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Statistical study and simulation of the acceleration of a vehicle into the 3D-method

Master Thesis

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DECLARATION

Declaration in Lieu of Oath / Eidesstattliche Erklärung

I hereby declare in lieu of oath that I composed the following thesis independently and with no additional help other than the literature and means referred to.

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Literatur und Hilfsmittel angefertigt habe.

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ABSTRACT

The objective of this Master Thesis is the statistical study and simulation of the acceleration and accelerator pedal position of a vehicle within the 3D-Method developed at "Institut für Fahrzeugtechnik" of the TU Braunschweig. This project has been realized with Matlab R2012a.

Nowadays, everything is studied through different analysis and simulations before the manufacture of a car or a new model of car, carried out in computers, in order to save money and time.

Here is where this project takes place. Real data from different kinds of drivers in different environs was collected, with the purpose of making a statistical studies and simulations with them. In this Master Thesis, the software programs Matlab and Simulink are going to be used.

The method, which is achieved, is named "3D parameter space", the "Institut für Fahrzeugtechnik" work in it, which is the institute where has been made this project, and which is going to be explained.

First of all, a statistical study of the speed takes place. Then, a statistical study of the acceleration, and simulation of a vehicle are developed to work with the accelerator pedal position, and its influence when some parameter is modified. Finally, this project is part of a greater project, so it will be implemented later as a part of it.

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FOREWORD

I want to thank and to dedicate this Master Thesis to a lot of people, because with it I finish my degree. This year has been special for me, because there are a lot of people that I would like to mention along these years who are or have been close to me.

In the academic aspect, I would like to thank to the "Universidad Pública de Navarra (UPNA)" for the opportunity with the Erasmus Program to go abroad this year to finish my degree, to know another country and culture, and to learn a new language. I would like to thank also to the "Technische Universität Braunschweig" and the "Institut für Fahrzeugtechnik" for having given me the opportunity to do my Master Thesis with them. I want to thank to my supervisor, for helping me with it, teaching me and giving me more knowledge about vehicles, Matlab and automotive engineering.

In the personal aspect, I want to thank to my whole family, especially and above all, my father, my sister and my mother who have always supported me along all these years, and without them, this would not have been possible. I want to thank to my friends, who live in Spain, because they have always been very important for me along these years in the difficult and in the good moments. And finally, I want to thank to all the friends that I have met this year, specially my "Spanish family" in Braunschweig, and specifically in Weststadt, and more specially some of them, who have supported me all along, and who have lived this experience with me. Thanks a lot to everybody.

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1. INTRODUCTION

1.1. Motivations

Nowadays, before the manufacture of a car or a new model of car, everything is studied before through different studies and simulations.

Here is where this project takes place. Real data from different kinds of drivers in different environs was collected, with the purpose of making a statistical studies and simulations with them.

Thanks to these simulations carried out with the computer, it is possible to save time and costs, which otherwise would increase. In this Master Thesis, the software programs Matlab and Simulink are going to be used.

The method, which is achieved, is named “3D parameter space”, the “Institut für Fahrzeugtechnik” work in it, which is the institute where has been made this project, and which is going to be explained. In this introduction it is described in which consist of and the reasons why it is done etc. to achieve a better understanding of the project that has been carried out throughout these months.

Then, it will be explained how the project which was presented to work, has been carried out, how it has been made and the results obtained at the end.

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2. STATE OF THE ART AND 3D PARAMETER SPACE

2.1. State of the Art

In this part it is going to be explained how this Master Thesis has been organized, to understand better what comes next. To achieve everything that has been described until now, the project was divided in five parts.

First of all, there is an introduction. In this part, the motivations and objectives of this project are going to be discussed. After that, the state of the art and the 3D-method is explained. In this part, is talked a few about the scheme of this Master thesis, i.e., the structure of this document, and how it has been organized are exposed. In the third section, the "3D parameter space" is described, the method which was developed in the "Institut für Fahrzeugtechnik", where this project has been performed. Therefore, it is going to be tried to explain briefly the idea of this project and how it has been made, before it is explained meticulously.

In second place, is had the initial situation, which consists of three chapters too. The first part is about the OGP which was given in the Institute, and it has been improved until is reached the objective which was proposed. So is explained what it was at the beginning and the objective to reach. The second part is the new model and how it has been gotten, the process, the problems that there were had and the final result. In the third part is talked about how it has been reached and how it affects in the next phase of this project.

In the third section will be described the part of this project, where has been worked with the acceleration. It is divided in three modules. In the first module, is continued working with the previous step, with the OGP, but instead the speed, in this case is used the acceleration. This entire module, like the previous one, is executed with MATLAB. The second module consists of a simple simulation of a vehicle in Simulink, in which in function of the acceleration pedal position, will be obtained different speeds and accelerations. The last module is the third one, where will be

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simulate the built module previously in Simulink, and it will be checked to confirm the right operation, another to create a set of tables for different acceleration pedal positions, another one to obtain the accelerator pedal position with the speed and acceleration of the vehicle, and a last one to study this last varying the rpm.

To finish, the results, the conclusions, with the future work and the discussion of the errors, the bibliography and the references, and the appendix. Here is resumed this entire project, synthesizing the results that have been obtained and the conclusions that can be deduced about it. Furthermore is talked about the application that it can have and the future work which can be developed and reached through this entire project; and the discussion of the errors that there are along the project or in the results. Is also had the bibliography which is very little, because is an innovate project and there is just not information. And the appendix to understand that there are in the CD.

2.2. 3D Parameter Space

In this section is going to be explained the method which is carried out in the "Institut für Fahrzeugtechnik", where has been accomplished this Master Thesis, the "3D Parameter Space", to understand better everything, which has been done after this paragraph, the objective of this project, and how it has been reached.

First of all, it is going to be explained why it arises, about CO_2, hybrid vehicles and their control, etc. And in the second part is explained the 3D method, in which consists, and how it is carried out.

Nowadays is known that fossil energy sources are finite and the problem with the CO_2. For that, car manufacturers are developing and optimizing alternative drive concepts. Furthermore, is worked in the continuous improvement of the active safety of the vehicle by advanced driver assistant systems, which sense the driving environment and the drivers behavior. With this information is managed to increase the efficiency of the driver system through an intelligent and predictive energy management.

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The differences in consumption result by real traffic, real road and driving style, although fixed shift points, the energy consumption of air conditioning are not taken into account. In driving style, the fuel consumption varies, it depends on the driver. There are defined three types of drivers: intelligent (and predictive), normal and sporty.

There are two kinds of control in hybrid vehicles, hybrid vehicles with conventional control strategy and hybrid vehicles with intelligent control strategy. This last one differs from the other one in terms of the additional information from the driving environment, and information about the driver too.

For a predictive control strategy can be used information from advanced driver assistance systems for environment detection, for example, the Global Positioning System (GPS), the Adaptive Cruise Control (ACC), the Traffic Sign Recognition (TSR), the Driving Style Detection, and the Car-2-x Communication.

For the analysis of the CO_2 potential of an intelligent hybrid control strategy in the cycle and in the customer use is considered a parallel hybrid, which is represented in the simulation with a conventional as well as with an intelligent control strategy.

The DRV method allows the acquisition, measurement and simulation of vehicles and their components in customer use. The DRV parameter space and the customer behavior are measured in a lot of driving tests, where normal drivers drive the vehicles in real traffic on representative roads.

The modular development platform for DRV simulation is based on variants. A statistical description of the road, the driver, and the vehicle model are required for the mathematical modeling of the driving process in customer use in the simulation, apart from the physical representation of the vehicle. The validation of the simulation model is done on the engine test rig.

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The control of the hybrid functions may be by the conventional control strategy or by the intelligent control strategy. Only the energy management is optimized, which results in the maximization of the recuperation energy, and also in intelligent energy application for the fuel consumption. The conventional control strategy is characterized by a conservative basic parameterization of the hybrid functions. The intelligent control strategy is realized by predictive drive control. It uses information to calculate a prediction of the speed, acceleration and gradient progression. The intelligent control strategy influences the state of charge of the battery, the distribution of the drive power, the use of the boosting function and the activation of the start/stop function.

To finish are had the results of the simulations. The comparison of both results shows the significantly higher recuperation share of the intelligent control strategy. First results of customer simulation show a significant potential in reduction of fuel consumption.

After that, is going to be explained the second part, the 3D method. The 3D-method is used to identify the customers' requirements and thus enabling to meet their demands. The 3D method allows the representation and acquisition of the customer behavior and the resulting representative requirements on the vehicle and its components. It is based on the 3D parameter space (driver, driving environs and driven vehicle), which is used to analyze the customer operation systematically. It includes driving tests where parameters related to the 3D parameter space are kept using sensors, when different types of drivers drive under real traffic conditions. These data contain information about driver, environment, road and traffic. This information is studied statistically and used as input parameters, which is used to reproduce the customer operation virtually in the context of the "3D Parameter Space".

The "3D Parameter Space" is characterized by different parameters: the driver behavior, the driving environs, and the driven vehicle. Using the 3D method for analyses requires introducing defined values for the 3D parameters, there are three different driving style, the parameter road includes four values: urban, extra urban, mountain and autobahn, and the vehicle parameter has four different types: light, average, full and full plus. The combination of these parameters results in 48.

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A simulation model with a few vehicle parameters is needed to determinate the requirements on not yet existing vehicles. A model is generated using a statistical driver model, which is parameterized by means of the statistically processed measuring data of the data base. The statistical road model generates a rectangular and road gradient profile during the simulation. The driver model reacts on changes in the orientation speed profile using the vehicles interfaces. The vehicle simulation model implements the driver actions, allowing the determination of time signals of interesting variables.

For an optimal vehicle concept, the adjustment of the individual components to the mentioned requirements does not lead to the desired results, due to several components have been approaching to the reality for a complete consideration of the vehicle system.

The results of the 3D simulation can be used as a basis for the constructive design of vehicle components for generating representative test cycles. The results of the load analyses for individual components respectively lead to 48 scalar load factors. In the load matrix, the maximum value for each component is determined from these variables and classified to the appropriate 3D customer type.

To compare characteristics, were performed extensive 3D measurements in different markets, such as the measurement of road. The measurement data was recorded and evaluated separately depending on the type of road.

In order to finish, the 3D method represents a great tool to provide information on the customer use in development phases. Furthermore, analyses show that experiences gained in customer operation can be used in field of electrified drivetrains, and international 3D measurements allow market specific vehicle developments.

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3. INITIAL SITUATION

3.1. Detecting Acceleration Maneuvers

Initially, the "3D Parameter Space" was introduced to familiarize with the method and the work which is carried out in the "Institut für Fahrzeugtechnik", and in this Master Thesis is based on. To start this project and to understand better what was going to accomplish, the first part of the Master Thesis was to introduce into the work which was going to do and the use of Matlab. This part was made in group and it is a study of the speed of a car. A set of files and data was given, and the objective was to improve it till to reach the main purpose trough different small tasks. The purpose was to achieve an approximate speed to real speed fulfilling a number of requirements.

At the beginning, there were three original files (Signalaufbereitung_6Gang_MT, Statistiken_erstellen_6Gang_MT, and OGP_Erzeugung) and four files of data from BMW. The data are the information which is needed to work, the first two files are studied but not modified, only the third file is modified. At first were had originally these results, which had to be improved to obtain the real purpose.

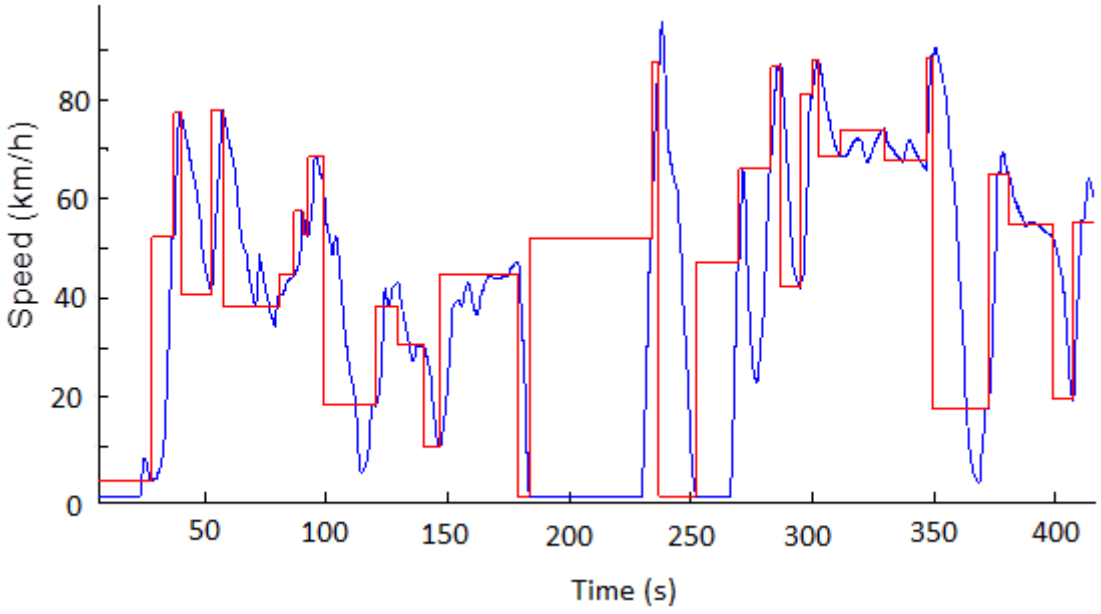

Fig 3.1.1: Real speed of a car and the original approximated speed given (1)

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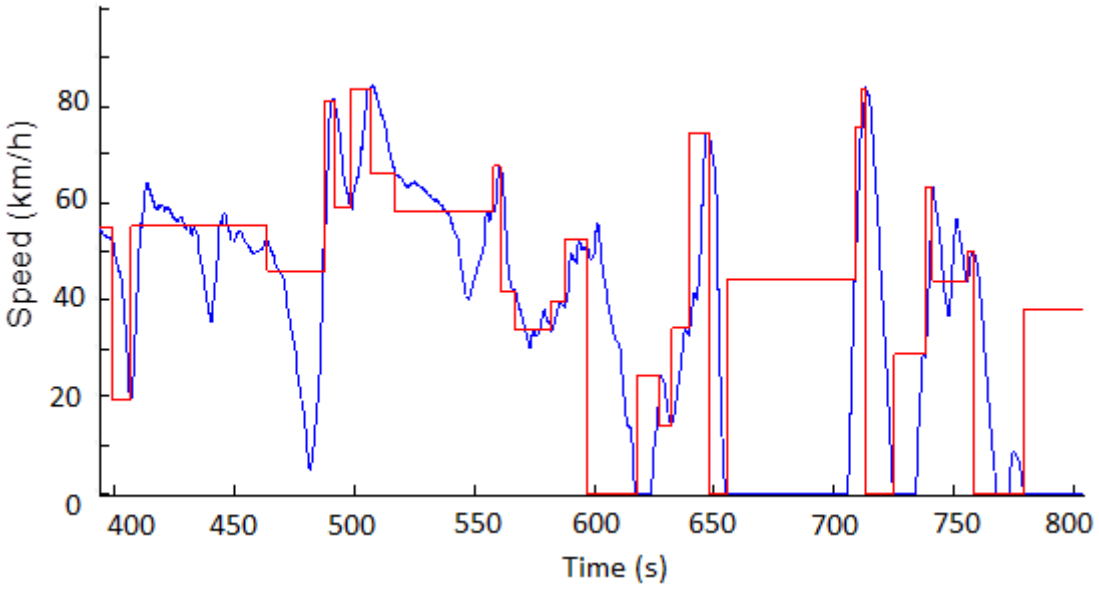

Fig 3.1.2: Real speed of a car and the original approximated speed given (2)

As can be watched it is not a very good approximation to real speed, because not collects or selects on right manner the maximums, the minimums, the plateaus, and often distorts quite the reality, moving away from a consistent approximation. So this is the task that starts this Master Thesis, to find a more real approximated solution.

This section was made among three Spanish Erasmus students: Miguel Pradini Aranda, José Ángel Lacalzada and Aitor Diaz de Cerio (the author of this Master Thesis). The first chapter after the theoretical explanation corresponds to the first task which makes up this project, before each one started with different assignments, and it is the classification of the speed. The main problem of this task is that there is not a certain value, which repeats periodically. Therefore, the problem is not possible, which was divided in smaller ones. Furthermore, there are two problems in addition to this disadvantage. On one hand, the interaction of external variables, which are independents of the driver and driver's desires, such as, the oscillation caused by gear shifts. And on the other hand, the need of identifying not only the global changes of speed, but also the changes of intensity with which the driver is accelerating. As follows is explained the steps taken to get the result which was asked.

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3.2. Model explanation

3.2.1. Detecting the Relevant Points

The first step to classify is to detect the local maximum and minimum values, due to almost all the points, which are interesting, belong to this group, with the exception of the changes of intensity of the acceleration.

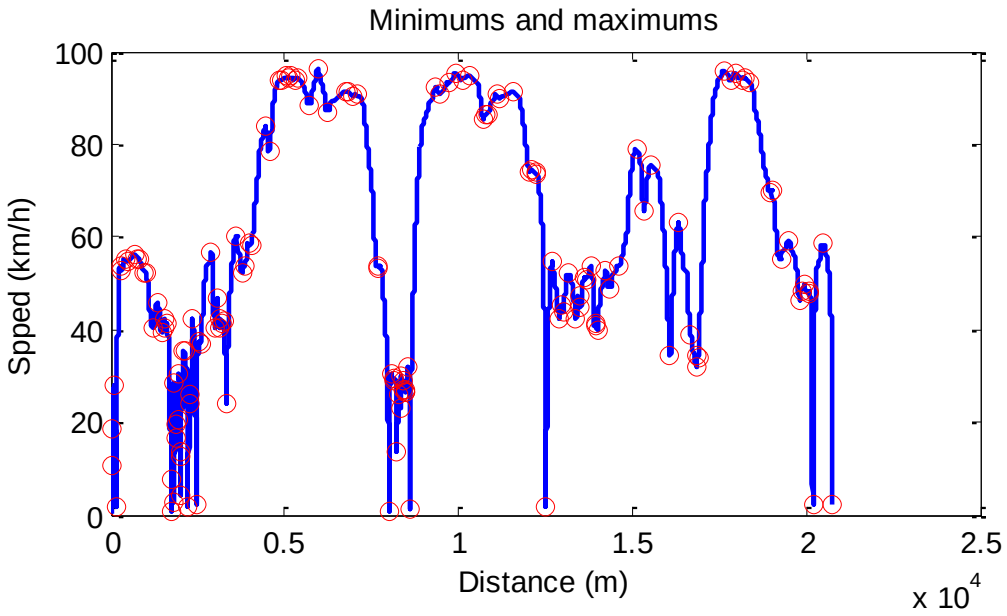

Figure 3.2.1.1: Graphic where is represented all the maximums and the minimums of the real and original speed function

Nevertheless, not all these points are of interest, therefore, must avoid taking two points, whose values were too close, are only taken when there is a relevant change of speed. This gap is set to be 5 km/h, although there is one additional complication. For instance, if the initial velocity is 50 km/h and want to be reached 100 km/h before slowing down again, is not wanted to observe a change in the “veck” vector each 5 km/h. Instead, would be considered one single change from 50 to 100 km/h. However,

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while is going along the vector with the speed and is produced a change of tendency in it, is not known yet if the speed, which is going to reach, is a relevant change of speed, in which case should be taken the previous point, or simply a small variation which will finish soon.

To carried out this idea, is required to keep a “candidate" value, and once have been confirmed that is true that there is a change of tendency in the velocity with a speed gap greater than 5 km/h, is allowed to take this previous value. This is the idea which has been developed in this initial task of this project, with the constantly updating of the potential value along the vector, and only keeping the latest value, which had been proved to be it, before relevant changes. So each time a change was identified, the point of reference for the accurate value is processed.

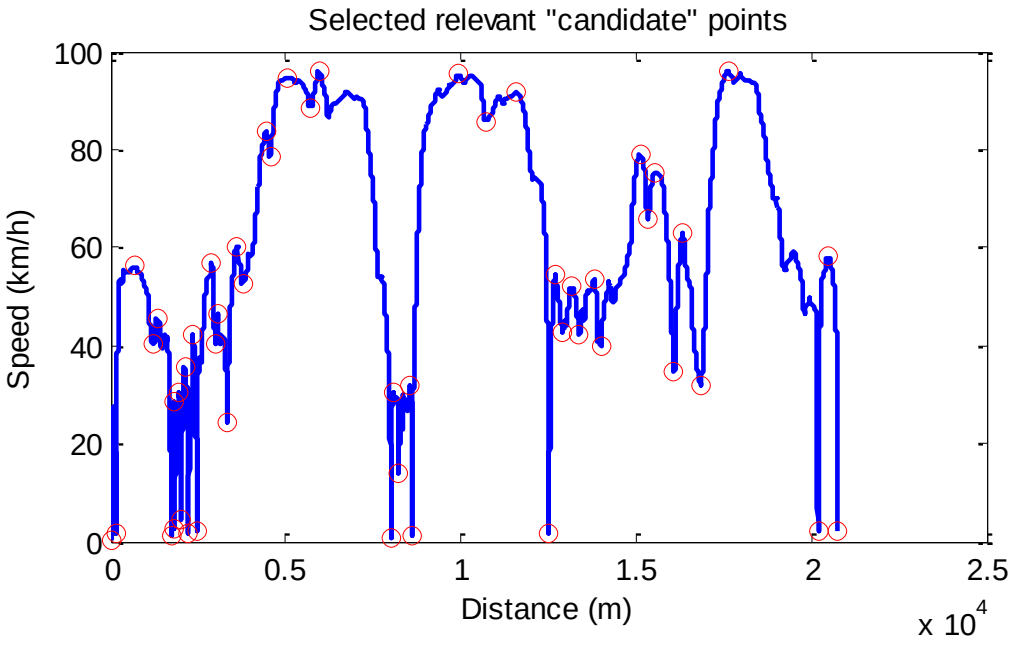

Figure 3.2.1.2: Graphic where is represented the relevant “candidate” points among all the maximums and the minimums of the real and original speed function

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3.2.2. Identifying the Changes of Intensity of Acceleration

Some driver behaviors, especially the braking and the acceleration are maneuvers which should be considered as different actions, because even if the average derived of these parts have the same sign, they hold back values quite different.

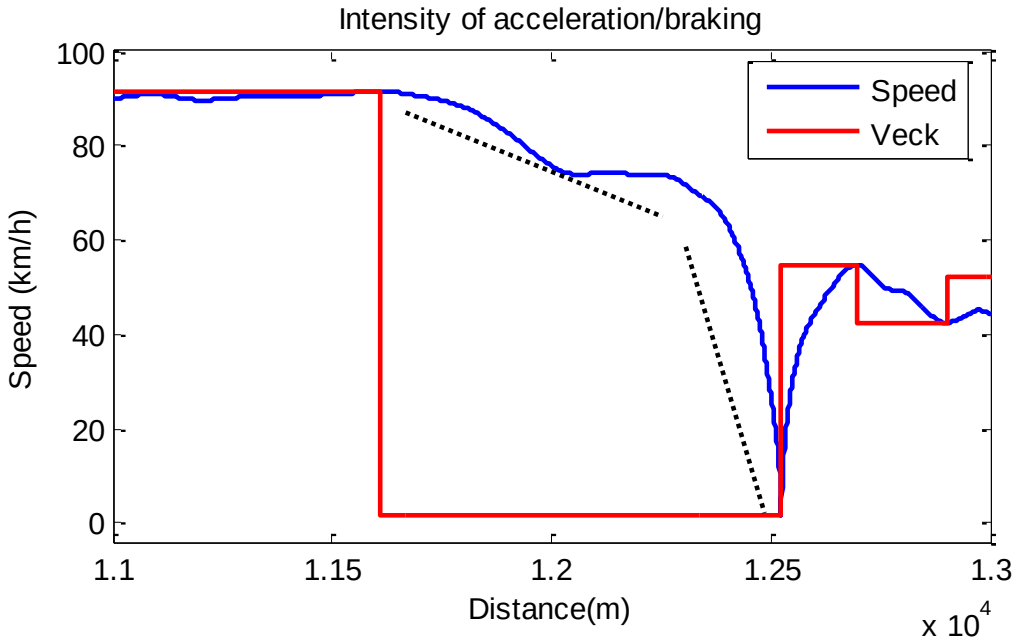

Figure 3.2.2.1: Graphic where is represented a significant change in the real speed of the vehicle

These situations do not always correspond to maximum values, so to identify them, must be gone along the speed vector a second time, once is already had the "candidate" values that rule the main changes of speed according to the driver's behavior. After that, is built a line connecting those points, where is represented the average speed change in that section, can compare distances of consecutive points to that line. The maximums and minimums extracted of that process are mainly the wanted points, given that the total distance exceeds a minimum value.

