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HMI For Hybrid-Gear Shift for Electric Vehicle Transformation

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Salma Nasr

ABSTRACT

Due to various regulations in the car industry following the significant environmental changes caused by global warming, a global trend to electrify vehicles has been developed in the past decades to reduce the exhaust gases and increase the driving experience efficiency.

In this thesis, a hybrid gear-shift system of an electrified vehicle, Fiat Panda, is being modeled and controlled.

And given the rising complexity of software used in vehicles nowadays, an organized and an international standard defined by International Organization for Standardization (ISO) is to be used, which is the ISO26262.

The plant as well as the vehicle management unit are modelled on Matlab/Simulink and then, Model-in-the-loop testing is done in the end to check whether the VMU satisfies the requirements.

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INTRODUCTION

(1)The use of electric motors instead of conventional internal combustion engines mainly existed in trains and other smaller vehicles. (2)Due to the advances in batteries, concerns about increasing oil prices, (3)and the desire to reduce greenhouse gas emissions global, a general trend of focusing on renewable energy and producing environment-friendly vehicles started in the twenty first century. Hence, many commercial and governmental entities (such as in the United States and the European Union) adopted the research and development of electric vehicles as well as the transformation of conventional ICE vehicles into electric vehicles.

(2)The market of PEVs, either Battery-Electric Vehicles (BEVs) or Plug-in Hybrid Electric Vehicles (PHEVs), significantly expanded in 2017 registering a year-on-year increase of 54% (compared with 38% in 2016), with China having the highest sales volume of electric cars globally, followed by the United States and Norway being the world leader in market share terms.

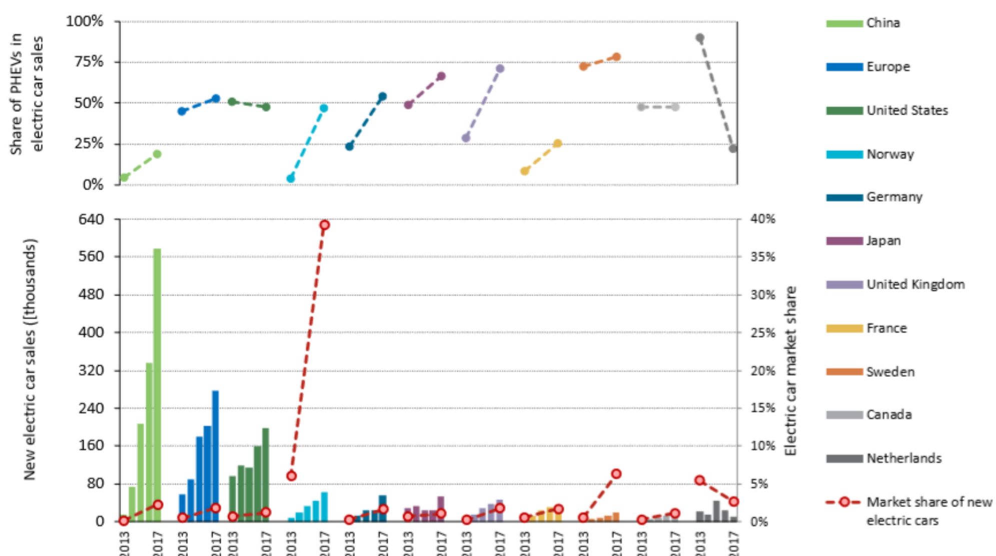


Figure 1 Market Share of Electric Vehicles

For this thesis, a vintage vehicle is transformed into an electric vehicle, however, due to some limitations of the old vehicle, the transmission system, as well as other parts of the car, had to be customized to accommodate the fact that the system is now using electricity as the driving power. Hence, it's not expected to be entirely similar to that of an electric vehicle or that of a conventional ICE vehicle. The vehicle of interest is a vintage Fiat Panda, model of 1980, and the system that is analyzed and controlled in this thesis is the transmission system.

- ## DESCRIPTION OF THE CUSTOMIZED TRANSMISSION SYSTEM:

In a typical ICE vehicle, the internal combustion engines are only able to generate usable torque and power in a narrow band of engine speeds. Hence, in order to accelerate the vehicle, a transmission system with multiple gear-ratios is used to step that down and keep the engine in its power band to ensure the most efficient and durable engine operation.

(4)On the contrary, electric vehicles do not require having a transmission system, because electric motors generate 100% of their torque at very low speeds, and as rpms increase, torque falls off at a fairly linear rate, at the same time that power is increasing.

