow Vehicle Stop-Manoeuvre 1* $DRIVE\_Rating6 = 6.6$



(b) *End-Acc Analysis Follow Vehicle Stop-Manoeuvre 2* $DRIVE\_Rating6 = 7.2$



(c) *End-Acc Analysis Follow Vehicle Stop-Manoeuvre 3* $DRIVE\_Rating6 = 6.7$



(d) *End-Acc Analysis Follow Vehicle Stop-Manoeuvre 4* $DRIVE\_Rating6 = 7.2$

Figure 106: *End-Acceleration Analysis Comparison: Follow Vehicle Stop*

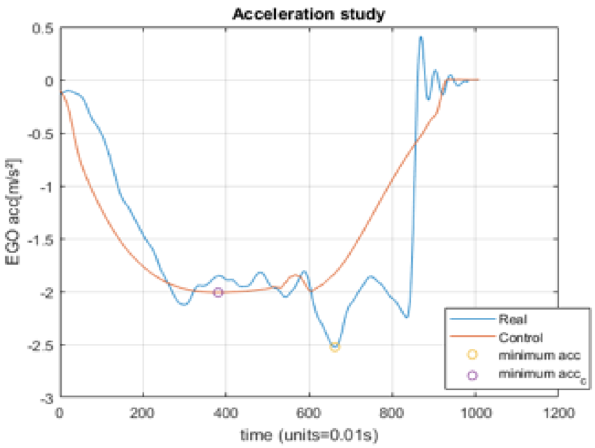
In this analysis amplitude, frequency and number of weak points are important.
There is not a huge difference among the presented calibrations.

5.3.7 Criterion 7: Position of the Minimum Acceleration

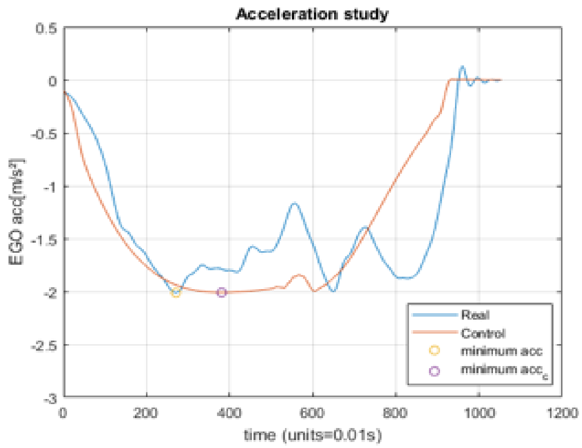
The study ends with a close-up vision of the position of the minimum acceleration position.

Relative Position of the Minimum Acceleration

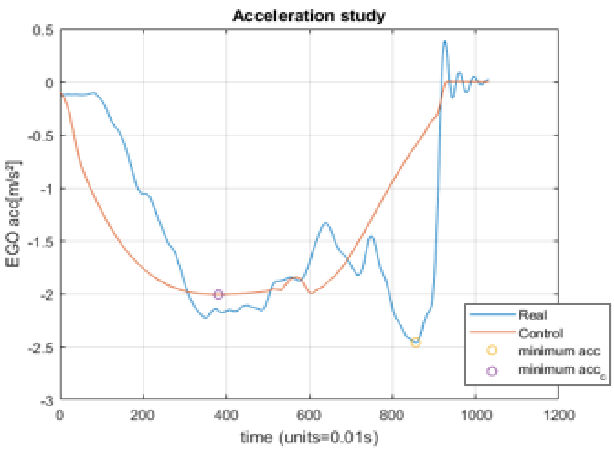
In Figure 107, the minimum achieved acceleration is holed in order to understand where it is positioned over the entire deceleration.



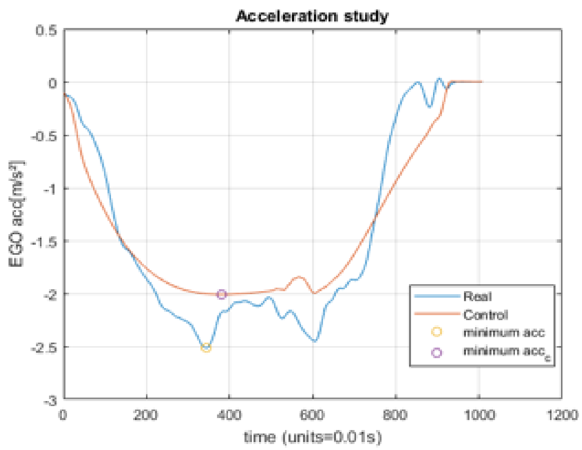
(a) *Relative Position FVS - Manoeuvre 1*
$DRIVE\_Rating7 = 8.1$



(b) *Relative Position FVS - Manoeuvre 2*
$DRIVE\_Rating7 = 9.3$



(c) *Relative Position FVS - Manoeuvre 3*
$DRIVE\_Rating7 = 6.8$



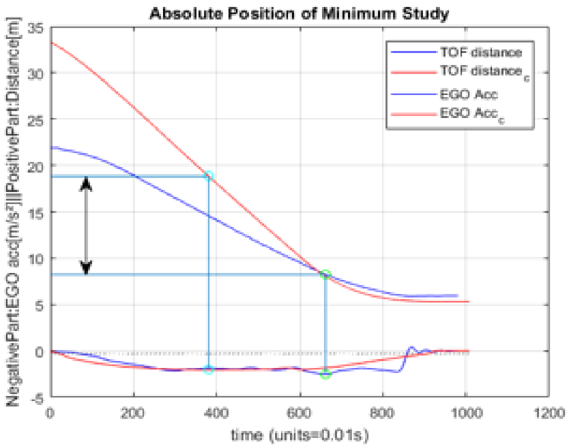
(d) *Relative Position FVS - Manoeuvre 4*
$DRIVE\_Rating7 = 9.7$

Figure 107: *Relative Position Analysis Comparison: Follow Vehicle Stop*

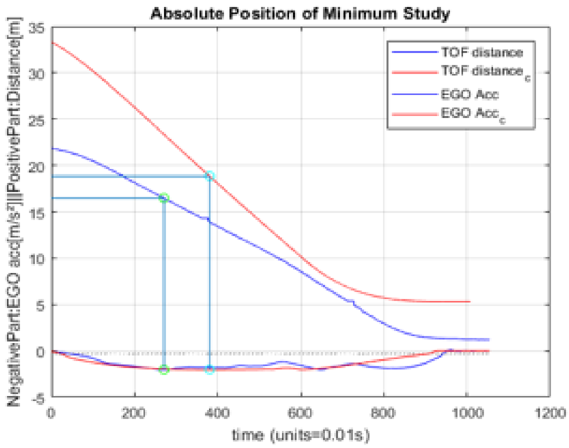
Due to the unquestionable similarity between the fourth manoeuvre and the controller manoeuvre, its rating is 9.7 and it is the highest.

Absolute Position of the Minimum Acceleration

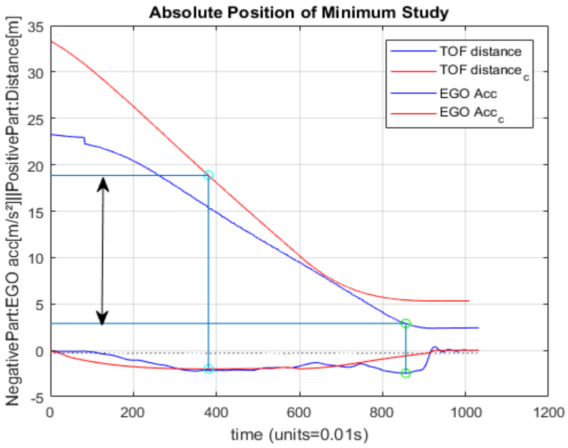
Finally, the minimum position is computed also in absolute terms considering the distance from TOF, the results are shown in Figure 108.
Wherever it is possible, some narrows are introduced to have a clear overview of the difference between the two curves.



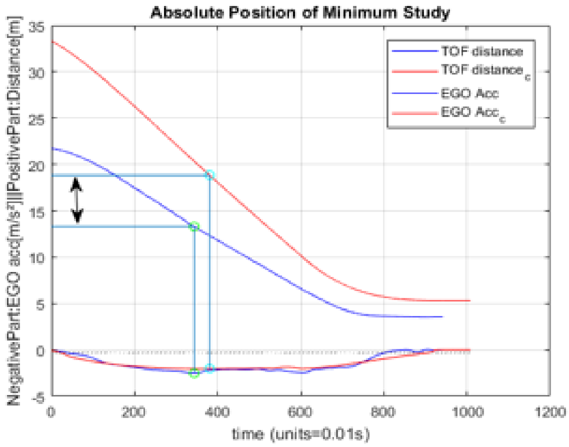
(a) *Absolute Position FVS - Manoeuvre 1* $DRIVE\_Rating7a = 6.1$



(b) *Absolute Position FVS - Manoeuvre 2* $DRIVE\_Rating7a = 9.1$



(c) *Absolute Position FVS - Manoeuvre 3* $DRIVE\_Rating7a = 4.1$



(d) *Absolute Position FVS - Manoeuvre 4* $DRIVE\_Rating7a = 7.9$

Figure 108: *Absolute Position Analysis Comparison: Follow Vehicle Stop*

5.3.8 Overall Rating

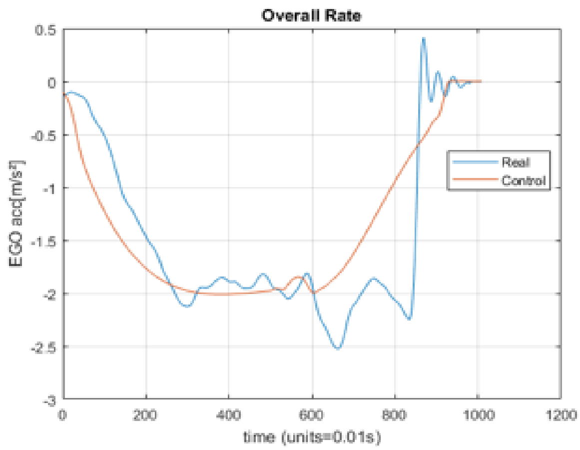
Since all the criteria are investigated and the four manoeuvres got a rating for all of it, an overall rating is also defined according to the following proposal.

$$Comfort = \frac{2Rate(1) + 4Rate(2) + 5Rate(2a) + 3Rate(4) + 2Rate(5) + 5Rate(6)}{21} \tag{96}$$

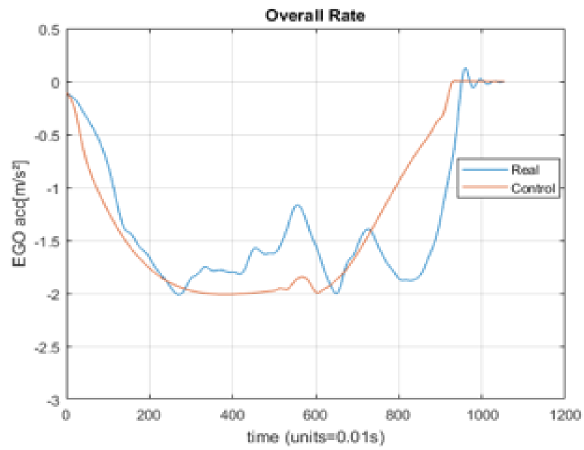
$$Safety = \frac{4Rate(3) + 3Rate(7) + 4Rate(7a)}{11} \tag{97}$$

$$DRIVE\_Overall\_Rate = 0.5Comfort + 0.5Safety \tag{98}$$

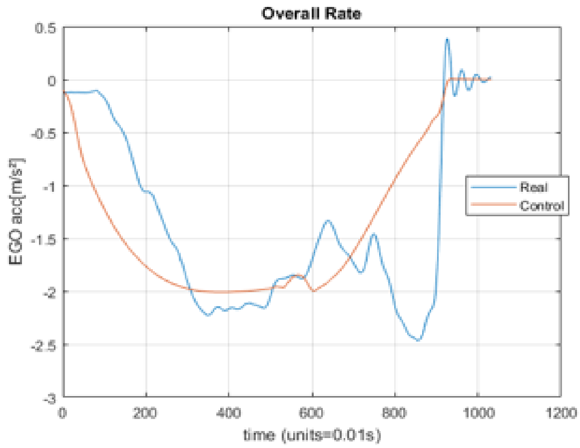
Figure 109 has in description for each manoeuvre the overall rate.



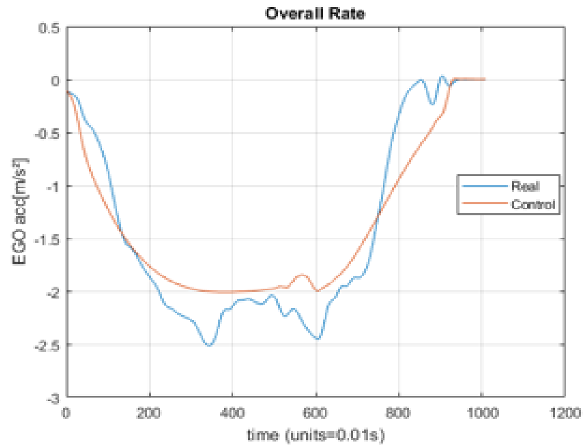
(a) *Manoeuvre 1 - Overall* $DRIVE\_Rating = 7.1$



(b) *Manoeuvre 2 - Overall* $DRIVE\_Rating = 8.3$



(c) *Manoeuvre 3 - Overall* $DRIVE\_Rating = 6.4$

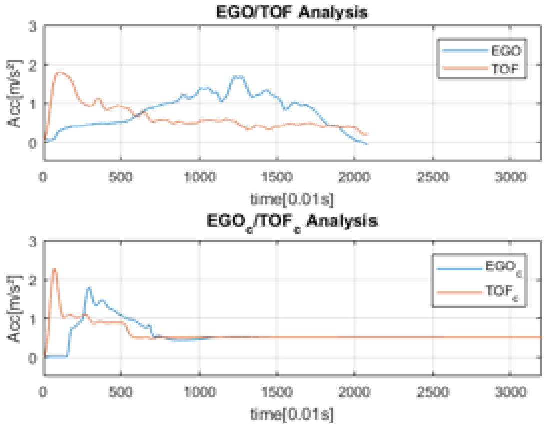


(d) *Manoeuvre 4 - Overall* $DRIVE\_Rating = 8.6$

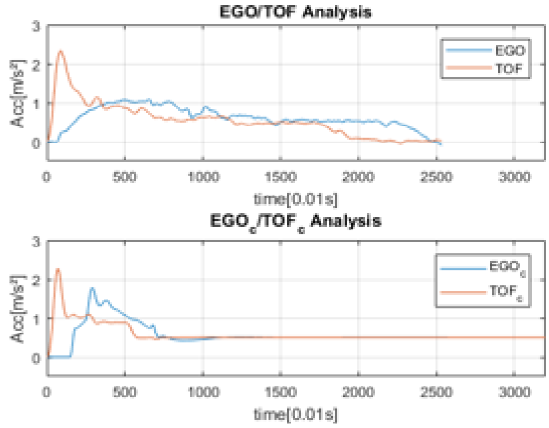
Figure 109: *Relative Position Analysis Comparison: Follow Vehicle Stop*

5.4 Follow Drive Away

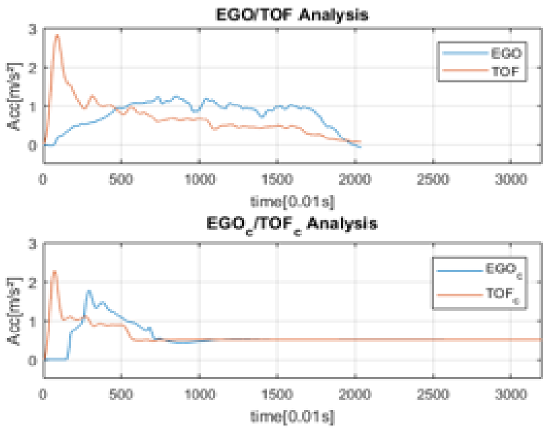
In this section, four different Follow Drive Away calibrations presented in Figure 110 are rated following the developed criteria in Paragraph 4.3.



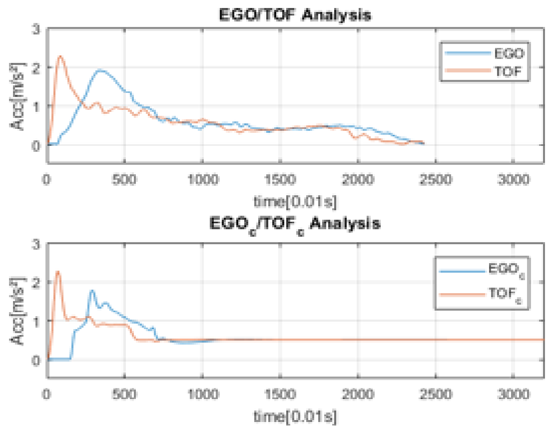
(a) *Follow Drive Away - Manoeuvre 1*



(b) *Follow Drive Away - Manoeuvre 2*



(c) *Follow Drive Away - Manoeuvre 3*

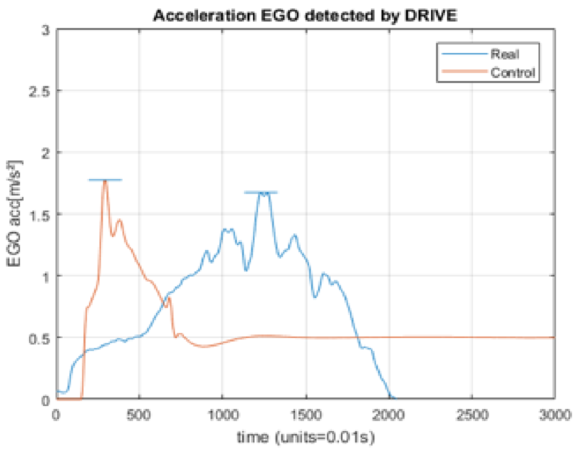


(d) *Follow Drive Away - Manoeuvre 4*

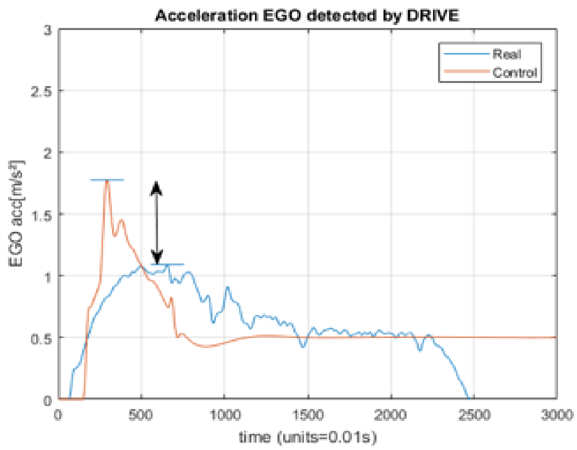
Figure 110: *Follow Drive Away: Manoeuvres*

5.4.1 Criterion 1: Maximum Acceleration

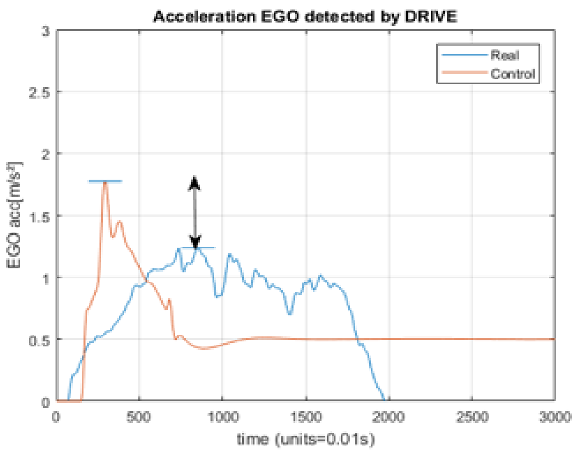
The first developed criterion is the Maximum Acceleration evaluation and it compares the maximum achieved acceleration during the manoeuvres.
In Figure 111, this criterion rated the four manoeuvres.