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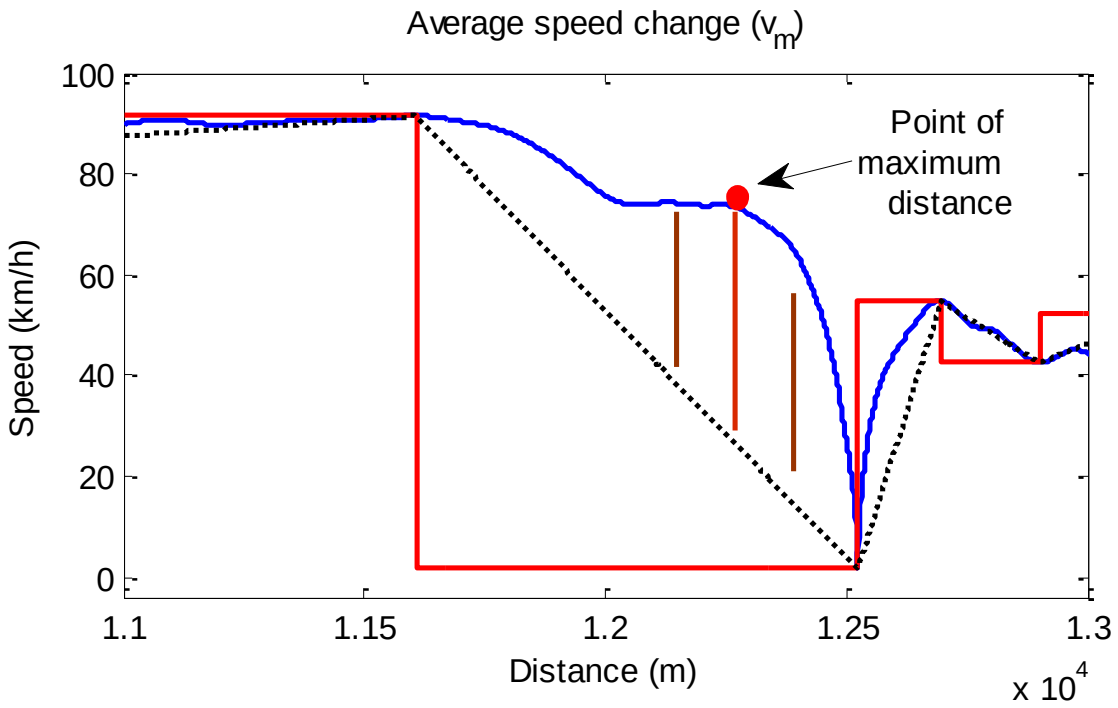

Figure 3.2.2.2: Graphic where is represented the average speed change in that section, can compare distances of consecutive points to that line

The next step is to analyze the result between the limits of that section, in smaller steps, to try to identify the values with the maximal and minimal differences to the average line. Nonetheless, this new part will result in the obtainment of more points, being not all of them necessaries.

3.2.3. Filtering

In consequence, must be filtered the total number of points, which are had, because not all the points comply the desired requirements. So now and on, is worked with the point which are had, namely, will not be added news points, and will only be subtracted from the selection, the points which do not help to the final purpose.

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There are three stages of filtering:

- **Stage 1:** are eliminated the detected points which origin was a gear shift.

- **Stage 2:** the points obtained at paragraph 3.2.2, which do not represent a change of acceleration big enough, are discarded by comparing the variation of the average derivative with the neighbor selected points.

- **Stage 3:** are deleted the points which are too close to each other, in other words, under the gap of 5 km/h, due to the fact that one was provided by the strategy in paragraph 3.2.1, and the other one in paragraph 3.2.2. The strategy to accomplish this is to assign a likelihood value to each point according to the values of the surroundings. This is the last step, but the most complex and the most difficult of the three filters to create and to run well.

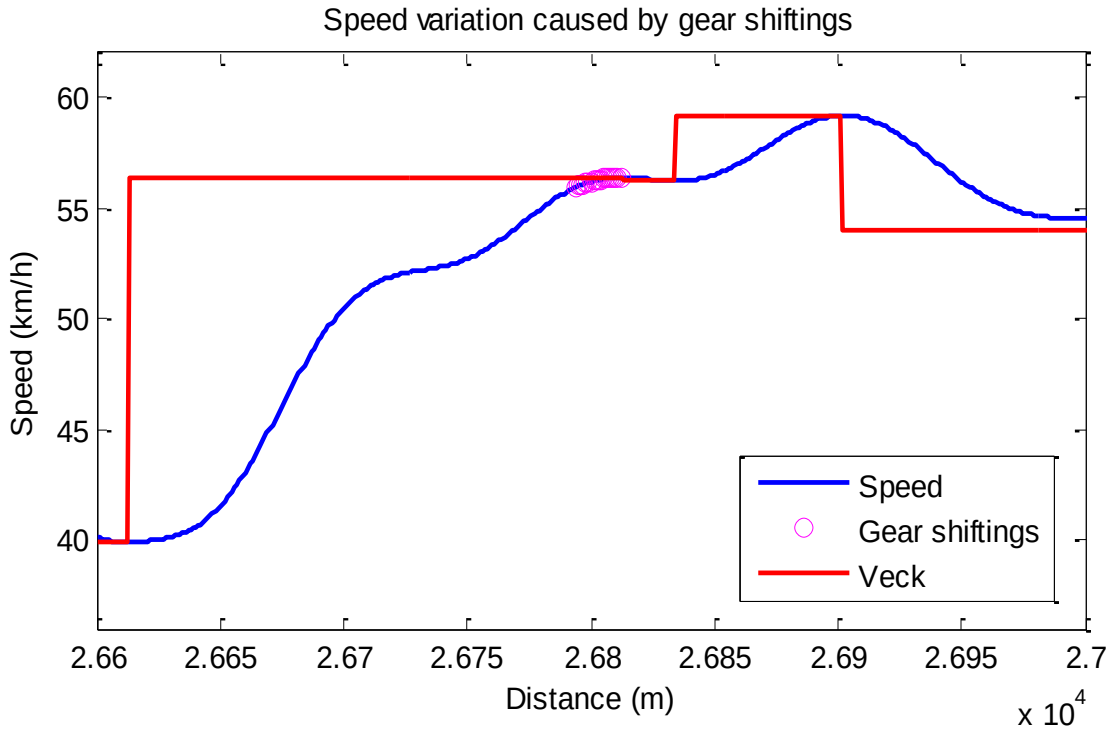

Figure 3.2.3.1: Graphic where is represented an example of an undesirable point obtained due to a gear shifting

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On the whole, the result obtained can be considered satisfactory and good, since it seems to be enough accurate, fulfilling the objectives of this first part of the project about the study of the speed.

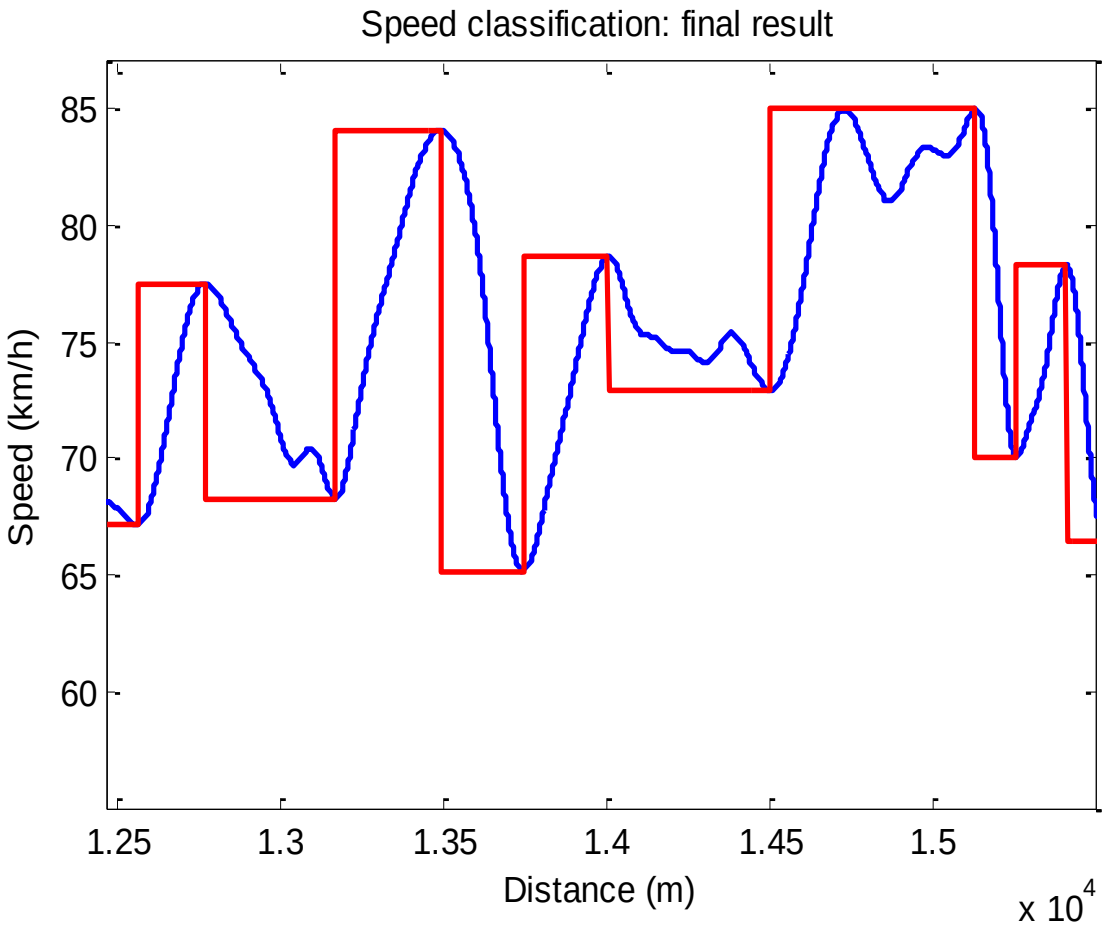

Figure 3.2.3.2: Graphic where is represented the real speed and the approximated gotten speed

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3.3. Problem

Finally, are explained discarded strategies, and that have not been used and the reasons, such as the acceleration, but in another cases can be used and to run.

Therefore, as has been said, were followed other strategies, like to try to identify the changes of the acceleration. However these strategies were worse for several reasons. The first strategy to be considered, and an obvious one, because their data are had, is identifying in the throttle position and brake pedal position profiles the significant variations.

On one hand, the brake pedal, as is normal, is used in braking maneuvers, so is been able to accomplish a good correlation between the significant points of speed and braking. On the other hand, the throttle position cannot be dealt in the same way, because even when the driver is trying to drive at a constant speed or changing the vehicle's speed, he has to accelerate to compensate variations or elements, due to the car enters in contact with driven environment, like friction between road and wheels, air resistance, etc. Nevertheless, this effect can hide the effect caused by other variables such as slopes, so it adds difficulty to the problem; however overtaking maneuvers must be identified as desired speed changes when they cause such changes. Besides, the acceleration required also a lot of processing and filtering with its own problems and more importantly it depended of the car model. The acceleration needs a separate study and work, which is carried out later in this Master Thesis, so it is not used now, but it is a possibility to improve this task.

The intuition makes thinking that a car with a powerful engine requires the throttle to be pushed softer to produce the same amount of acceleration and consequently the same change in the speed. For this reason it is not possible to set a universal comparison value that covers any possible car, and this information is not included in the Matlab files. Although at the beginning it could seem more intuitive, this made that the strategy was discarded.

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4. ACCELERATION

4.1. Acceleration Study in Matlab

This new section is different from the previous chapter, although both parts are linked. In this new paragraph is worked another variable of the car, the acceleration.

Previously, until now, has been worked the speed of the car. The velocity of a vehicle has been seen and studied through Matlab. With the data that were provided, the speed was worked, until the fixed objective was reached. This data were in different files which have been made in Matlab. In these files it can be found that the data contains different variables like the speed, the acceleration, the gear shift, the brakes, etc. With these variables it has been reached the objective to approximate the velocity graphic to the real speed on the significant points.

In view of that, now, the variable of the car, after the speed, which is going to be worked, is the acceleration, which is the purpose of this project. In these chapter, is going to be worked this variable, but not like in the previous section. In other words, is not only studied the acceleration with Matlab, if not also with Simulink. Therefore, besides the work in Matlab, such as with the velocity, is simulated a vehicle to study its behavior depending on the acceleration.

First of all, in this section can be seen the study in Matlab, which is similar to the previous part of the Thesis, and which is explained then.

Afterwards, in the next two chapters, the focus of work changes. Is going to be used the Simulink, because is going to be simulated the behavior of a vehicle in function of the acceleration, as will see later. In the first of them, will be built a model of a car, a simple model, instead of a real model, due to the complexity to make a real one in Simulink, with the time, the knowledge, the technology and the suitable means to carry it out in the department. It is going to be checked to prove the right operation

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of the model and after that it is going to be modified to obtain the steps that are necessary to achieve the final result. It is explained in the chapter 4.2 with higher detail.

Finally, in the last chapter of this section, the final step and the final simulation are made with all the information that is necessary to accomplish the aim fixed in this project. It is going to be explained in detail in the chapter 4.3.

To begin with this new variable, it starts with the first part, the study on Matlab. To carry out this work a code, which is going to be explained now, has been written. The code consists of three great sections. The first one is shared in two parts; the most important one is to find the characteristic points, in other words, from graph obtained in the previous case to the speed, the relevant points in the graphic where the vehicle is increasing the velocity. It will be explained in greater detail next. After that, are located the velocity plateau points, where the speed in the graphic is more or less constant into a range of values which is considered acceptable to call it plateau.

The second one is to calculate the average acceleration among these points. This is carried out with the variable “DKI” from the data, which is the accelerator pedal position (APP), so in every moment the APP is calculated, when the acceleration is named. As was worked to obtain the approximated speed from the real values of speed which were measured through different sensor and were processed to study, the real values of acceleration pedal position are had to calculate the approximated acceleration pedal position. Catching the range of values, which is where the velocity increases or until the beginning of a plateau, is calculated the average acceleration pedal position in this range with the real values of acceleration pedal position.

The last part is to represent this average acceleration in a graphic. For that, the acceleration, like in that case, is drawn in the same graphic, where was represented the speed previously.

With this last one, the study in Matlab of the acceleration is finished. After that the

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study in Simulink will start. But before, now, the code is going to be explained in more detail, and the results that have been obtained. The code can be watched in the CD, which is with the Master Thesis.

Firstly, it is to find the most characteristic acceleration points. This aim is executed in two different tasks. In first place the points which represent a speed increase are found. The representative points, which were selected to represent the speed in the previous chapter, are taken, and into this range of points are selected these new points. The sections between points where the speed increase are the wanted ones. For that the points whose speed is upper or equal than the last speed point are located, and if not the points whose speed is lower than the last speed point and lower than the next speed point, as beginning of a upslope speed; and they are saved. The first and the last point are taken too, all the points are classified, from low to high time, and saved in a vector.

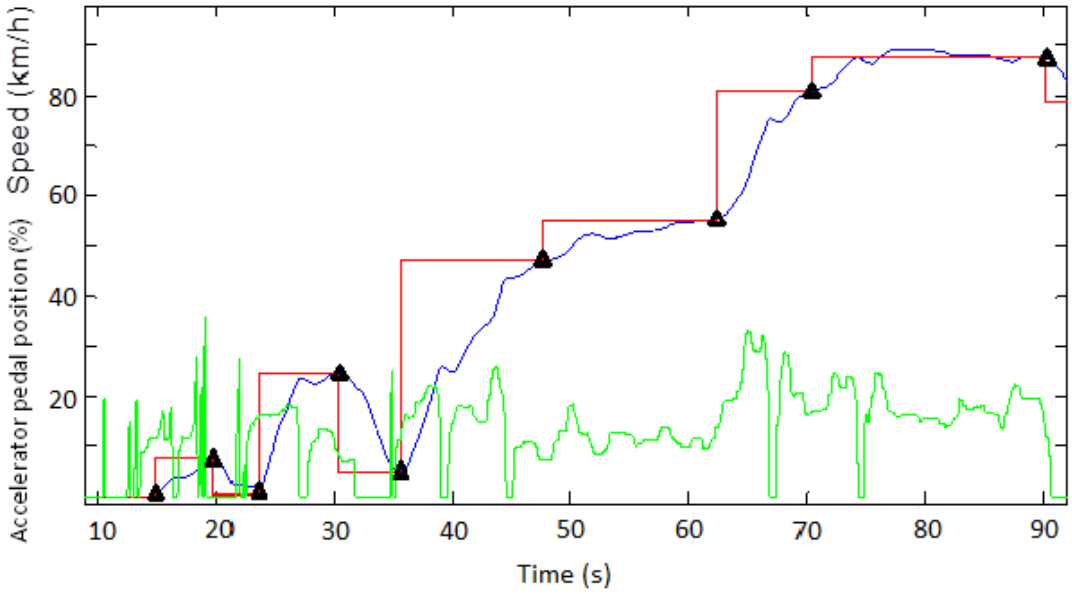

Fig 4.1.1: The points which represent a speed increase

In the second place the points which represent the beginning of a velocity plateau are found, where the speed in the graphic is more or less constant into a range of values which is considered acceptable to call it plateau. First of all two continuous points which were saved in the previous vector are selected, and it is watched if the slope is positive, in other words, if the next speed point is higher than the first one.

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After that, it is analyzed all the points in the speed range between these two points. It is taken a range that is not fixed, it depends on the data, and it can be modified. In this study it is selected in first case that the one point was the highest speed; the range of time was, between the first point of all and the next that is studied, higher than 3 and with the previous slope positive; and the range of speed was, between the end point and the point is studied, lower than 5, and the range of time between the same points was higher than 15. If all these conditions are fulfilled, then this point inside the range is saved in a vector, this value is the beginning of the plateau, and the last point of the range is saved in another one. This process is made with all the values till the final one. Now, it has to link the two vectors, the vector of the first part, and the new one which contains the beginning of the plateau. So is returned to analyze the vector of the first part, once more between two continuous points. Inside this two values, the vector which has saved the final points previously is studied, if the point of the first part is the same that the one of this vector is not saved, but if it is different is saved the point of the first vector in another new one. At the end these new ones, which are the values of the first part without repeated points and the beginning values of a plateau are saved and classified in function of the time, having the vector which is looked for with the relevant points.

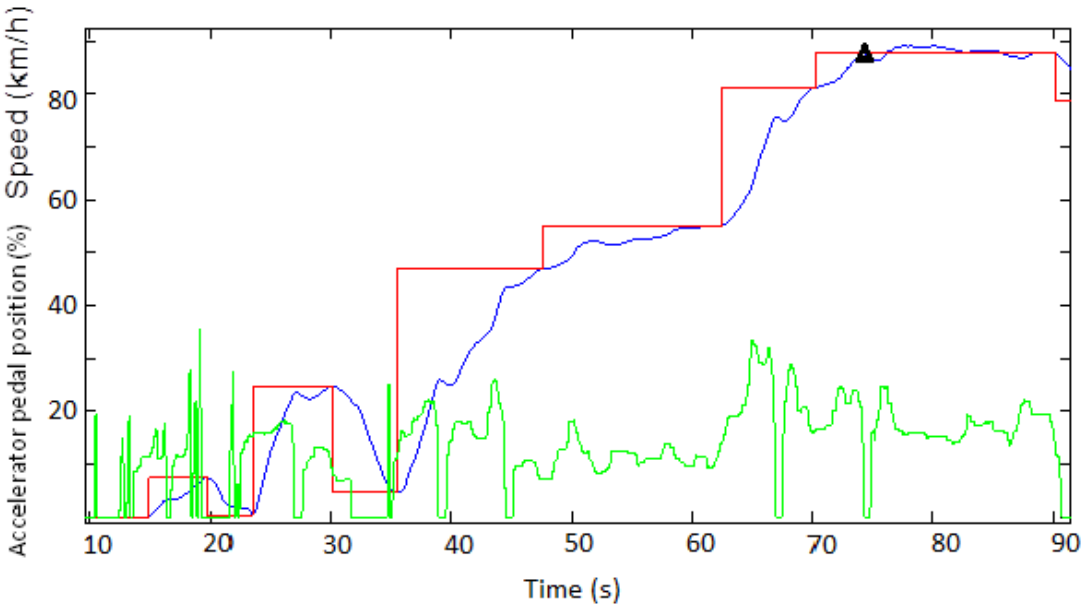

Fig 4.1.2: The points which represent the beginning of a velocity plateau

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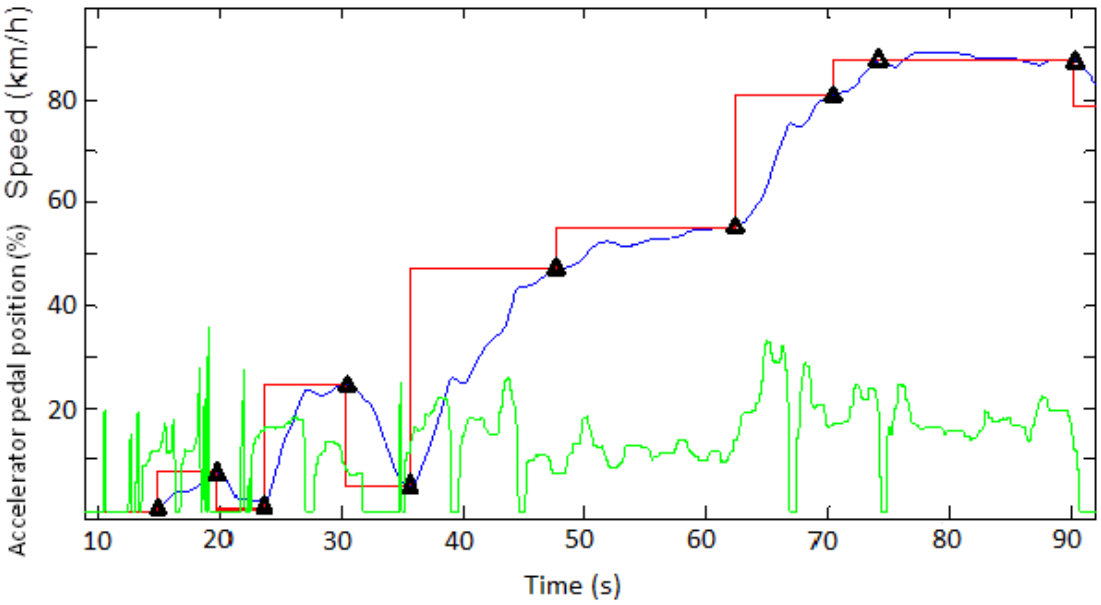

Fig 4.1.3: All the representative points to calculate the average acceleration

Secondly, the average acceleration among these points is calculated. Once selected all the points needed to carry out the proposed objective, can be executed this step. All the points are saved and classified, according to the time, in a vector. Two continuous points are selected, if the speed of the first is lower than the second one, the average acceleration pedal position is calculated adding all the real acceleration pedal positions values between these points and dividing by the number of values taken, as an average is calculated, and the valor of this average is saved in a new vector. If the speed of the first is not lower than the second one, then the average value is zero, and is saved in the same new vector. And so with all the pairs of points, which are had in the first vector, and at the end a zero is adding in the new vector to finish it.

Lastly, is represented this average acceleration in a graphic. The new vector which represents the average acceleration is taken, and it is drawn in the same graphic, where was represented the speed previously. This is made; creating a new last vector, where from one point to the next point is given the correct average value corresponding from the vector of the previous part, and at the end it is given the last average value. Once this vector, which represents what was looked for, is had, it is drawn in function of the time, obtaining the graphic that was the purpose of this part of the Thesis.

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In order to finish, can be appreciated this work in the different graphics along this part, and these last graphics. It can be watched the acceleration pedal position, its average value when the representative speed increase and at the beginning of a plateau representative speed, which was the aim of this part of the Thesis, working with Matlab.

