Doctoral Program in Engineering Sciences at ITESO

VEHICLE DYNAMICS AND CONTROL SIMULATION PLAYGROUND: THE USER MANUAL

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March 5, 2025
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Abstract

This user manual provides documentation for a Simulink and MATLAB model designed to support students and researchers in the fields of vehicle dynamics, control systems, and electric motor applications. The model is publicly available to facilitate learning, experimentation, and validation of custom models or control strategies. By sharing this resource, we aim to contribute to the advancement of clean and intelligent mobility, particularly in the development of electric and autonomous vehicles.

I. INTRODUCTION

This project is a MATLAB/Simulink model that simulates the longitudinal and lateral dynamics of a vehicle, incorporating electric motors as the main actuators. The goal is to provide a flexible and modular environment for studying and developing controllers for electric and autonomous vehicles.

It might feels frightening to face for the very first time to vehicle dynamics or control theory applied to it. A lot of math, many physical models that maybe don't fully understand at the first explanation. But don´t worry, you are not alone. You will discover that once the fear is gone, this is an amazing and fascinating topic to dive in.

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Now, getting to the topic, let me warn that this is not a complete model that contemplates all known science about the vehicle. At the moment of writing this, it is only an introductory model, but the intention is to grow it and introduce more dynamics making it more precise. However, maybe the best strategy is to build different versions of the model, because you don't always need the whole complexity; sometimes you only need a fraction or a simplified model. We will see the best approach along the time.

This model, at this time, is intended to comprehend the dynamics involved in vehicle displacement. That is, the physical forces and phenomenons acting on the vehicle when we drive it from one place to another. Don't forget that this is a 1 ton, or more, of iron rolling over rubber on asphalt, and many things occur in that process that we are not aware of.

Lets start with few definitions and concepts: **Vehicle Dynamics**: refers to the study of how vehicles move in response to driver inputs, road conditions, and external forces. It involves multiple subsystems, including longitudinal, lateral, and tire dynamics. In Fig. 1 shows to the left, the longitudinal dynamics and to the right the lateral dynamics which are described below.

Longitudinal Dynamics: Deals with vehicle motion along the forward/reverse direction. Involves acceleration, braking, and traction forces. Key factors: engine power, braking force, rolling resistance, and aerodynamic drag.

Lateral Dynamics: Governs the vehicle's motion side to side (yaw, sway). Determines steering response, cornering, and stability. Key factors: steering angle, tire slip angle, and centrifugal force.

Tire Dynamics: Describes how tires generate grip and forces on the road. Includes tire slip, friction, and deformation under load. Governed by models like the Pacejka "Magic Formula". These dynamics together define a vehicle's handling, stability, and safety in various driving conditions.

Now, as in the case of autonomous driving, we want the vehicle to follow a certain reference path. In this regard, a method that was popularized in the DARPA Grand Challenge (2004, 2005) and Urban Challenge (2007) was so called **waypoints** which are predefined reference points used in navigation to guide a vehicle along a specific path. In the context of autonomous vehicles, waypoints represent positions in 2D or 3D space that the vehicle follows to reach its destination. We have global waypoints: Large-scale path planning waypoints, often obtained from a GPS map.Define the general route from the start to the final destination. Local Waypoints: Short-range points used for fine control and path smoothing. Generated dynamically based on sensor data and road conditions. Each waypoint typically includes: Position (x, y, z), Defines location in world coordinates. Orientation (yaw, pitch, roll), Defines heading direction. Velocity or Time Stamp, Used for trajectory planning.

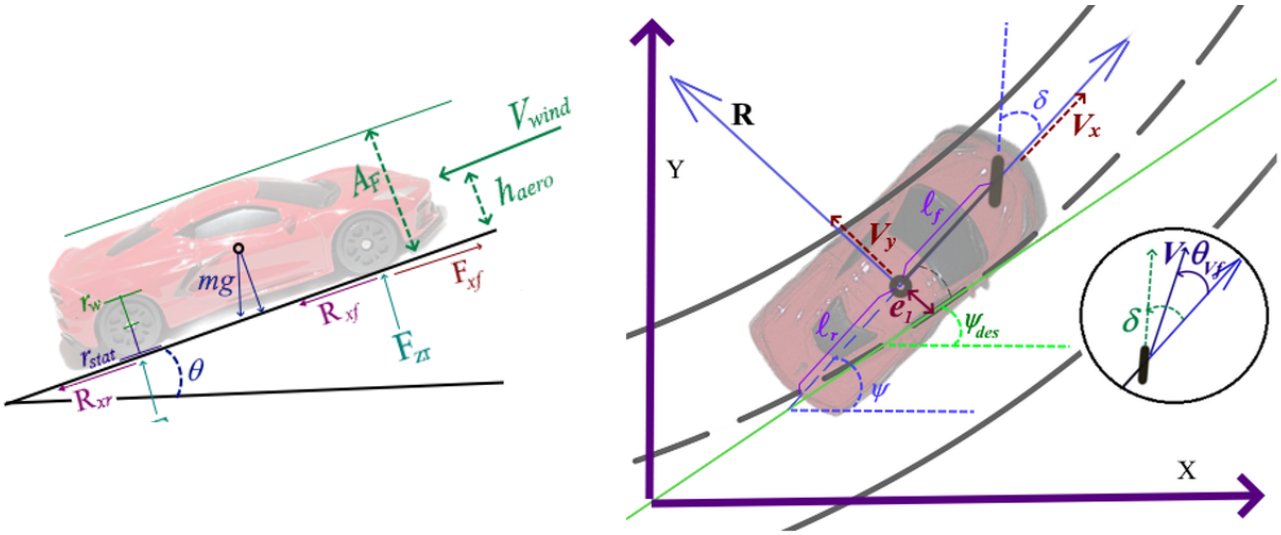

Figure 1: Typical scheme of the longitudinal and lateral dynamics

II. QUICK START

The intention of this section is to guide you to perform the first simulation of the vehicle and show you the first insights you can get at first hand.

Download the repo in Github from [1]. Fig. 2 shows the root directory of the repository. For now, we will be interested only in the highlighted directory named **./VehicleModel**. Go inside.