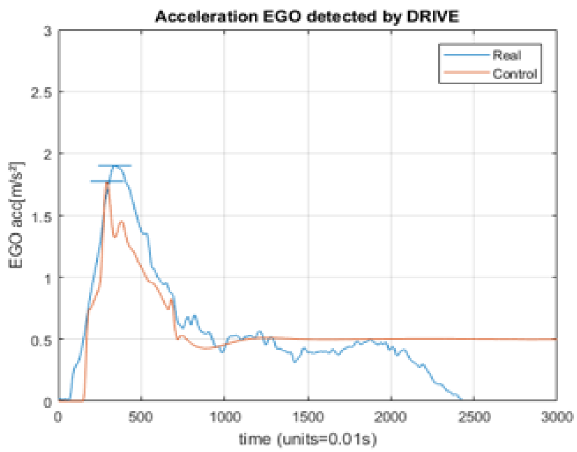
(a) *Acceleration Follow Drive Away - Manoeuvre 1*
$DRIVE\_Rating1 = 9.4$



(b) *Acceleration Follow Drive Away - Manoeuvre 2*
$DRIVE\_Rating1 = 6.1$



(c) *Acceleration Follow Drive Away - Manoeuvre 3*
$DRIVE\_Rating1 = 7.0$



(d) *Acceleration Follow Drive Away - Manoeuvre 4*
$DRIVE\_Rating1 = 9.3$

Figure 111: *Maximum Acceleration Comparison: Acceleration Follow Drive Away*

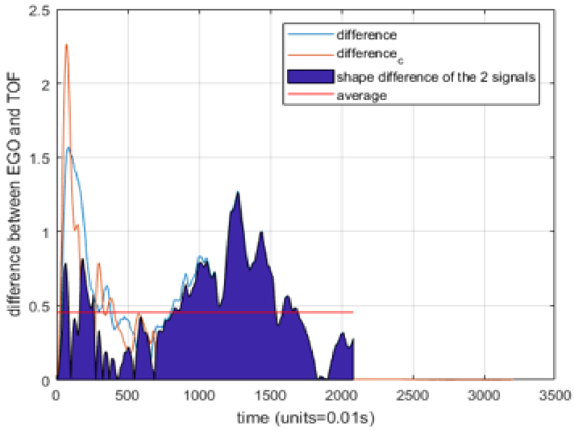
The first and fourth manoeuvres have a maximum acceleration closer to the ideal one.

5.4.2 Criterion 2: Acceleration Shape Comparison

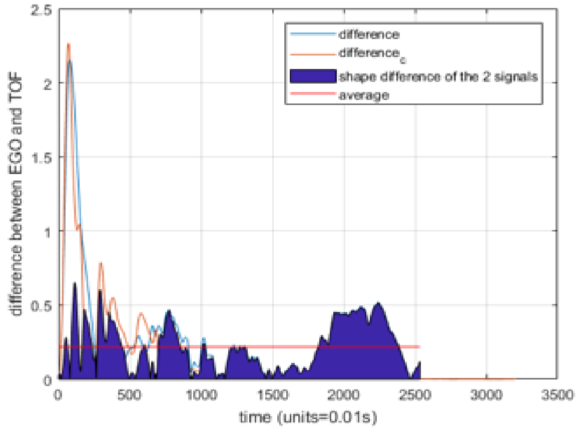
The second criterion compares Ego and TOF accelerations in two different steps that are discussed above in Paragraph 4.3.2.

2 Acceleration Shape Comparison: Ego versus TOF

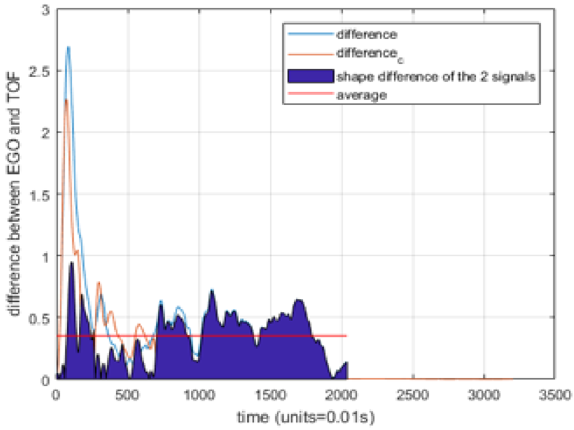
The results are shown in Figure 112



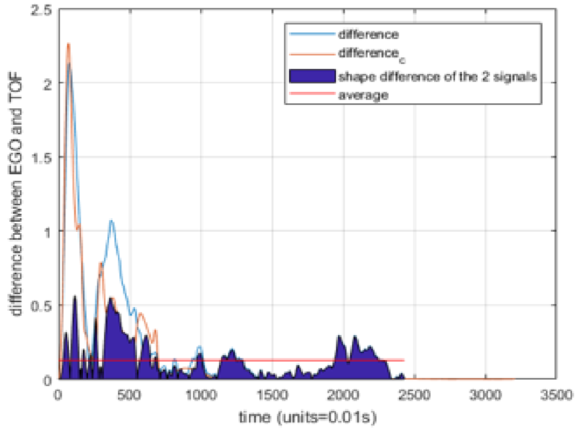
(a) *Shape Comparison Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating2 = 6.8$



(b) *Shape Comparison Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating2 = 8.5$



(c) *Shape Comparison Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating2 = 7.5$



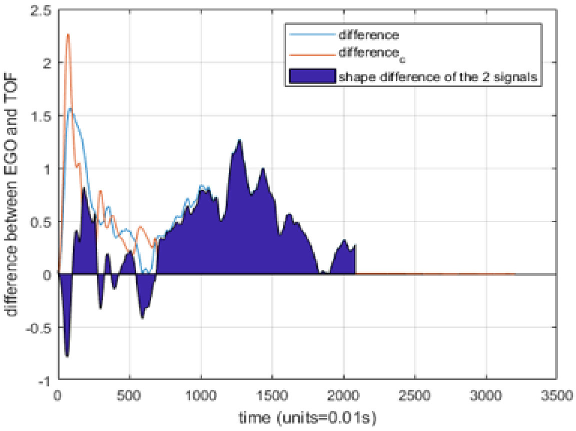
(d) *Shape Comparison Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating2 = 9.1$

Figure 112: *Acceleration Shape Comparison: Ego versus TOF - Follow Drive Away*

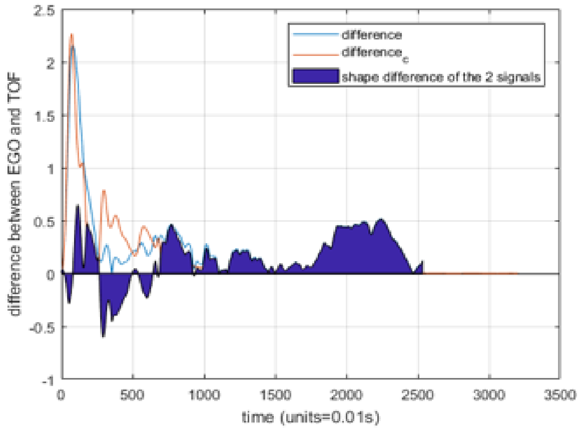
Observing the results, it is evident that the major differences are deployed during the first manoeuvre while the fourth is quite similar to the reference signal.

2a Acceleration Shape Comparison: Major Differences Detected

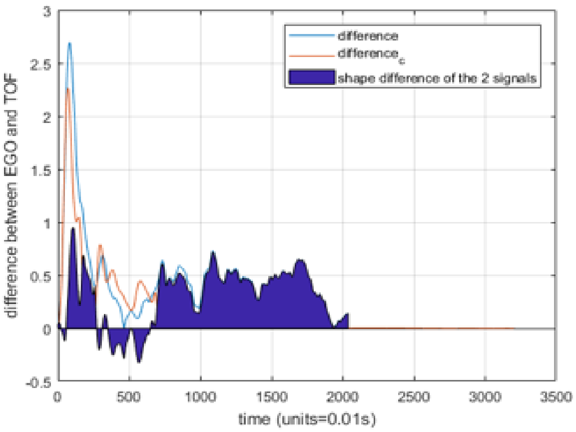
Criterion 2a studies the differences between the two signals along the entire period.
The evaluation is presented in the following Figure 113.



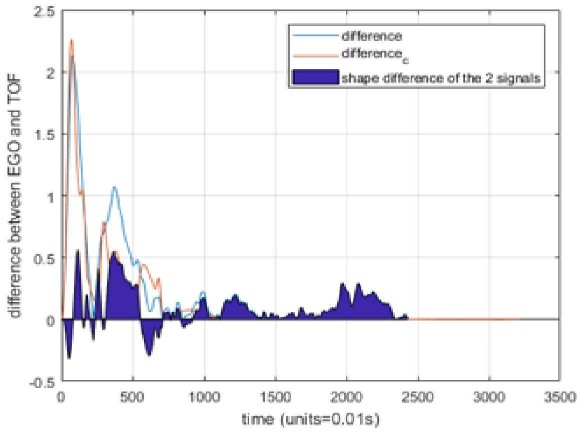
(a) *2a Shape Comparison Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating2a = 7.5$



(b) *2a Shape Comparison Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating2a = 9.9$



(c) *2a Shape Comparison Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating2a = 9.8$



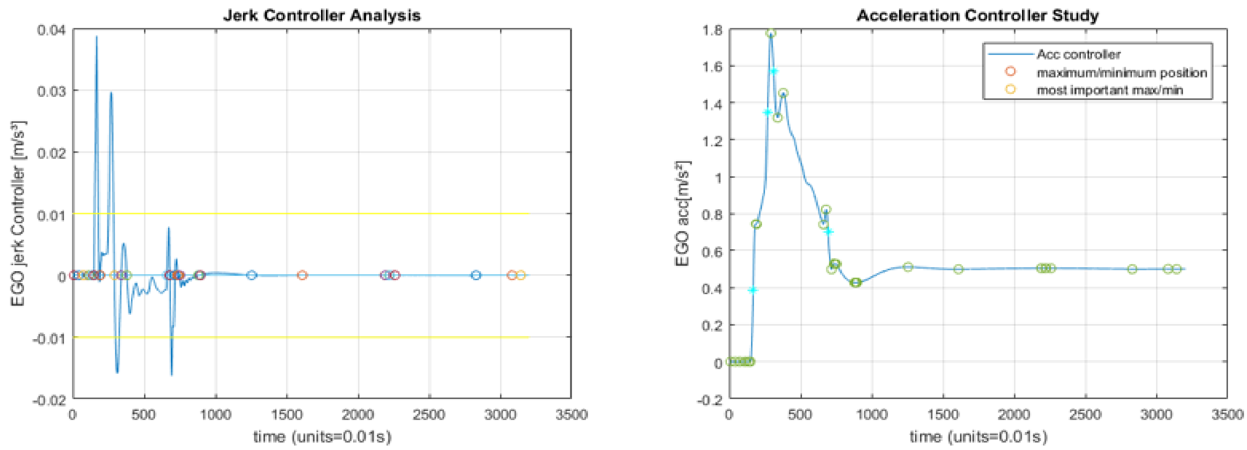
(d) *2a Shape Comparison Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating2a = 9.9$

Figure 113: *Acceleration Shape Comparison: Major Differences Detected - Follow Drive Away*

The first calibration shows the biggest differences with the compared signal and it is graphically shown and rated worst than the others.

5.4.3 Criterion 3: Jerk Evaluation

This section rated jerk of the studied manoeuvres as a comparison with the controller. In Figure 114, the controller behaviour is shown.

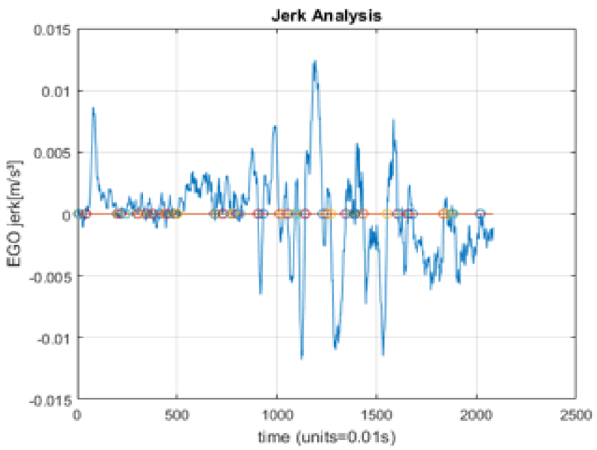


(a) *controller Jerk Evaluation* (b) *controller Acceleration (Jerk)*

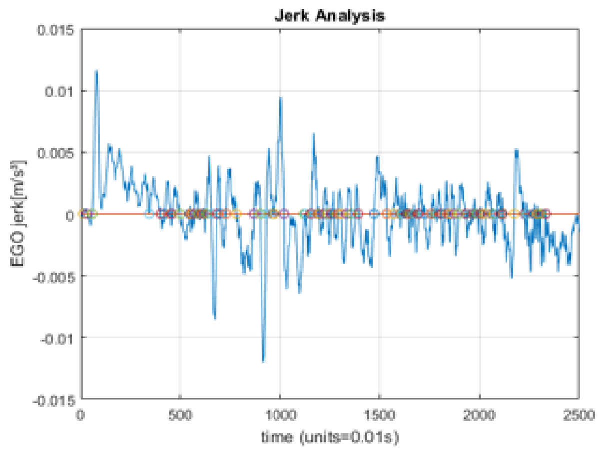
Figure 114: *Controller as reference: Jerk Evaluation*

3 Jerk: Smoothness Analysis

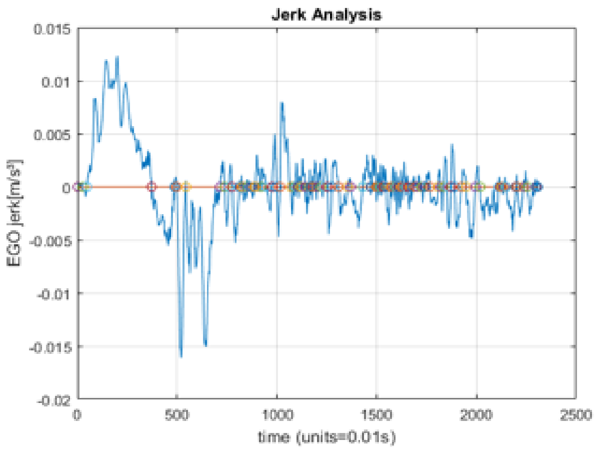
This criterion investigates the smoothness of the manoeuvre.
In Figure 115 the differences among the manoeuvres are highlighted.



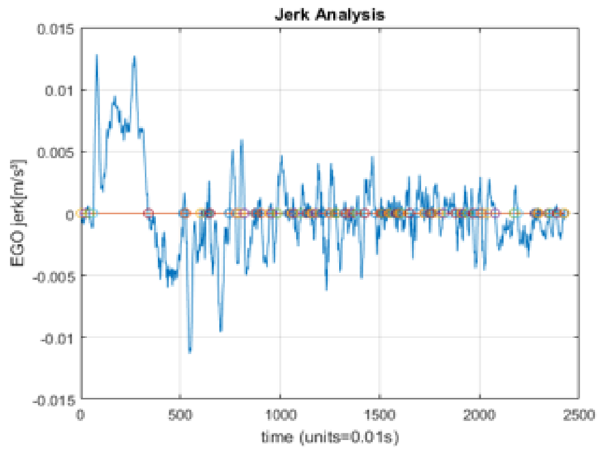
(a) *Jerk Evaluation Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating3 = 8.9$



(b) *Jerk Evaluation Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating3 = 9.4$



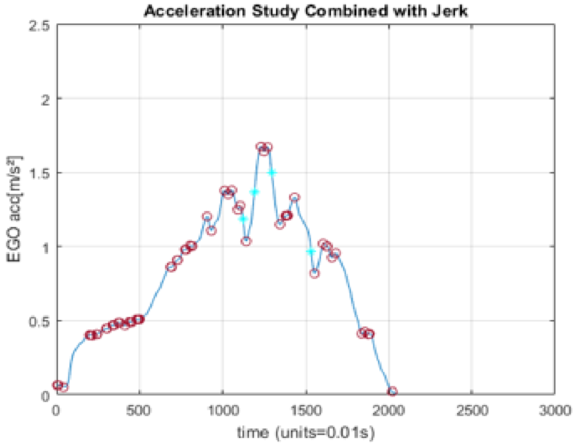
(c) *Jerk Evaluation Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating3 = 9.4$



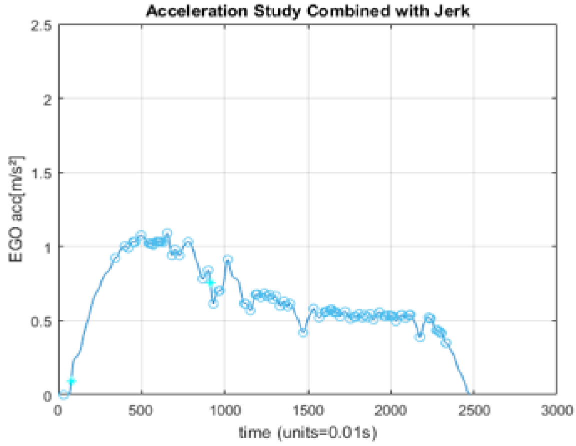
(d) *Jerk Evaluation Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating3 = 9.4$

Figure 115: *Jerk Study: Smoothness Analysis - Follow Drive Away*

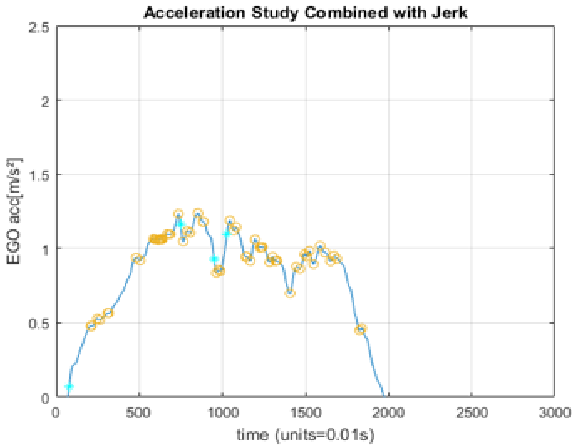
The first manoeuvre is the most oscillating one as it is visible from the plot and the rating.
The next Figure (Figure 116) gives a clear idea of the weak points detected during jerk evaluation.