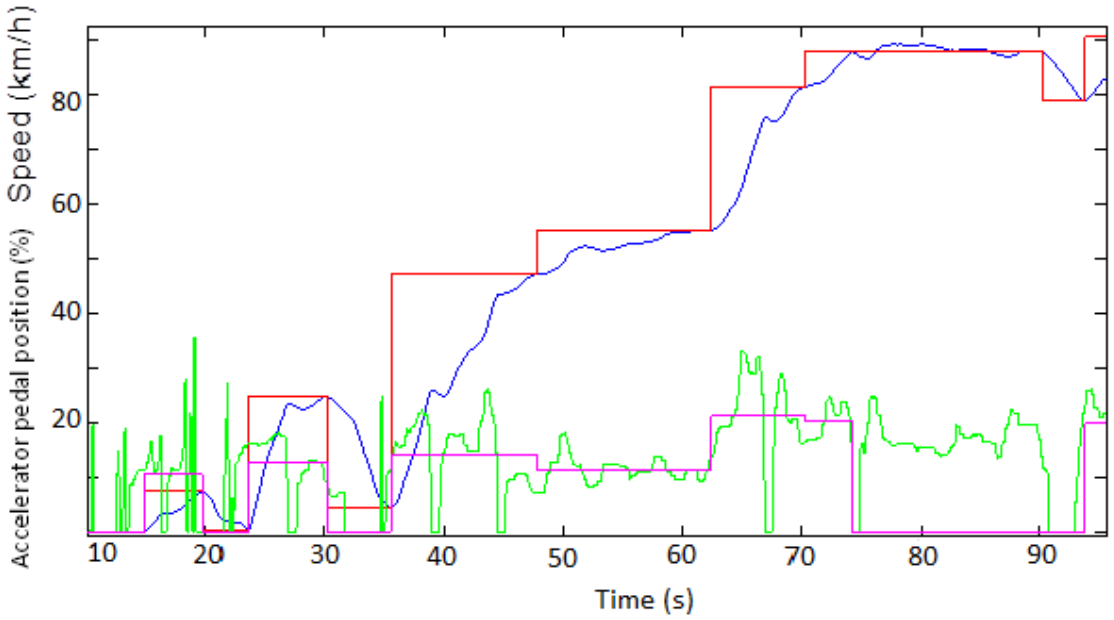

Fig 4.1.4: The objective of this chapter of the Mather Thesis, the studio of the acceleration in Matlab

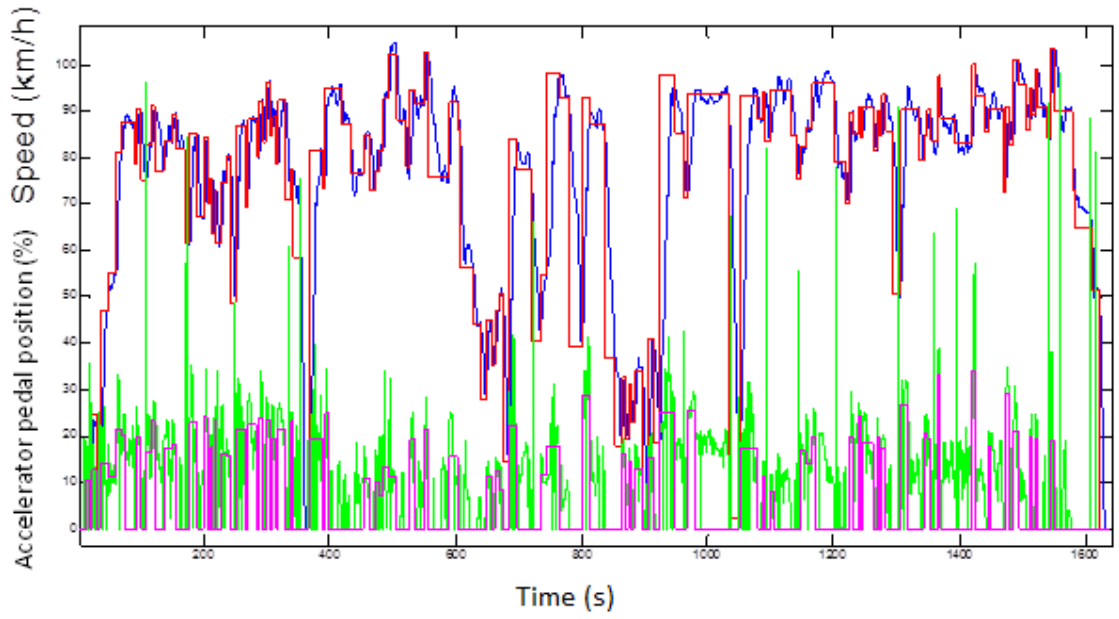

Fig 4.1.5: A complete graphic with the study of the acceleration in Matlab

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4.2. Vehicle Simulation

4.2.1. Introduction

Since few years ago, virtual dynamic system simulation has become very important in the design and development stage, as the vehicle procedures can be examined without expensive measurements and with reduced time. The driveline is a fundamental part of the vehicle that transforms the energy from the combustion in the engine to kinetic energy of the vehicle. It is of great importance that the driveline is done as efficient as possibly, to lead to better performance and lower fuel consumption. The driveability and comfort must be high for the driver. To reach this it is important to be able to simulate its behavior, and for that it is important to have a model of it. It is going to be described a simplify simulation of the powertrain of a vehicle to this purpose. The main elements of the powertrain include the engine, clutch, gearbox and transmission, and the car body.

In this part of the thesis a study of a driveline modeling is made. A modular programming approach in Simulink environment is used for the simulation. Have not been used components from the Simulink library, like engines or transmission models which are done yet. Every part and their components have been defined by mathematical equations together with standard components or blocks from the library.

Nowadays is increasing for the drivers a better development of efficient vehicles. Accurate off-line models can be used in vehicle design and development, which can provide advantages, for example reducing cost and time. The power train provides the driving torque necessary for handling and vehicle acceleration. Although the model is developed and validated for a specific engine, due to take into account the data which have been provided, is generic enough to be used for a wide range of spark ignition engines.

The main objective in the simulation is being able to obtain the throttle pedal position with the acceleration and the speed. Now the next step is to make a

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description from the different blocks, parts and subsystems of the powertrain model which are going to be used in the simulation.

4.2.2. Basic Equations

The driveline is the system that transfers the signals from the driver (gear lever, accelerator and brake pedal) via the combustion in the engine to vehicle speed. It is represented in the figure 4.2.2.1. The different parts and subsystems of the driveline are an engine, clutch, gearbox, transmission, propeller shaft, final drive or differential, drive shafts and wheels. In order to understand better what is going to be simulated will be explained the fundamental equations for the powertrain. Furthermore, some basic equations regarding the forces which actuate on the wheels are obtained. These equations are influenced by the complete dynamics of the vehicle, which means that the effects, for example, from the vehicle mass and from the aerodynamics will be described by the equation describing the wheels.

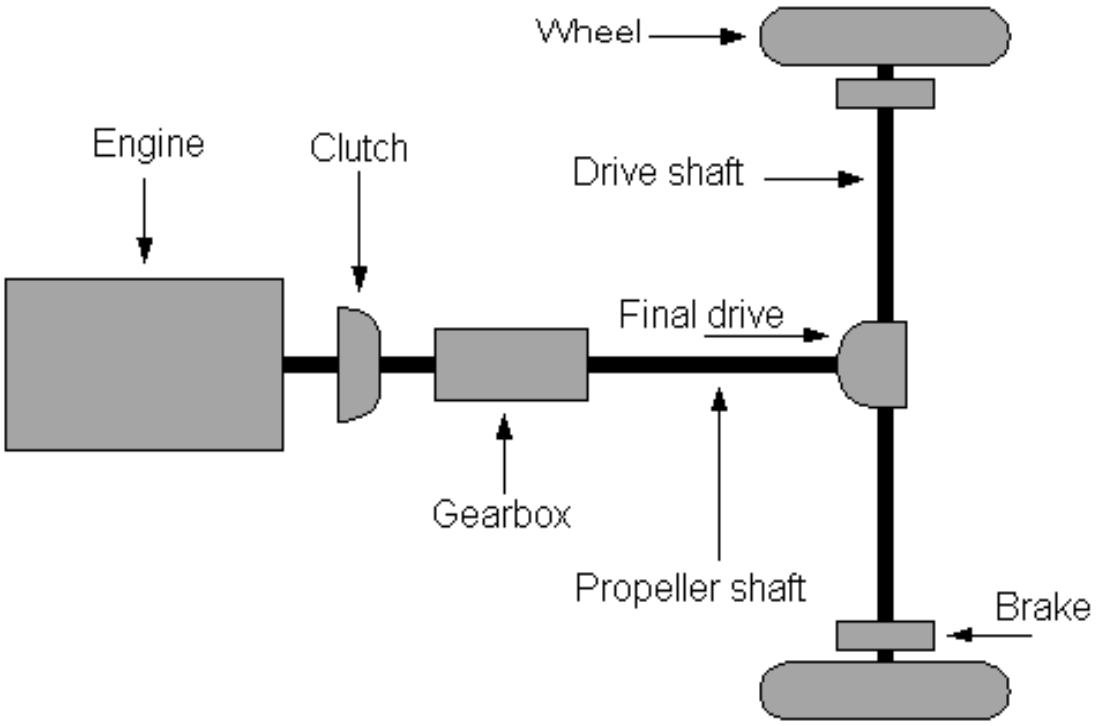

Fig 4.2.2.1: Driveline for a rear-driven vehicle

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- **Engine:**

Engine is the power source in the drivetrain and is controlled with the accelerator pedal. The output from the engine is the torque resulting from the combustion (T_e), and the resulting engine speed, the internal friction from the engine (T_{fe}), and the external load from the clutch (T_c). The generalized Newton's second law of motion gives this model:

$$J_e \cdot \dot{\omega}_e = T_e - T_{fe} - T_c \qquad (4.2.2.1)$$

where J_e is the moment of inertia of the engine and $\dot{\omega}_e$ is the angular acceleration of the flywheel.

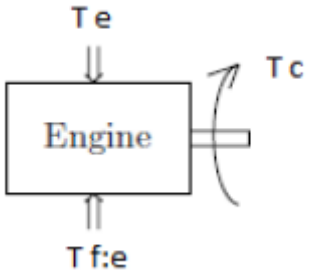

Fig 4.2.2.2: Subsystem of a vehicular engine with its input and output torque

- **Clutch:**

The function of a friction clutch in vehicles equipped with a manual transmission is that a clutch disc connects the flywheel of the engine and the input shaft of the transmission. In this project there will not be any clutch, because this is material for another project, so this model is simpler.

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- **Gearbox and Transmission:**

A transmission has a set of gears, commonly five or six, to change the gear ratio from the engine to the wheels, and each one has its conversion ratio i_t. The relation between the input and output torque of the transmission is given by this ratio:

$$T_{ti} \cdot i_t = T_{to} \quad (4.2.2.2)$$

$$\omega_{ti} = \omega_{to} \cdot i_t \quad (4.2.2.3)$$

where T_{to} is the torque of the transmission output and ω_{ti} and ω_{to} is the rotational speed of the transmission input and output, respectively.

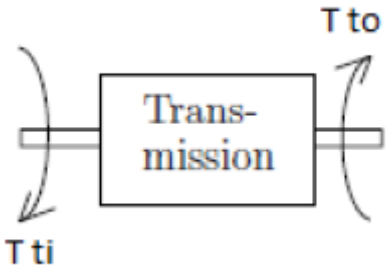

Fig 4.2.2.3: Subsystem of a vehicular transmission with its input and output torque

- **Propeller shaft:**

The propeller shaft connects the transmission output with the differential. In this thesis is assumed to be rigid and no friction between the parts. So it has no effect in the torques equation.

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- **Differential:**

The differential is characterized in the same way as the transmission, although has only one conversion ratio (i_{fd}) for all the gears. It allows the driven wheels to have different speeds, necessary to be able to drive the car in curves. Is assumed no friction into the final drive, which gives the following model for the torques input and output:

$$T_{fdi} \cdot i_{fd} = T_{fdo} \tag{4.2.2.4}$$

$$\omega_{fdi} = \omega_{fdo} \cdot i_{fd} \tag{4.2.2.5}$$

where T_{fdi} is the torque of the differential input and T_{fdo} is the torque of the differential output. ω_{fdi} and ω_{fdo} are the rotational velocity of the differential input and output, respectively.

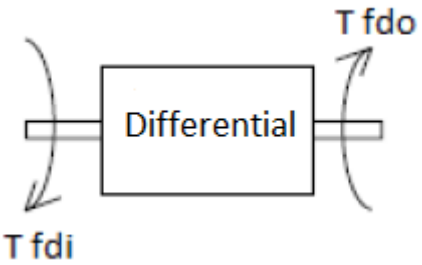

Fig 4.2.2.4 Subsystem of a vehicular differential with its input and output torque

- **Drive shafts:**

The drive shafts connect the final drive with the wheels. In this model it is assumed that the speed for the two drive shafts and the two wheels is the same. For that, they are modeled as if it was only one drive shaft. Actually, the speed differs between the wheels when a vehicle is making a curve because the wheels which are in the interior have less distance to make due to the smaller radio. However, this effect is not taking

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into account in this thesis. The equation with no friction between the wheels and the drive shafts is:

$$T_d = T_w \tag{4.2.2.6}$$

where T_d is the torque in the drive shafts and T_w is the torque in the wheels which are connected to them.

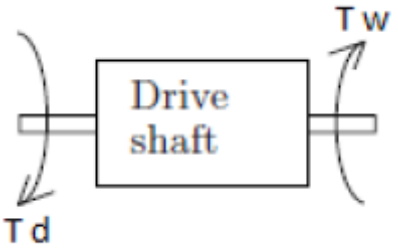

Fig 4.2.2.5: Subsystem of the drive shafts with its input and output torque

- **Wheels and car body:**

The wheels are the part of the driveline, which are in contact with the ground. In this contact is transformed the rotational motion to translational motion. The tyre is very complex to model, for example, a rolling wheel is deformed which causes rolling resistance.

The vehicle body forms a part of the chassis. Sometimes the suspensions and wheels are included.

The second part of the car is considered to have one inertia for the wheels and the entire car body, including the transmission and the final drive. So the equation is formulated as follows:

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$$J_{car} \cdot \dot{\omega}_w = T_{f\,do} - T_w \qquad (4.2.2.7)$$

where J_{car} is the moment of inertia of the car body, and $\dot{\omega}_w$ is the rotational acceleration of the wheels. Therefore, with this last variable, the acceleration and the velocity of the vehicle can be calculated.

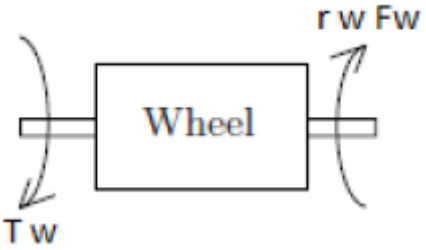

Fig 4.2.2.6: Subsystem of the wheels with its input and output torque

Once the torque of the wheels is calculated, an analysis of the external forces which actuate in the car and wheel must be done in order to calculate parameters such as the speed or the acceleration of the vehicle.

Regarding to the figure, the forces equilibrium is formulated.

$$F_w = m_{car} \cdot a_{car} + F_a + F_r + m_{car} \cdot g \cdot \sin\alpha \qquad (4.2.2.8)$$

where F_w is the force which actuate in the wheels due to the torque that is transferred. F_a is the force due to the aerodynamics of the vehicle, F_r is the rolling resistance and $m_{car} \cdot g \cdot \sin\alpha$ the gravitational force. Each of these forces will be explained in a more extensive way in the section in which the car body is simulated.

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4.2.3. Engine Model

The driveline is the system that transfers the signals from the driver (gear lever, accelerator and brake pedal) via the combustion in the engine to vehicle speed, as has been said previously. The engine is the power source in the drivetrain and is controlled with the accelerator pedal

The engine model is developed by applying the Newton´s second law to the rotational dynamics of the engine.

A simple look-up table is used to represent the data of the relationship between engine torque, throttle opening and the engine speed in revolutions per minute, instead of using physical equations. In a Lookup Table from Simulink, which is based on an engine map for the data, which are going to be analyzed, are entered throttle opening positions and torque values for different engine speeds. From previous experiments these values are obtained. The engine speeds are between 800 and 4050 rpm, and the values for the throttle opening are between 0 and 100% (in the model is worked with values between 0 and 1), which is the percent that the throttle pedal position is in this moment. The torque values are obtained by interpolation in Simulink to obtain the torque at any other speed and throttle position.

Using a derivative function in Simulink and applying it to the rotation velocity that is used as an input data, can be calculated the rotational acceleration of the engine.

Once all these parameters are known, therefore the torque which is transmitted to the clutch can be calculated, and the next step is reached. In this case, the torque, which can be calculated, is transmitted to the transmission because this is a model simpler.

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In the figure 4.2.3.1 the sub block of the engine can be watched in Simulink, where the inputs are the accelerator pedal position (APP) and the speed recirculated from the transmission, and the output is the torque of the engine which goes to the transmission.

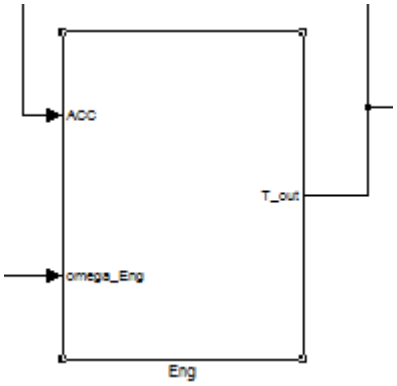

Fig 4.2.3.1: Block diagram of the engine subsystem in Simulink environment

The block diagram of the engine model developed in Simulink is shown in the Fig 4.2.3.2.

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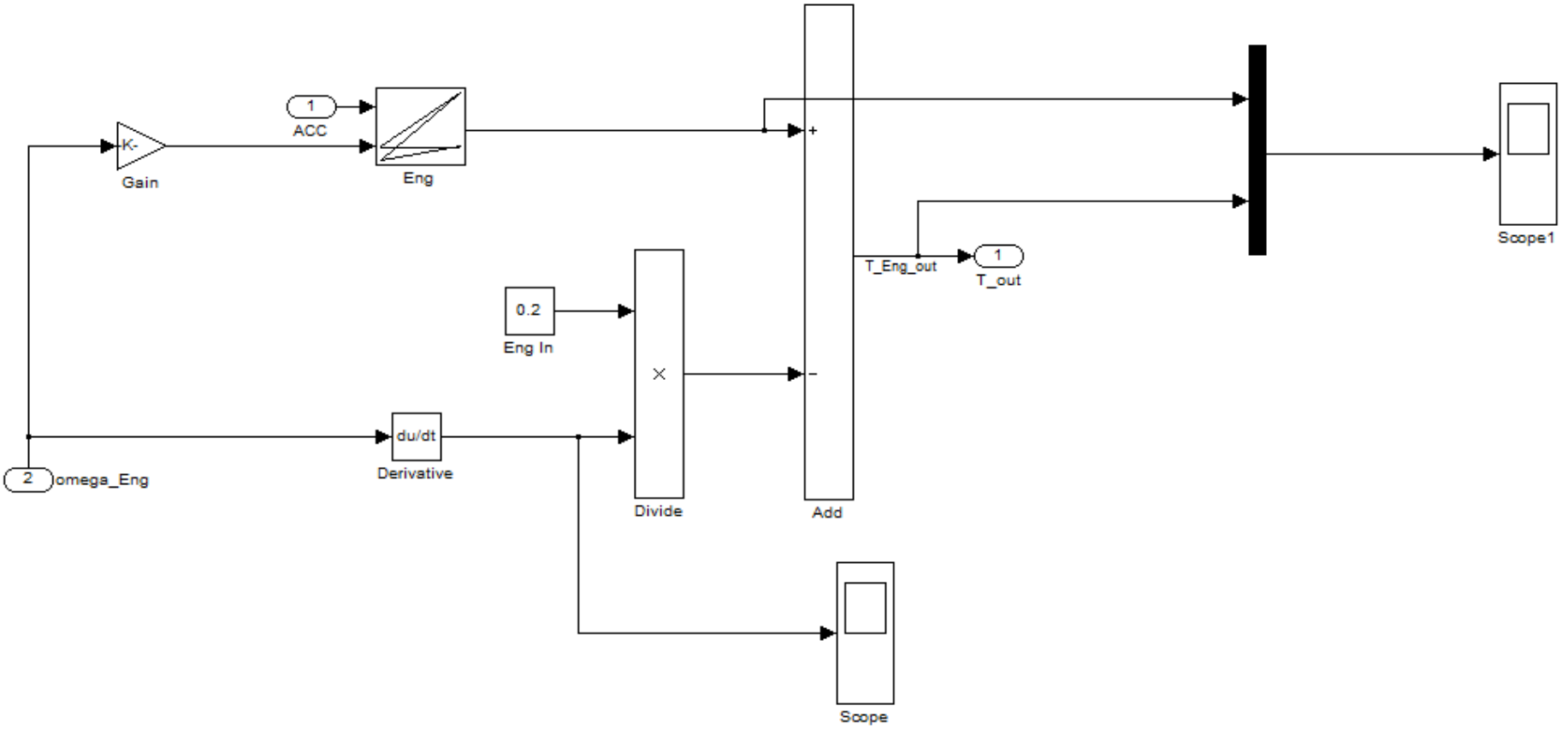

Fig 4.2.3.2: Simulink top level diagram of the engine model

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4.2.4. Gearbox and Transmission Model

In this part, it is going to be seen the design and function of the manual gearbox, the transmission, and the modeling of them. This is not only the gearbox, but also the differential or final drive is going to be taken into account. Thus, these sub block will represent the part of the power train which goes from the transmission input, just after the clutch, in this case just after the engine because is a simpler model, to the final drive.

In first place, the gearbox modeled will have eight gears, which is the gearbox with which is going to be worked. In the next step the transmission and differential ratios must be calculated for the data given. With the gear from the gearbox, the engine velocity and the mean speed of the front wheels is going to be performed this part. There are two parts of the drive line which move independently, when a gear shift is made. One of them is the engine and the first part of the clutch, although in this case there is not a clutch, and the other one is the second part of the clutch, that doesn't exist in this model, going through the transmission, differential, propeller shaft and wheels, until the car body.

The gearbox is modeled in the following way. It is made with the Simulink block named Stateflow. In it is simulated a gearbox which have eight gears. It has been programmed as it is explained now. When the input velocity in the gearbox is upper 3500 rpm, the car increases a shift, and when the input velocity in the gearbox is lower than 1200 rpm, the car decreases a shift. It can be appreciated in the figure 4.2.4.2.

In the figure 4.2.4.1 can be watched the sub block of the gearbox in Simulink, where the inputs are the speed recirculated from the transmission, and the two, and the output is the gear of the car.

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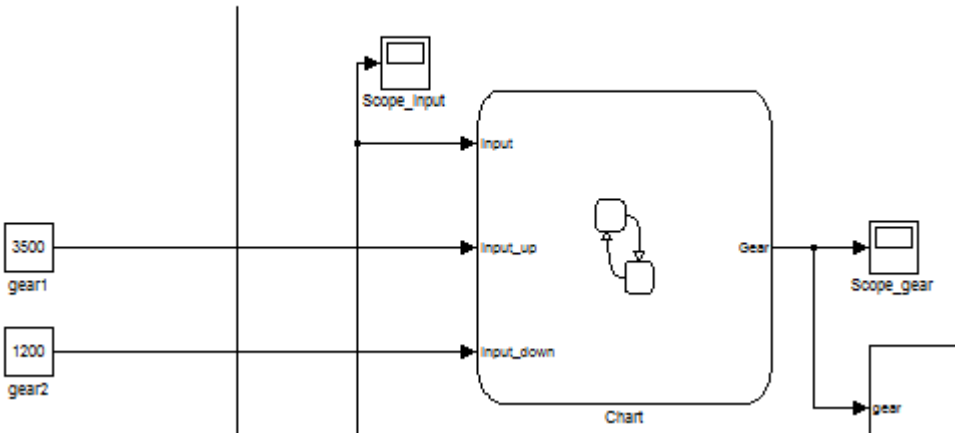

Fig 4.2.4.1: Block diagram of the gearbox subsystem in Simulink environment

In the Figure 4.2.4.2 the model built in Simulink for the block diagram of the transmission and differential is shown.