That, however, doesn't mean that electric vehicles cannot have transmission systems, it simply means that they are not necessary.

A comparison between the range of speed corresponding to the torque in the ICE vehicle and the electric vehicle is shown in the following graph

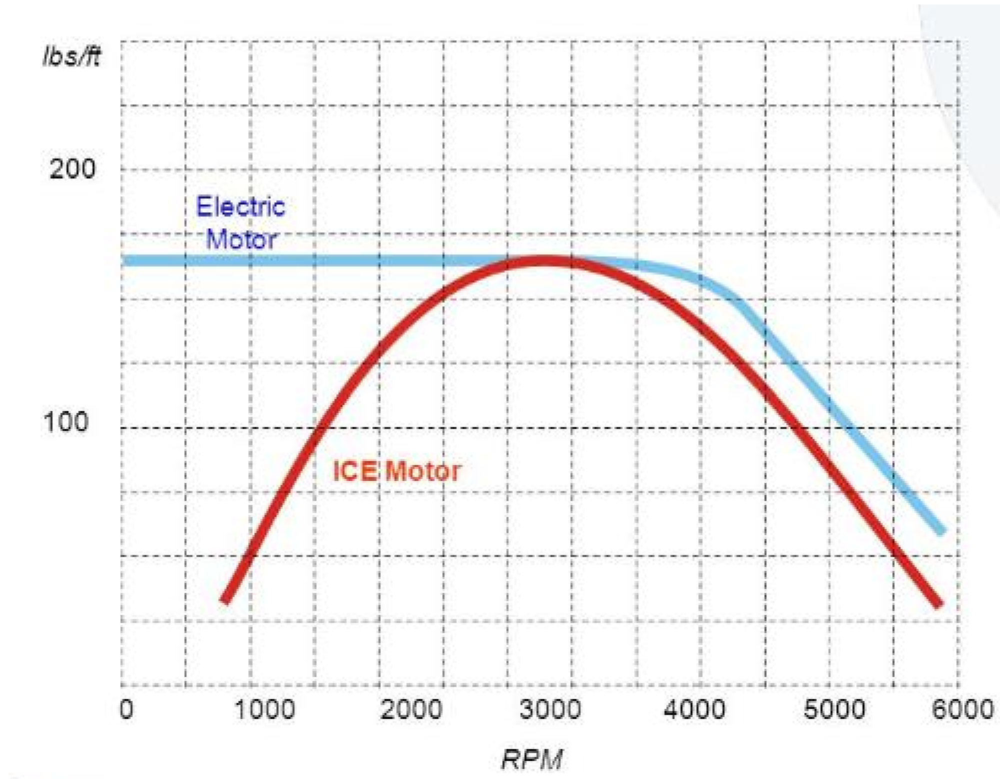


Figure 2 Electric Motor Vs. ICE Torque-Speed Diagram

Back to the vehicle of interest, a hybrid transmission system is used, which is not quite like the regular manual transmission system nor the automatic transmission system.

The main features of the new and hybrid system are:

- There is no clutch.
- The shifting lever is that of the old vehicle (having five speeds, neutral and reverse position). However, the transition to the third, fourth and fifth gear is mechanically blocked.
- The reverse position of the lever puts the vehicle in the parking state.
- To make the vehicle move backwards, a push button is added next to the shifting lever. If pushed by the driver, the vehicle accelerates in the opposite direction.

- METHODOLOGY:

Given the growing complexity and functionalities of the software, software failures can make the controlled system safety-critical. This problem cannot be easily solved by extensive testing and it’s not possible to test everything at the vehicle level because:

- Huge number of possible operating conditions
- Failures may depend on precise timing sequences
- Huge number of (possibly intermittent) faults
- Random memory corruption

Therefore, remaining testing will be conducted by end user and this might cause crucial situations.

In order to solve such problem, A disciplined and controlled approach to development must be applied, with defined verification and validation steps, which is, in this case, the ISO26262 international standard.

The ISO26262 is specific for the automotive industry. It applies to safety-related road vehicle electronic and electrical (E/E) systems, and addresses hazards due to malfunctions providing requirements for the whole lifecycle of the E/E system (including hardware and software components).