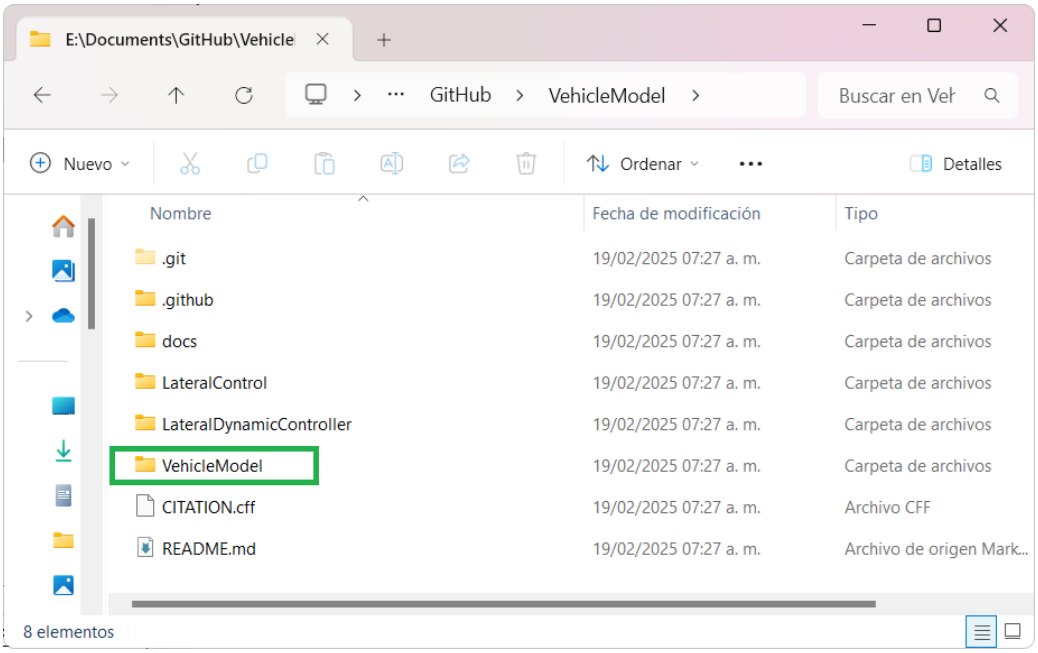

Figure 2: Root folder in the repository.

In Fig. **??** you can see the files within. the marked files are the ones we are interested for the

moment. Let me explain you them. the most important files is **LongLatDriveline.slx** since this is the main simulink model where our virtual vehicle is running. The file **VehicleData.sldd** is a Simulink data file that contains all parameters we can tune, according the characteristics we want for our vehicle. Finally, the file **waypoints.mat** constains the route that our vehicle will follow; this route can be modified, but we will see how to do that, further in the document.

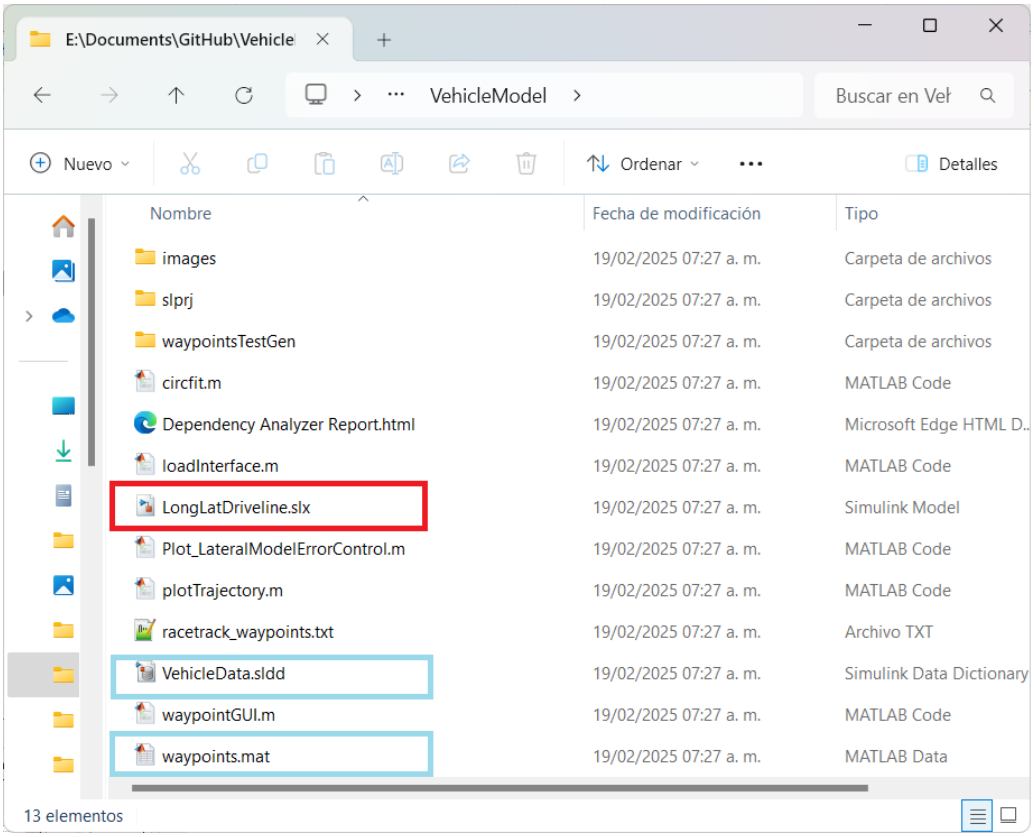

Figure 3: Main working files for simulation.

Open Matlab and select **VehicleModel** as working directory as in Fig. 4 and double click the file **LongLatDriveline.slx**

When the Simulink model is open, it will appear a window called *Initial conditions* as shown in Fig. 5. This window will contain, by default, the initial position and initial orientation detected in the way-point file **waypoints.mat** located in the root directory. If you want to use this initial state of the vehicle, just click in ”Accept”. However, you can change it. It is recommended not to change them too far from the detected position because this might cause the lateral controller get lost and never find the route. If you don’t want to change any previous initial conditions setting, just close the window.