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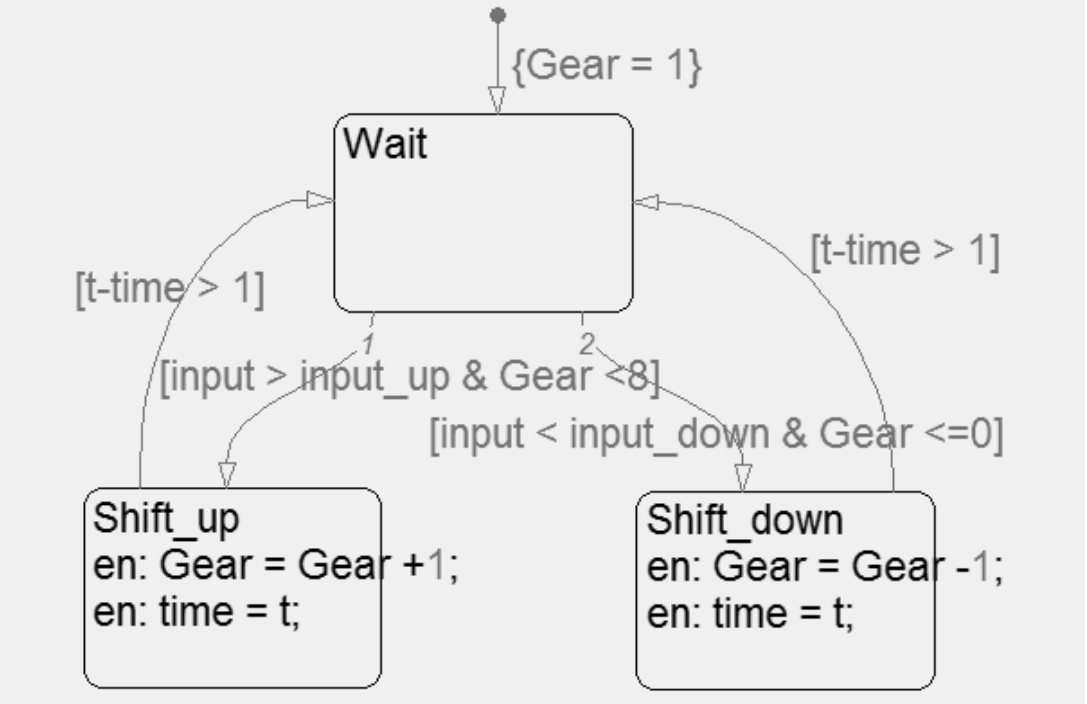

Fig 4.2.4.2: Simulink top level diagram of the gearbox model

The modeling of the transmission must be only for the changing gear ratio. To make a simpler model, and then a faster simulation, some simplifications have been done. There is one gear efficiency and bearing friction all together for the whole transmission and that will be the mechanical efficiency for the transmission. It is going to be constant for all the different cases and it will take a value of 0.9.

After that the ratios are calculated, a lookup table is built for the transmission model to construct the relation between each gear and its corresponding ratio. So now, the torque, which exits the transmission, can be also calculated, as well as the speed which goes into it. To do that, is necessary to use the previous equations: the two from the transmission, (4.2.2.2) and (4.2.2.3); and the two from the differential, (4.2.2.4) and (4.2.2.5), which were described in the section 4.2.2.

Finally the final torque which is the same as the input for the drive shaft is calculated applying the Newton´s second law to the rotational dynamics.

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In the figure 4.2.4.3 the sub block of the car body can be watched in Simulink, where the input is the torque from the transmission, and the outputs are the velocity of the wheels, which is recirculated to the transmission, and the two things, which want to be measured, the acceleration and the speed of the car.

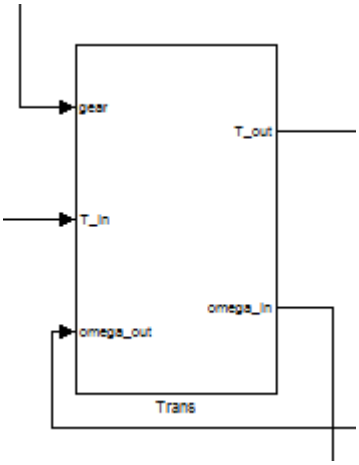

Fig 4.2.4.3: Block diagram of the transmission subsystem in Simulink environment

In the Figure 4.2.4.4 the model built in Simulink for the block diagram of the transmission and differential is shown.

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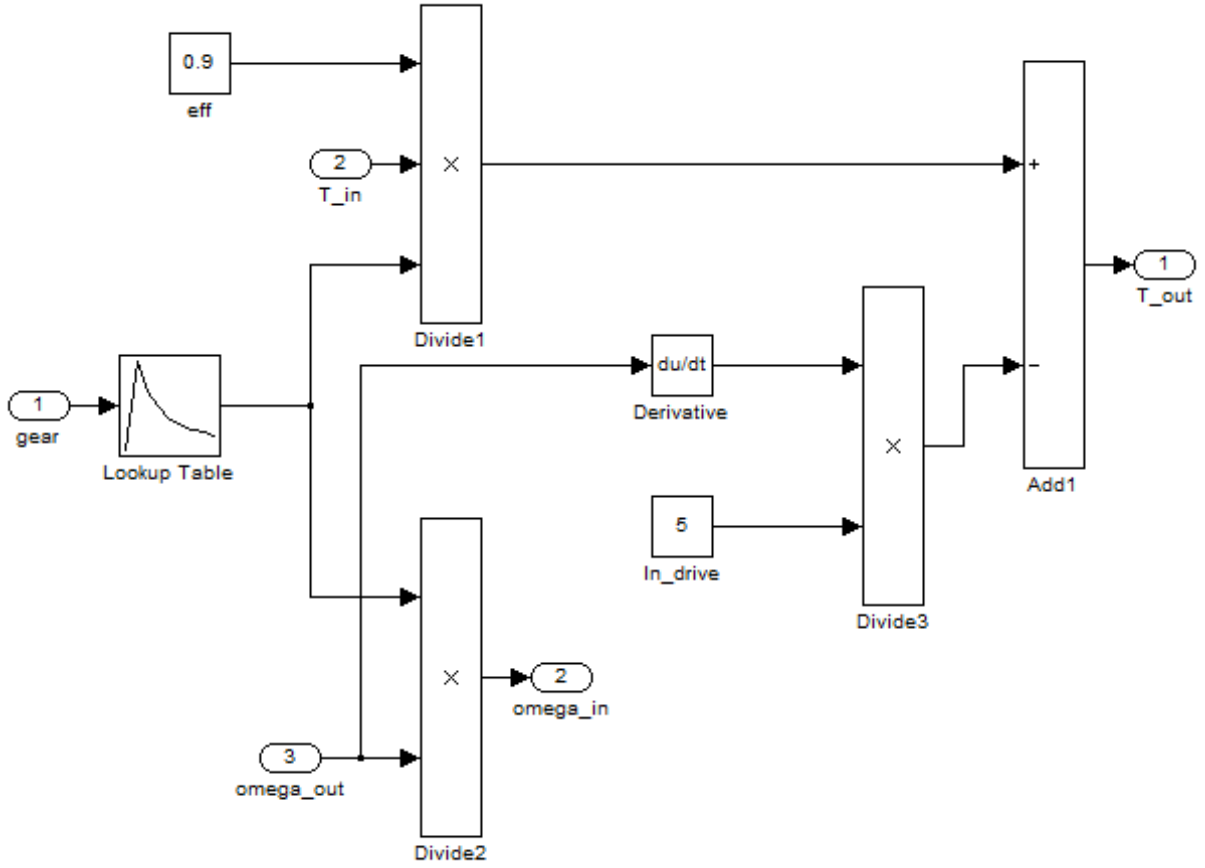

Fig 4.2.4.4: Simulink top level diagram of the transmission model

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4.2.5. Car Body Model

In this new chapter, it is going to be shown the forces which act on a vehicle with mass (m) and speed (v). For the longitudinal direction is sufficient to treat the car body with the Newton's second law to make a dynamic description with equations.

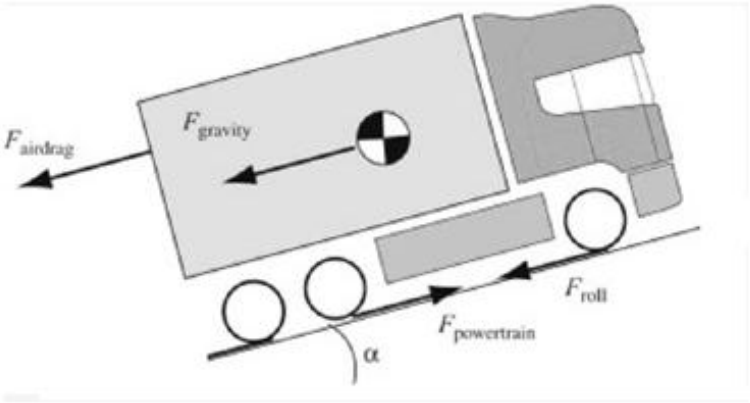

Figure 4.2.5.1: Longitudinal forces acting on a vehicle

The forces that actuate, after an analysis is made to the vehicle and wheels, are:

$$\mathrm{F_w} = \mathrm{m_{car}} \cdot a_{car} + \mathrm{F_a} + \mathrm{F_r} + \mathrm{m} \cdot \mathrm{g} \cdot \sin(\alpha) \qquad (4.2.5.1)$$

The friction force F_w is calculated by multiplying the torque input of the car body, which is the one that the wheels have, and exits from the transmission sub block, per the effective radio of the wheel. For the effective radio, is taken a standard value, but it depends on the tires of the vehicle which is being analyzed. But furthermore, F_w can be described by the sum of the following forces:

- F_a, is the air drag. It represents the braking force from the air drag, and it is proportional to the squared velocity. It is approximated by

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$$F_a = \frac{1}{2} \cdot c_w \cdot A_a \cdot \rho_a \cdot v^2 \qquad (4.2.5.2)$$

where c_w is the drag coefficient, A_a the maximum vehicle cross section area. These two parameters depend on the vehicle. ρ_a is the air density, and v^2 is the squared speed . However, for example, effects from open or close windows will make the theoretical force less accurately and more difficult to model.

- F_r is the rolling resistance, which originates from tires deformation. The center of normal pressure is shifted in the direction of rolling, which produce a torque about the axis of rotation of the tire, the rolling resistance moment or torque. In a free rolling torque the applied wheel torque is zero. In consequence, a horizontal force at the tire ground contact patch must exit to maintain equilibrium. This horizontal force is generally known as the rolling resistance.

  The rolling resistance is treated as a force acting through the axis, and depends on the speed of the vehicle. The expression which is used to model it is:

$$F_r = 150 \cdot \tanh\,(1000 \cdot v) \qquad (4.2.5.3)$$

  where the number 150 is a constant value for the rolling resistance, and the function tanh of the vehicle speed, which modifies this resistance.

- $m \cdot g \cdot \sin(\alpha)$ is the gravitational force, where m the mass of the vehicle, g is the gravity and alpha is the slope of the road. Although the slope of the road is not shown in the data provided, this force is substantially smaller than the other two (F_a and F_r), for this reason, in this project, for all the cases it is considered zero.

So now, after that the parameters of the equation are known, introducing all the values can be calculated the acceleration of the vehicle, and adding one integrator for

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the velocity and another one for the position in our sub model, the speed and position of the car are easier to calculate.

To finish, with the velocity of the car and the velocity of the different parts of the model, such as the speed of the wheels or the speed of the transmission, is made a complete recirculation until the engine, the first part of the model, and everything is recalculated.

In the figure 4.2.5.2 the sub block of the car body in Simulink can be watched, where the input is the torque from the transmission, and the outputs are the velocity of the wheels, which is recirculated to the transmission, and the two things, which want to be measured, the acceleration and the speed of the car.

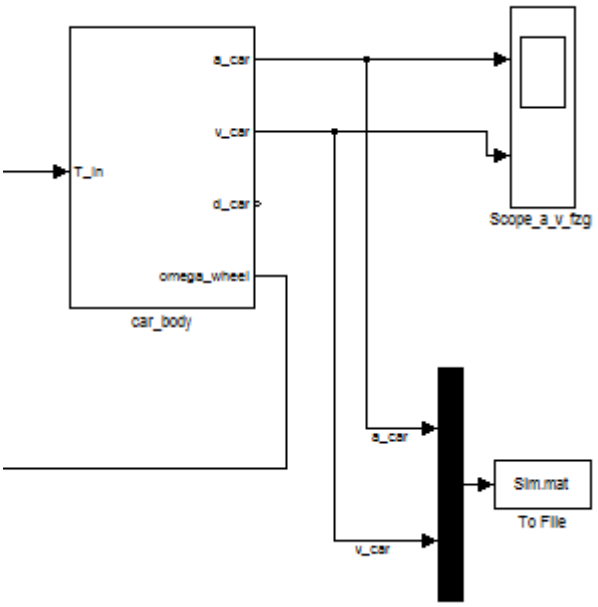

Fig 4.2.5.2: Block diagram of the car body subsystem in Simulink environment

The block diagram of the car body model developed in Simulink is shown in the Fig 4.2.5.3.

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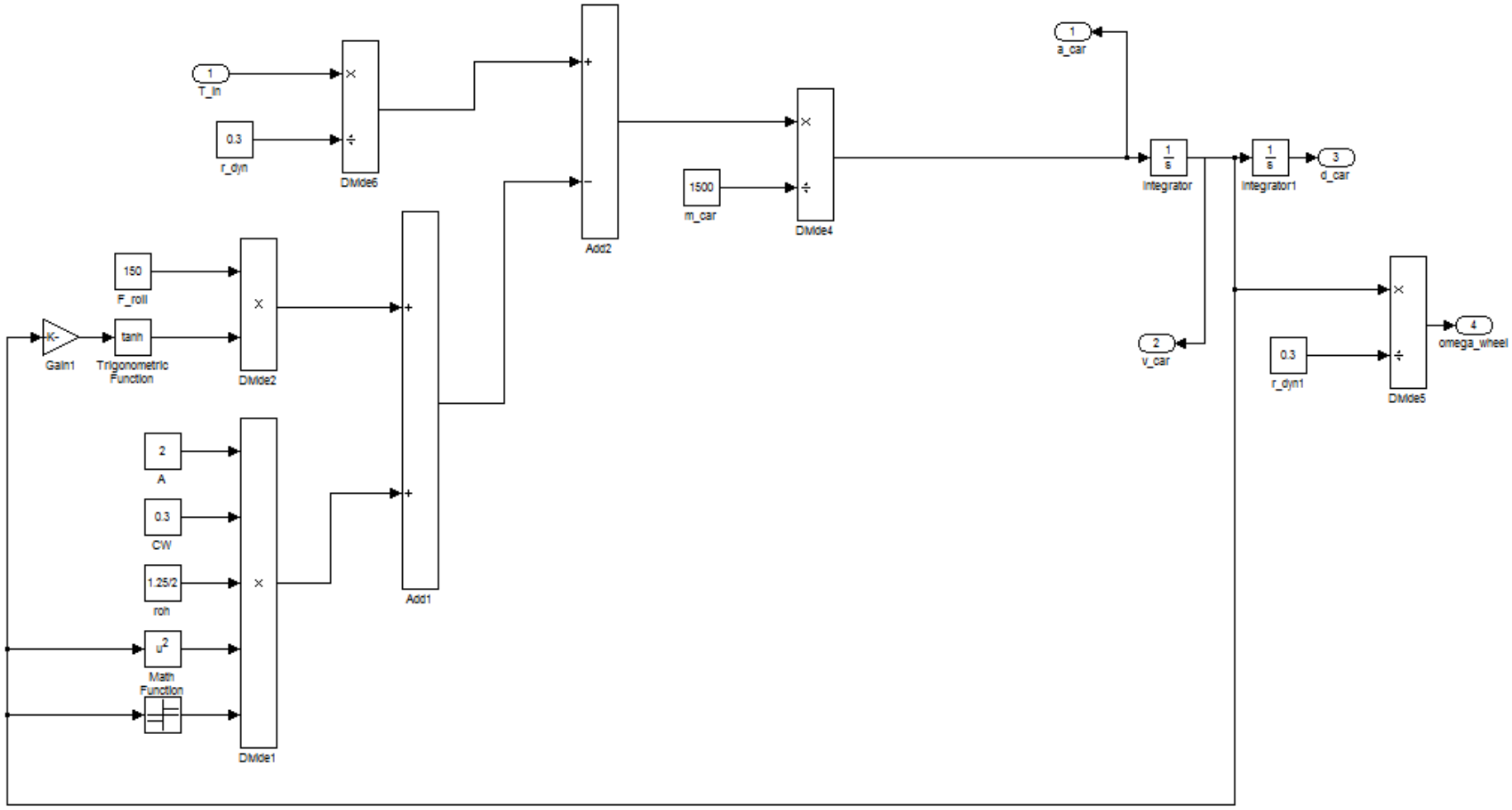

Fig 4.2.5.3: Simulink top level diagram of the car body model

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4.2.6. The Complete Power Train Model

In this last section about the modeling of the car, the parts described previously will be connected to each other, in order to form a complete power train model with driver and vehicle model. Every sub blocks are connected in Simulink in the way which has been explained before, and then.

To connect the engine to the transmission:

$$\omega_e = \omega_{ti} \tag{4.2.6.1}$$

$$T_e = T_{ti} \tag{4.2.6.2}$$

To connect the transmission to the wheels or car body:

$$\omega_{to} = \omega_w \tag{4.2.6.3}$$

$$T_{to} = T_w \tag{4.2.6.4}$$

There is not a difference between the wheels and the car body in this project, so these two parts do not need to be connected.

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4.3. Simulations

4.3.1. Checking the Operation of the Model

In this section, it is going to be simulated the model, which has been built and explained in the previous chapter. For that, it is necessary to introduce a new sub block in the model, which will change depending on the simulation which was made, and the purpose of it, which simulate the accelerator pedal position (APP).

In this Simulation, the right performance of the model wants to be checked, before it is started to work. For this case, the accelerator pedal position is a block with a constant value. Therefore, it is going to be simulated the operation of the model for an accelerator pedal position, for example, 80%.

For that it is necessary to put the new block with a constant value of 0.8, due to the engine. The sub block engine has a block inside where is received this information, and it has been programmed to work with values between 0 and 1, where 0 means that the accelerator pedal position is 0%, and 1 means that the accelerator pedal position is 100%, so if it is made to 80%, the right value is 0.8. The time simulation is 50 seconds.

In the figure 4.3.1.1 the sub block of the engine in Simulink can be watched, and the sub block of the accelerator pedal position, where the inputs of the engine are the accelerator pedal position (APP), which in this case has a constant value of 0.8 (80%), and the speed recirculated from the transmission, and the output is the torque of the engine which goes to the transmission.

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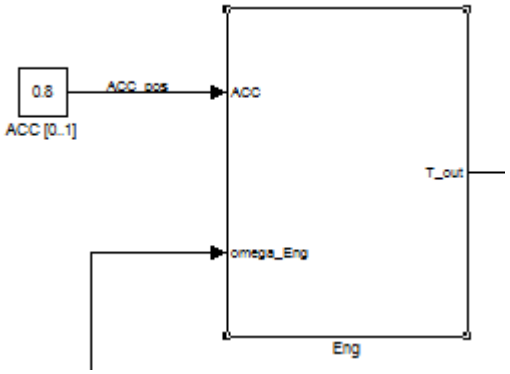

Fig 4.3.1.1: Block diagram of the APP to check the model in Simulink environment

The block diagram of the model is shown in the Fig 4.3.1.2 for checking the right operation of it developed in Simulink.

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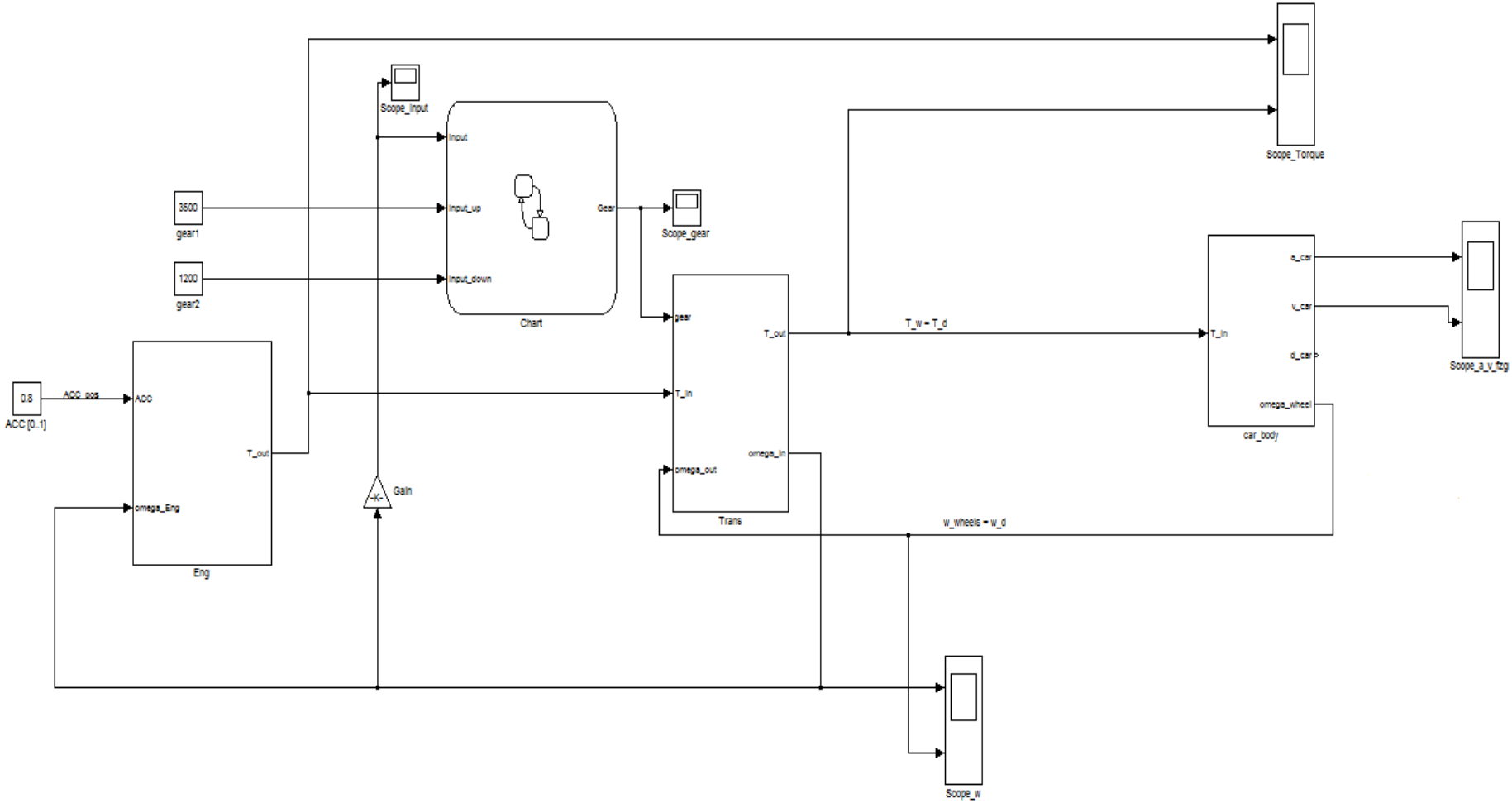

Fig 4.3.1.2: Simulink top level diagram of the checking model

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The results that have been obtained after the simulation are the following graphics, where can be seen the right operation of the model.

In the figure 4.3.1.3 the input velocity in the gearbox can be watched, which is the output velocity of the transmission, in rpm.