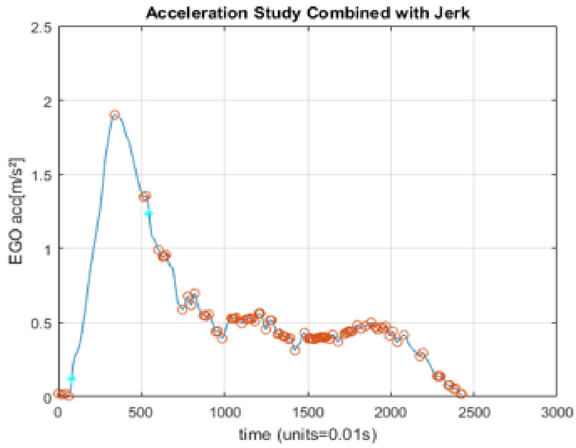
(a) *Jerk Evaluation Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating3 = 8.9$



(b) *Jerk Evaluation Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating3 = 9.4$



(c) *Jerk Evaluation Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating3 = 9.4$

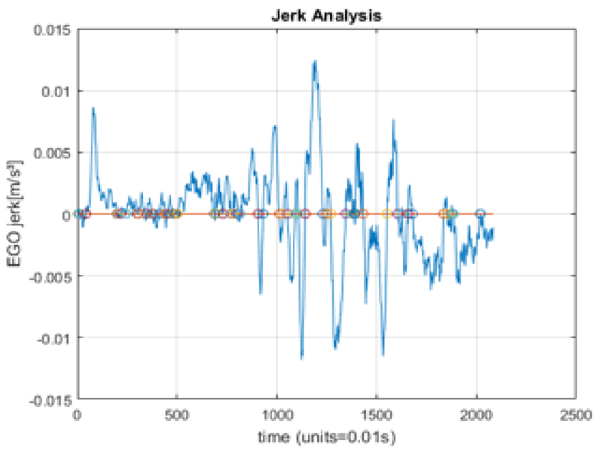


(d) *Jerk Evaluation Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating3 = 9.4$

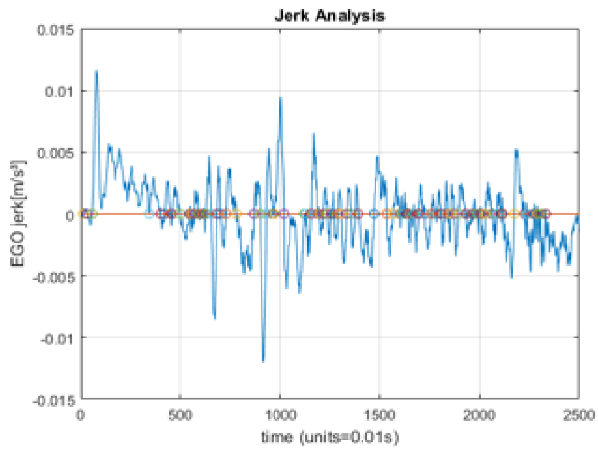
Figure 116: *Jerk Study: Smoothness Analysis - Follow Drive Away*

3a Jerk: Gradient Analysis

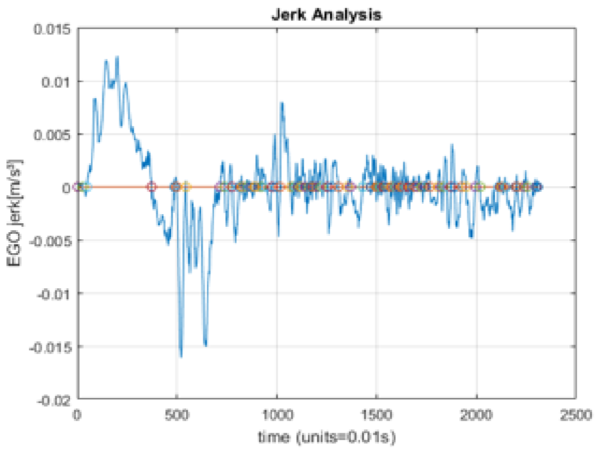
This criterion investigates the maximum reached jerk of the manoeuvre, thus the gradient of the acceleration.
In Figure 117, the differences among the manoeuvres are highlighted.



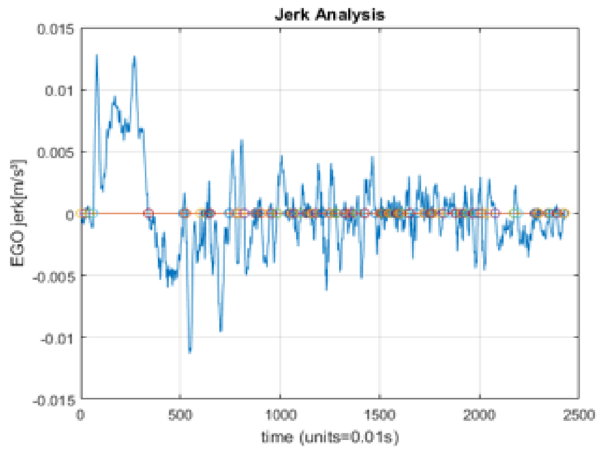
(a) *Gradient Analysis Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating3a = 9.6$



(b) *Gradient Analysis Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating3a = 9.6$



(c) *Gradient Analysis Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating3a = 9.9$



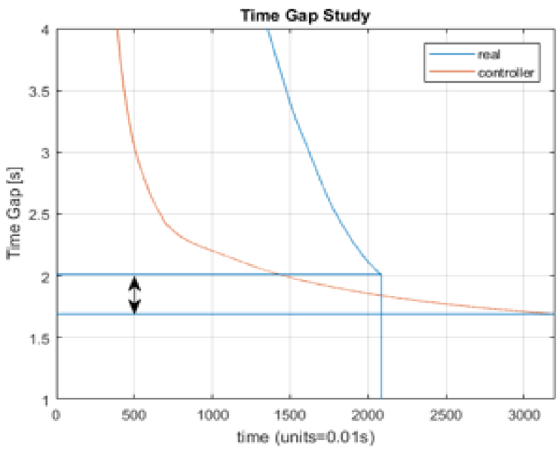
(d) *Gradient Analysis Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating3a = 9.9$

Figure 117: *Jerk Study: Gradient Analysis - Follow Drive Away*

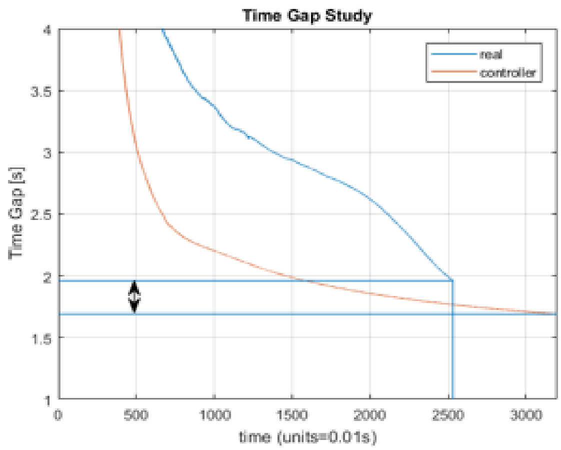
The threshold is fixed at $|0.01[m/s^3]|$ and it is evident that all the manoeuvre are closer to it.

5.4.4 Criterion 4: Minimum Time Gap

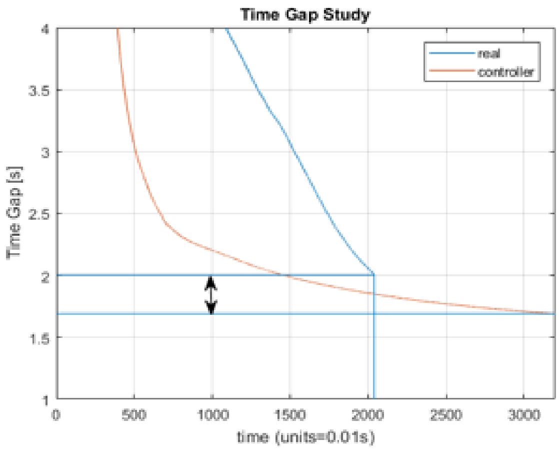
Figure 118 shows the minimum recorded time gap that normally is at the end of the manoeuvre, since it describes the distance between the vehicles.
Two different rating parameters are decided for the time gap evaluation and it is tangible from the results.



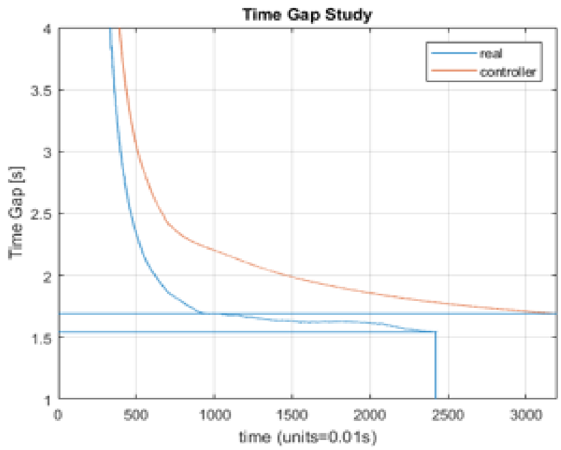
(a) *Minimum TimeGap Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating4 = 9.9$



(b) *Minimum TimeGap Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating4 = 9.9$



(c) *Minimum TimeGap Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating4 = 9.9$



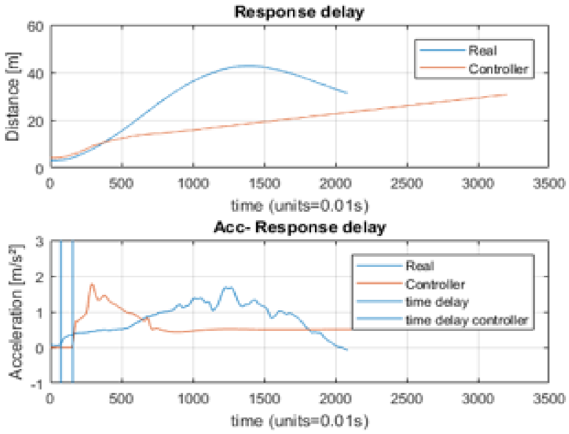
(d) *Minimum TimeGap Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating4 = 9.4$

Figure 118: *Minimum Time Gap Analysis - Follow Drive Away*

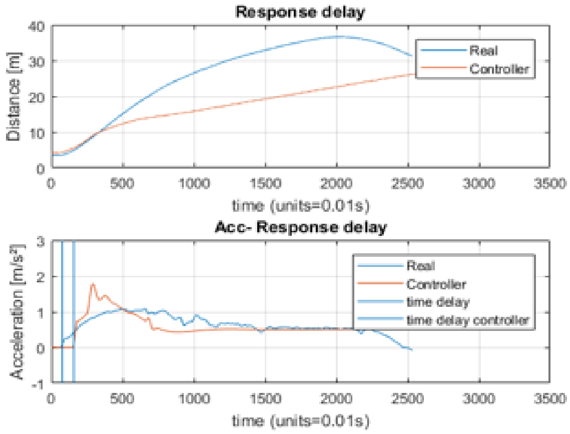
In terms of difference among the different manoeuvres, there was always less than 1 second, but if Ego gets closer to TOF compare to the reference signal, the rating is sensible worst, i.e. *Manoeuvre 4*.

5.4.5 Criterion 5: Response Delay Evaluation

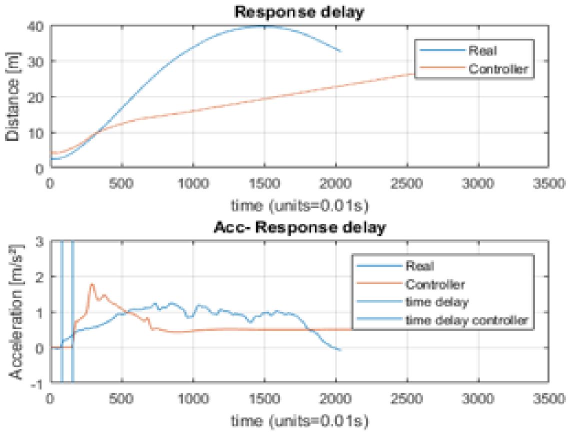
Figure 119 shows the results concerning the response delay evaluation.



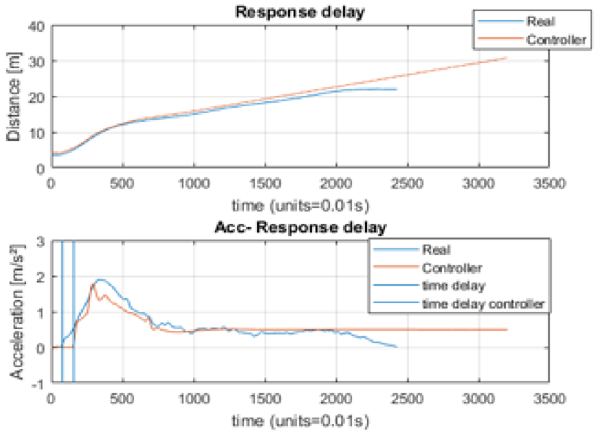
(a) *Response Delay Follow Drive Away - Manoeuvre 1* $DRIVE\_Rating5 = 8.9$



(b) *Response Delay Follow Drive Away - Manoeuvre 2* $DRIVE\_Rating5 = 9.0$



(c) *Response Delay Follow Drive Away - Manoeuvre 3* $DRIVE\_Rating5 = 9.1$



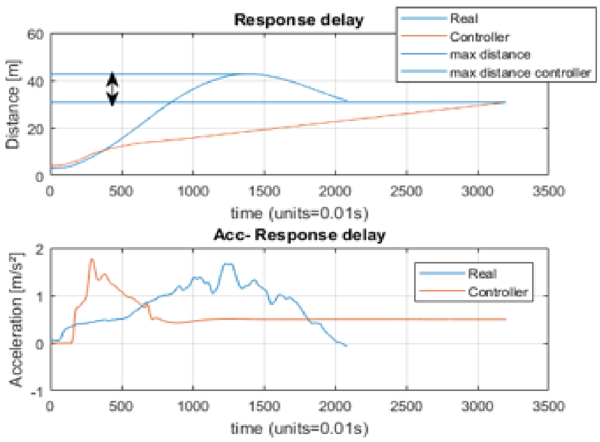
(d) *Response Delay Follow Drive Away - Manoeuvre 4* $DRIVE\_Rating5 = 9.0$

Figure 119: *Response Delay Evaluation - Follow Drive Away*

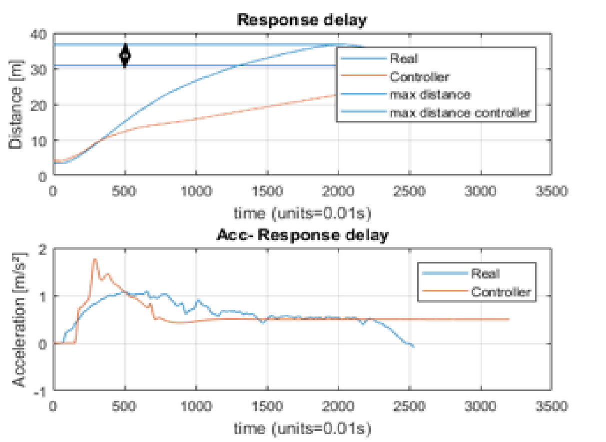
Comparing the signals to the reference one, all of them have an amount delay quite similar and the results reflect it.

5.4.6 Criterion 6: Maximum Distance Evaluation

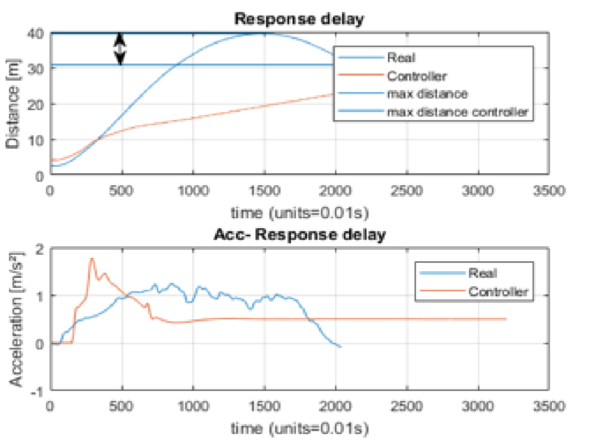
Figure 120 shows the maximum distance evaluation criterion.



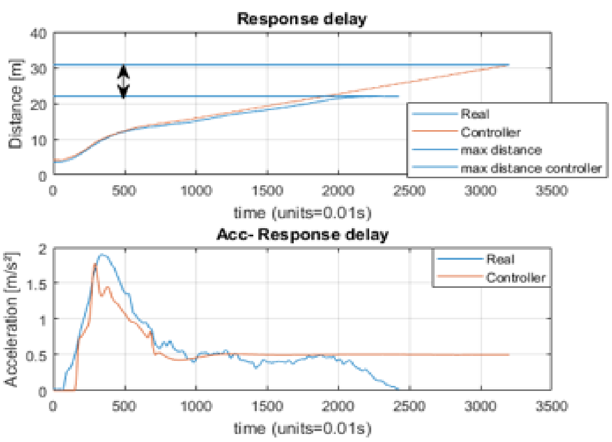
(a) *Maximum Distance Evaluation FDA - Manoeuvre 1* $DRIVE\_Rating6 = 8.0$



(b) *Maximum Distance Evaluation FDA - Manoeuvre 2* $DRIVE\_Rating6 = 8.9$



(c) *Maximum Distance Evaluation FDA - Manoeuvre 3* $DRIVE\_Rating6 = 8.5$



(d) *Maximum Distance Evaluation FDA - Manoeuvre 4* $DRIVE\_Rating6 = 8.0$

Figure 120: *Maximum Distance Evaluation - Follow Drive Away*

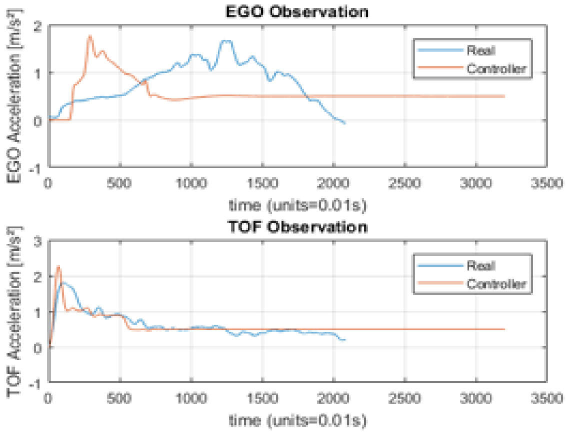
5.4.7 Overall Rating

The division among the different contributions of safety and comfort parameters are presented in Paragraph 4.3.7. Here, it is shown the chosen weighted contributions.