The open model will have the appearance as shown in Fig. 6

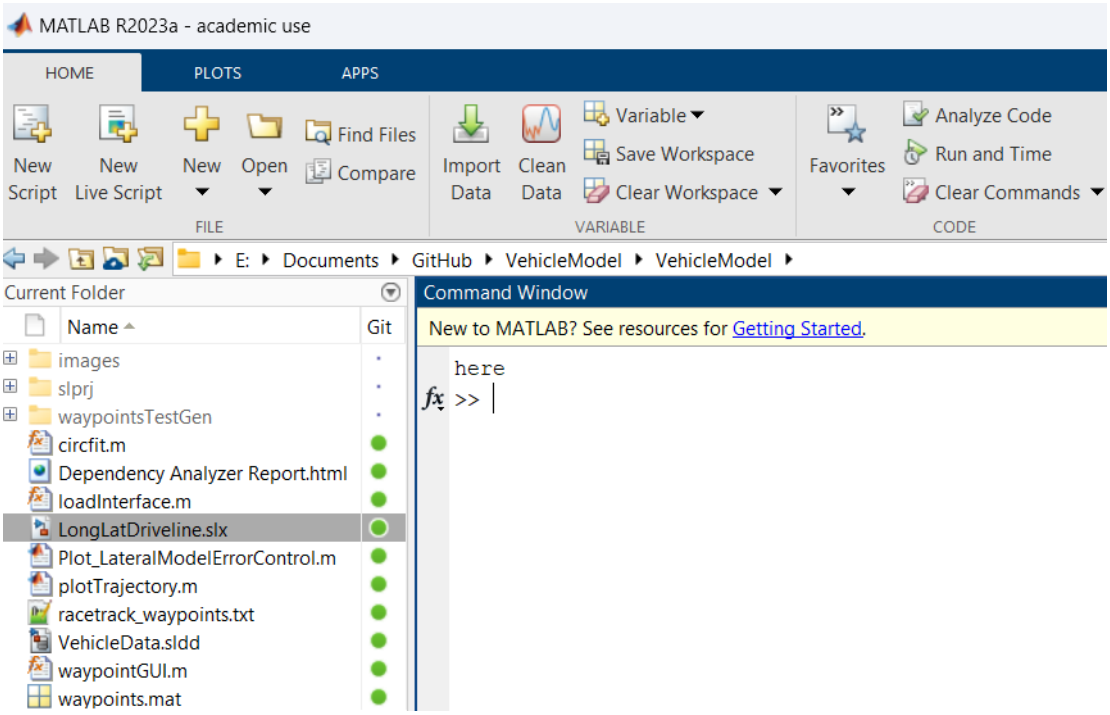

Figure 4: Working folder in matlab.

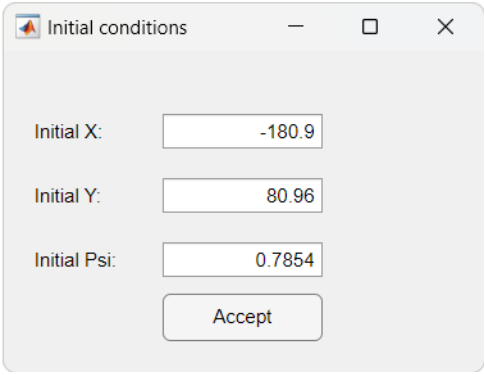

Figure 5

The Model is divided in two sections. The upper part corresponds to the longitudinal dynamics and the lower part are the lateral dynamics.

Now, let's verify that we have all the settings needed for our first run. For this first run, we won't use any electric motor as actuator or power element. So, let's verify that we have the simplest configuration.

First, in the Simulink window, locate the "*Model Settings*". A common place where to locate is shown in Fig. 7

Now, be sure that the settings are as follows in Fig. 8. The important configurations are in the

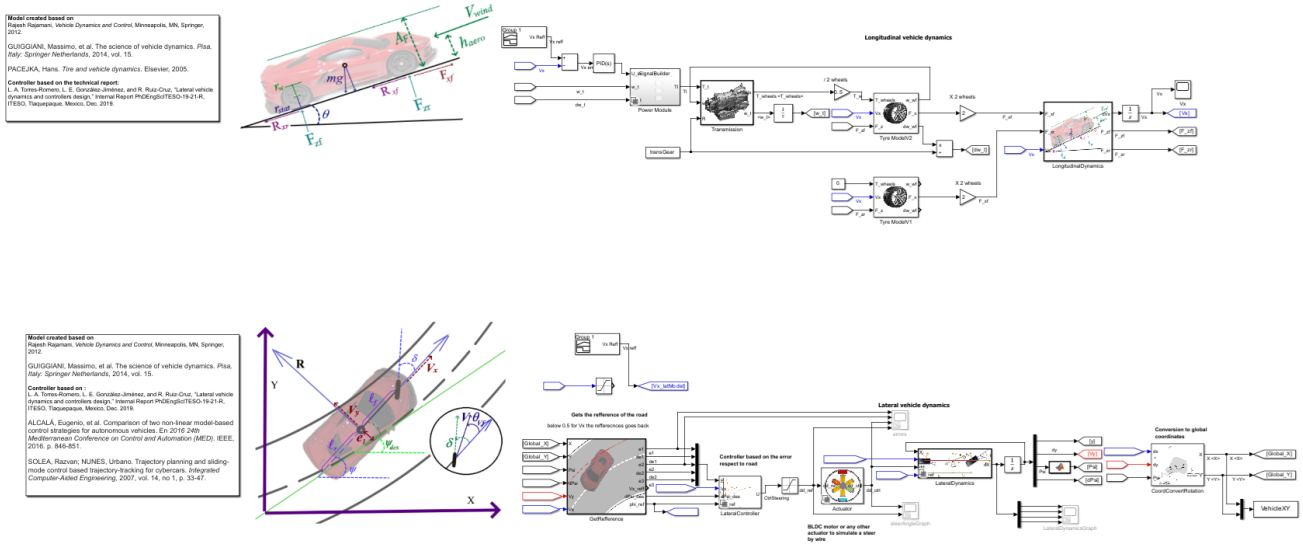

Figure 6: Simulink main model.