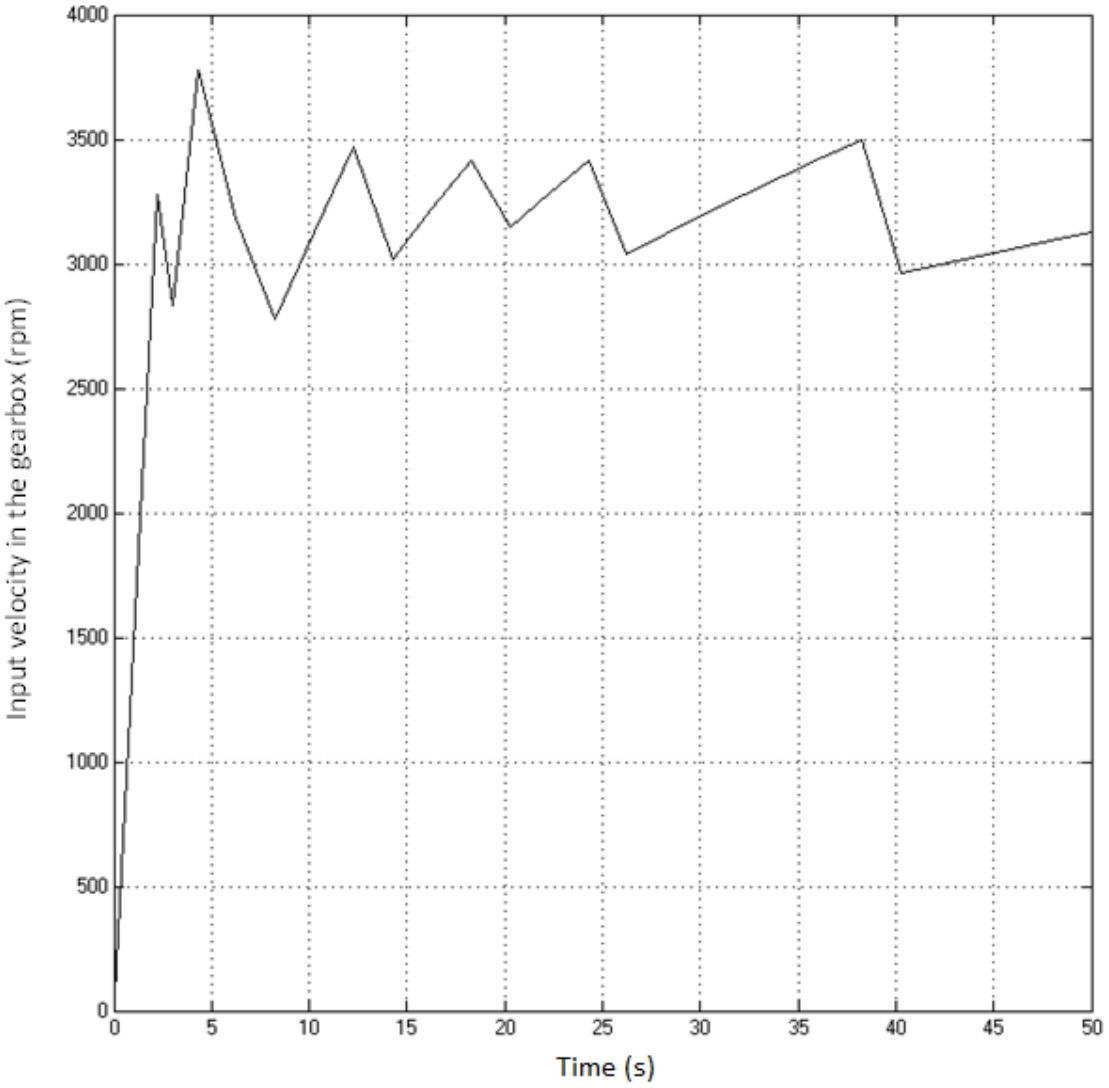

Fig 4.3.1.3: Graphic of the input velocity in the gearbox in rpm versus the time

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In the figure 4.3.1.4 the gearshifts from 0 to 8can be watched, when is simulated the model during 50 seconds.

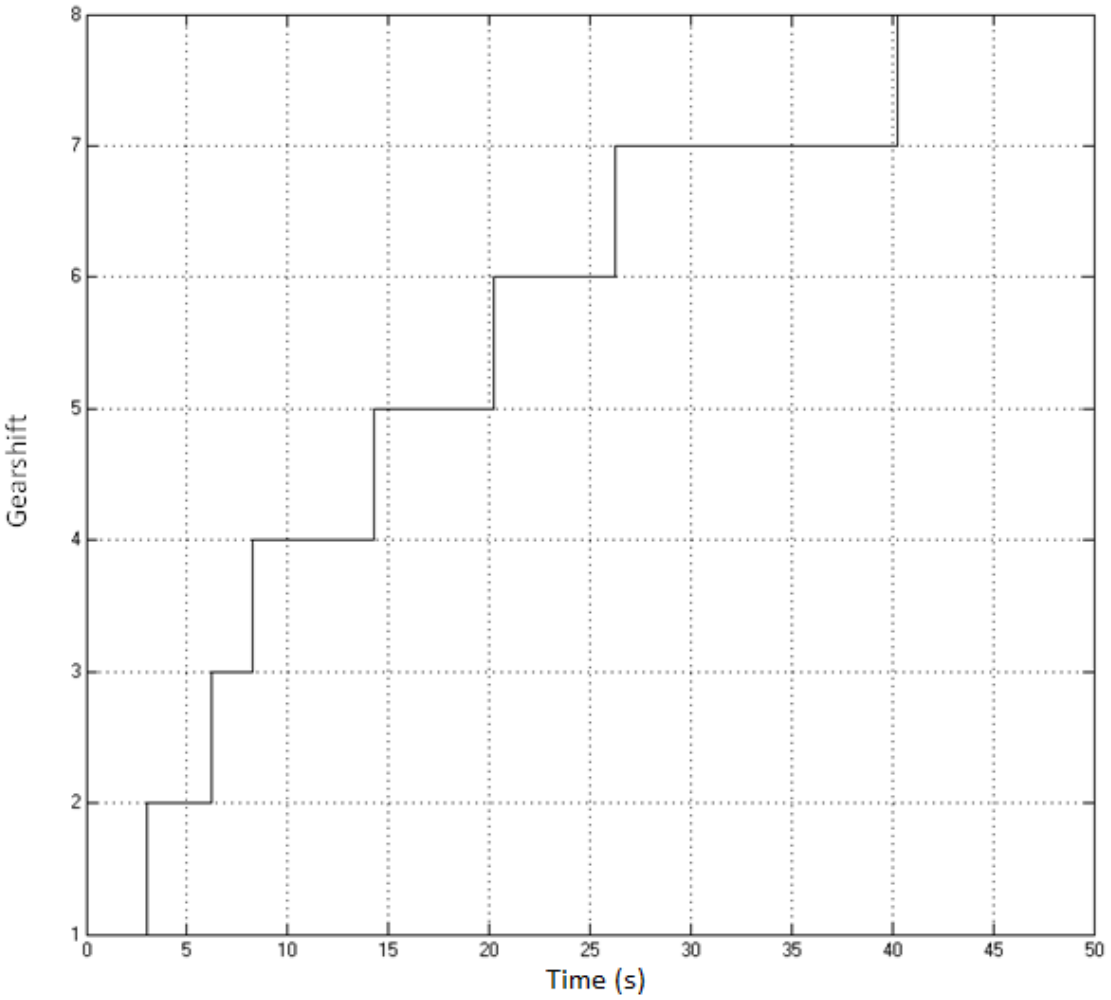

Fig 4.3.1.4: Graphic of the simulated gearbox with the gearshifts versus the time

When the two graphics are studied, the figure 4.3.1.3 and the figure 4.3.1.4, it can be watched that the car increases one gearshift, when the input velocity in the gearbox is a minimum, in other words, when the rpm go to decrease to increase; or when the rpm are decreasing and there is a change of slope. This can be seen when the car go from 1 to 2 shift, this is the first case, and when the car go from 2 to 3 shift, this is the second case.

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In the figure 4.3.1.5 it can be watched, in the first graphic the output velocity from the transmission, which is the input velocity in the engine, in rad/s, and in the second graphic the output velocity from the car body, which is the input in the transmission, in rad/s too.

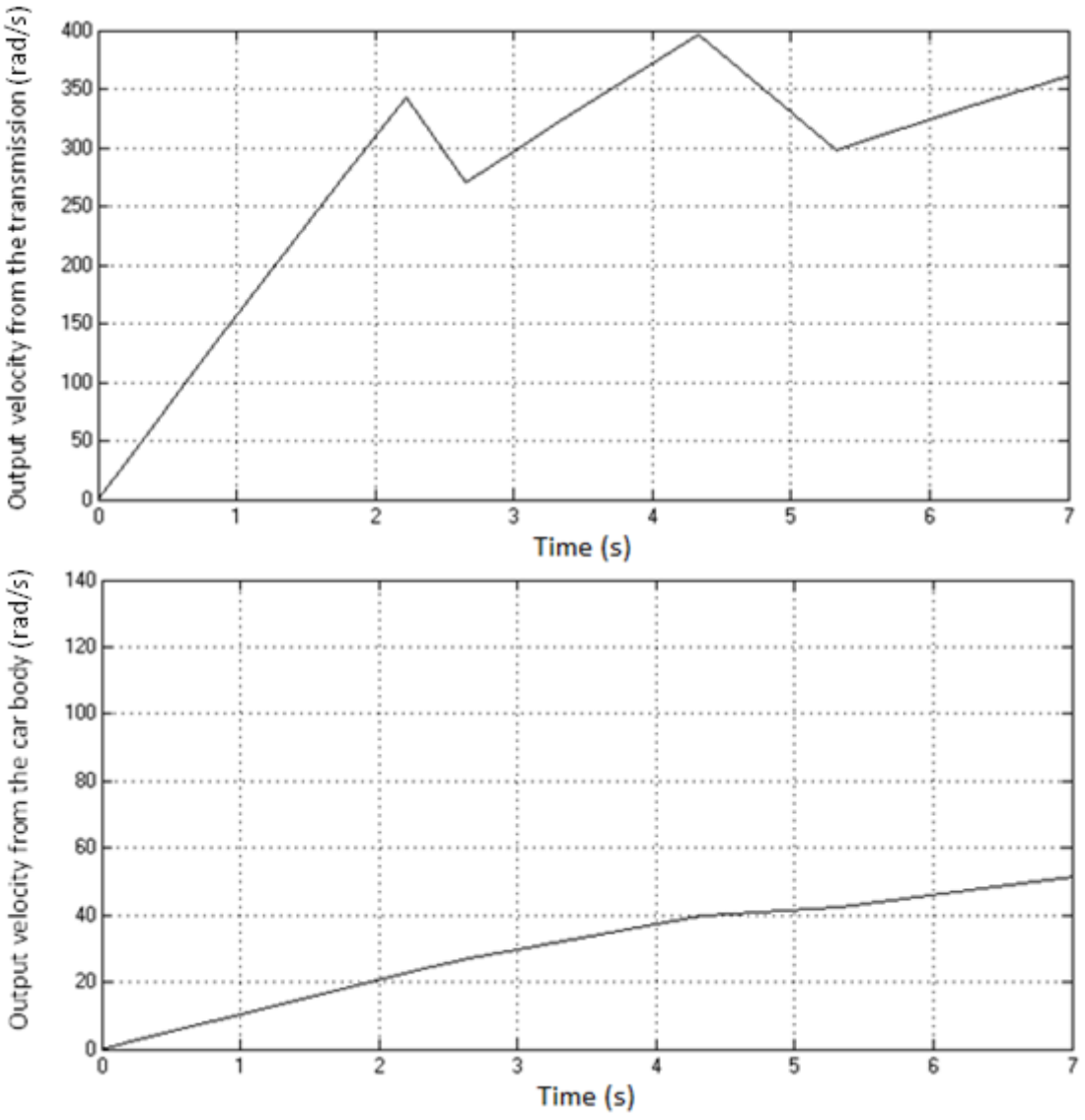

Fig 4.3.1.5: The above graphic is the output velocity from the transmission, which enters in the engine, versus the time, and the below graphic is the output velocity from the car body, which enters in the transmission, versus the time

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In the figure 4.3.1.6 it can be watched, in the first graphic the output torque from the engine, which is the input in the transmission, in N·m, and in the second graphic the output torque from the transmission, which is the input in the car body, in N·m too.

In the figure 4.3.1.7 it can be watched, in the first graphic the acceleration of the car in m/s^2, and in the second graphic the speed of the car in m/s, to 80% accelerator pedal position.

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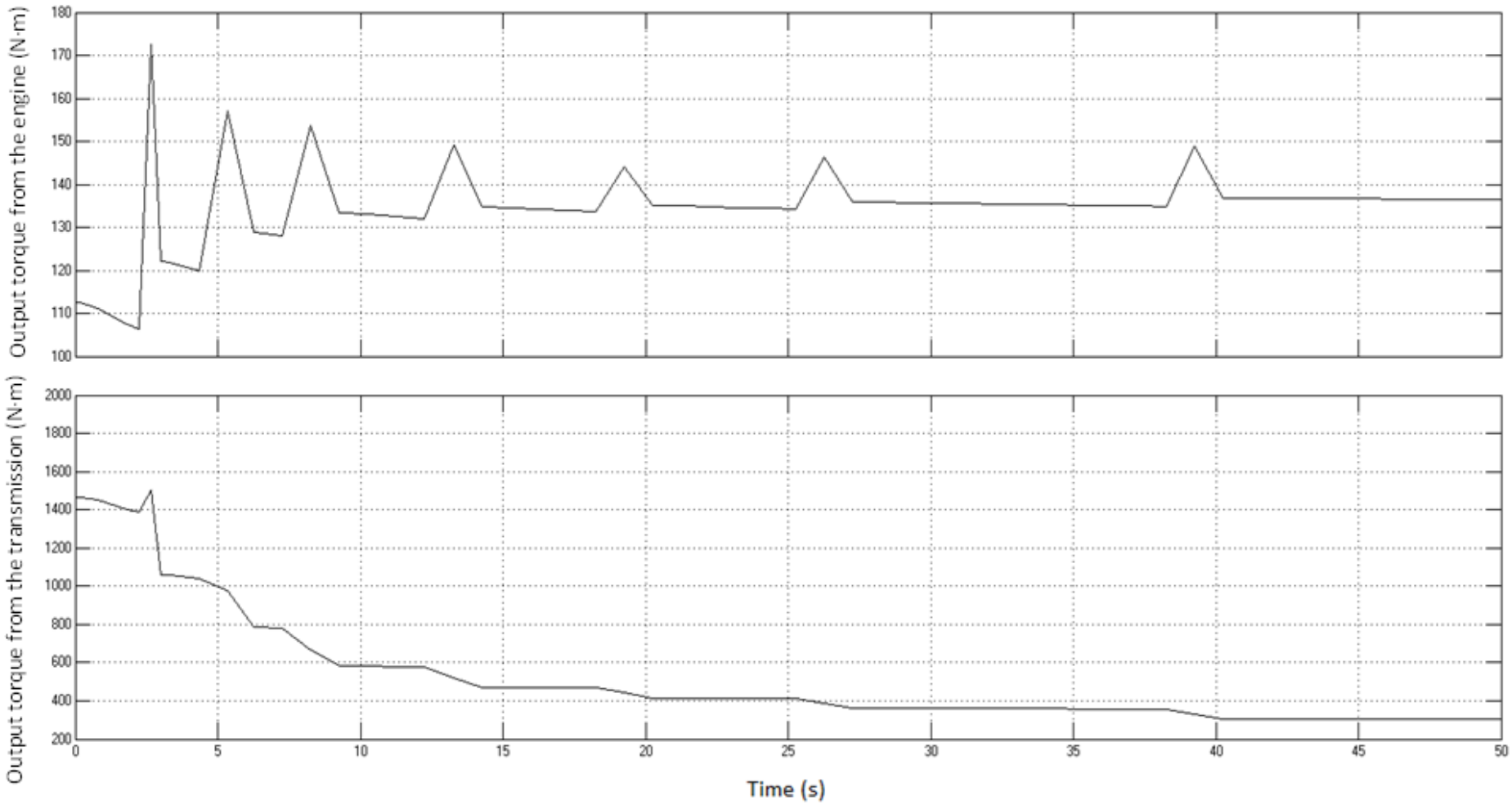

Fig 4.3.1.6: The above graphic is the output torque from the engine, which enters in the transmission, versus the time, and the below graphic is the output torque from the transmission, which enters in the car body, versus the time

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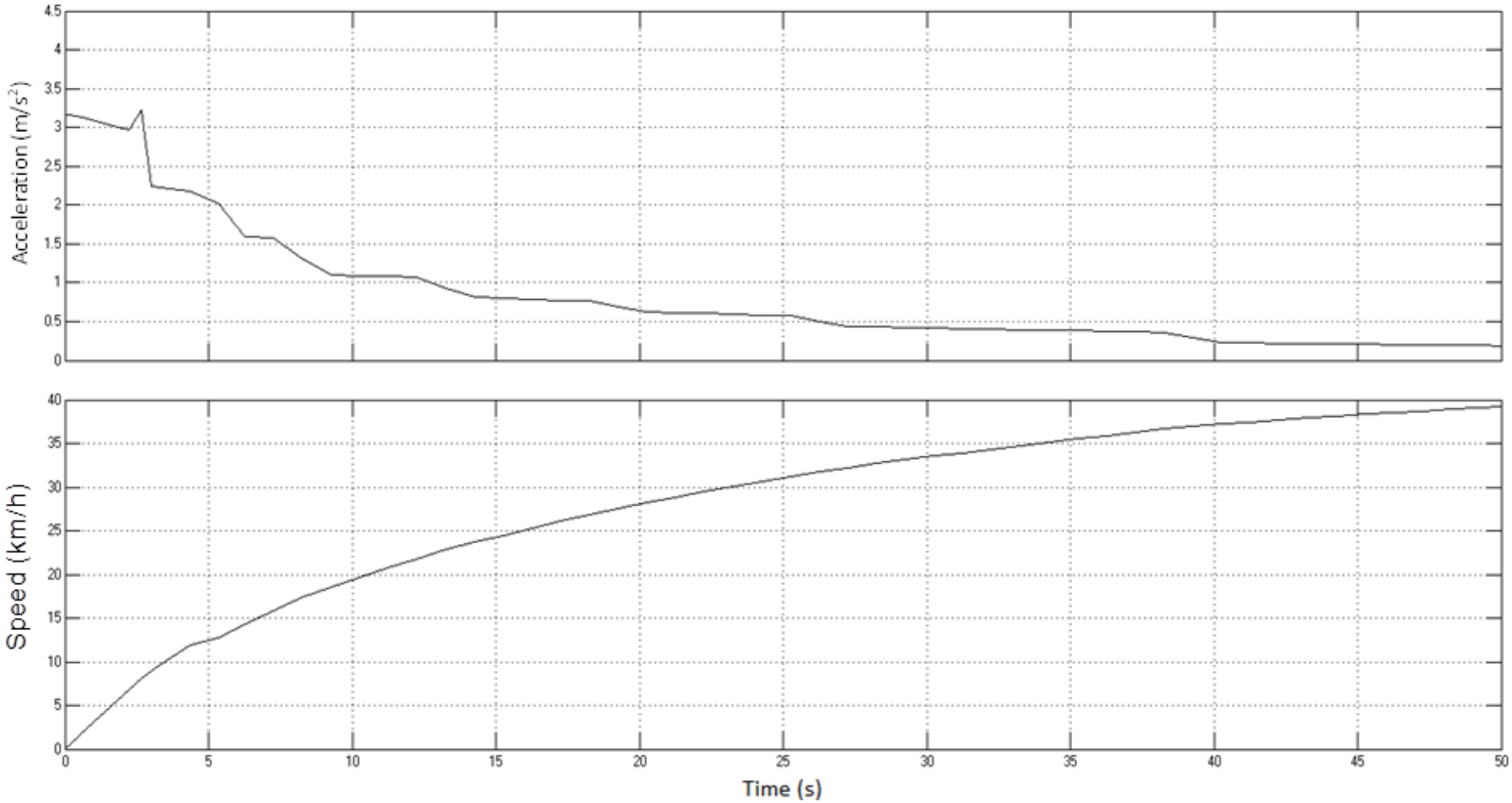

Fig 4.3.1.7: The above graphic is acceleration of the car versus the time, and the below graphic is the speed of the car versus the time, to 80% accelerator pedal position

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4.3.2. Creating Tables for Different APP

In this part, it is going to be simulated the previous model, which has been built and explained to create tables with the time, acceleration and speed of the car to different accelerator pedal positions. Therefore, it is necessary to change the sub block in the model, which change the accelerator pedal position (APP), to obtain one table for each position.

That is to say, in this Simulation the accelerator pedal position is not constant like in the previous model; otherwise it changes for each table. So not to change manually in each moment the value of the APP, it is automated through an easy Matlab code that has been created for this purpose.

Consequently, this code switches the APP automatically from 0.1 to 1, in steps of 0.02. Thus for each value the code calls to the simulation through the new sub block, named “Throttle”, which is in the same position where in the last case was the constant value of the APP, and in that moment has been deleted and replaced for this new one, creating and saving a table for each one, in a kind of archive “.mat”, being a “timeseries” table. This code can be seen and studied in the CD.

In the figure 4.3.2.1 the sub block of the engine in Simulink can be watched the sub block of the engine in Simulink, and the sub block of the accelerator pedal position too, where the inputs of the engine are the accelerator pedal position (APP), which in this case is called by a Matlab program to simulate all the tables to the different accelerator pedal position, and the speed recirculated from the transmission, and the output is the torque of the engine which goes to the transmission.

In the figure 4.3.2.2 the sub block of the car body in Simulink can be watched, and the sub block to create and to save the tables too, which are necessary in the next chapter, being the input the torque of the car body which comes from the transmission, and being the output of the car body the acceleration and the speed of the car, which are the data of the new tables.

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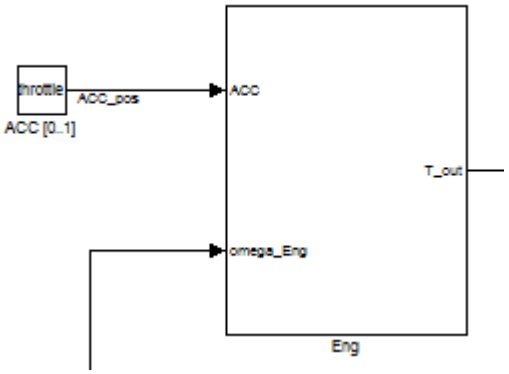

Fig 4.3.2.1: Block diagram of the throttle to create the tables for different APP in Simulink environment

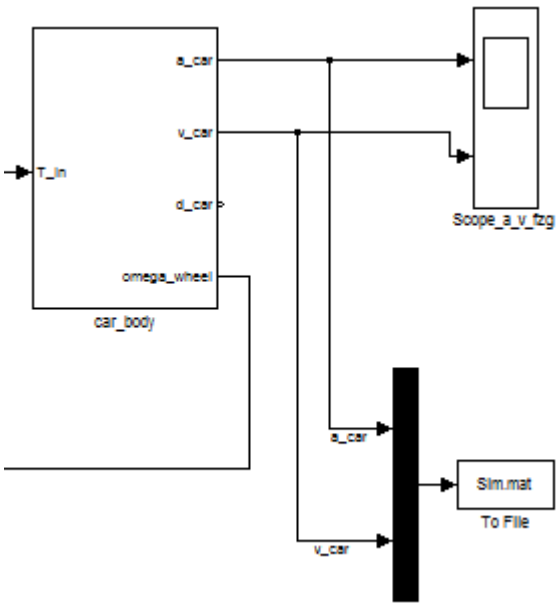

Fig 4.3.2.2: Block diagram of the end of the model to create the tables for different APP in Simulink environment

In the Fig 4.3.2.3 the block diagram of the model to obtain the tables for different accelerator pedal positions developed in Simulink is shown.