ISO26262 suggests using the following design flow

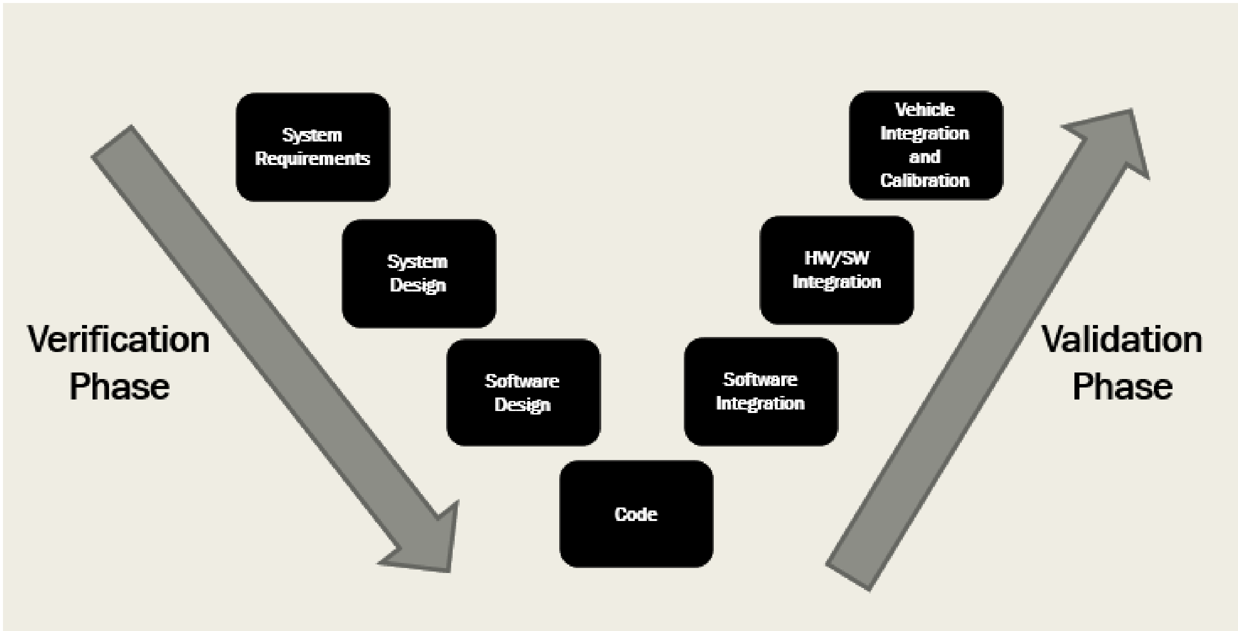


Figure 3 Design Flow

- **Left-Hand Side:**

  The left-hand side of this V-cycle is called the verification phase which comprises of the steps shown in the previous figure. This phase is going to be the focus of this thesis where both the plant and its controller are designed and modelled followed by generating the corresponding code.

  - **System Requirements and System Design:**

    Where both the plant, which is the system of interest, as well as the controller, which is the algorithm used to control the plant, are modelled according to the ISO26262 standard.

- **Model in The Loop:**

  After determining the exact requirements of the system and designing the flowcharts, the modelling is translated in a native simulation tool which is, in this case, Simulink and Stateflow.
  The simulation helps refining both models and evaluating the design alternatives.