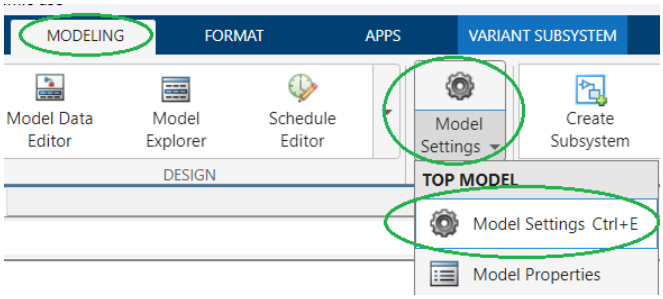

Figure 7: Model settings location.

solver section. *Type* = "Fixed-step", *Solver* = "Auto", and *Fixed-step size* = 0.002

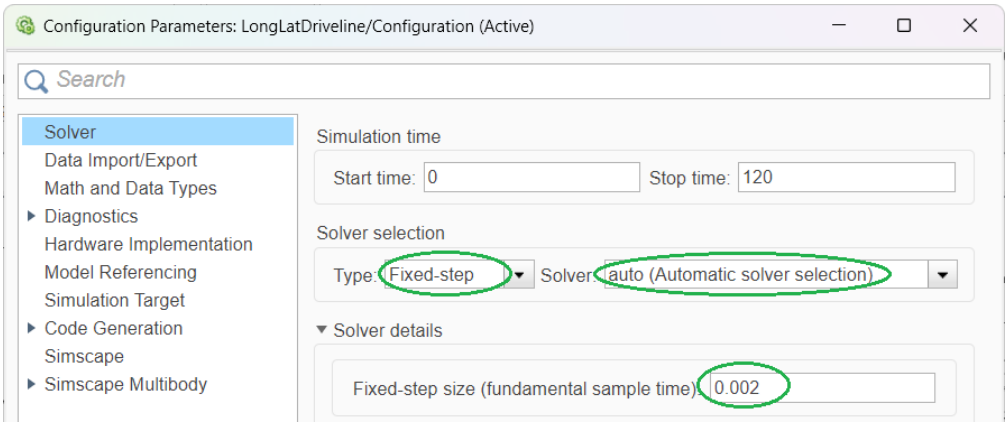

Figure 8: Model settings.

now, let's verify the variant blocks configurations. For longitudinal dynamics be sure that the power module block is *Direct signal (Signal builder)* and for the lateral dynamics, the lateral controller

block, the controller *Ackermann error feedback* control is selected, for the actuator block, *No actuator* shall be selected, and for the LateralDynamics block, *simplified model* shall be selected. Figs. 9 and 10 show these blocks.

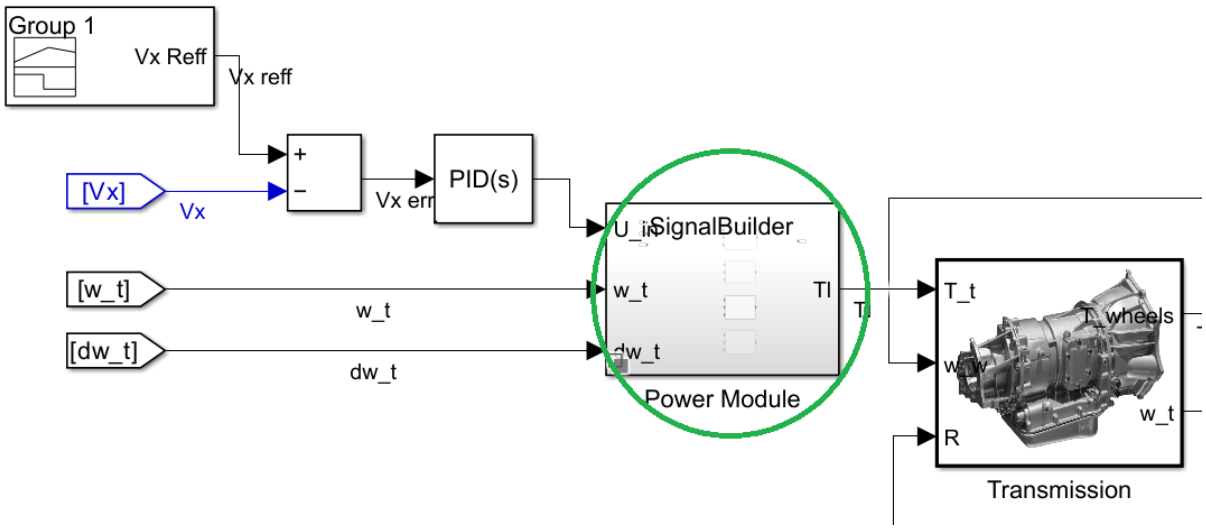

Figure 9: Power block.

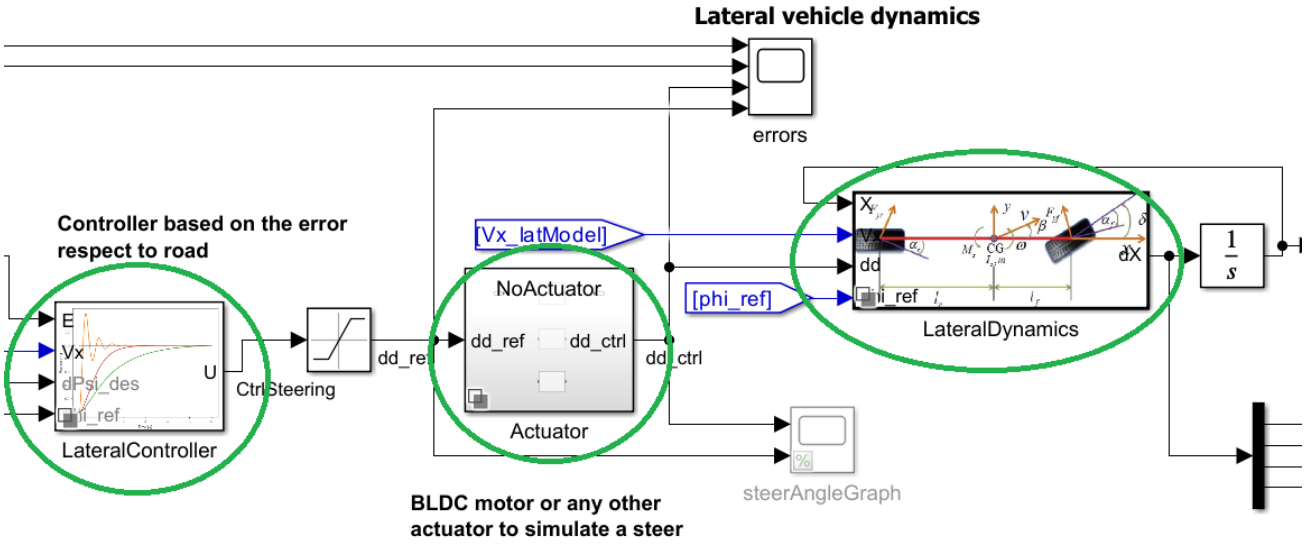

Figure 10: Lateral blocks selection.