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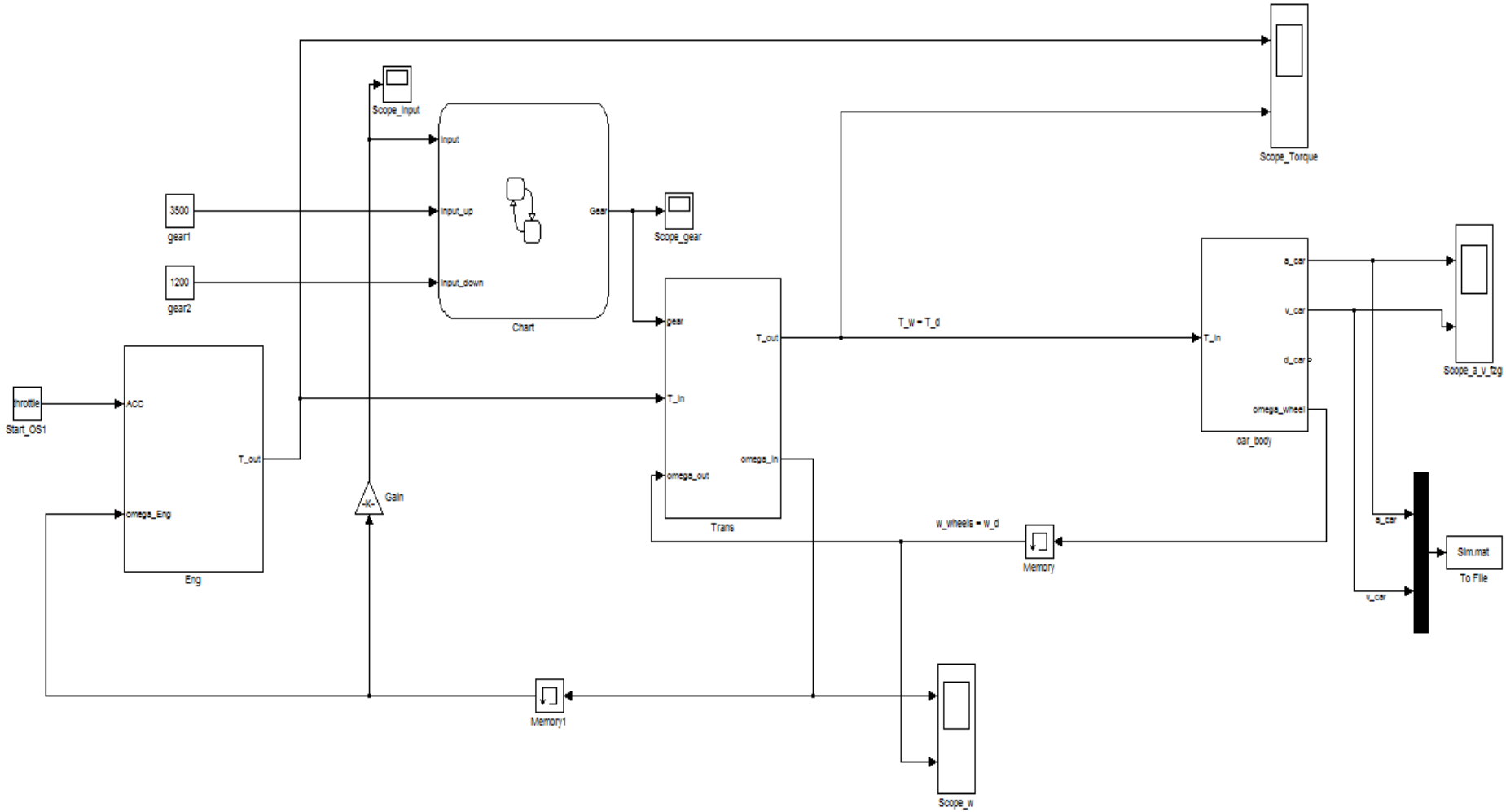

Fig 4.3.2.3: Simulink top level diagram of the model to obtain the tables

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4.3.3. Obtaining the Accelerator Pedal Position (APP)

In this chapter, it is going to be simulated the same model, which has been created and explained to obtain the accelerator pedal positions. Moreover, it is necessary to change the sub block of the APP in the model.

Therefore, in this Simulation, the sub block, which is the accelerator pedal position in the previous simulations, changes again. In practice, it is going to be used a new Simulink sub block, the n-D Lookup Table.

With the n-D Lookup Tables, it is wanted to obtain new tables, the Design of Experiments (DoE), and with them the accelerator pedal position. In this table, the constant acceleration is in the column (the y axis), and the initial speed is in the row (the x axis); the final speed depends on the table which was chosen. Watching and searching in this table it can find the accelerator pedal position to reach one speed from an initial speed, with a determinate acceleration. The n-D Lookup Table has these three dimensions. And with this obtain the APP. Later this is explained better.

In the figure 4.3.3.1 the sub block of the accelerator pedal position in Simulink can be watched, where the inputs of this block are a value of acceleration, an initial speed and a final speed, being the output the APP, which is one of the inputs of the engine.

In the figure 4.3.3.2 the end of the sub block of the car body in Simulink can be watched, and the sub block to watch the speed and the acceleration of the car too, being the input the torque of the car body which comes from the transmission, and being the output of the car body the acceleration and the speed of the car. The speed is compared with the final speed that is wanted to obtain, and it is represented everything until the moment which is reached.

The block diagram of the model is shown in the Fig 4.3.3.3, to obtain the accelerator pedal position through the previous tables obtained in Simulink for a determinate acceleration, an initial speed and a final speed of the vehicle.

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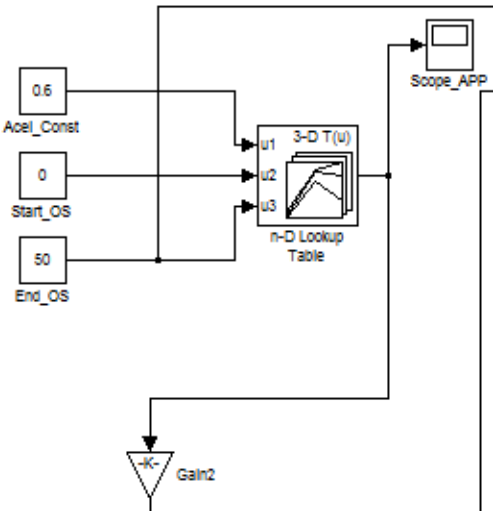

Fig 4.3.3.1: Block diagram of the throttle to obtain the APP to an initial speed, a final speed and a determinate acceleration in Simulink environment

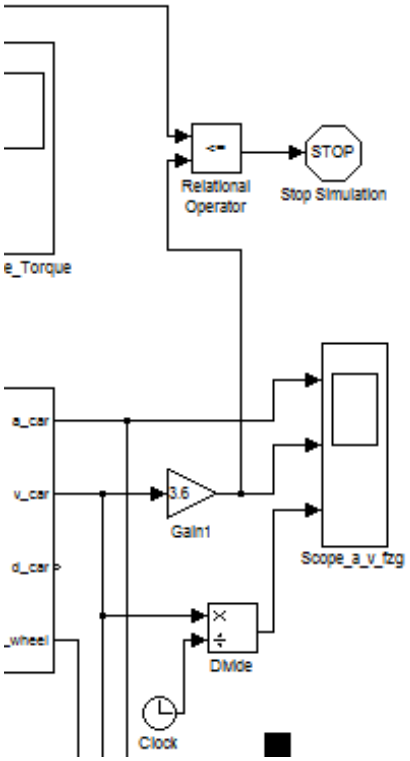

Fig 4.3.3.2: Block diagram of the end of the model to obtain the APP to an initial speed, a final speed and a determinate acceleration in Simulink environment

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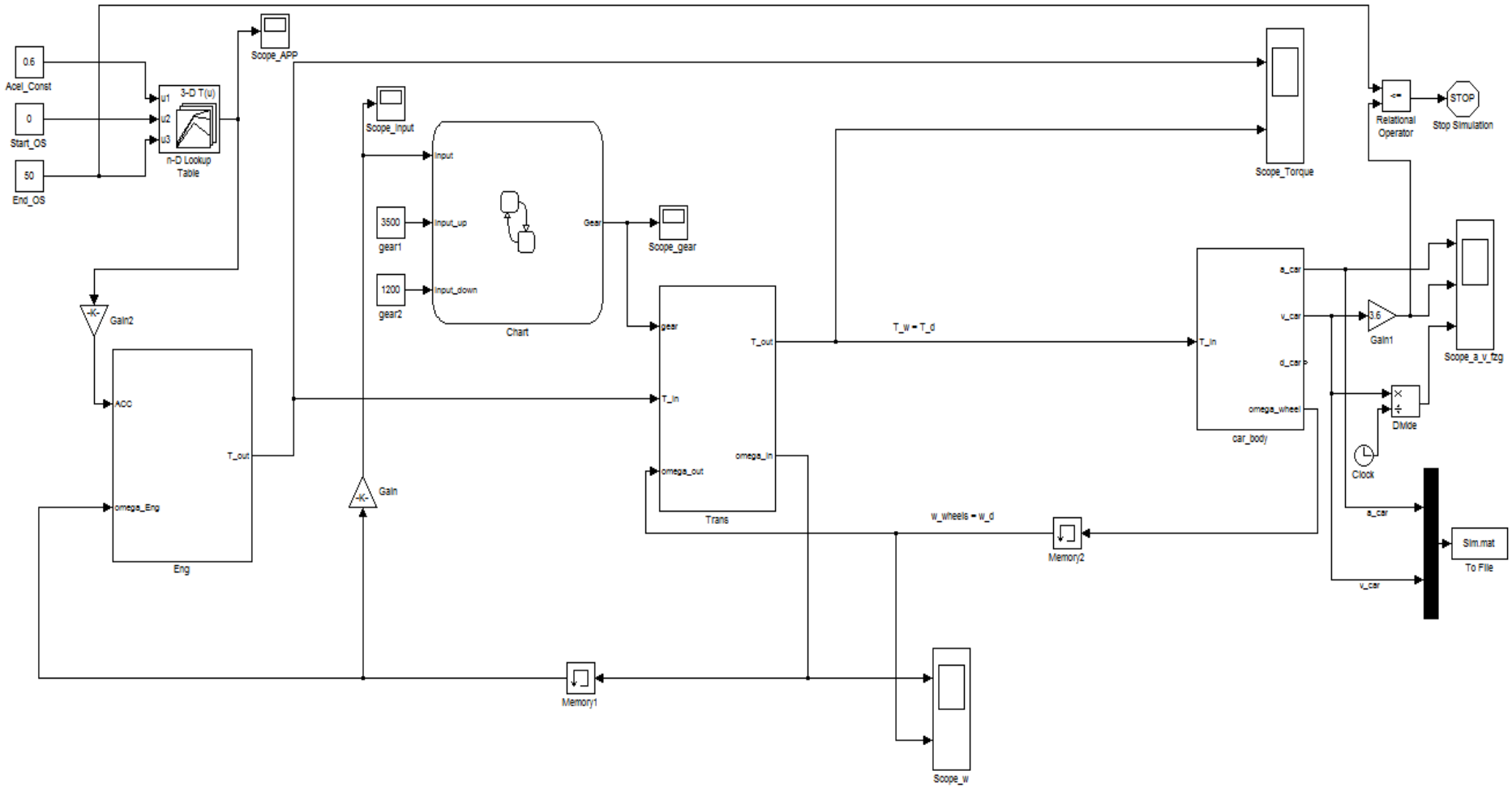

Fig 4.3.3.3: Simulink top level diagram of the model to obtain the accelerator pedal position

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After a simple explanation and the figures which make up this model, it is going to be explained then.

First of all, this chapter begins with a Matlab code, which can be seen and studied in the CD, to use the tables from the previous chapter in the new sub block, the n-D Lookup Table. In this code a great matrix is created, which will contain all the data to obtain the APP, and where are charging the previous tables, and from them the speed and the time are taken. With them the empty matrix is filled, calculating the start and the final speed, and the acceleration. At the end it is had a full matrix of 3 dimensions, where the first parameter is the acceleration, the second parameter is the initial speed, and the third parameter is the final speed. The result obtain in the matrix is the accelerator pedal position. To obtain a value of the APP from the matrix, the sub block n-D Lookup Table is used in Simulink.

The n-D Lookup Table has 3 inputs, related to the three dimension of the matrix. The acceleration have values from 0 to 10, 0.1 by 0.1; the initial and the final speed have values from 0 to 245 km/h, 5 by 5; all of this in the table, being the table data the matrix created in Matlab with the code. This sub block makes interpolations and extrapolations. The only thing, that has to be made, is to put in the inputs the values that are wanted, in another words, in first place the determinate acceleration, in second place the initial speed, and in third place the final speed. Once the code runs and the simulation model will be obtained from the output of this sub block the acceleration pedal position. Furthermore, it can be watched at the end the graphics for the acceleration and the speed of the car until is reached the final desired speed.

It can be chosen any value to the inputs which are within the range which is being studied. If the valor is the same which is in the table data, is gotten a value which is a real one. However, if the chosen value is not in the table data, the simulation interpolate thank to this new sub block, getting a value very close to reality, being able to conclude that the difference is so small that is taken the result as valid. So the purpose of this chapter has been reached with success.

Now can be seen two examples: one accurate simulation and one interpolate simulation.

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The first one is from 0 km/h to 50 km/h, with a real value of 0.6 m/s^2, obtaining a 30.55% of APP, as can be seen. After 23.15 seconds is reached the 50 km/h to 0.6 m/s^2. In the second one, from 0 km/h to 50 km/h too, with a real value of 0.85 m/s^2, it is gotten a 35.85% of APP, as can be watched. After 16.34 seconds is reached the 50 km/h to 0.85 m/s^2, although in the simulation it is reached 0.8501 m/s^2 in 16.3399 seconds, so the difference is negligible, and the purpose of this project is considered that has been reached successfully.

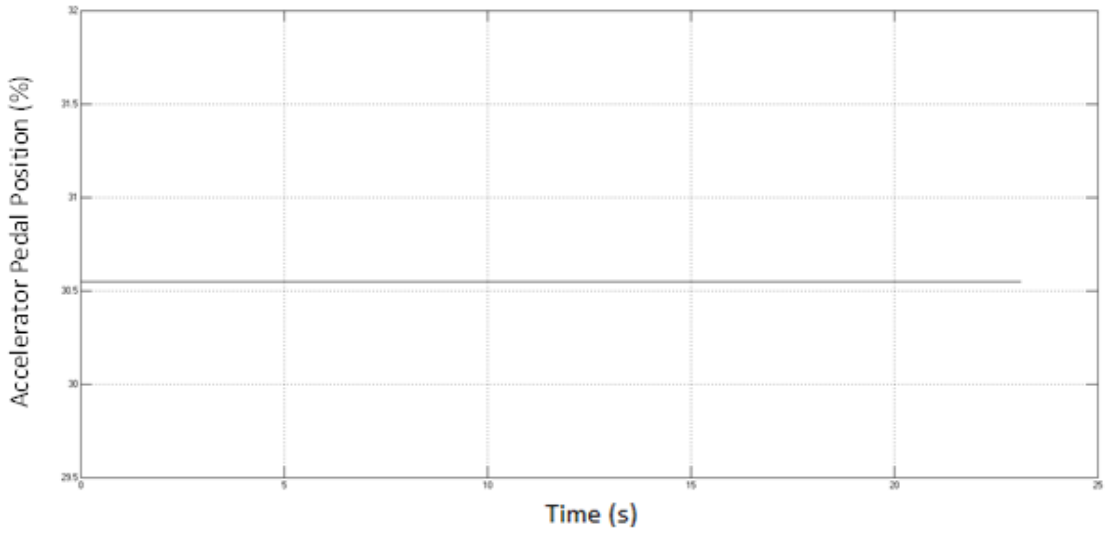

Fig 4.3.3.4: From 0 km/h to 50 km/h to 0.6 m/s^2 (real value), the APP is 30.55%

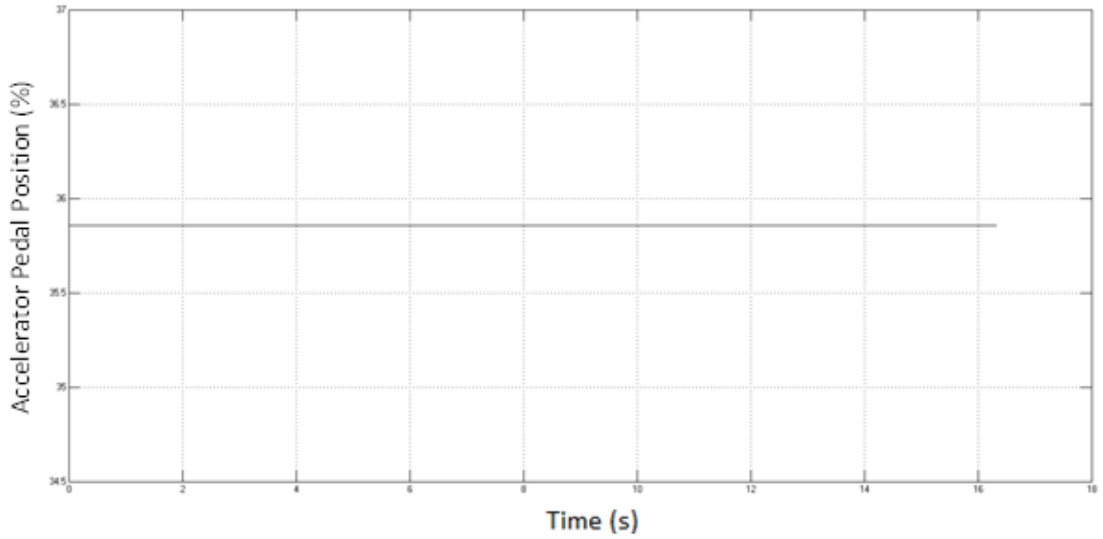

Fig 4.3.3.5: From 0 km/h to 50 km/h to 0.85 m/s^2 (interpolate value), the APP is 35.85%

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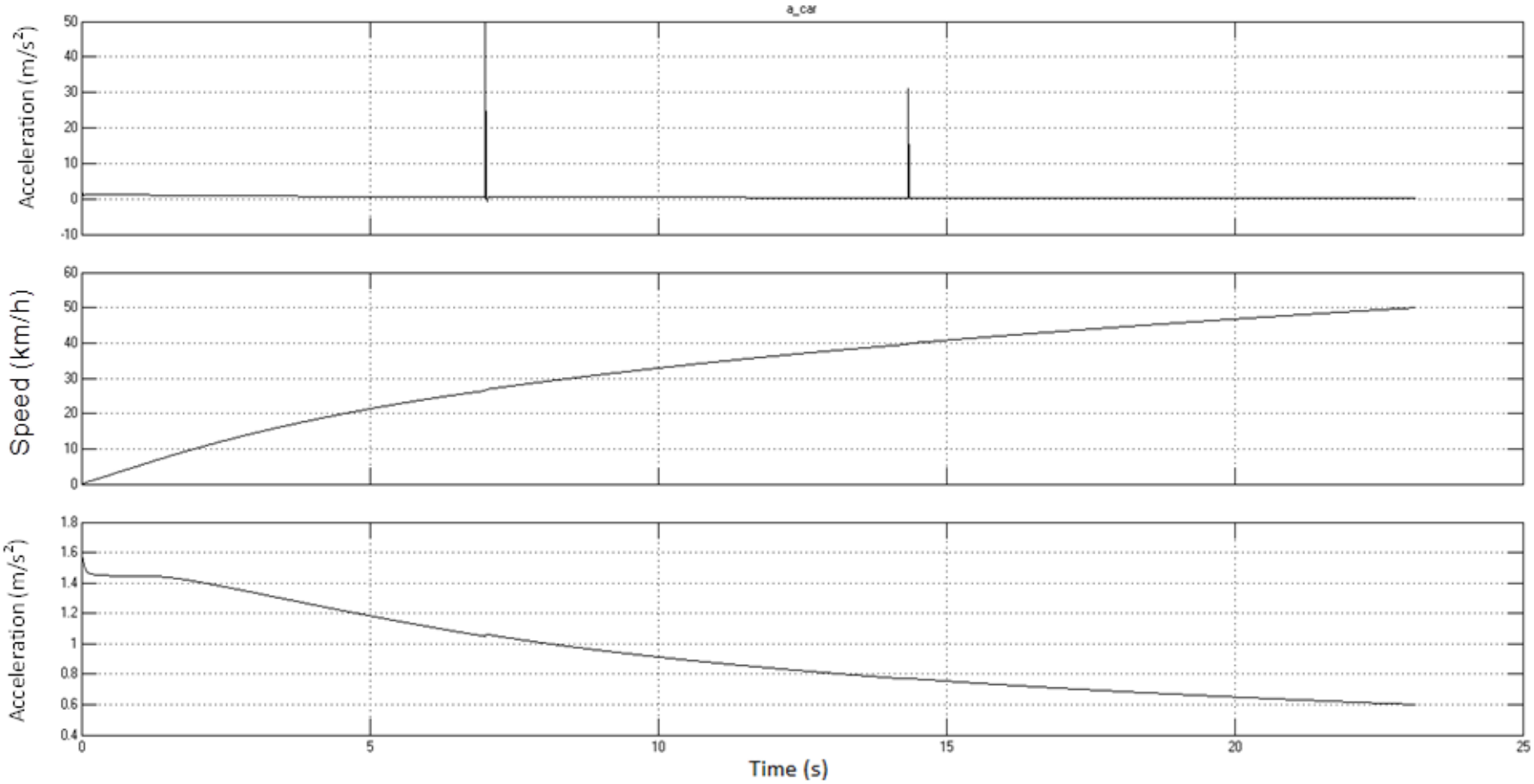

Fig 4.3.3.6: To 30.55 % APP, the output acceleration, the speed and the acceleration of the vehicle from 0 km/h to 50 km/h, to 0.6 m/s^2 (real value)

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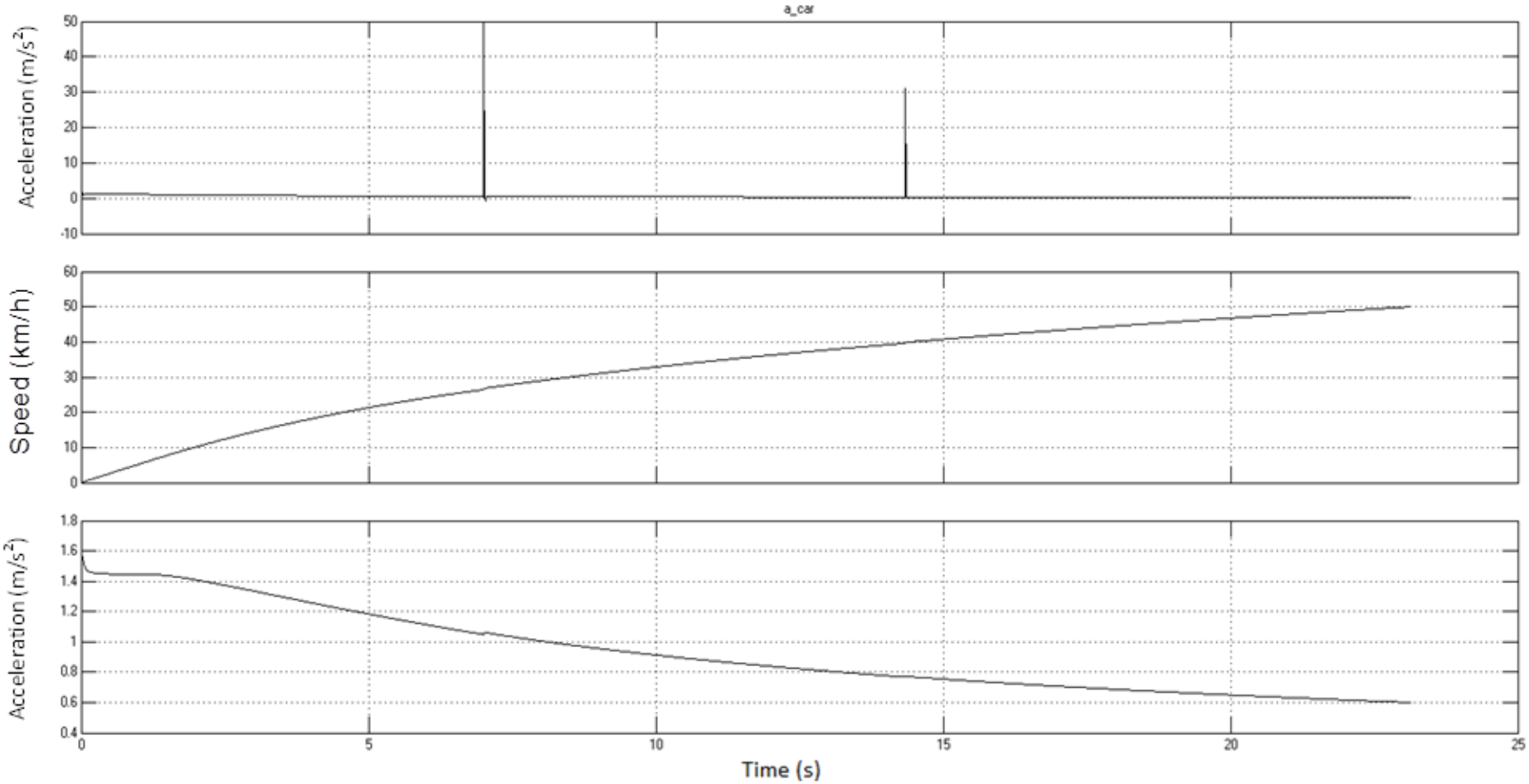

Fig 4.3.3.7: To 35.85 % APP, the output acceleration, the speed and the acceleration of the vehicle from 0 km/h to 50 km/h, to 0.85 m/s^2 (interpolate value)

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4.3.4. Study of the APP varying the maximum limit of the rotational velocity in the gearbox

In this chapter, it is going to be simulated the same model, which has been created and explained in the previous chapter, but it has been modified, because now it is going to be studied how affect the variation of the maximum limit of the rotational velocity (rpm) in the gearbox at the accelerator pedal position. In this paragraph it will be explained how it has been made and reached the objective, and it will continue in the chapter of results and conclusion, where will be exposed the results and written the conclusions about it.