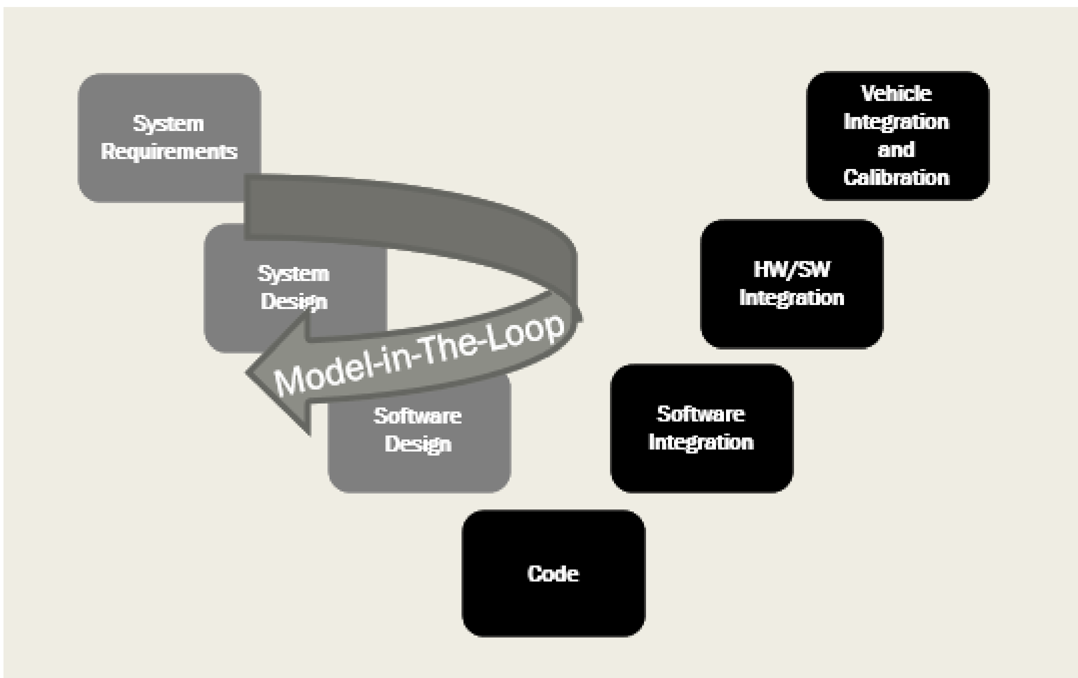


Figure 4 Model in the Loop Testing

- **Optimization and Code Generation:**

  Now that the model exists entirely in Simulink, some rules are followed to generate the corresponding code to be implemented on the real system.

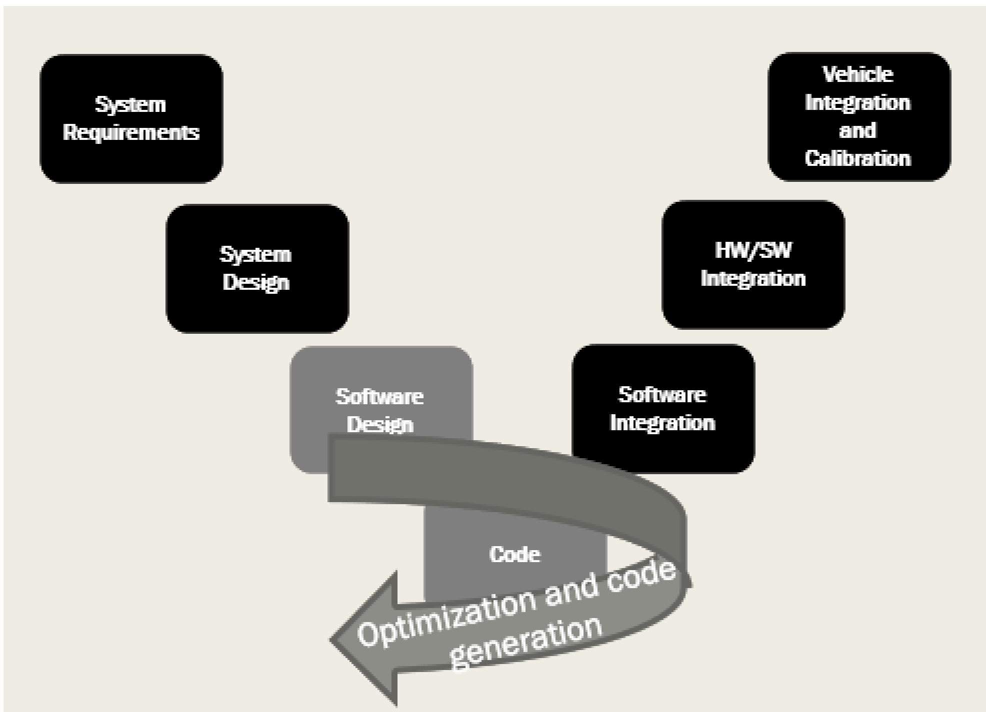


Figure 5 Optimization and Code Generation

- THE OVERALL LAYOUT OF THE THESIS:

Having already explained the purpose of the thesis, the overall organization is going to be as follows:

- Describing the general scheme of the system.
- Building the manager including flowcharts of the different standard and non-standard operations from the driver point of view
- Translating the system and the controller into a Simulink model
- Model-in-the-loop (MIL) testing and observing the behavior of the system.