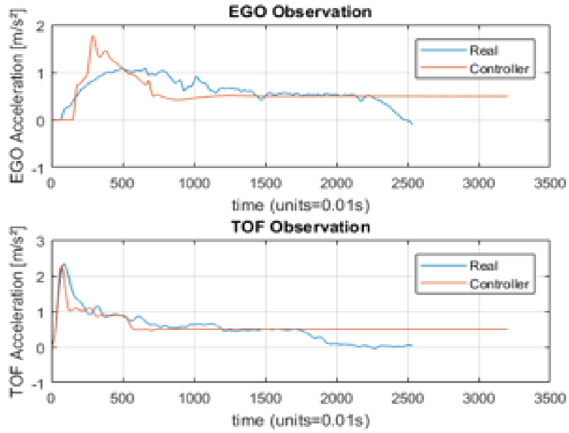
$$SAFETY = \frac{3RATE(4)}{4} \tag{99}$$

$$COMFORT = \frac{5RATE(1) + 5RATE(2) + 4RATE(2a) + 4RATE(3) + 2RATE(3a)}{} + ..$$
$$.. + \frac{3RATE(5) + 5RATE(6)}{28} \tag{100}$$

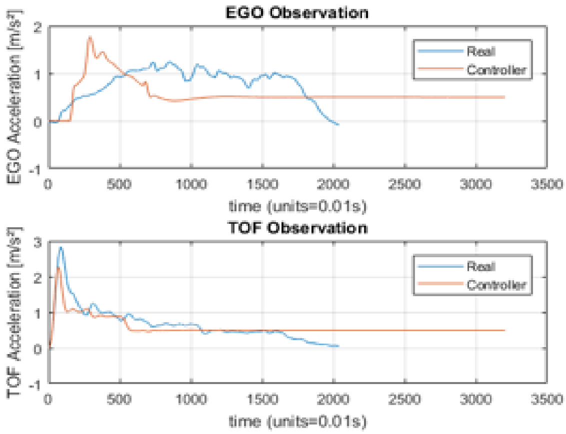
The overall results are quite closer. The results are shown in Figure 121:



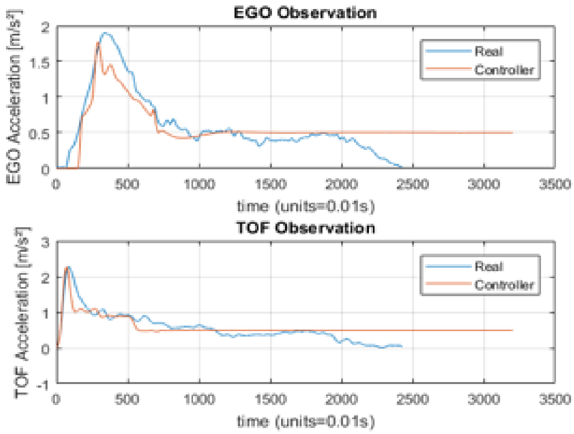
(a) *Manoeuvre 1 Overall DRIVE_Rating* = 8.5



(b) *Manoeuvre 2 Overall DRIVE_Rating* = 8.7



(c) *Manoeuvre 3 Overall DRIVE_Rating* = 8.6



(d) *Manoeuvre 4 Overall DRIVE_Rating* = 9.2

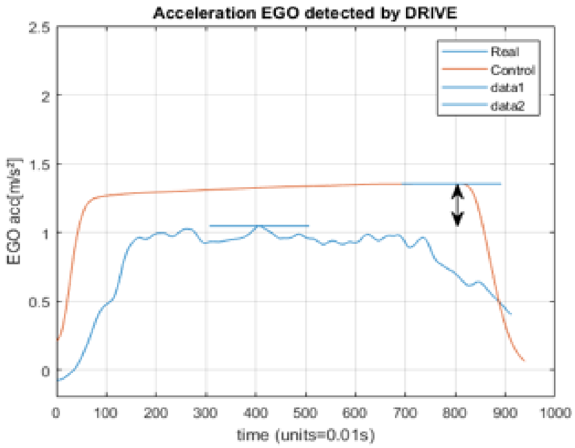
Figure 121: *Overall Rating - Follow Drive Away*

5.5 TOF free-lane Cut-Out: Low speed

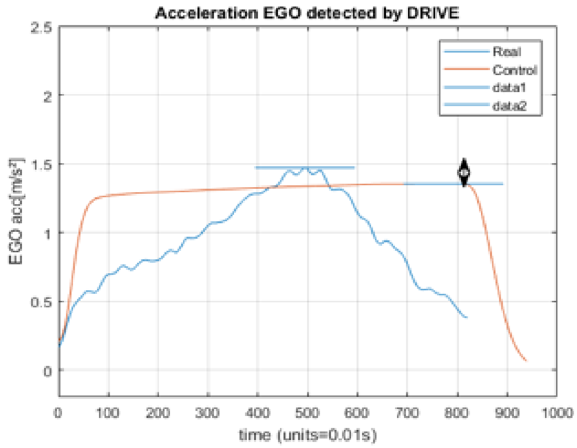
This manoeuvre was presented in Paragraph 2.2.4.
In the following section, four different calibrations are shown and evaluated with four different criteria discussed in Chapter 4. Maximum acceleration, response delay, jerk and acceleration shape are investigated.

5.5.1 Criterion 1: Maximum Acceleration

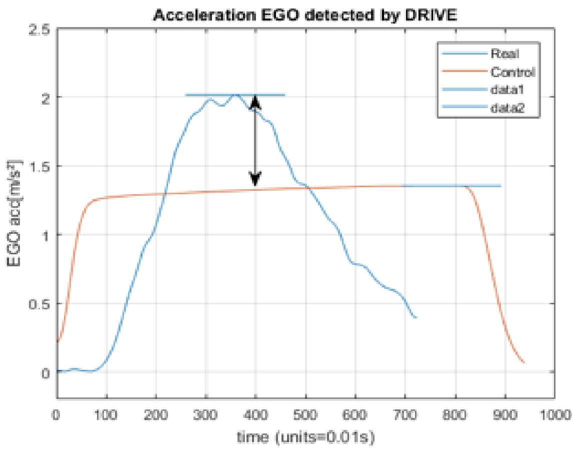
In Figure 122, the maximum acceleration comparison is deployed.



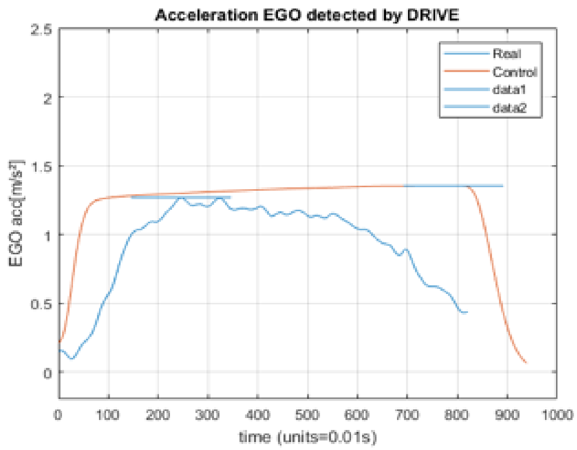
(a) *Acceleration TOF Cut-Out - Manoeuvre 1*
$DRIVE\_Rating1 = 8.4$



(b) *Acceleration TOF Cut-Out - Manoeuvre 2*
$DRIVE\_Rating1 = 9.4$



(c) *Acceleration TOF Cut-Out - Manoeuvre 3*
$DRIVE\_Rating1 = 7.7$



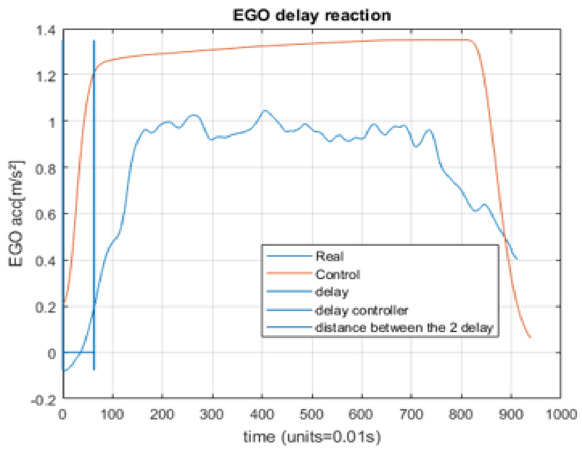
(d) *Acceleration TOF Cut-Out - Manoeuvre 4*
$DRIVE\_Rating1 = 9.6$

Figure 122: *Maximum Acceleration Comparison: TOF free-lane Cut-Out low speed*

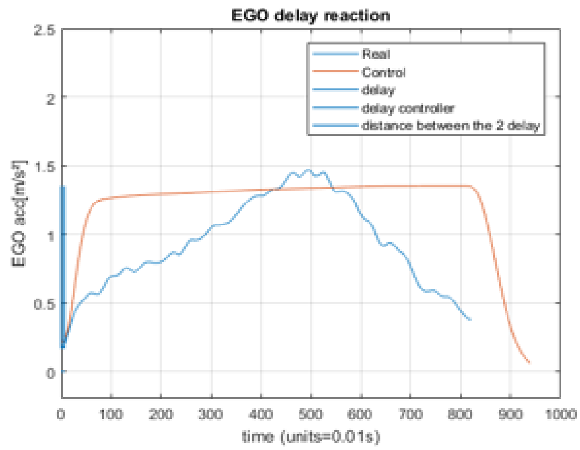
It is evident that the worst calibration is the third one that got a rating of 7.7 out of 10.

5.5.2 Criterion 2: Response Delay Evaluation

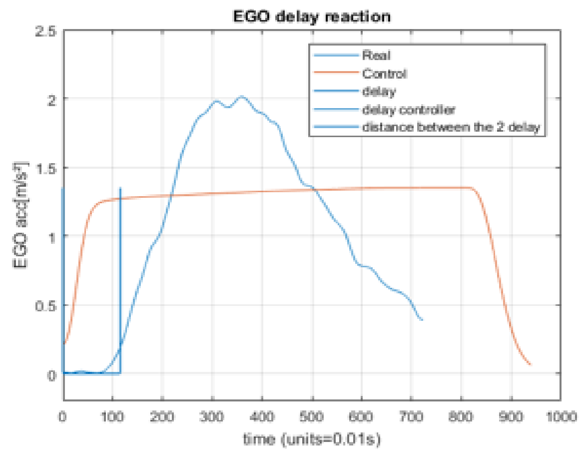
In Figure 123, some vertical lanes are introduced to give the feeling of the delay among the two signals.



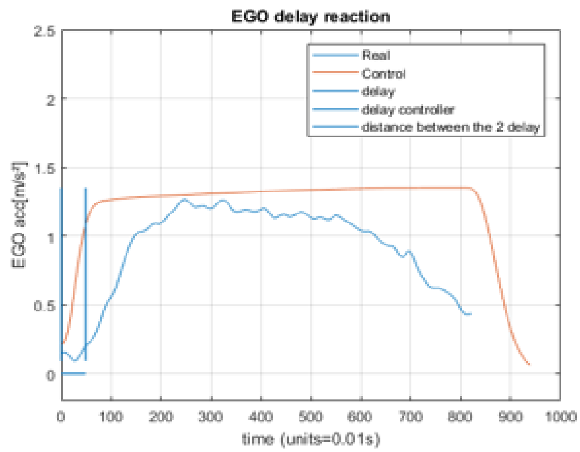
(a) *Response Delay TOF Cut-Out - Manoeuvre 1* $DRIVE\_Rating2 = 7.0$



(b) *Response Delay TOF Cut-Out - Manoeuvre 2* $DRIVE\_Rating2 = 10$



(c) *Response Delay TOF Cut-Out - Manoeuvre 3* $DRIVE\_Rating2 = 4.0$



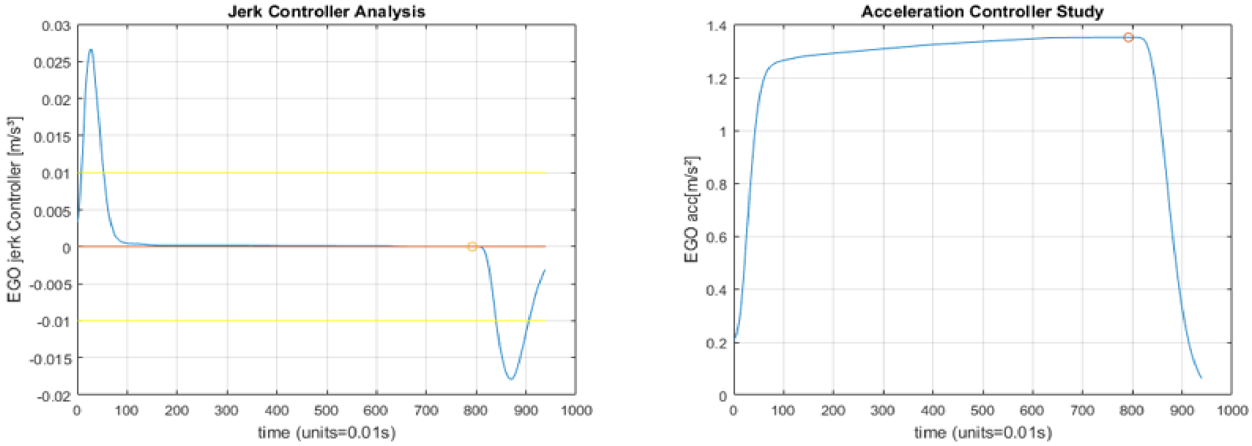
(d) *Response Delay TOF Cut-Out - Manoeuvre 4* $DRIVE\_Rating2 = 8.0$

Figure 123: *Response Delay Evaluation: TOF free-lane Cut-Out low speed*

The third calibration has a delay longer than 1 second and the rating is 4.0 since in this case the reaction is too lazy.

5.5.3 Criterion 3: Jerk Evaluation

During this evaluation, the controller is involved, too.
In Figure 124, the controller behaviour is presented.



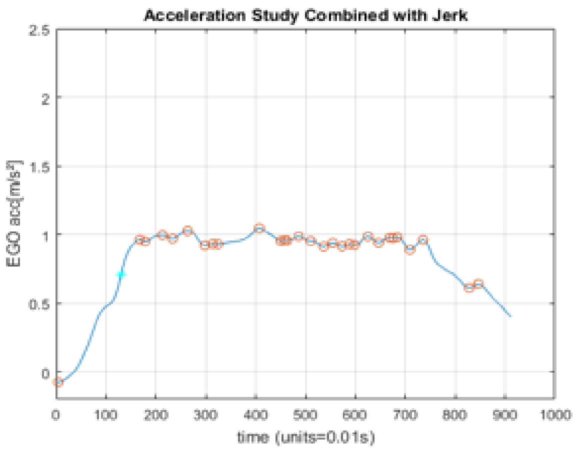
(a) *controller Jerk Evaluation* (b) *controller (Acceleration) Jerk Evaluation*

Figure 124: *controller Jerk Evaluation*

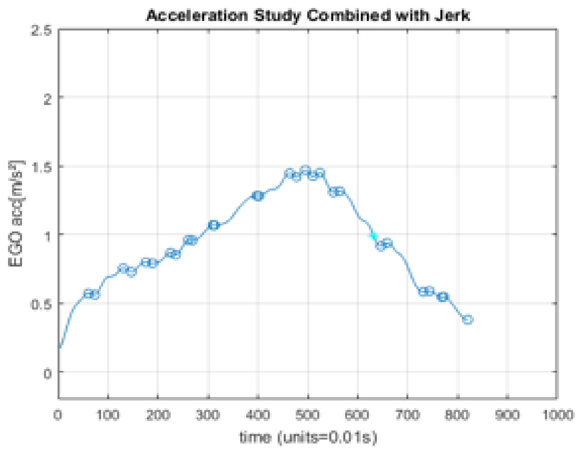
All the following analysis are compared with it. It's highly important to observe that the jerk of the controller has a peak over 0.025. Since it performs the manoeuvre strongly, also the real vehicle is allowed to react in the same way.
The analysis is composed of two parts as discussed above several times.

3 Jerk: Smoothness Analysis

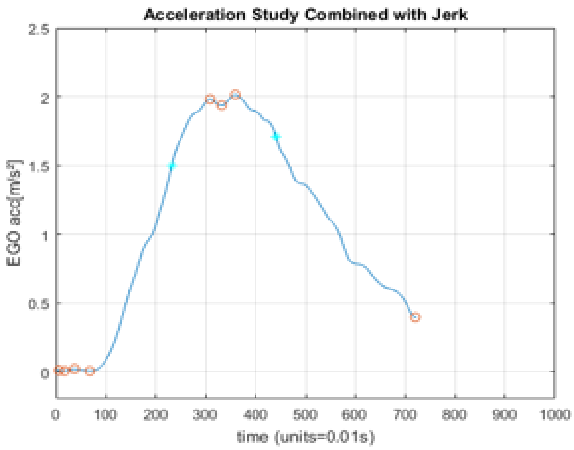
Smoothness analysis aims to discuss how often the jerk changes its positivity, thus how many strong bumps there are in the function.