In this point, we have everything ready. Just click run and wait until the simulation finalizes. When the simulation ends, if the vehicle completed the task, a pop up message with the message "You have arrived" appears, and a window with the trajectory appears too as in Fig. 11. Figs. 12 and 13 show

and example of the data you can get from the simulation. for example, how the vehicle is accelerating, or the errors respect the road, in this case, Fig. 13 shows e1 and e2 that correspond to the lateral error and orientation error. From here, your next steps could be running several times this simulation, putting several scopes throughout the model to see the behavior of the dynamics. You can explore further the model, change dynamic blocks, actuators, controllers, etc. In later chapter you can see how to do so. It is required a brief explanation modifying these elements because you will need to modify some configurations of the simulation in order to get good results, otherwise you might get errors or incorrect results; however, in this quick start you have the basic to start up.

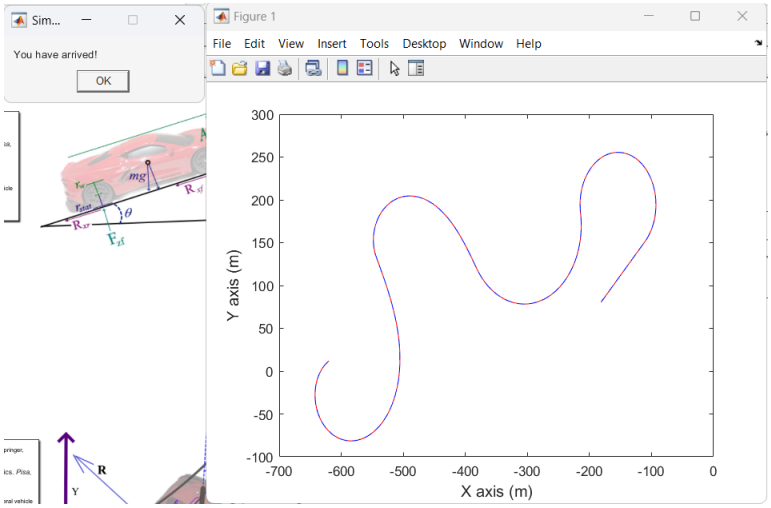

Figure 11: Trajectory and message of completed task at the end of the simulation.

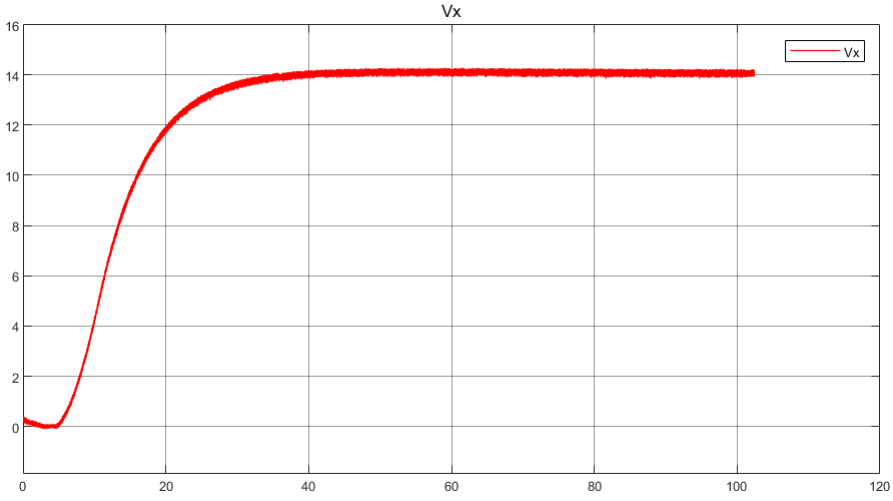

Figure 12: Longitudinal velocity profile.

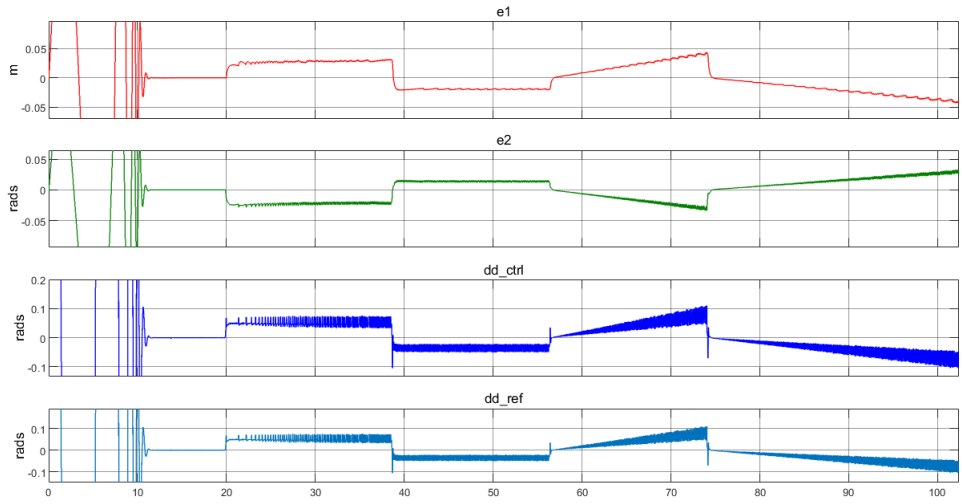

Figure 13: Lateral errors and response of the actuator.

III. LATERAL DYNAMICS SECTION

Now, that you could run once the model following the quick start section, let us take a look at the elements of the lateral dynamics section. Fig. 14 shows the elements of the lateral section. Elements marked in blue with numbers are the principal elements, whereas the blocks marked with letters in yellow circles are auxiliary elements.