First of all, the tables needed to the simulation are going to be created, like it has been done in the chapter 4.3.2. Each of these tables contains the next data of the car: time, acceleration and speed. It is created tables for different accelerator pedal position and different rpm. In this case not only varies the APP, the maximum limit of the rotational velocity (rpm) in the gearbox changes too. It is between 1500 rpm to 3900 rpm, increasing this value, 100 by 100 rpm. To each value of rotational velocity, the APP varies from 0.1 to 1, in steps of 0.1. Therefore, it is necessary to change the sub block in the model, which change the accelerator pedal position (as in chapter 4.3.2), and the sub block that changes the maximum limit of the rotational velocity (rpm) in the gearbox, to obtain the table.

That is to say, in this Simulation the accelerator pedal position is not constant, and the maximum rpm too; otherwise it changes for each table. So not to change manually in each moment the value of the APP and the maximum rpm, it is automated through an easy Matlab code that has been created for this purpose.

Consequently, this code switches the maximum value of the gearbox and the APP automatically. Thus for each value of rpm the code calls to the simulation through the new sub block, named “Rotational”, which is in the same position where in the last case was the constant value of the maximum rpm, which was 3500 rpm; and it is had the sub block, named “Throttle”, to modified the APP. So a table for each one is created and saved, firstly for one value of rpm and for all values of APP, after it is changed the rpm and another time all the values of APP, and so on until it is had all the

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tables; in a kind of archive ".mat", being a "timeseries" table. This code can be seen and studied in the CD.

Secondly, once all the tables are had, is done something similar to chapter 4.3.3. It is going to be simulated an approximated model to the model from these chapter, which has been created and explained to obtain the accelerator pedal positions.

Therefore, in this Simulation, the sub block, which is the accelerator pedal position, is going to be the Simulink n-D Lookup Table again.

With the n-D Lookup Tables, it is wanted to obtain the table with the accelerator pedal positions. In this table the value of rpm is in the column (the y axis), and the determine acceleration is in the row (the x axis); the initial and the final speed depends on the table which was chosen. Watching and searching in this table it can find the accelerator pedal position to reach one speed from an initial speed, with a determinate acceleration and a determine rpm. The n-D Lookup Table has these four dimensions. And with this obtain the APP.

This part begins with a Matlab code, which can be seen and studied in the CD, to use the gotten tables in the new sub block, the n-D Lookup Table. In this code a great matrix is created, which will contain all the data to obtain the APP, and where are charging the previous tables, and from them the speed and the time is taken. With them the empty matrix is filled, calculating the start and the final speed, the acceleration and the rpm. At the end a full matrix of 4 dimensions is had, where the first parameter is the rpm, the second parameter is the acceleration, the third parameter is the initial speed, and the fourth parameter is the final speed. The result obtain in the matrix is the accelerator pedal position. To obtain a value of the APP from the matrix, it is used in Simulink the sub block n-D Lookup Table.

The n-D Lookup Table has 4 inputs, related to the four dimension of the matrix. The rpm have values from 1500 to 3900, 100 by 100; the acceleration have values from 0 to 10, 0.1 by 0.1; the initial and the final speed have values from 0 to 245 km/h, 5 by 5; all of this in the table, being the table data the matrix created in Matlab with the code.

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This sub block makes interpolations and extrapolations. The only thing that has to be made is to put in the inputs the values that are wanted, in another words, in first place the rpm, in second place the determinate acceleration, in third place the initial speed, and in fourth place the final speed. Once run the code and the simulation model will be obtained from the output of this sub block the acceleration pedal position. Furthermore, it can be watched at the end the graphics for the acceleration and the speed of the car until is reached the final desired speed.

It can be chosen any value to the inputs which are within the range which is being studied. If the valor is the same which is in the table data, a value which is a real one is gotten. However, if the chosen value is not in the table data, the simulation interpolate thank to this new sub block, getting a value very close to reality, being able to conclude that the difference is so small that is taken the result as valid. So the purpose of this chapter has been reached with success.

Finally, the results, which are gotten after the simulation and their explanations, are in the chapter results, which is just in the next paragraph. Then in the conclusions are the ideas which are obtained from this work.

In the figure 4.3.4.1 the sub block of the engine in Simulink can be watched, and the sub block of the accelerator pedal position too, where the inputs of the engine are the accelerator pedal position (APP), which in this case is called by a Matlab program to simulate all the tables to the different accelerator pedal position and different rpm, and the speed recirculated from the transmission, and the output is the torque of the engine which goes to the transmission. The maximum limit of the rotational velocity in the gearbox varies. In the figure 4.3.4.2 the sub block of the accelerator pedal position in Simulink can be watched, where the inputs of this block are a determinate acceleration, an initial speed, a final speed and the rpm, being the output the APP, which is one of the inputs of the engine. In the Fig 4.3.4.3 the block diagram of the model to obtain the tables for different accelerator pedal positions and different rpm developed in Simulink is shown. In the Fig 4.3.4.4 the block diagram of the model to obtain the accelerator pedal position through the previous tables obtained in Simulink for a determinate rpm, a determinate acceleration, an initial speed and a final speed of the vehicle is shown.

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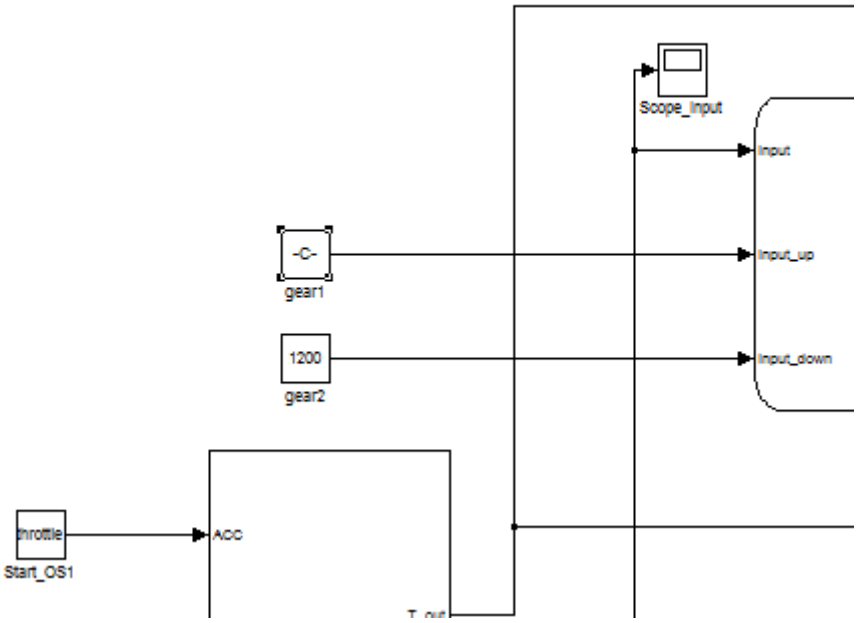

Fig 4.3.4.1: Block diagram of the throttle to create the tables for different APP and different rpm in Simulink environment

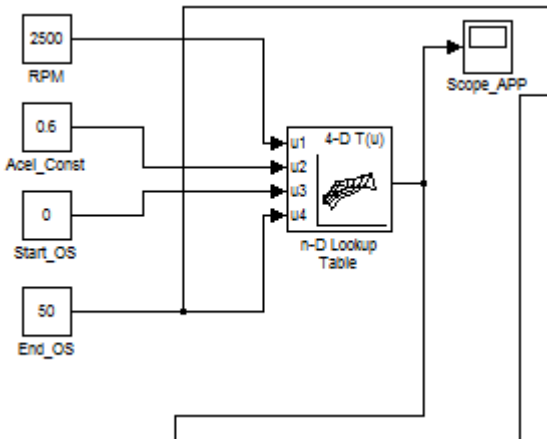

Fig 4.3.4.2: Block diagram of the throttle to obtain the APP to an initial speed, a final speed, a determinate acceleration and a determinate rpm in Simulink environment

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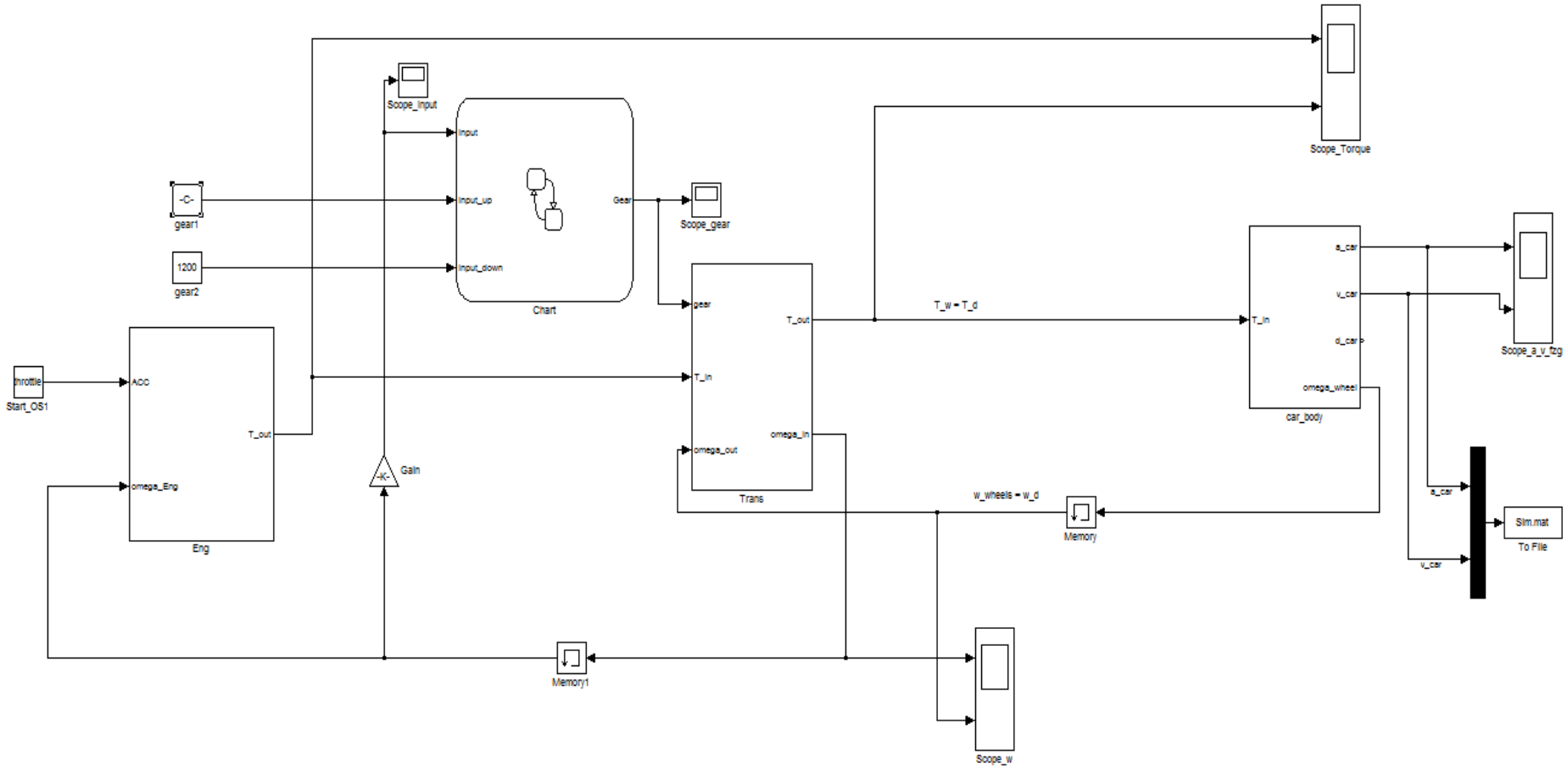

Fig 4.3.4.3: Simulink top level diagram of the model to obtain the tables to different APP and different rpm

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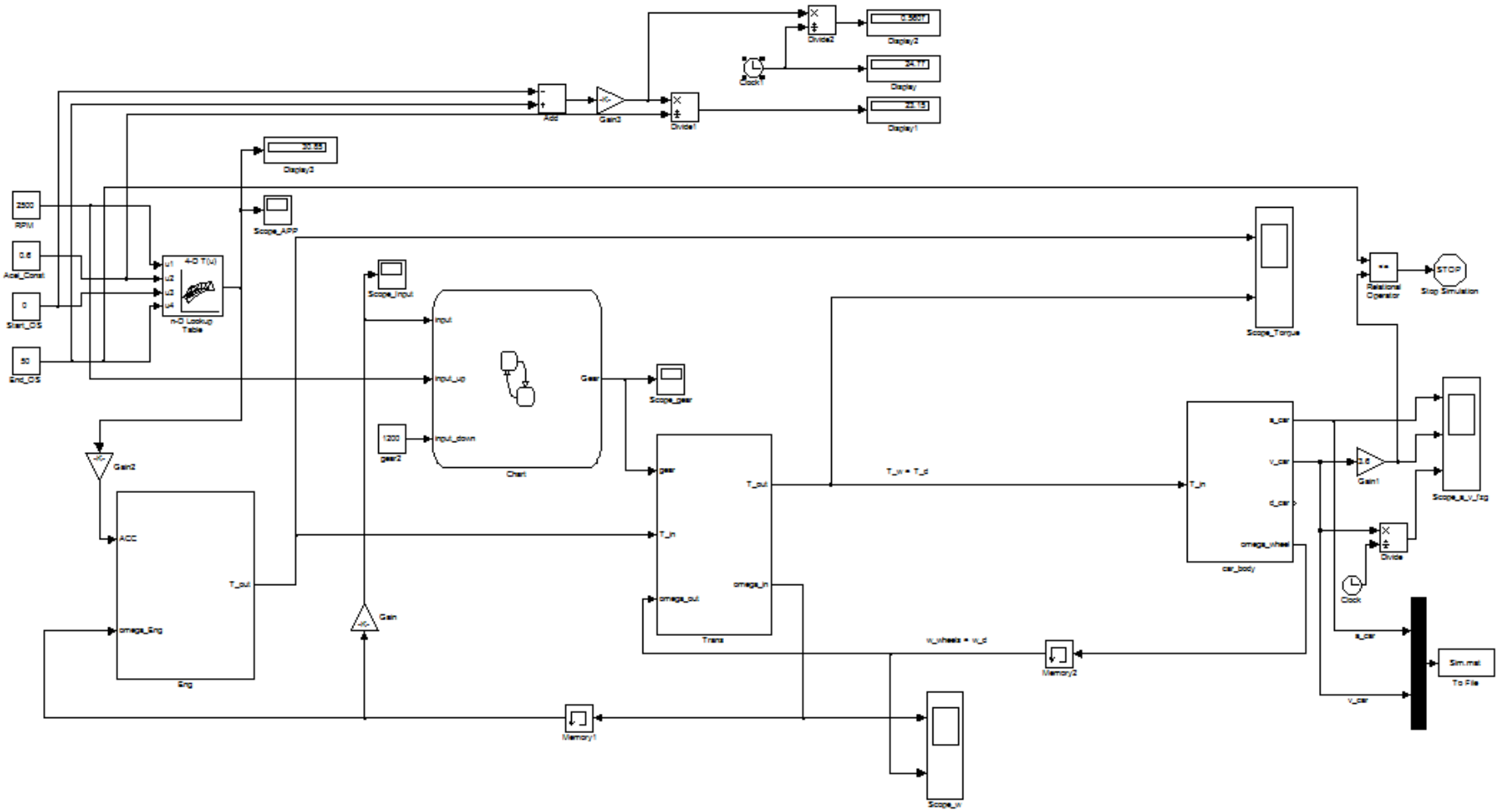

Fig 4.3.4.4: Simulink top level diagram of the model to obtain the accelerator pedal position varying the rpm

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5. RESULTS

In this new chapter, it is going to be commented the results, which have been reached along the realization of the entire project. Along the project, it has been explained the different problems or purposes to get, how were solved, and the results which were obtained.

Across this Master Thesis, after each chapter, once the objective was raised, it was explained how it had been executed and done, the results which had been reached were exposed and their explanations or conclusions. Firstly with the statistical study of the speed in Matlab in the chapter 3. Then the statistical study of the acceleration in Matlab in the chapter 4.1. Afterwards the simulation of the car in Simulink, creating the model and checking its operation in the chapter 4.2 and 4.3.1. Later the creation of the tables to different acceleration pedal positions in chapter 4.3.2, to obtain subsequently in the next chapter, 4.3.3, the accelerator pedal position in function of a determinate speed, an initial speed and a final speed.

All of them have been discussed in their respective sections. Not to repeat, in this chapter it is only going to be exposed the results and the explanations of the last one, the study of the APP varying the maximum limit of the rotational velocity in the gearbox, which has been raised, and explained how it has been solved in the chapter 4.3.4. So now it can be watched the results and their comments. The conclusions of this Master Thesis and this paragraph can be read in the next one, called Conclusions.

Once has been created all the tables, and the model to simulate the vehicle, it is been able to simulate it and to obtain different results. It is going to be analyzed any of the results which can be gotten. It is only to be varied the maximum limit of the rotational velocity (rpm) in the gearbox, in other words, the determine acceleration, the initial speed and the final speed are always going to be the same values in all the simulations, is only changed the rpm, to study its influence in the accelerator pedal position and in the time to reach what is wanted. After that, it will be varied the acceleration too, to understand the behavior of the vehicle better.

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Here four examples can be watched, the first of them when the maximum limit of the rotational velocity in the gearbox, in other words, the rpm are 3500 rpm, the second of them when the rpm are 1500 rpm, the third of them when the rpm are 2500 rpm, and the last one when are had 3900 rpm. All of them with an acceleration of 0.6 m/s^2, an initial speed of 0 km/h, to reach a final speed of 50 km/h.

In the first one when the rpm are 3500, to achieve from 0 km/h, a final speed of 50 km/h delays 23.97 seconds, reaching an acceleration of 0.5795 m/s^2. In this case the accelerator pedal position has a value of 30.13 %.

In the second one when the rpm are 1500, to achieve from 0 km/h, a final speed of 50 km/h delays 23.15 seconds, reaching an acceleration of 0.6 m/s^2. In this case the accelerator pedal position has a value of 39.74 %.

In the third one when the rpm are 2500, to achieve from 0 km/h, a final speed of 50 km/h delays 24.77 seconds, reaching an acceleration of 0.5608 m/s^2. In this case the accelerator pedal position has a value of 30.85 %.

In the fourth and last one when the rpm are 3900, to achieve from 0 km/h, a final speed of 50 km/h delays 24.33 seconds, reaching an acceleration of 0.5709 m/s^2. In this case the accelerator pedal position has a value of 30.21 %.

Then, it can be watched in the table 5.1, comparing the different mentioned values for each case, to study better this part and to be able obtain a serial of conclusions.

Table 5.1: Table resume of the values to study the APP varying the maximum limit of the rotational velocity in the gearbox, from 0km/h to 50 km/h, and 0.6 m/s^2

	1500 rpm	2500 rpm	3500 rpm	3900rpm	Original
APP (%)	39.74	30.85	30.13	30.21	30.55
Time (s)	23.15	24.77	23.97	24.33	23.15
Real acceleration (m/s^2)	0.6	0.5608	0.5795	0.5709	0.6

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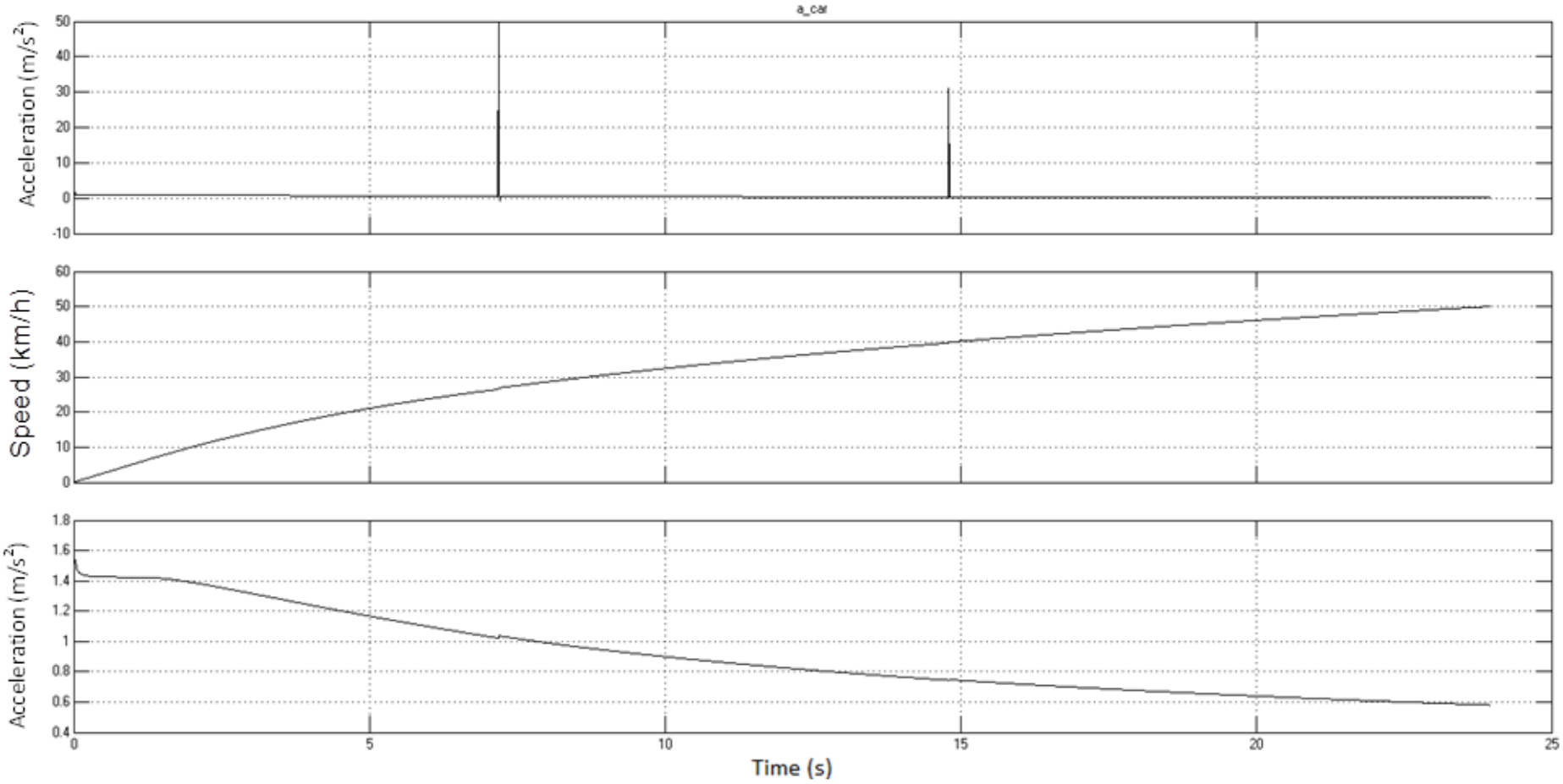

Fig 5.1: To 30.13 % APP, the output acceleration, the speed ,the acceleration and the rpm of the vehicle from 0 km/h to 50 km/h, to 0.6 m/s^2, to 3500 rpm