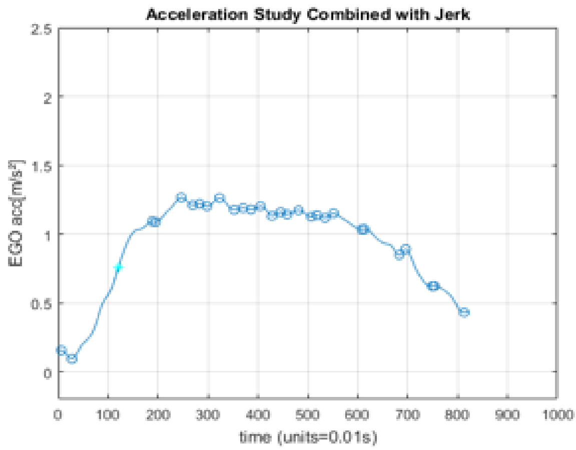
(a) *Smoothness Analysis TOF Cut-Out - Manoeuvre 1* $DRIVE\_Rating3 = 10$



(b) *Smoothness Analysis TOF Cut-Out - Manoeuvre 2* $DRIVE\_Rating3 = 10$



(c) *Smoothness Analysis TOF Cut-Out - Manoeuvre 3* $DRIVE\_Rating3 = 10$



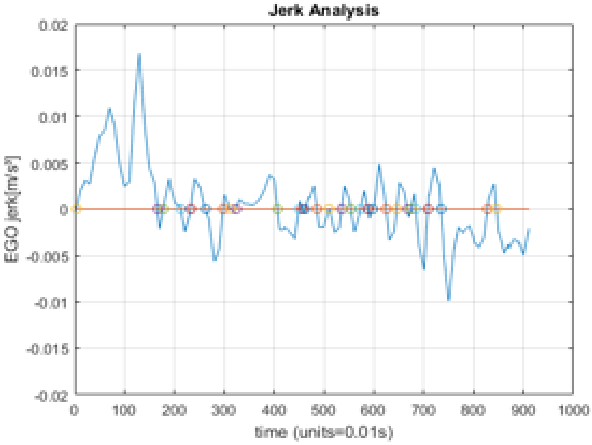
(d) *Smoothness Analysis TOF Cut-Out - Manoeuvre 4* $DRIVE\_Rating3 = 10$

Figure 125: *Smoothness (Jerk) Analysis: TOF free-lane Cut-Out low speed*

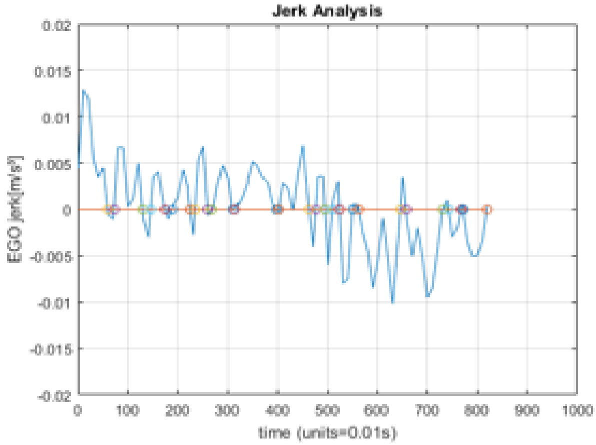
It is clear that for this manoeuvre, normally it is smooth. The smoothness is still investigated due to the fact that, if it is present, it high affects the comfort inside the vehicle.

3 Jerk: Gradient Analysis

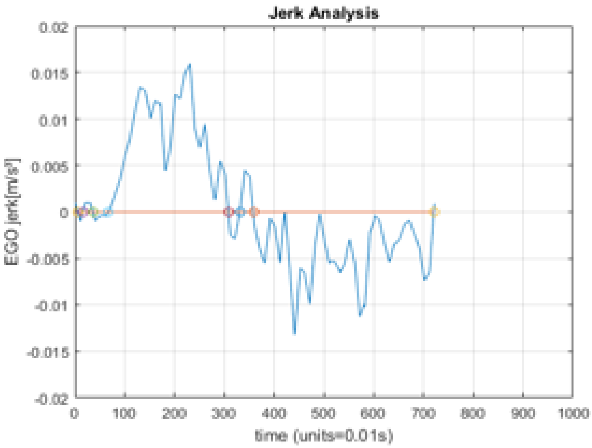
Figure 126 shows the jerk of the different calibrations.



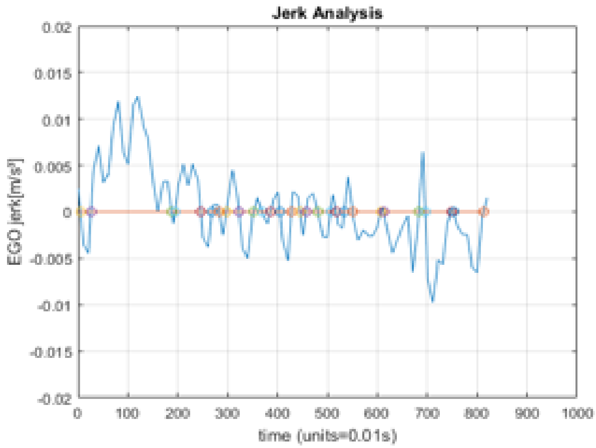
(a) *Gradient Analysis TOF Cut-Out - Manoeuvre 1* $DRIVE\_Rating3a = 9.8$



(b) *Gradient Analysis TOF Cut-Out - Manoeuvre 2* $DRIVE\_Rating3a = 10$



(c) *Gradient Analysis TOF Cut-Out - Manoeuvre 3* $DRIVE\_Rating3a = 9.9$



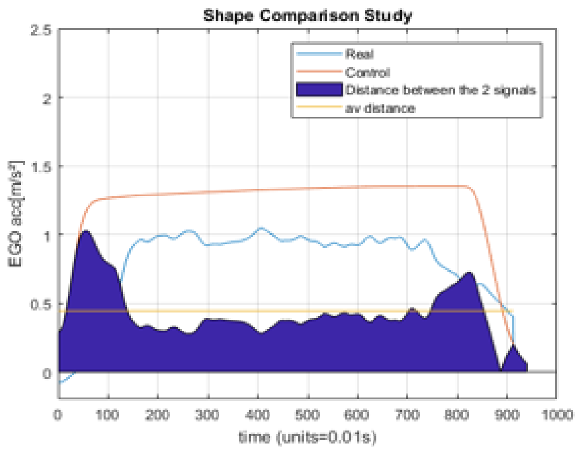
(d) *Gradient Analysis TOF Cut-Out - Manoeuvre 4* $DRIVE\_Rating3a = 10$

Figure 126: *Gradient (Jerk) Analysis: TOF free-lane Cut-Out low speed*

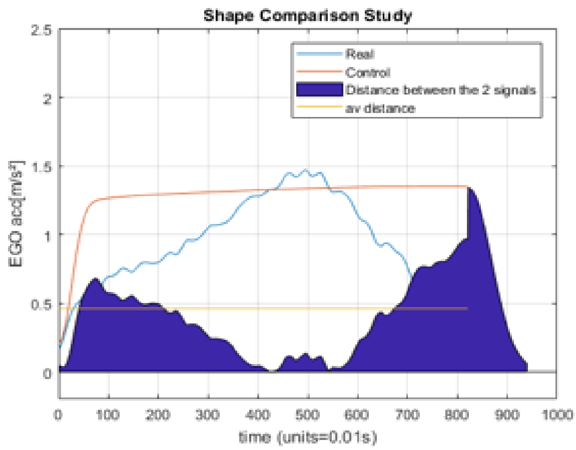
As it was mentioned in the introduction part of the criterion results, here the maximum jerk is compared with the controller and it is quite high. It gives a high rating to all the manoeuvres.

5.5.4 Criterion 4: Acceleration Shape Comparison

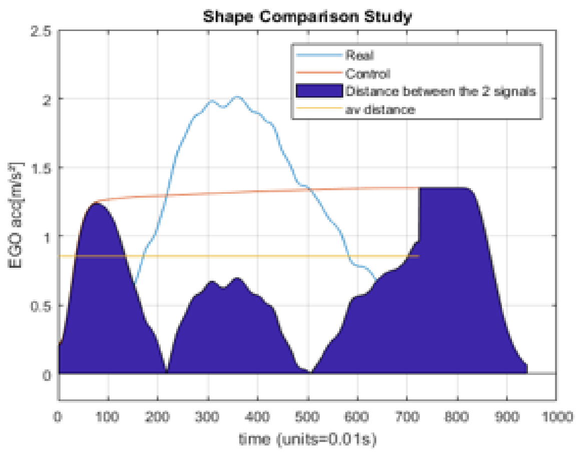
The last criterion is composed of two parts: firstly, the acceleration differences shape is investigated in Figure 127; then, a comment of the shape is given.



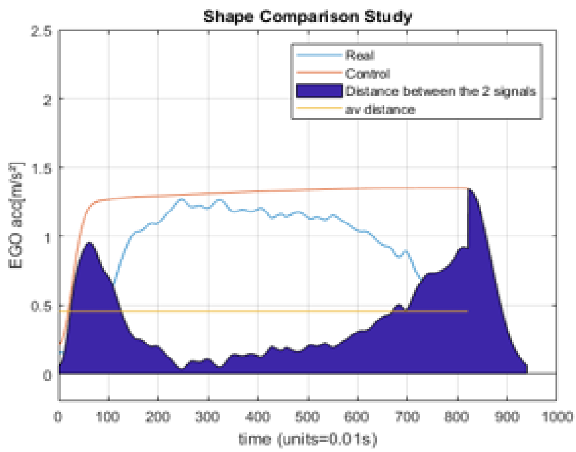
(a) *Acceleration Shape TOF Cut-Out - Manoeuvre 1* $DRIVE\_Rating4 = 7.7$



(b) *Acceleration Shape TOF Cut-Out - Manoeuvre 2* $DRIVE\_Rating4 = 7.6$



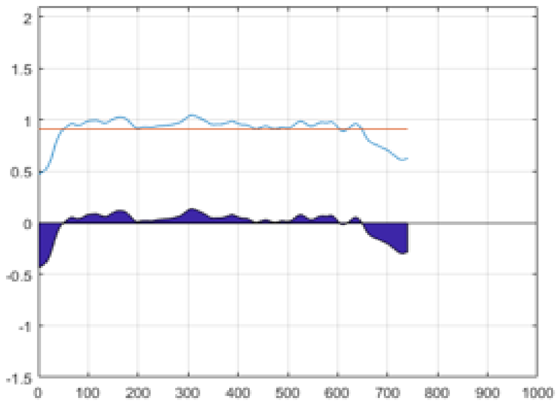
(c) *Acceleration Shape TOF Cut-Out - Manoeuvre 3* $DRIVE\_Rating4 = 5.6$



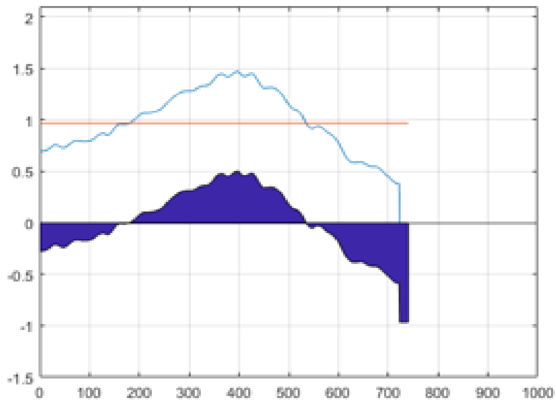
(d) *Acceleration Shape TOF Cut-Out - Manoeuvre 4* $DRIVE\_Rating4 = 7.7$

Figure 127: *Acceleration Shape Comparison: TOF free-lane Cut-Out low speed*

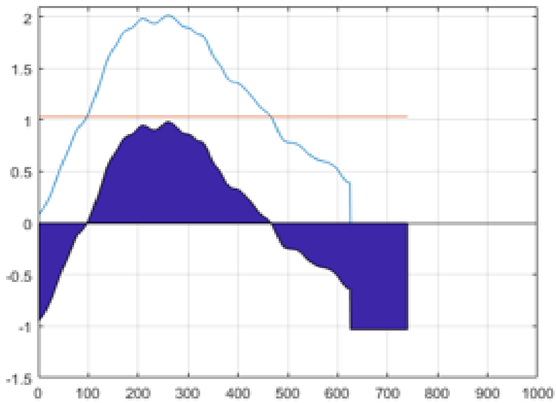
The worst results is achieved by the third manoeuvre.
The comment to the shape is made in Figure 128



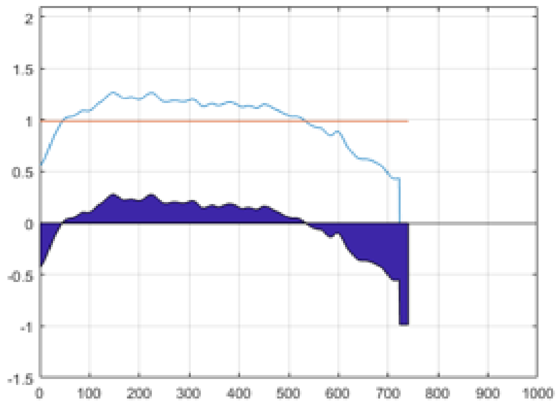
(a) *Acceleration Shape TOF Cut-Out - Manoeuvre 1*
Comment = Rectangular



(b) *Acceleration Shape TOF Cut-Out - Manoeuvre 2*
Comment = Triangular



(c) *Acceleration Shape TOF Cut-Out - Manoeuvre 3*
Comment = Triangular



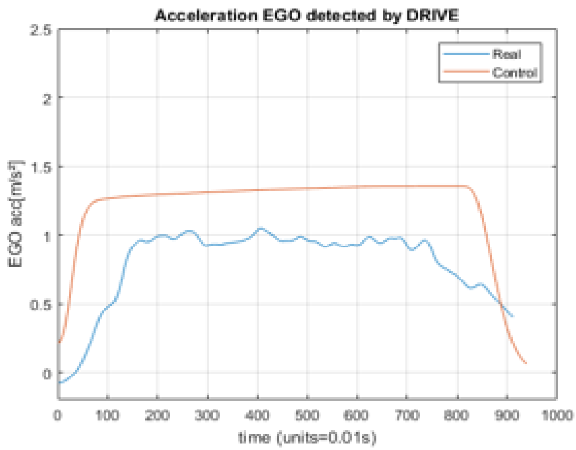
(d) *Acceleration Shape TOF Cut-Out - Manoeuvre 4*
Comment = Rectangular

Figure 128: *Acceleration Shape Comment: TOF free-lane Cut-Out low speed*

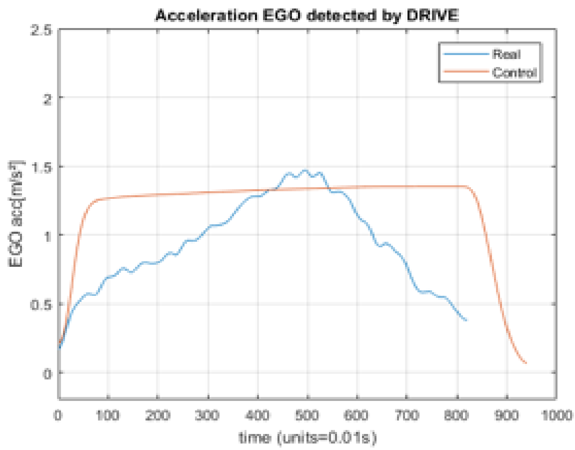
5.5.5 Overall Rating

In Figure 129, the overall result is weighted as follows.

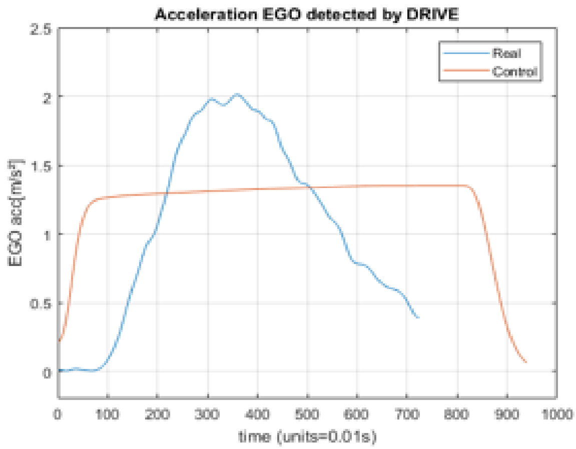
$$DRIVE\_Overall = \frac{5RATE(1) + 5RATE(2) + 2RATE(3) + 2RATE(3a) + 5RATE(4)}{19} \tag{101}$$



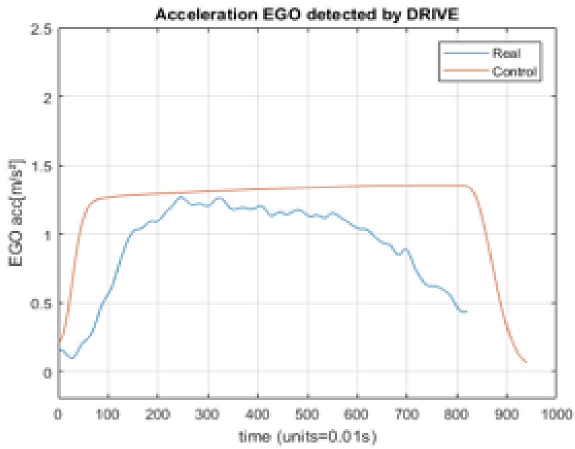
(a) *TOF Cut-Out - Manoeuvre 1*
$OverallDRIVE\_Rating = 7.1$