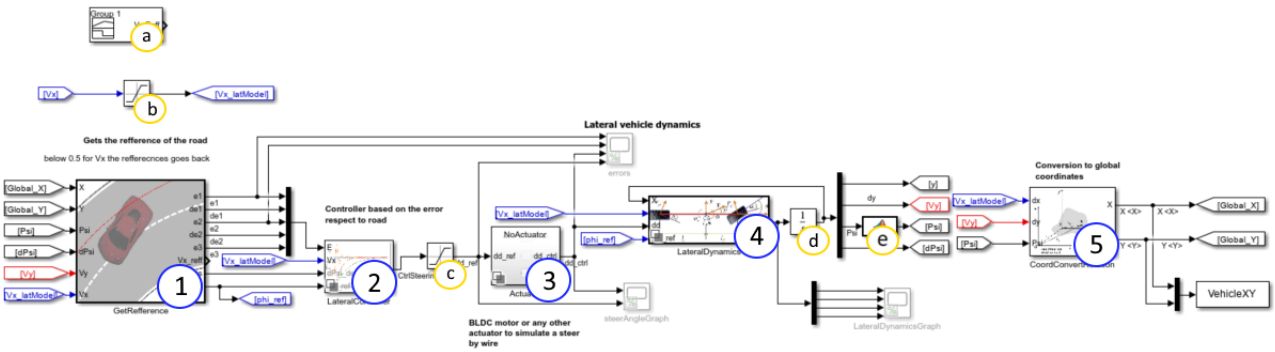

Figure 14: Lateral dynamics elements.

First, let us explain the principal elements:

1. **GetRefference block**. This element takes the way-points stored in the variable *racetrackwaypoints* and calculates, based on the current state of the vehicle, lateral error **e1**, orientation error **e2**, and their derivatives **de1**, and **de2**. **Vx_reff** is the reference speed defined in the way-points variable; this is used as a reference control in the longitudinal section. **dPsi_des** is the desired calculated

orientation, based on the way-points. **phi_ref** is the superelevation of the road; this is calculated based on a generic and simplistic equation for road design; be aware of this if the superelevation feature is relevant for you.

2. **LateralController block**. This is a Simulink variant block. Here, different lateral controllers are implemented. You only have to choose your desired controller by selecting the variant. Here, is where you can create your own controller version.

3. **Actuator block**. As the same for the lateral controller, this is a Simulink variant where you can choose or implement your own actuator, such as an electric motor which will keep the steering angle commanded by the lateral controller block.

4. **LateralDynamics bolck**. This is a variant block with different versions of the lateral vehicle dynamics. You can also choose or create new versions here as well.

5. **CoorConvertRotation block**. This block is in charge to get the current coordinates of the vehicle based in the state variables of the model. These coordinates are a feedback of GetRefference block which is used to calculate the errors against the road.

There are some minor elements that work as auxiliary elements. These elements are identified in Fig. 14 with letters (a to e) within yellow circles.

a. *Signal builder block*. This block is used when you want to provide a specific longitudinal speed to the lateral section. In this case, you might ”comment out” the longitudinal section and connect the *Vx_latModel* label (before the saturation block) to this.

b. *Saturation block*. This is to establish limits to the vehicle speed that feeds the lateral section. Sometimes, some disturbances or over-impulses might come from the longitudinal dynamics and this block will stop this. Another scenario is when, in this current version of the lateral section, is not prepared to receive negative speed (reverse), so, this block will prevent the reverse that will crash the simulation.

c. *Saturation block*. This saturation block after the controller block is to stop over-impulses coming from the LateralController block. Ideally, your control should not reach the limits of the saturation because then that means that you are losing the effects of your control. However, some times the initial over-impulse might cause the vehicle to get lost and never reach the goal. Once your control

is capable to reach the end of the trajectory, comment-through this block and make a fine tuning of the parameters of your controller.

d. *Integrator block*. This block integrates the dynamic system. Take care of the initial conditions within this block. The initial conditions are updated at start-up of the model. You can modify these conditions through the window dialog "Initial conditions" or manually in this block.

e. *wrapTo2Pi*. This block limits the value of the orientation angle ψ to keep it within the range $[0, 2\pi]$

A. *Choosing a lateral dynamic controller*

To select a different controller for the lateral dynamic control, just make right click in the lower left corner of the LateralController block, like in the Fig.15 , select *Label Mode Active Choice* and a list with all controllers will appear. Just select the one you desired.

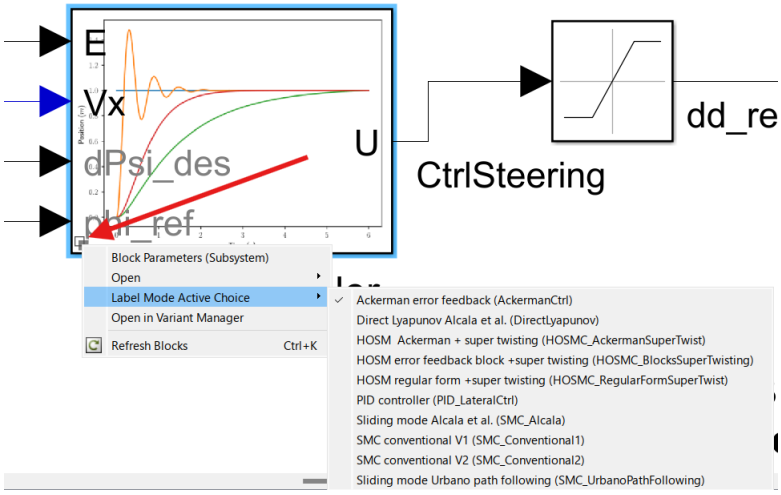

Figure 15: Variant selection of the lateral controller.

Below, is a list with a brief description of the controllers.

Table 1: LATERAL CONTROL ALGORITHMS

Name	Description
Ackermann error feedback	This implements the method of Ackermann taken the lateral error model as basis.
Direct Lyapunov Alcala et al.	This implementation is based on [2].
HOSM Ackerman + super twisting	This control eliminates the linear part error using the Ackerman technique and the non linear disturbances using super-twisting
HOSM error feedback block + super twisting	This control eliminates the linear part error using control by blocks technique and the non linear disturbances using super-twisting
HOSM regular form + super twisting	
PID controller	Simple PID controller.
Sliding mode Alcala et al.	This implementation is based on [2].
SMC conventional V1	This implementation is based on [3].
SMC conventional V2	
Sliding mode Urbano path following	This implementation is based on [4].