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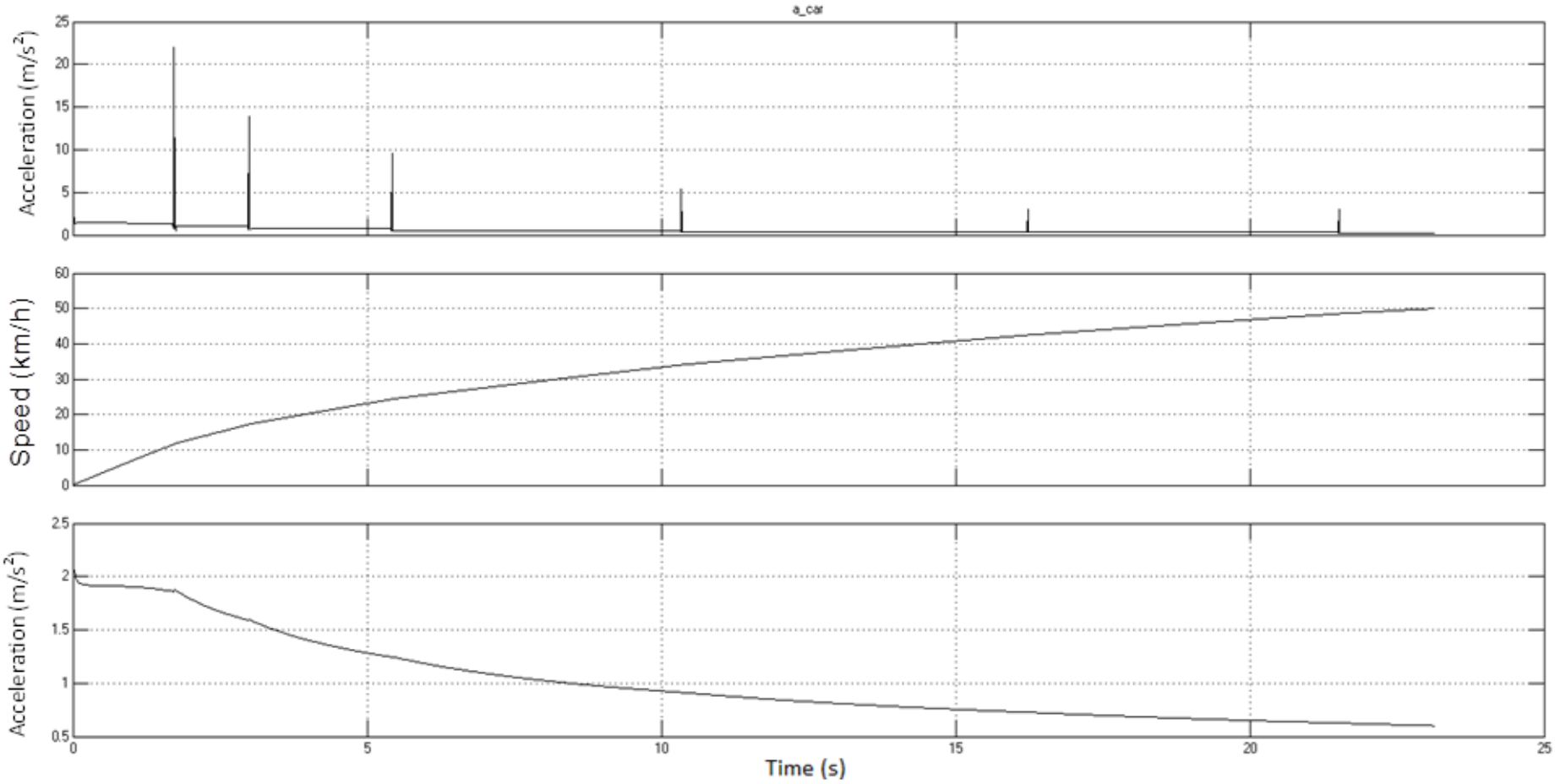

Fig 5.2: To 39.74 % APP, the output acceleration, the speed ,the acceleration and the rpm of the vehicle from 0 km/h to 50 km/h, to 0.6 m/s^2, to 1500 rpm

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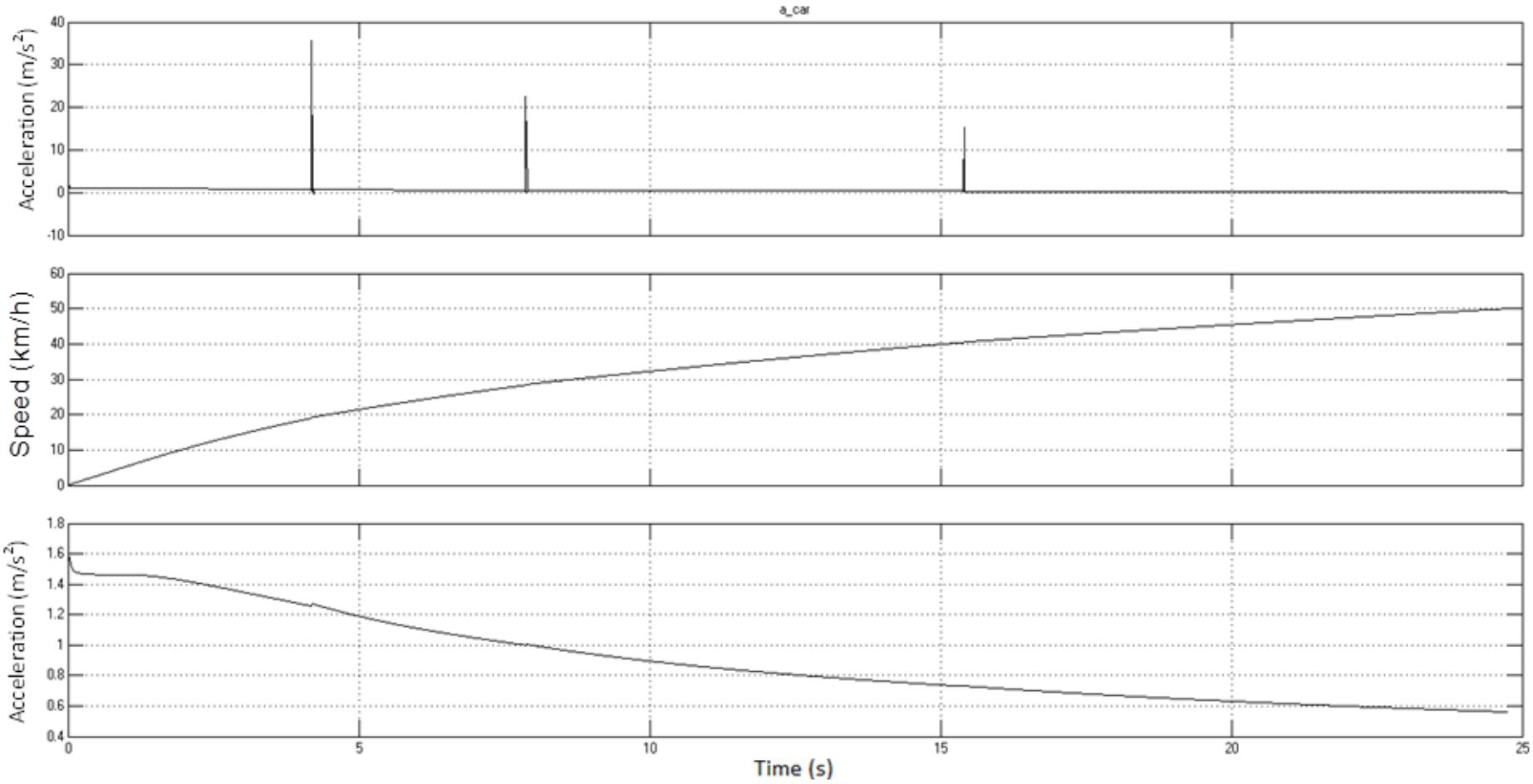

Fig 5.3: To 30.85 % APP, the output acceleration, the speed ,the acceleration and the rpm of the vehicle from 0 km/h to 50 km/h, to 0.6 m/s^2, to 2500 rpm

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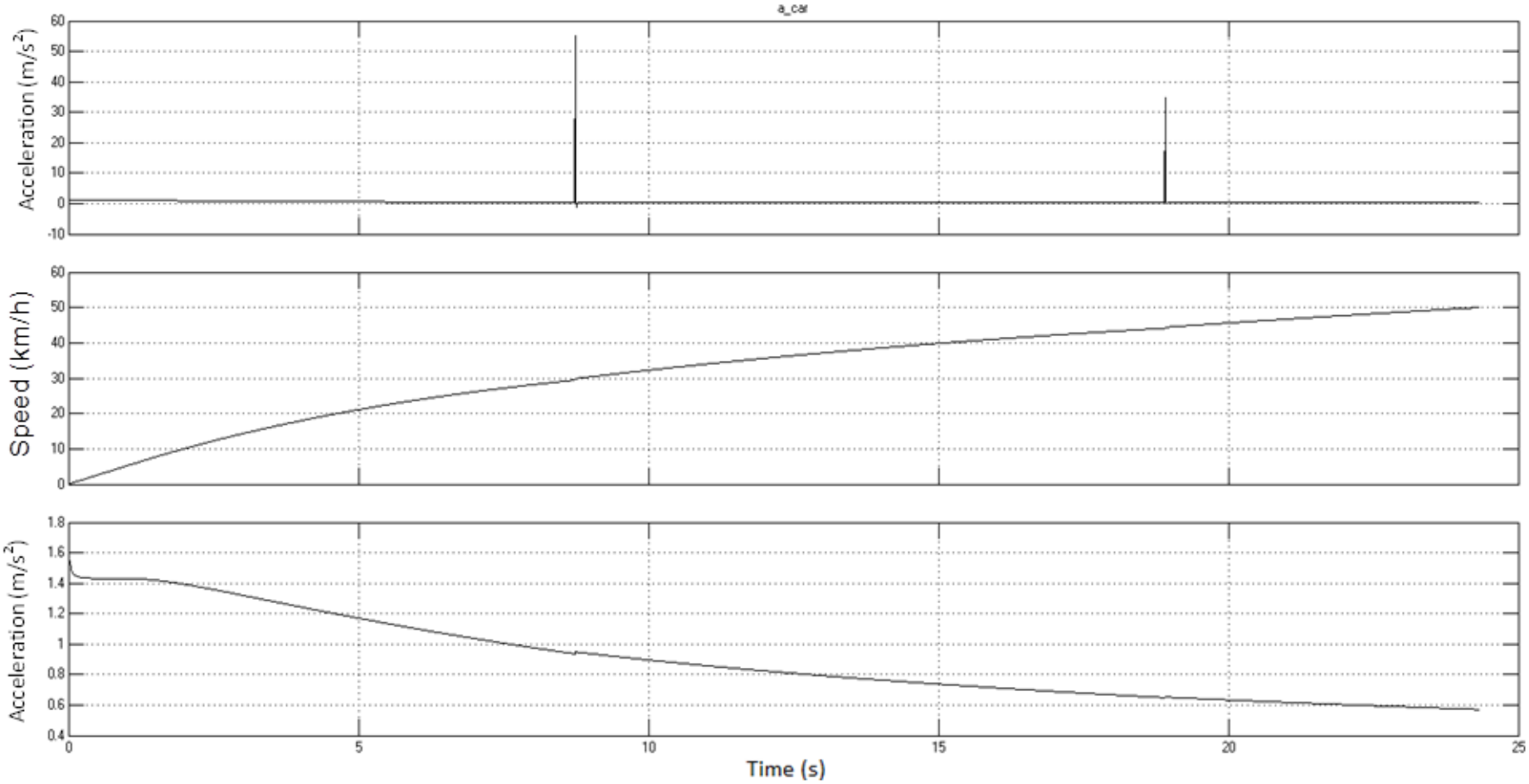

Fig 5.4: To 30.21 % APP, the output acceleration, the speed ,the acceleration and the rpm of the vehicle from 0 km/h to 50 km/h, to 0.6 m/s^2, to 3900 rpm

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It is taken into account the values of these four samples, and one from the original, to the chapter 4.3.3, with an acceleration of 0.6 m/s^2, an initial speed of 0 km/h and a final speed of 50 km/h, such as in these samples, obtaining an acceleration of 0.6 m/s^2 in 23.15 second and accelerator pedal position of 30.55 %.

How it can be appreciated, the lower is the value of the maximum limit of the rotational velocity in the gearbox, the greater is the percentage of accelerator pedal position, until 3500 rpm, from it rises again.

The acceleration in none of these cases is just the value pretended, only in the first one when the maximum limit is 1500 rpm. In the rest of cases is next but not accurate.

The time is variable, because when the variable is 1500 rpm, is the lower value time, in 2500 rpm is the higher one, when is 3500 rpm descends, and in 3900 rpm, back up again.

Comparing with the original value on chapter 4.3.3, when the maximum limit was 3500 rpm, all is different. The same value now, its APP is lower, the acceleration too, and the time is higher. To 1500 rpm, everything is equal that in the original, less the APP which is higher. To 2500 rpm, the APP and the time are higher, however the acceleration is lower. And to 3900 rpm, the APP and the acceleration is lower, while the time is higher.

In the new cases the data of the APP is caught 10 by 10 %, and then the simulation interpolates. In the old case the data of the APP was taken 2 by 2 %, having more data and being lower the error in the interpolation. This can be the motive why exist these differences, which are minimum.

Finally, it has been able to watch the graphics of these samples (Figures 5.1, 5.2, 5.3, 5.4), which have been studied, and then is developed a more exhaustive study about this.

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Table 5.2: Table complete of the values to study the APP varying the maximum limit of the rotational velocity in the gearbox, from 0km/h to 50 km/h, and 0.6 m/s^2

rpm	t (s)	APP (%)	a (m/s^2)
(7th) 1500	23.15	39.74	0.6
(6th) 1600	23.35	38.02	0.5948
1700	23.68	36.5	0.5865
(5th) 1800	24.04	35.15	0.5778
1900	24.32	34.17	0.5712
2000	24.57	33.24	0.5653
2100	24.77	32.4	0.5608
2200	24.86	31.66	0.5587
(4th) 2300	24.86	31.36	0.5587
2400	24.83	31.09	0.5594
2500	24.77	30.85	0.5608
2600	24.67	30.65	0.563
2700	24.54	30.48	0.566
2800	24.39	30.35	0.5695
2900	24.23	30.25	0.5733
3000	24.06	30.17	0.5773
(3th) 3100	24.02	30.15	0.5783
3200	23.98	30.14	0.5792
3300	23.96	30.13	0.5798
3400	23.95	20.126	0.58
3500	23.97	30.127	0.5795
3600	24.01	30.13	0.5785
3700	24.08	30.15	0.5768
3800	24.19	30.17	0.5742
3900	24.33	30.21	0.5704

The conclusion that can be done is the next, with the table 5.2. The time increases and the acceleration decreases from 1500 rpm to 2300 or 2400 rpm, when the vehicle arrives at most from 5th gearshift to 4th gearshift. Then the time decreases and the acceleration increases from 2300 or 2400 rpm to 3400 or 3500 rpm. The APP decreases from the beginning to this point too. Finally, from 3400 or 3500 rpm to 3900 rpm, the time increases again, the acceleration decreases again, and the APP increases now. This is the behavior of the vehicle varying the maximum limit of the rotational velocity in the gearbox.

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Table 5.3: Table complete of the values to study the APP, the real acceleration and the real and simulation time, varying the maximum limit of the rotational velocity in the gearbox, and varying the acceleration, from 0km/h to 50 km/h

rpm	a_{wanted} (m/s^2)	a_{real} (m/s^2)	APP (%)	t_{real} (s)	$t_{simulation}$ (s)
1500	0.3	0.3793	29.75	36.62	46.3
	0.6	0.6	39.74	23.15	23.15
	1	1.001	57.89	13.89	13.88
	1.5	1.5	78.25	9.259	9.26
	2	2.007	94.76	6.944	6.92
2000	0.3	0.4594	29.51	46.3	30.23
	0.6	0.5655	33.25	23.15	24.56
	0.85	0.85	43.4	16.34	16.34
	1	1.001	48.79	13.89	13.88
	1.5	1.5	66.64	9.259	9.26
	2	1.998	83.29	6.944	6.95
2500	0.3	0.5095	29.37	46.3	27.26
	0.6	0.5607	30.85	23.15	24.77
	1	1.001	43.77	13.89	13.88
	1.5	1.5	58.65	9.259	9.26
	2	1.998	73.57	6.944	6.95
3000	0.3	0.5398	29.28	46.3	25.73
	0.6	0.5775	30.17	23.15	24.05
	1	1.001	40.38	13.89	13.88
	1.15	1.15	48.22	12.08	12.08
	1.5	1.5	52.75	9.259	9.26
	2	1.998	65.22	6.944	6.95
3500	0.3	0.5385	29.29	46.3	25.79
	0.6	0.5797	30.13	23.15	23.96
	1	0.9985	39.06	13.89	13.91
	1.2	1.2	43.5	11.57	11.57
	1.5	1.5	50.17	9.259	9.26
	2	1.998	61.38	6.944	6.95
3900	0.3	0.5221	29.33	46.3	26.6
	0.6	0.5711	30.21	23.15	24.32
	1	0.9942	38.31	13.89	13.97
	1.2	1.2	42.44	11.57	11.57
	1.5	1.5	48.54	9.259	9.26
	2	1.998	58.85	6.944	6.95

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In the last table, the table 5.3, it is been able to see the variation of the real acceleration (a_{real}), the real time (t_{real}), the time of simulation ($t_{simulation}$) and the APP, modifying the maximum limit of the rotational velocity in the gearbox, and the acceleration (a_{wanted}).

As it can be watched, the real acceleration and the wanted acceleration are different, but there is one moment in each value of rotational velocity, from which they are equal or they are very close. The greater is the maximum limit of the rotational velocity in the gearbox, the higher is the value of acceleration where it happens.

Six representative examples have been taken to demonstrate it. In the first one, to 1500 rpm, this moment happens when the acceleration is 0.6 m/s^2; being both times 23.15 s and the APP 39.74 %. In the second one, to 2000 rpm, this moment happens when the acceleration is 0.85 m/s^2; being both times 16.34 s and the APP 43.4 %. In the third one, to 2500 rpm, this moment happens when the acceleration is approximately 1 m/s^2; being both times 13.89 and 13.88 s and the APP 43.77 %. In the fourth one, to 3000 rpm, this moment happens when the acceleration is 1.15 m/s^2; being both times 12.08 s and the APP 48.22 %. In the fifth one, to 3500 rpm, this moment happens when the acceleration is 1.2 m/s^2; being both times 11.57 s and the APP 43.5 %. And in the sixth and last one, to 3900 rpm, this moment happens when the acceleration is 1.2 m/s^2; being both times 11.57 s and the APP 42.44 %.

Along these cases, the greater is the rpm, the higher is the acceleration, and the lower is the time; being the APP higher until 3000 rpm, and lower from this point. This phenomenon can be possible, due to the interpolation. It is been able to be affected when is done the interpolation in the Matlab code creating the Matrix in the last order in it, or the interpolation which is carried out in the n-D Lookup Table, when the APP is asked from the parameters which are wanted.

This problem can be a future work, to be studied and developed with more time in a close future. Finally, in the next chapter, it can be read the conclusions of this part and this project.

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6. CONCLUSIONS

In this chapter are found the conclusions of this Master Thesis, particularly focused in the last work done in it.

- The statistical study of the velocity results in a good approximation to reality, taking into account the most significant points of it.

- The same happens with the statistical study of the acceleration, only taking the acceleration and velocity plateau points, ignoring the decelerations.

- The model simulation, which has been built and simplified, is a simple one which works correctly, and allows a right simulation and study of the acceleration and accelerator pedal position.

- The creation of the tables for different APP, and their later use to obtain the APP, from the acceleration, initial velocity and the final velocity that wants to be achieved, being a real value, an interpolate or an extrapolate value. It works successfully.

- Lastly, is carried out a study of the APP varying the maximum limit of the rotational velocity in the gearbox. At a glance, it is been able to say that it affects the results.

- The greater is the maximum limit; the lower is the APP, to 3500 rpm (the original value). Then the greater is this maximum limit; the higher is the APP. Also, the greater is the maximum limit; the lower is the time to reach the desired speed from 1500 rpm to 2300 or 2400 rpm, and from 3400 or 3500 rpm to 3900 rpm. However, the greater is the maximum limit; the higher is the time from 2300 or 2400 rpm to 3400 or 3500 rpm.

- To different accelerations, the greater is the maximum limit of the rotational velocity in the gearbox, the higher is the acceleration, and the lower is the time; being the APP higher until 3000 rpm, and lower from this point. This can be possible due to the interpolation. In discussion of errors, it is better explained.

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6.1. Future Work

This project could be improved, and it could be continued, because it could develop more in other aspects, even supplemented by other. In other words, these are some of the aspects that can be work in the future.

Firstly, the first chapter can be improved, related to the speed of the vehicle. The approximated speed can be better if are demanded more points to get it. It can be used the acceleration now or another aspects that have been commented in the paragraph of problems, which can be developed with more time.

Secondly, the statistical study of the acceleration of the vehicle can be improved. The approximated acceleration can be better if are modified the located points to study it. Improving the previous chapter, this can be improved, and the points are better, and here the moment that are selected the plateau points, this part depends on very much the data that is had, in other words, on the vehicle, the driver and driver's behavior, and the driving environs. All of these things with more time.

Thirdly, the simulation of the vehicle can be improved. The model is a simple one of the vehicle, where the different parts of the car have been simplified, or even deleted. To the correct running of the simulation of the vehicle is accepted successfully, because it works, create the tables for different APP, and to an initial speed a final speed and a determined acceleration, the APP is reached, which is the purpose of this Master Thesis. All of them are very well and are reached a satisfying results and conclusions, but it can be better if the model is improved. This is reached if the model is more complete, developing the different parts of the vehicle or adding the clutch. More cases can be studied, not only varying the maximum limit of the rotational velocity (rpm) in the gearbox, and improve this study, with more time.

Finally, this project is part of another great project, and it can be complemented with the other parts. If the driving environ, such as the wind, the road, the geography, etc., and the clutch, are taken into account, the result obtained will be better. With more time it can be a good project to carry out to develop the 3D Parameter Space.

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6.2. Discussion of the errors

This part is focused on the most important part of the Master Thesis, the study of the APP, which has been watched more extended in the chapter of results.

Firstly, in the statistical study of the speed, and the acceleration, the error can be due to the specifications. Sometimes some filters or values were necessary to obtain the specifications, and they could fail in other cases or with another data, but we do not have the way to know it. The build of the model is simple and does not have problems, like when the tables were created.

In the first study of the accelerator pedal position, which consists on obtaining the APP, the error is in the interpolation and extrapolation. When the value is a real value, that the n-D Lookup Table has in its information, there is no problem, the result is the same that the theoretical one. However, when the specification, which are wanted, are not in the table, the sub block interpolates or extrapolates, and the result is very close to theoretical one, the error is in the hundredths or thousandths, being the error ±0.001.

The second study of the accelerator pedal position consists on a study of the APP, when the maximum limit of the rotational velocity (rpm) in the gearbox is changed. As it can be studied and watched before, there is a problem, that may be due to the interpolation too. It is a part to continue working in the future. When the acceleration and the rpm are varied, we have an error in the results that we have. To a maximum limit the time is not the correct to reach the final speed, until the acceleration is the marked, in red, in the table 5.3, when the time is the same as the theoretical time for this acceleration. This is the conclusion which can be deduced from these results. The correct values are these ones for these maximum limits. The error can be due to the interpolation when is created the matrix, or the interpolation in the n-D Lookup Table.

Finally, it is more or less the conclusions and the errors, which can be talked in this Master Thesis, there is been able to be someone more, but these are the most important ones.

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8. APPENDIX

In this Appendix has been able to be explained how is the CD, where are the Matlab codes developing along the Master Thesis to understand better and to work with them on the computer. The Matlab, the Simulink and other files created in this project, and which are the purposes of it, are on the CD attached to this document.

In the CD there are six folders. In the first one, it is the Matlab work about speed, from chapter 3. In the second one, it is the Matlab work about acceleration, from chapter 4.1. In the third one, it is the Simulink work about creation and checking the model, from chapter 4.3.1. In the fourth one, it is the Simulink work about creation of tables for different APP, from chapter 4.3.2. In the fifth one, it is the Simulink work about obtaining the APP, from chapter 4.3.3. And in the sixth and last one, it is the Simulink work about Study of the APP varying the maximum limit of the rotational velocity in the gearbox, from chapter 4.3.4, 5 and 6.

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