(b) *TOF Cut-Out - Manoeuvre 2*
$OverallDRIVE\_Rating = 8.1$



(c) *TOF Cut-Out - Manoeuvre 3*
$OverallDRIVE\_Rating = 5.7$



(d) *TOF Cut-Out - Manoeuvre 4*
$OverallDRIVE\_Rating = 7.6$

Figure 129: *Overall Rating: TOF free-lane Cut-Out low speed*

5.6 TOF free-lane Cut-Out: High speed

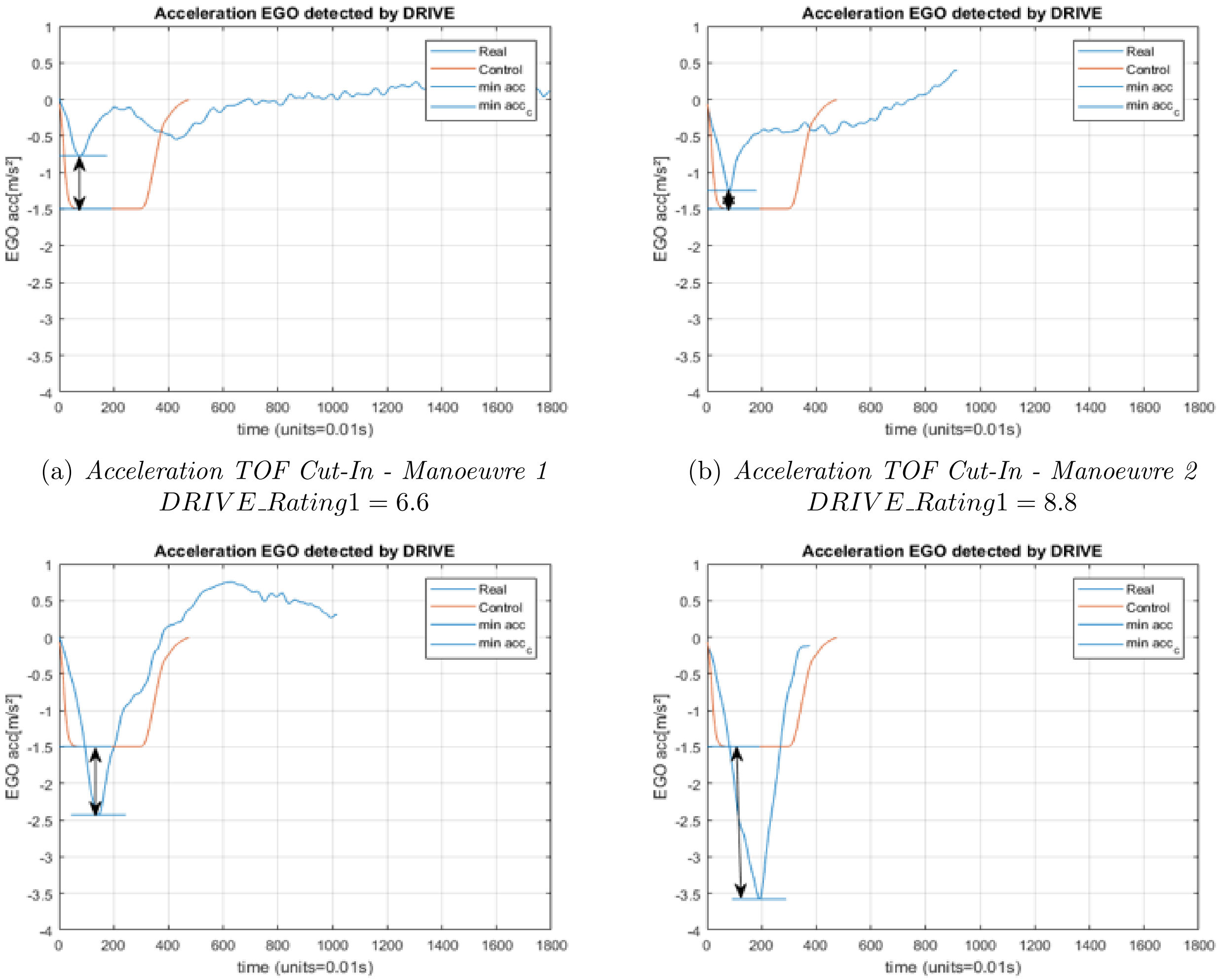
Thanks to the benchmark made in AVL, there were other data related to the TOF free-lane Cut-Out manoeuvre made at high speed ($100[km/h]$). In Appendix A, the TOF free-lane Cut-Out at high speed with four different calibrations is attached to verify the efficiency and the validity of the new developed methodology.

5.7 TOF free-lane Cut-In

It is the last studied manoeuvre. It is explained how it is performed in Paragraph 2.2.5. The following section is composed of eight subsections that investigate all the studied criteria developed for this manoeuvre in chapter 4.

5.7.1 Criterion 1: Minimum Acceleration

Figure 130 investigates the minimum achieved acceleration.



(a) *Acceleration TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating1 = 6.6$

(b) *Acceleration TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating1 = 8.8$

(c) *Acceleration TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating1 = 7.3$

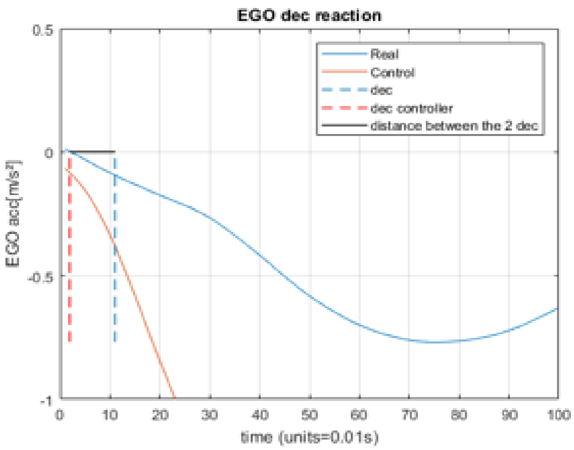
(d) *Acceleration TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating1 = 5.9$

Figure 130: *Minimum Acceleration Comparison: TOF free-lane Cut-In*

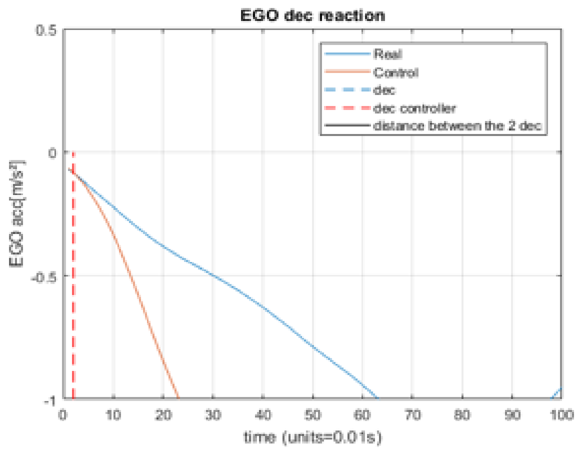
Since the biggest difference is developed by the fourth manoeuvre, it got the lowest rate.

5.7.2 Criterion 2: Response Delay Evaluation

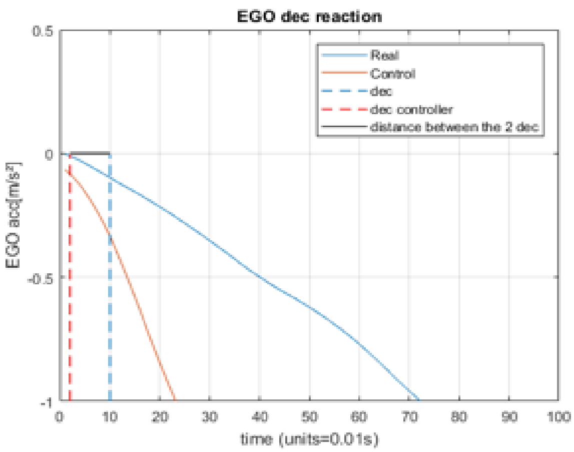
The response delay is investigated in Figure 131.
However, the delay is less than 0.10[s] for all the manoeuvres. It does not allow to get a feeling of the differentiation of the rating.



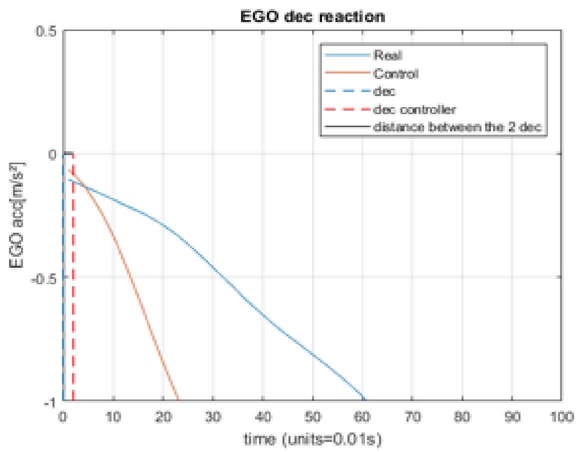
(a) *Response Delay TOF Cut-In - Manoeuvre 1*
$DRIVE\_Rating2 = 10$



(b) *Response Delay TOF Cut-In - Manoeuvre 2*
$DRIVE\_Rating2 = 10$



(c) *Response Delay TOF Cut-In - Manoeuvre 3*
$DRIVE\_Rating2 = 10$



(d) *Response Delay TOF Cut-In - Manoeuvre 4*
$DRIVE\_Rating2 = 10$

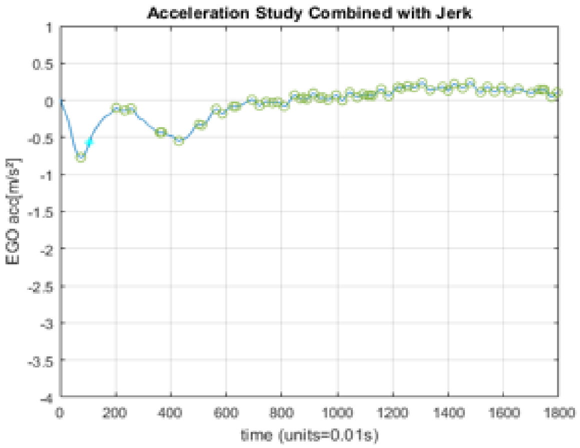
Figure 131: *Response Delay Evaluation: TOF free-lane Cut-In*

5.7.3 Criterion 3: Jerk Evaluation

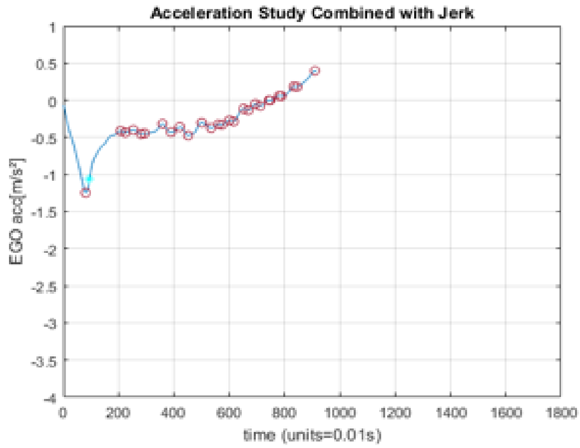
The following analysis, as already saw for all the previous manoeuvres, it is composed of two parts.

3 Jerk: Smoothness Analysis

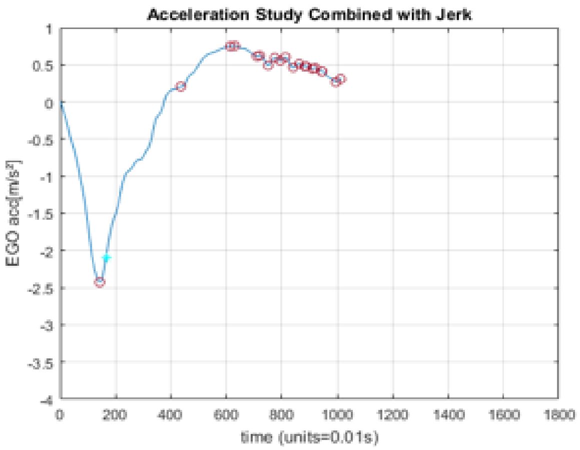
The conditions to find the relative bumps in the acceleration are composed of a threshold at $0.01[m/s^3]$ and two consecutive points that exceed with a different sign the threshold. Figure 132 shows the acceleration with the weak points.



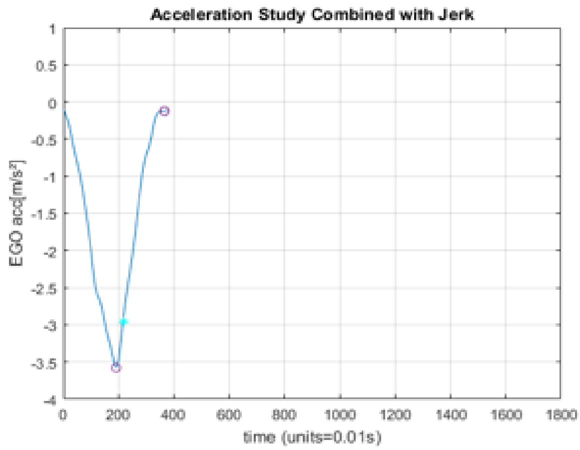
(a) *Smoothness Analysis TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating3 = 10$



(b) *Smoothness Analysis TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating3 = 10$



(c) *Smoothness Analysis TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating3 = 7.4$

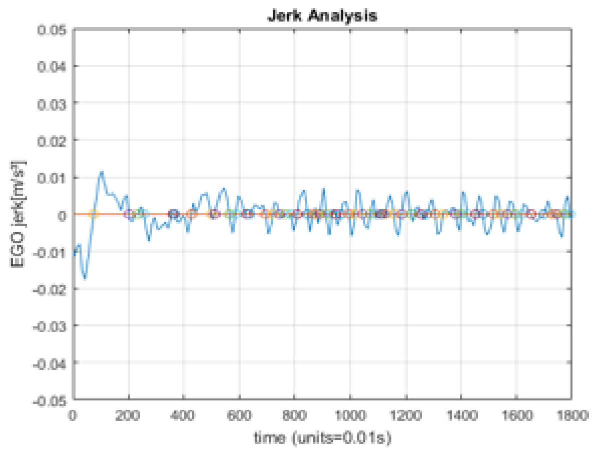


(d) *Smoothness Analysis TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating3 = 7.5$

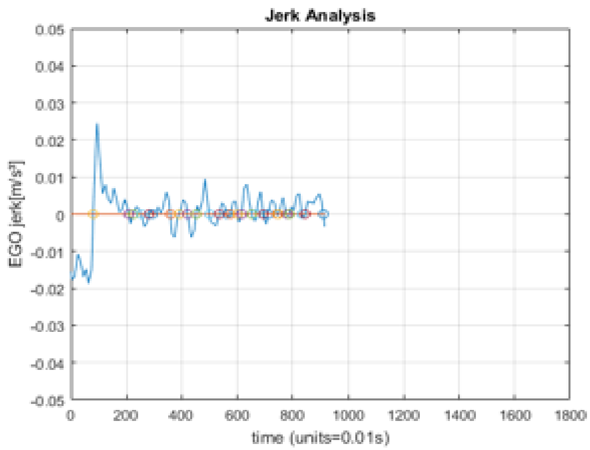
Figure 132: *Smoothness (Jerk) Analysis: TOF free-lane Cut-In*

3 Jerk: Gradient Analysis

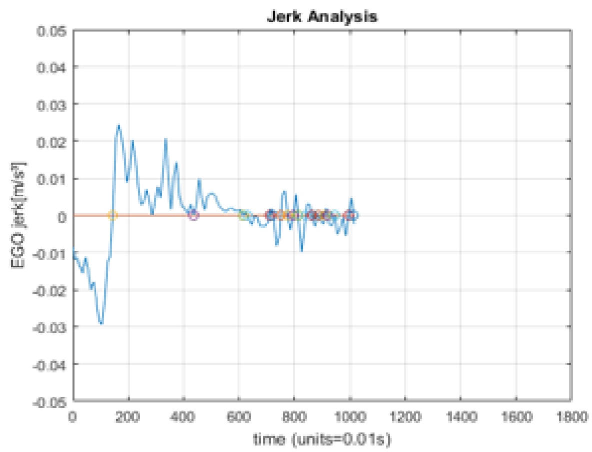
Figure 133 shows the jerk functions. It investigates the maximum and the minimum achieved jerk.



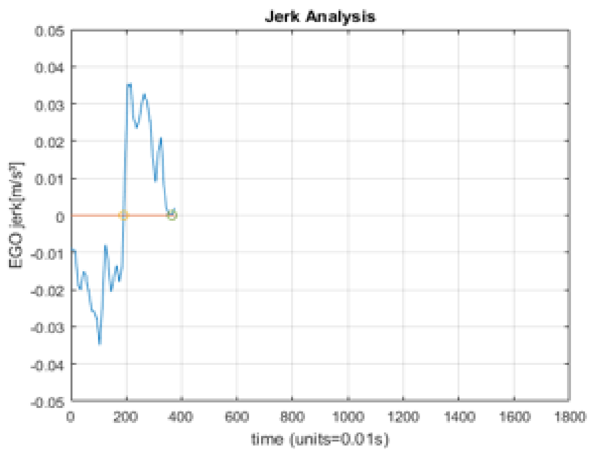
(a) *Gradient Analysis TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating3a = 8.5$



(b) *Gradient Analysis TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating3a = 7.9$



(c) *Gradient Analysis TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating3a = 7.5$



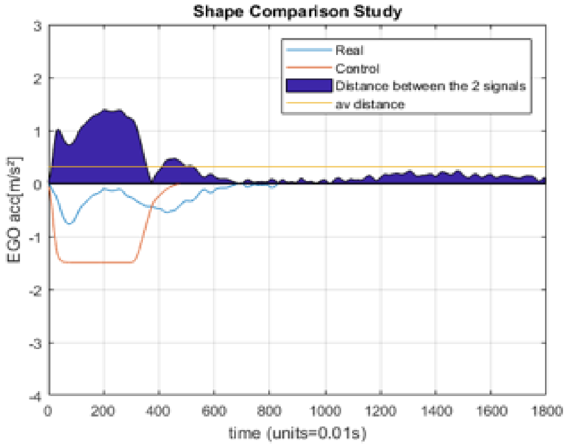
(d) *Gradient Analysis TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating3a = 5.8$

Figure 133: *Gradient (Jerk) Analysis: TOF free-lane Cut-In*

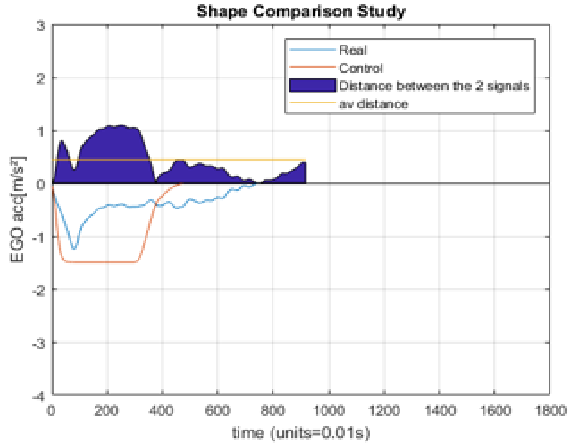
It is obvious that the worst rating is given to the fourth calibration.

5.7.4 Criterion 4: Acceleration Shape Comparison

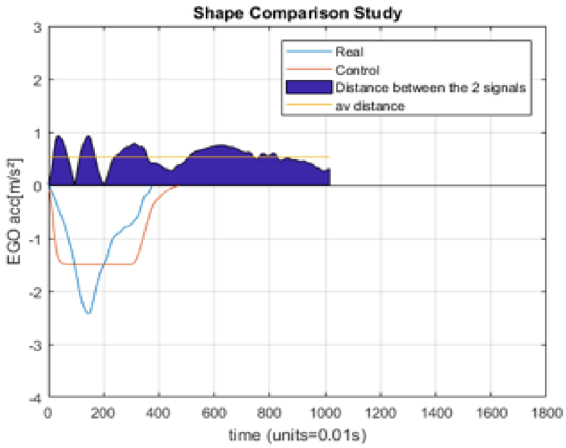
The differences among the signals are analysed by Figure 134.