B. *Choosing a steering actuator*

C. *Choosing a lateral model*

IV. LONGITUDINAL DYNAMICS SECTION

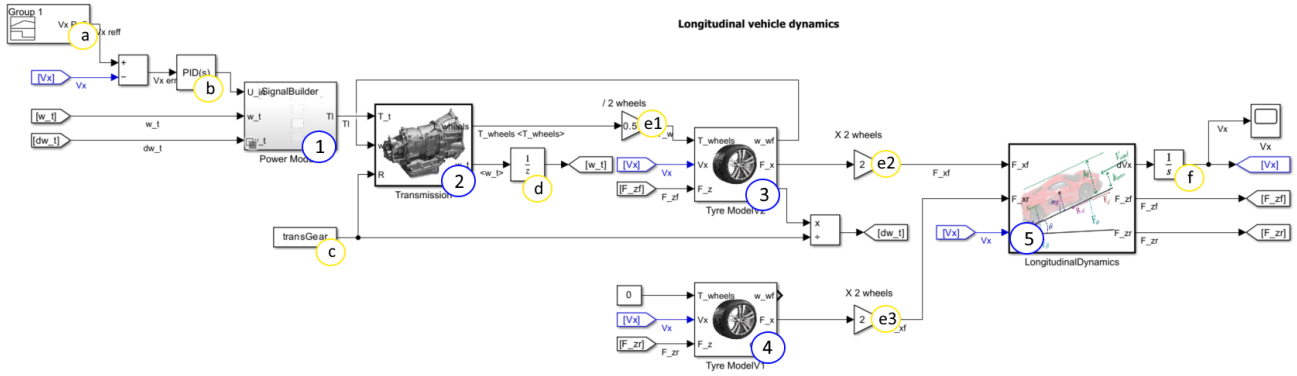

Figure 16: Longitudinal dynamics elements.

1. **Power module**. This is a variant module is intended to define the main source of traction of the vehicle. There is a variant where there is no implementation at all, and it is only a direct connection and then, as in the image, the PID is the source of torque; use this if you want to simulate the dynamic but you are not very interested in the power source. Adding an electric motor makes the simulation slower. The output of this module is **Tl**, which is the torque load delivered by the power source. The inputs **w_t** and **dw_t** are the angular speed and angular acceleration of the gear that connects the power module and the transmission. **U** is the control input.
2. **Transmission**. dynamic of the transmission. Basically converts the input torque to the output torque according the gear relation. The block receives as input **T_t**, **w_w** and **R** which are the input torque coming from the power source, the angular speed of the wheels, and the gear ratio, respectively. The outputs are **T_wheels**, and **w_t** which are the torque delivered to the wheels and the angular speed of the gear that connects the main power with the transmission.
3. **Frontal tire block**. This is the front tires module. This block represents represents only one tire. that is the reason the input torque is divided by two and the force delivered as output is multiplied by two, to simulate that we have two frontal tires. This is a limitation of the bicycle model.
4. **Rear tire block**. The same as the last one, but it is a different instance to handle different properties versus the frontal tires.
5. **LongitudinalDynamics block**. This block contains the main physic equations of the second Newton's law that are involved to hove the vehicle forward, including the aerodynamics equations.

Now, the auxiliary elements that glue the components are:

a. *Signal builder*. This block creates the speed profile for reference.

b. *PID*. Block to control the main power module.

c. *transGear*. Constant block with the gear ratio.

d. *Delay block*. In order to create an algebraic loop, it is required to add an delay block.

e1. *Gain block*. block that divides the incoming torque between to tires.

e2. *Gain block*. Block that multiplies the force generated by the tire block by two frontal tires.

e3. *Gain block*. Block that multiplies the force generated by the tire block by two rear tires.

f. *Integrator block*. Solves the differential equations of the longitudinal dynamics.

V. CREATING NEW ROUTES

Introduction

The Waypoint Generator GUI is a MATLAB-based tool that allows users to create waypoint sequences for different driving test strategies. Users can select predefined strategies, configure parameters, and generate waypoints that can be saved and visualized.

Getting Started

1. **Launch the GUI:**
   - Run the `waypointGUI` function in MATLAB to open the interface.

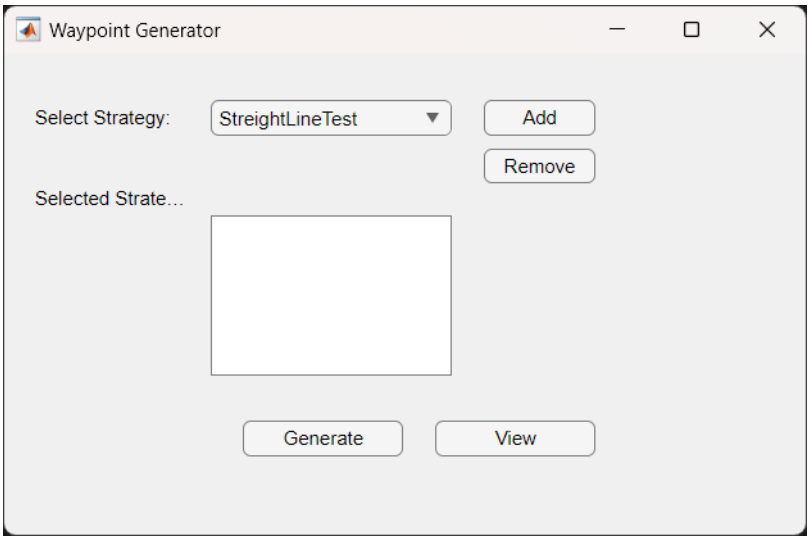

Figure 17: GUI to create new way-point files.

2. **Select a Test Strategy:**
   - Choose a strategy from the dropdown menu labeled **"Select Strategy"**.
   - Available strategies:
     - `StreightLineTest`
     - `ConstantSpeedVariableRadiusTest`
     - `ConstantSteeringWheelAngleTest`
     - `VariableSteeringWheelAngleTest`
3. **Add a Strategy:**

- Click the **"Add"** button to configure and add the selected strategy.
- If the strategy requires parameters, a dialog box will appear to input values such as distance, speed, radius increment, or steering angle.
- Click **"OK"** to confirm and add the strategy to the list.

4. **Remove a Strategy:**

- Select a strategy from the **"Selected Strategies"** list.
- Click the **"Remove"** button to delete it.

5. **Generate Waypoints:**

- Click the **"Generate"** button to create waypoints based on the selected strategies.
- The waypoints are saved in a file named `waypoints.mat`.
- A success message will appear once the waypoints are saved.