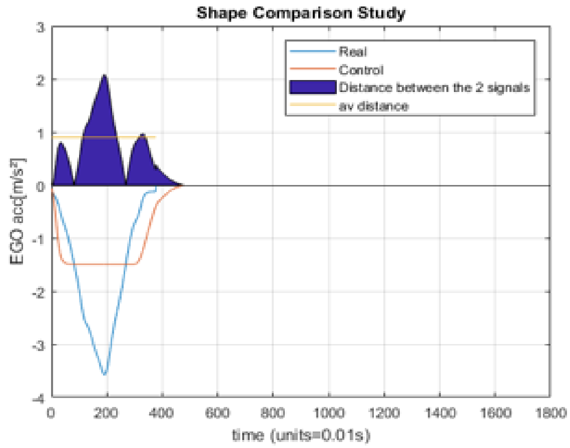
(a) *Acceleration Shape TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating4 = 8.5$



(b) *Acceleration Shape TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating4 = 7.9$



(c) *Acceleration Shape TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating4 = 7.5$

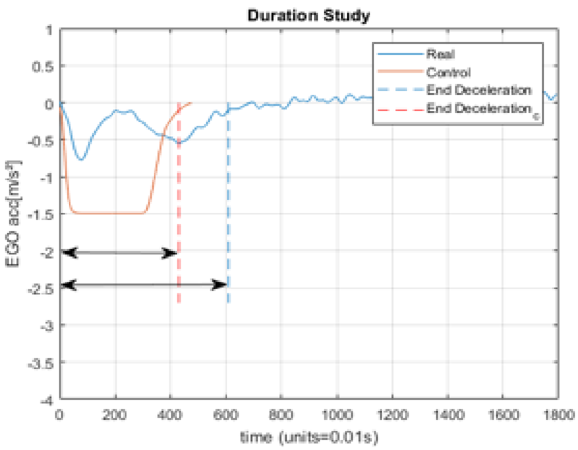


(d) *Acceleration Shape TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating4 = 5.8$

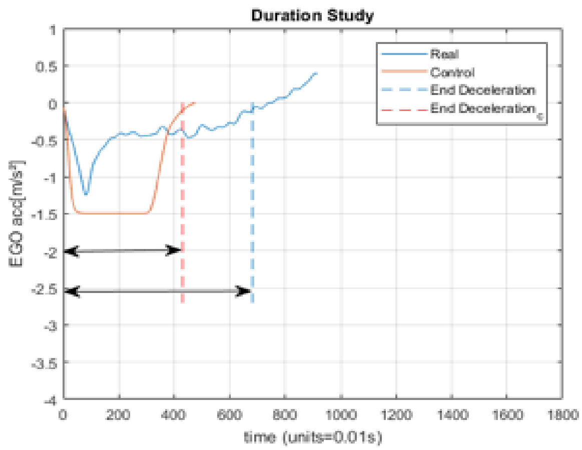
Figure 134: *Acceleration Shape Comparison: TOF free-lane Cut-In*

5.7.5 Criterion 5: Duration Analysis

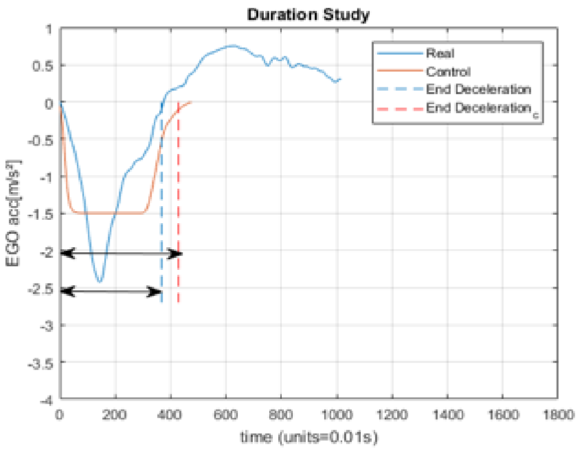
In Figure 135, the duration analysis is shown.



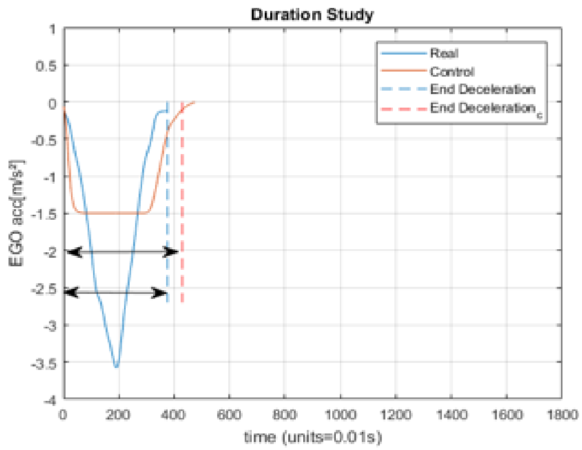
(a) *Duration Analysis TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating5 = 7.9$



(b) *Duration Analysis TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating5 = 7.4$



(c) *Duration Analysis TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating5 = 9.0$



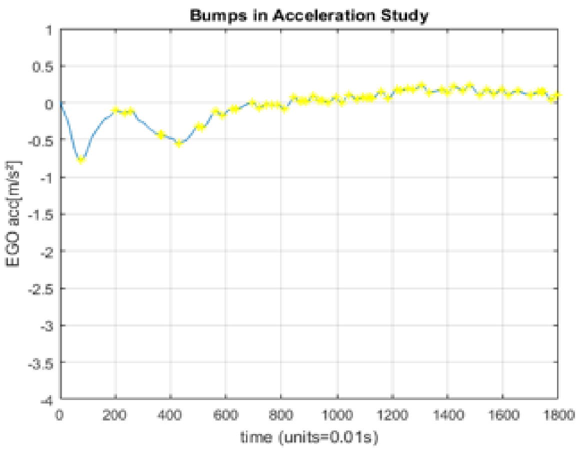
(d) *Duration Analysis TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating5 = 9.1$

Figure 135: *Duration Analysis: TOF free-lane Cut-In*

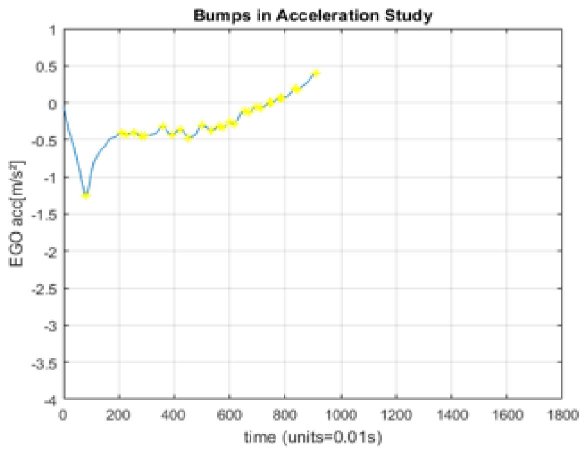
It is the first criteria that gives the best result to the fourth manoeuvre.

5.7.6 Criterion 6: Bumps in Acceleration Analysis

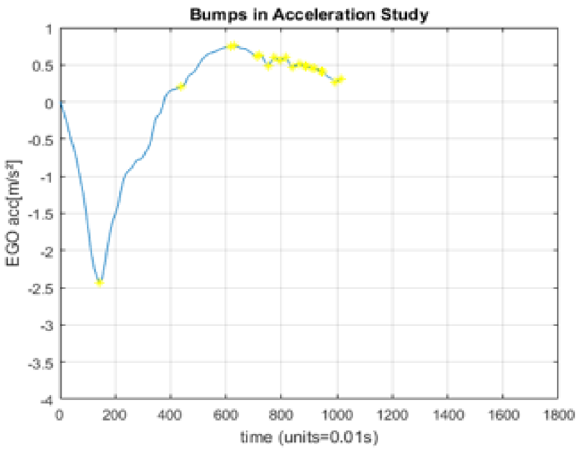
Figure 136 shows the bumps in the acceleration signal. It evaluates all the single irregularities in the signal.



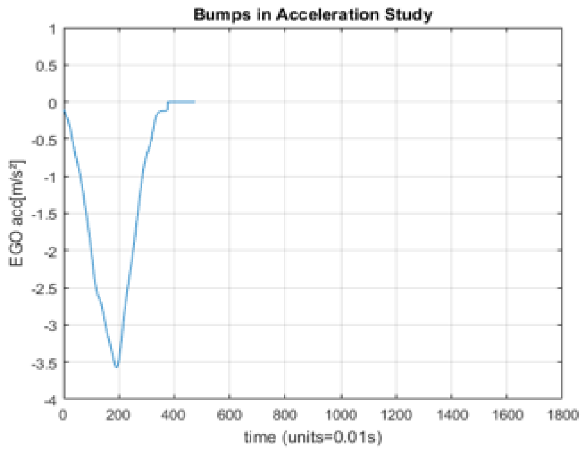
(a) *Bumps Analysis TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating6 = 4.6$



(b) *Bumps Analysis TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating6 = 4.0$



(c) *Bumps Analysis TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating6 = 3.4$



(d) *Bumps Analysis TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating6 = 10$

Figure 136: *Bumps in Acceleration Analysis: TOF free-lane Cut-In*

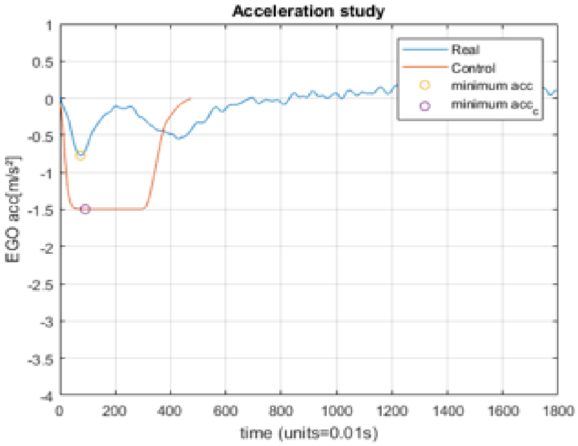
The best result is obtained by *Manoeuvre 4*.

5.7.7 Criterion 7: Position of Minimum Acceleration

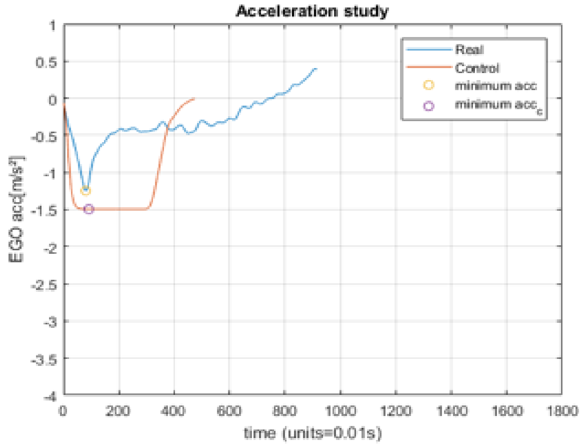
The position of the minimum acceleration is investigated.

Relative Position of the Minimum Acceleration

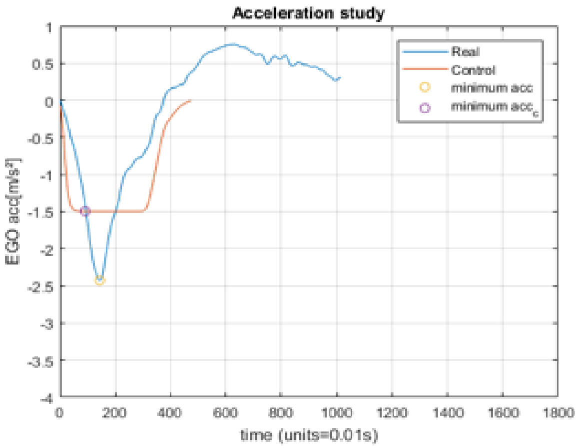
In Figure 137, the minimum achieved acceleration is holed in order to understand where it is positioned over the entire deceleration.



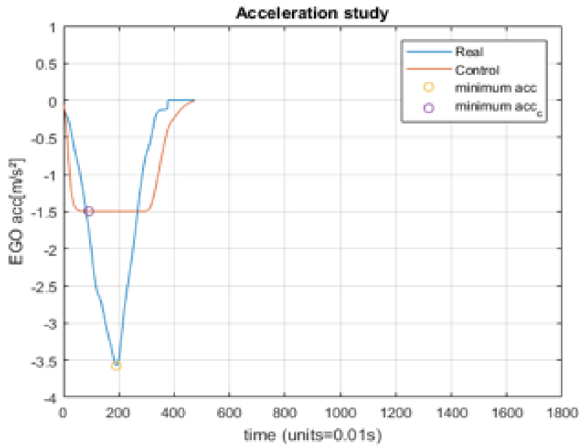
(a) *Relative Position TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating7 = 8.9$



(b) *Relative Position TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating7 = 9.3$



(c) *Relative Position TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating7 = 9.6$

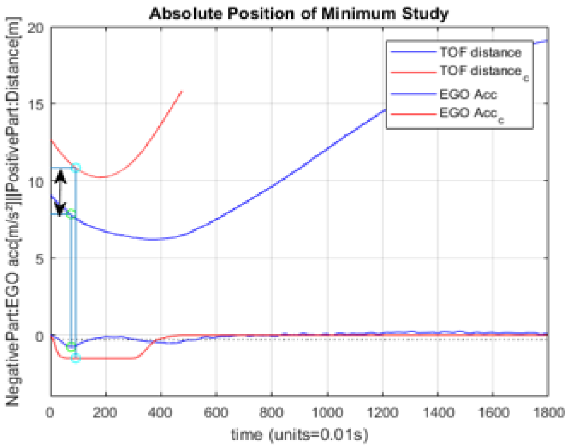


(d) *Relative Position TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating7 = 7.8$

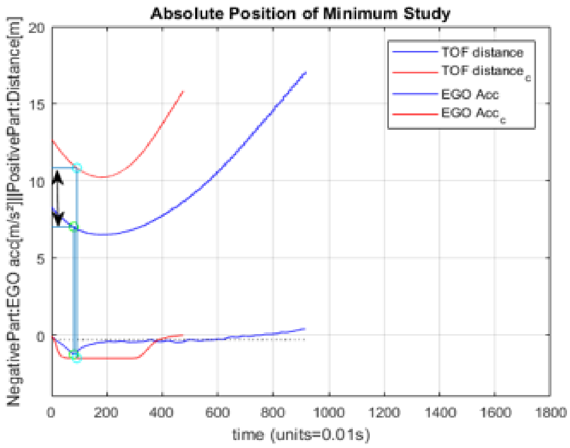
Figure 137: *Relative Position Analysis Comparison: TOF free-lane Cut-In*

Absolute Position of the Minimum Acceleration

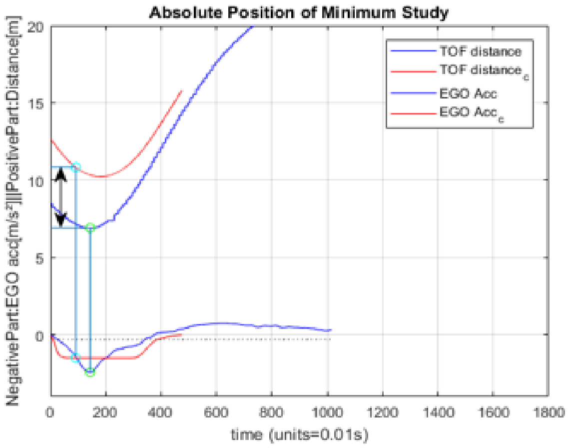
The minimum position is computed also in absolute terms considering the distance from TOF, the results are shown in Figure 138.
Some narrows are introduced to have a clear overview of the difference between the two curves.



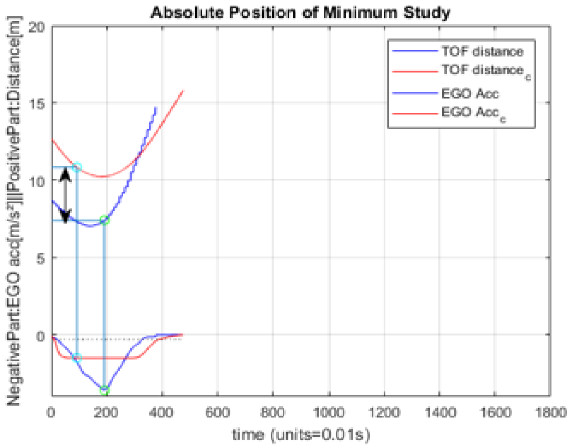
(a) *Absolute Position TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating7a = 8.1$



(b) *Absolute Position TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating7a = 7.5$



(c) *Absolute Position TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating7a = 7.5$



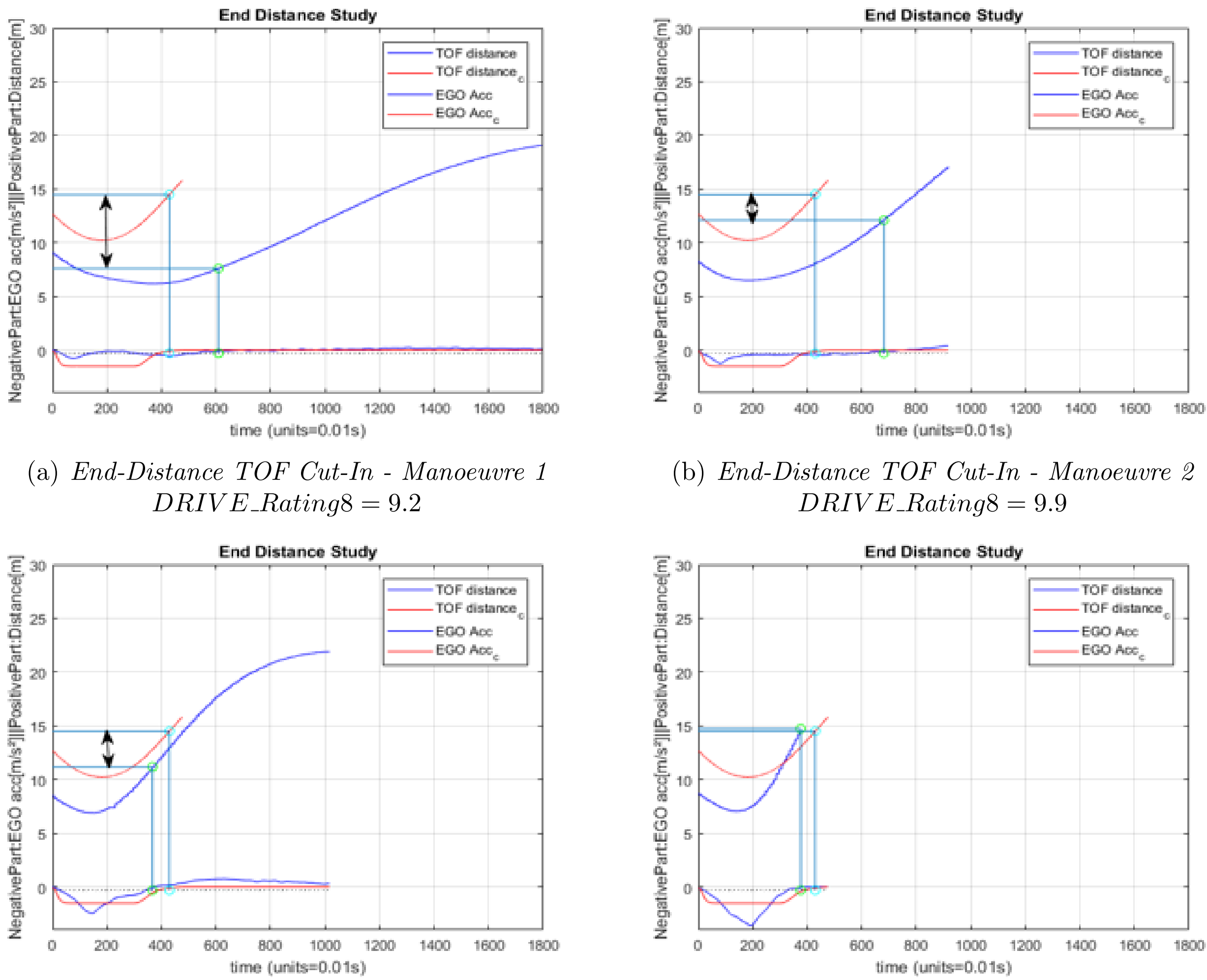
(d) *Absolute Position TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating7a = 7.8$

Figure 138: *Absolute Position Analysis Comparison: TOF free-lane Cut-In*

The results are quite close.

5.7.8 Criterion 8: End-distance Analysis

Finally , also the end-distance is estimated in Figure 139.



(a) *End-Distance TOF Cut-In - Manoeuvre 1* $DRIVE\_Rating8 = 9.2$

(b) *End-Distance TOF Cut-In - Manoeuvre 2* $DRIVE\_Rating8 = 9.9$

(c) *End-Distance TOF Cut-In - Manoeuvre 3* $DRIVE\_Rating8 = 9.8$

(d) *End-Distance TOF Cut-In - Manoeuvre 4* $DRIVE\_Rating8 = 9.9$

Figure 139: *End-Distance Comparison: TOF free-lane Cut-In*

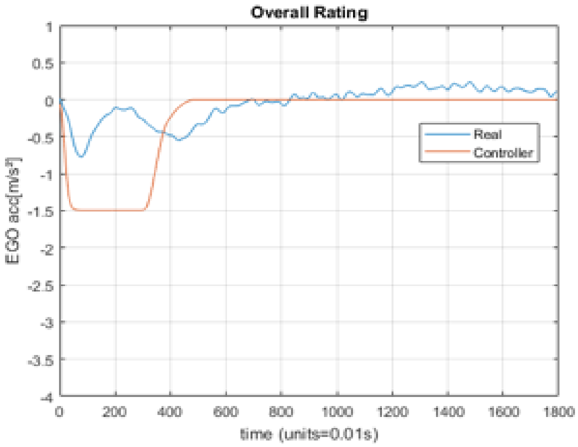
5.7.9 Overall Rating

The overall rating is weighted as follows:

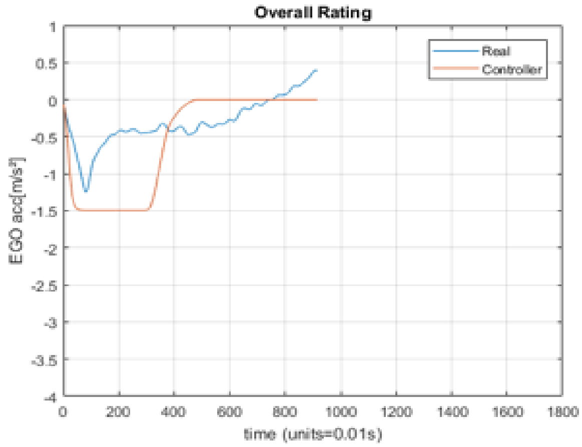
$$SAFETY = \frac{5RATE(2) + 3RATE(8)}{8} \tag{102}$$

$$COMFORT = \frac{5RATE(1) + 3RATE(3) + 5RATE(3a) + 3RATE(4)}{} + \dots$$
$$\dots + \frac{1RATE(5) + 3RATE(6) + 1RATE(7) + 1RATE(7a)}{22} \tag{103}$$

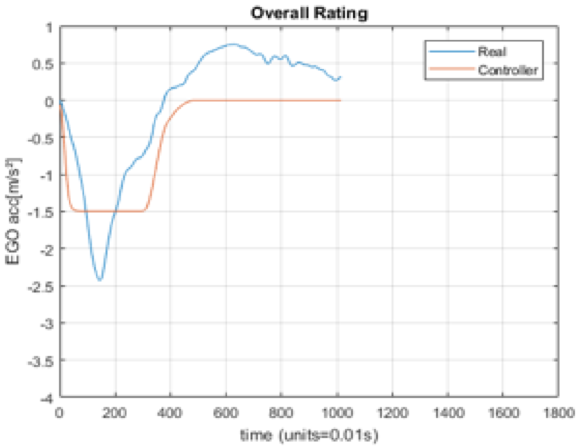
The results are presented in Figure 140.



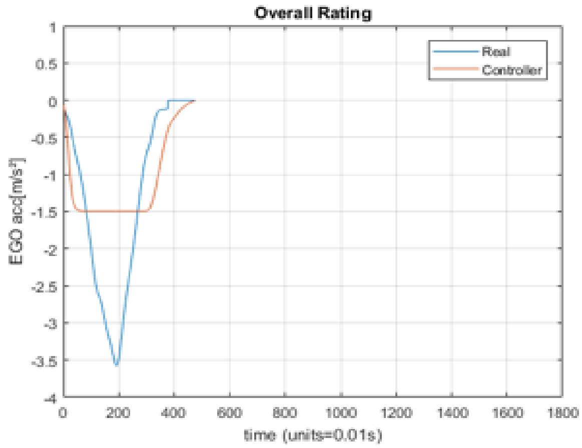
(a) *TOF Cut-In - Manoeuvre 1*
$OverallDRIVE\_Rating = 8.8$



(b) *TOF Cut-In - Manoeuvre 2*
$OverallDRIVE\_Rating = 9.0$



(c) *TOF Cut-In - Manoeuvre 3*
$OverallDRIVE\_Rating = 8.0$



(d) *TOF Cut-In - Manoeuvre 4*
$OverallDRIVE\_Rating = 8.1$

Figure 140: *Overall Rating: TOF free-lane Cut-In*

6 Conclusion

At the end of this work, a new rating methodology is developed.
Compared to the old one, it is flexible since the reference signal can be changed according to a new parametrization of the controller. This methodology allows to consider different people perceived impressions.
At the beginning of this work, several research regarding trustiness, acceptance and motion sickness are reported since the big issue nowadays it is not related to the creation of an autonomous vehicle, but to the acceptance and the adoption of it. Many people do not trust in autonomous vehicles, due to the strong disclosure made by media. A small group of people realizes how many incidents can be avoid adopting them. All of these considerations create a new research field related to the acceptance of autonomous driving.
During the entire study, the analysis of the acceleration signals of benchmark data delighted some common characteristics. The attention is directed to TOF-Approach, Follow Vehicle Stop and Follow Drive Away.
The acceleration signal shape reminds a Gaussian curve (see Figure 141).

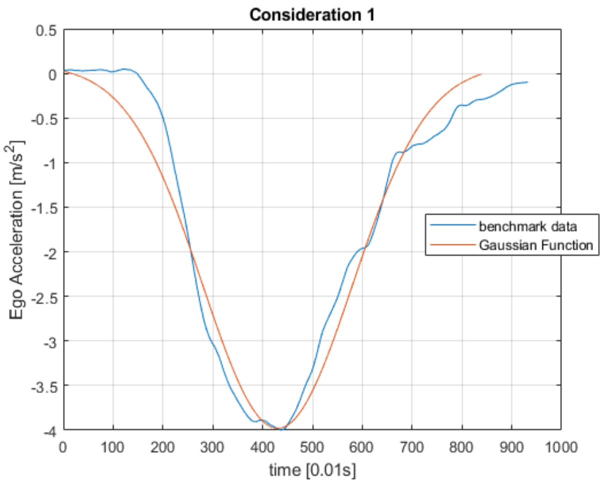


Figure 141: *Comparison between TOF-Approach acceleration and Gaussian curve*

The examined controller creates a trajectory according to the equations discussed in Paragrapher 3.1. They allow to create all the trajectories with a minimum initial and final jerk. The acceleration signal is always symmetrical, thus the minimum/maximum acceleration is achieved in the middle of the performed manoeuvre. In Chapter 1, the differences among people where investigated. Some people can be defined as 'anxious' when they are driving. For them, if the manoeuvre is performed as the controller does, it could be too stressful, since during their normal driving activities they prefer to decelerate or accelerate early. Conversely, if the driver is 'aggressive' or he/she drives more sportingly, he/she usually performs the manoeuvre later, e.g. the minimum deceleration in TOF-Approach is positioning after the middle point.
Instead using a polynomial equation, it could be more useful to substitute it with another function where the position of the minimum point is adjustable concerning the driver characteristics, delaying or anticipating it. Also the overall shape is adjustable with some parameters, for instance using a Gaussian curve, changing the variance, the roughness of the manoeuvre changes as well.
However, the main goal is to find a function that can be adjustable according to roughness and position of the minimum/maximum point and it should also have a starting and final deceleration almost flat, to maintain the jerk as minimum as possible.

All of these considerations fit well with some statistical distributions as Gamma or Chi-square distribution.
Figure 142 shows the gamma distribution

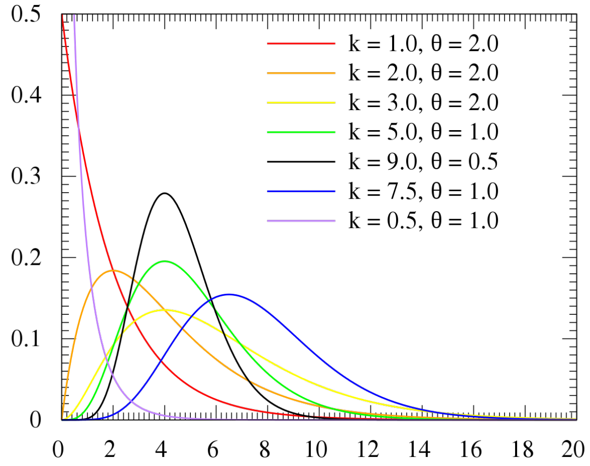


Figure 142: *Gamma distribution [27]*

7 Appendix A

7.1 TOF-Approach: High Speed

8 Appendix B

The MatLab® code of some interesting parts of the code are attached in this section to give some example of how the rating is elaborated.

8.1 TOF-Approach (Paragrapher 4.1.2)→Jerk Evaluation

```
vec=find(Acc_c < -0.002);
offset=vec(1);
time=1:length(Acc_c);

figure(2)
plot(Acc)
hold on
plot( (time-offset), Acc_c)
grid on
hold on
ylabel('EGO acc[m/s^2]')
xlabel('time (units=0.01s)')
legend('Real','Control')
title('Acceleration Study 2')
axis([0 1300 -5 0.5])


Duration_comp=((length(Acc_c)-offset)-length(Acc))/100;

acc_punkt= diff(Acc);

y=0*ones(length(Acc));

k=1;

%find of the zeros in jerk function (if they are near-> deleted)
for i=1:length(acc_punkt)
    if i>=2
        if(acc_punkt(i)<0 && acc_punkt(i-1)>0 || acc_punkt(i)>0 && acc_punk
            Var(k)=i;
            if k>2
                if (Var(k)==Var(k-1)+1)
                    k=k;
                else
                    k=k+1;
                end
            else
                k=k+1;
            end
        end
    end
end
```

```
figure(3)
plot(acc_punkt)
grid on
hold on
plot(y)
hold on
plot(Var,0,'o')
ylabel('EGO jerk[m/s^3]')
xlabel('time (units=0.01s)')
title('Jerk Evaluation')
axis([0 1300 -0.04 0.04])


figure(4)
plot(Acc)
grid on
hold on
ylabel('EGO acc[m/s^2]')
xlabel('time (units=0.01s)')
title('Acceleration Study Combined with Jerk')
axis([ 0 1300 -5 0.5])

for k=1:length(Var)
    figure(4)
    plot(Var,Acc(Var),'o')
end

%finding the most relevant ones

end_of_for_loop = length(Var);

minima_maxima_length = end_of_for_loop - 1;

minima = zeros(minima_maxima_length, 2);
maxima = zeros(minima_maxima_length, 2);

t=1;

for k=2:end_of_for_loop

    mini = 0;
    maxi = 0;

    for z=Var(k-1):Var(k)

        if acc_punkt(z) < mini
              mini = acc_punkt(z);
              minima(t, 1)= acc_punkt(z);
              minima(t, 2)= z;
```

```
        elseif acc_punkt(z) > maxi
              maxi = acc_punkt(z);
              maxima(t, 1)= acc_punkt(z);
              maxima(t, 2)= z;
        else
        end

    end

    t=t+1;
end

for t=1:minima_maxima_length
    if minima(t,1)>-0.01
       minima(t,1)=0;
    else
    end
    if maxima(t,1)<0.01
       maxima(t,1)=0;
    else
    end
end

z=1;
for i=1:minima_maxima_length
    if (minima(i,1)~=0)
        peak_m(z,1)=minima(i,1);
        peak_m(z,2)=minima(i,2);
        figure(4)
        hold on
        Acc(peak_m(z,2));
        plot(peak_m(z,2),Acc(peak_m(z,2)),'c*')
        z=z+1;
    end
    if (maxima(i,1)~=0)
        peak_m(z,1)=maxima(i,1);
        peak_m(z,2)=maxima(i,2);
        figure(4)
        hold on
        Acc(peak_m(z,2));
        plot(peak_m(z,2),Acc(peak_m(z,2)),'c*')
        z=z+1;
    end
end

peak_length=length(peak_m(:,2));

%smoothness study
for i=1:minima_maxima_length
```

```
    matrix(i,1)=minima(i,1);
    matrix(i,2)=minima(i,2);
    matrix(i,3)=maxima(i,1);
    matrix(i,4)=maxima(i,2);

end

 T=0;

for i=1:length(Acc)
    if (Acc(i)<-0.3)
        T=T+1;
    end
end

 smoothness(1,1)=0;
 smoothness(1,2)=T/100;
  j=1;
 if minima_maxima_length>1
    for i=1:(minima_maxima_length-2)
        if (matrix(i,1)~=0 && matrix(i+1,3)~=0)
            smoothness(j,1)=matrix(i+1,3)-matrix(i,1);
            smoothness(j,2)=(matrix(i+1,4)-matrix(i,2))/100;
            j=j+1;
        elseif (matrix(i,3)~=0 && matrix(i+1,1)~=0)
                smoothness(j,1)=matrix(i,3)-matrix(i+1,1);
                smoothness(j,2)=(matrix(i+1,2)-matrix(1,4))/100;
                j=j+1;
        end
        if (matrix(i,1)~=0 && matrix(i+2,3)~=0)
            smoothness(j,1)=matrix(i+2,3)-matrix(i,1);
            smoothness(j,2)=(matrix(i+2,4)-matrix(i,2))/100;
            j=j+1;
        elseif (matrix(i,3)~=0 && matrix(i+2,1)~=0)
                smoothness(j,1)=matrix(i,3)-matrix(i+2,1);
                smoothness(j,2)=(matrix(i+2,2)-matrix(1,4))/100;
                j=j+1;
        end
    end
 end

parameter_rating_2=3; %time of the peak interesting
smoothness_rating2_amp=1/exp(max(smoothness(:,1))/-minAcc_c)*10;
smoothness_rating2_freq=(1/(1+exp(-parameter_rating_2*1.2*(max(smoothness(:
num_peaks_smoothness=length(smoothness(:,1));


z=1;
for i=1:length(Acc)
    if Acc(i)<=-0.3
```

```
        dec_time(z)=time(z)+1;
        z=z+1;
    end
end

RATE(2)=((0.3*smoothness_rating2_amp+0.7*smoothness_rating2_freq))*(-0.01*r

DRIVE_Rating_2= round(RATE(2),1)

%% Gradient (jerk) analysis

number_strong_gradient=length(peak_m(:,1));

for i=1:length(peak_m(:,1))
    rate_gradient(i)=(1-5*abs(peak_m(i,1)))*7+3;
end



y=ones(length(Acc));
figure(3)
plot(0.01*y,'y')
hold on
plot(-0.01*y,'y')

RATE(3)=min(rate_gradient);

DRIVE_Rating_3 = round(RATE(3),1)
```

8.2 Follow Drive Away (Paragrapher 4.3.2)→ Acceleration Shape Comparison: Major Differences

```
figure(14)
plot(dist)
hold on
grid on
plot(dist_c)
area(evaluation2)
ylabel('difference between EGO and TOF')
xlabel('time (units=0.01s)')
legend('difference','difference_c','shape difference of the 2 signals')

%shape = zeros(length(evaluation2));

for i=1:length(evaluation2)
    if evaluation2(i)>1
        shape(i)=2;
    elseif evaluation2(i)>0.5
        shape(i)=1;
    elseif evaluation2(i)<-1
        shape(i)=-2;
    elseif evaluation2(i)<-0.5
        shape(i)=-1;
    else
        shape(i)=0;
    end
end

num_diff=0;
num_diff1=0;

for i=1:length(shape)/2
    if shape(i) == -1
        num_diff=num_diff+1;
    elseif shape(i) == 1
        num_diff1=num_diff1+1;
    elseif shape(i) == -2
        num_diff1=num_diff+2;
    elseif shape(i) == 2
        num_diff1=num_diff1+2;
    end
end
for j=i:length(shape)
    if shape(i) == 1
        num_diff=num_diff+1;
    elseif shape(i) == -1
        num_diff1=num_diff1+1;
    elseif shape(i) == 2
        num_diff1=num_diff+2;
```

```
    elseif shape(i) == -2
        num_diff1=num_diff1+2;
    end
end

RATE(3)=7*(1-(num_diff/length(shape)*0.6+0.4*num_diff1/length(shape)))+3;

DRIVE_Rating_2a=round(RATE(3),1)
```

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