6. **View Waypoints:**

- Click the **"View"** button to visualize the generated waypoints on a 2D plot.
- The waypoints will be displayed as a path with X and Y coordinates.

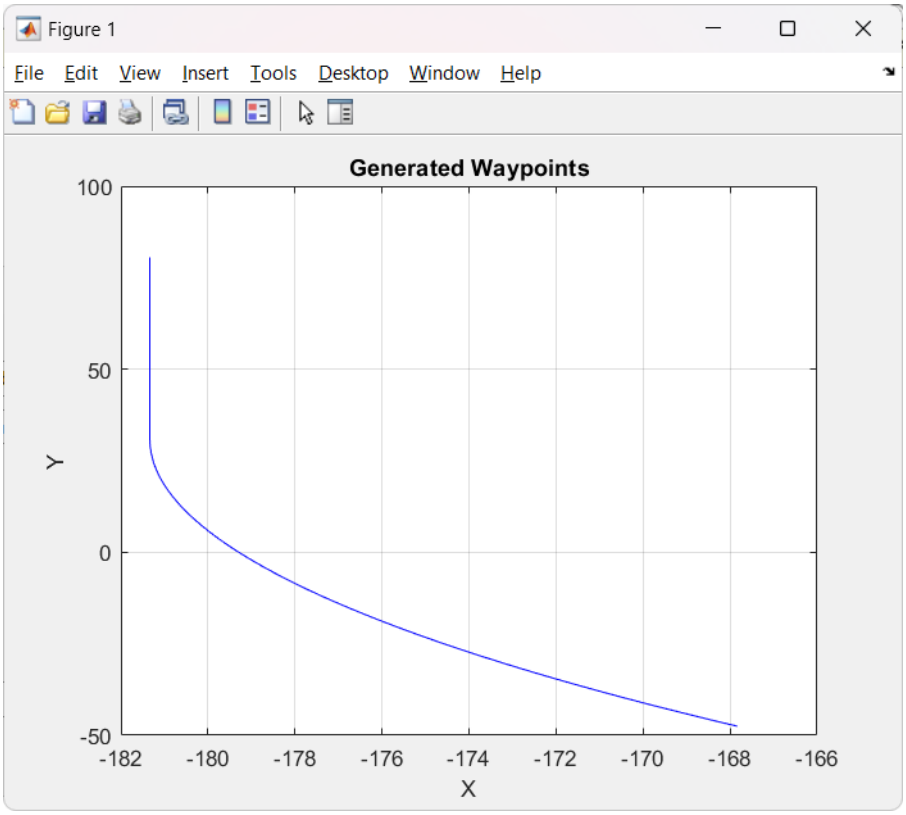

Figure 18: GUI to create new way-point files.

Closing the Application

- Closing the GUI will automatically clean up and remove any added paths related to the tool.

Additional Information

- The waypoints are generated using the `GenerateWaypoints` function, which applies the selected strategy to create a continuous path.
- Ensure all required files are in the working directory before running the GUI.

For further modifications or custom strategies, users can edit the MATLAB scripts accordingly.

VI. CARLA INTEGRATION

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VII. TABLES

TABLE II: ENVIRONMENT DATA

	Matlab Name	Sym	Unit	Val
1	g	g	m/s^2	9.81
2	V_wind	V_{wind}	m/s	0
3	theta	θ	rad	0

TABLE III: VEHICLE DATA

Matlab Name	Sym	Unit	Tesla ms val	src	Mustang val	M-E src	Lucid val	src
lr	l_r	m	1.58					
lf	l_f	m	1.1					
transGear	R		0.1027	[5]				
Iz	I_z	Nm	2873					
m	m	Kg	2238.932	[6][7]				
Nf	N_f		2					
Nr	N_r		2					

TABLE IV: COMMERCIAL VEHICLE DATA FOR COMPARISON

Feature	Sym	Unit	Tesla ms val	src	Mustang val	M-E src	Lucid val	src
Transmission efficiency	η	-	0.97	[5][8]				
Acceleration 0–60 mph	-	s	3.2	[7]				
Acceleration 0–100 km/h	-	s	-					
Torque	-	Lb-ft	687	[7]				
EM motor type	-	-	3 IM Cu					
Electric Motor Output	-	Hp/kw	691/515	[7]				
Battery Range	-	Miles/km	275/442	[7]				
EM max speed	-	rpm	16000	[8]				
EM speed at max power	-	rpm	5k-8.6k	[8]				
EM speed at max torque	-	rpm	5.1k	[8]				
EM max power front	-	kW	193	[8]				
EM max power rear	-	kW	375	[8]				
EM max torque	-	NM	967	[8]				

TABLE V: AERODYNAMIC DATA

Matlab Name	Sym	Unit	Tesla ms val	src	Mustang val	M-E src	Lucid val	src
xx	ρ	kg/m^3	1.225	[5]				
xx	A_F	m^2	2.341157	[9]				
xx	$C_d A_F$	m^2	0.57599	[9]				
xx	C_d	-	0.24	[9]				
xx	h_{aero}	m	-					

TABLE VI: TIRE DYNAMICS

Feature	Sym	Unit	Tesla ms val	src	Mustang val	M-E src	Lucid val	src
Model			Pirelli Sottozero 3	-				
tire stiffness	C_σ							
Effective radius	r_{eff}							
Static radius (with load)	r_{stat}	-						
Radius of wheel (no load)	r_w	m	0.352					
Tire Size	-	-	P245/45WR19	[10]				
Rolling Resistance Coefficient	C_r	kg/t	$7.8 \leq RRC \leq 9.0$	[8]				

TABLE VII: TYRE FORCE PROFILE

Generic model Name	Sym	Unit	Val
Name Model			Generic
C_ar	$C_{\alpha r}$		80000
C_af	$C_{\alpha f}$		80000
D	D		3
C	C		1.5
B	B		20
E	E		0
sh	Sh		0
sv	Sv		0

TABLE VIII: BLDC ELECTRICAL MOTOR FOR STEERING

		BLDC Electrical Motor	
Name	Sym	Unit	Val
Name Model			Generic
R	R	Ω	0.35
L	L	H	0.001
M	M	H	0
J	J	Kgm^2	0.00018
P	P		4
b	b	$N\,ms\,rad^{-1}$	0.0034
lambda	λ	$V/rad/s$	0.0433