CONTEXT DESCRIPTION

The system described generically in the introduction can be simplified into six main modules ordered as shown in the following scheme

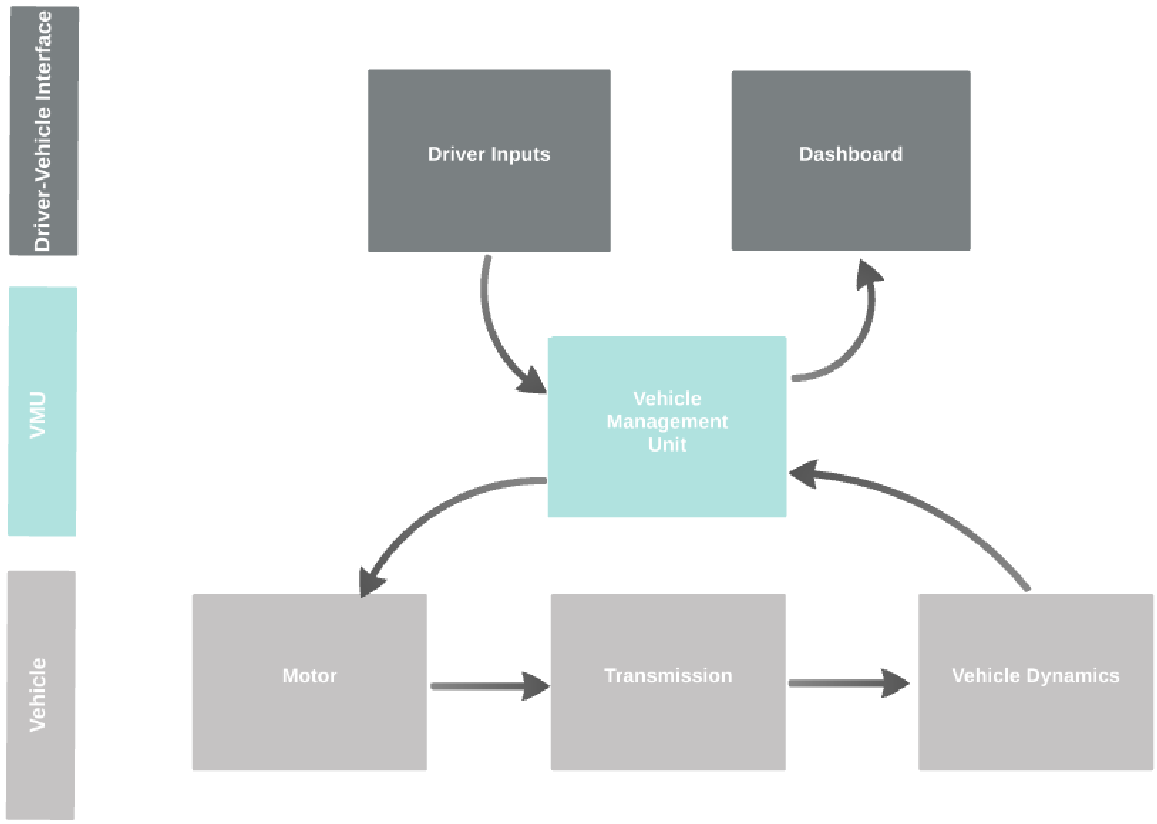


Figure 6 System Overall Scheme

- ## DRIVER INPUTS:

The driver inputs block represents the desires of the driver in terms of acceleration, deceleration or gear selection. The relevant driver inputs to the traction control module are the following four inputs:

- **Accelerator Pedal:**

  Through the angle of the acceleration pedal the driver expresses his desire either in acceleration or deceleration which is then translated into the corresponding torque value

- **Brake Pedal:**

  The exact angle of the brake pedal is irrelevant to the traction control. It only matters whether it's above or below around 3%, because only a percentage above 3% is considered as a brake pedal push.

- **The Shift Lever:**

  As mentioned in the introduction, the shifting lever of the vehicle of interest is quite different from the shifting lever of either a regular automatic-drive or manual-drive vehicle.

  It can take up to four positions which are: parking, neutral, 1st gear and 2nd gear.

- **Reverse Push Button:**

  Since the reverse position in the shifting lever is taken by the P-state, the driver can express his desire in moving backward by pushing this button right next to the lever.

- ## VEHICLE MANAGEMENT UNIT:

Given the Driver Inputs, the Vehicle Management Unit is responsible for applying a specific logic to determine the corresponding torque, considering the current vehicle speed and the motor speed.

The VMU is responsible not only for determining the correct torque to be requested from the motor, but also for notifying the driver about the state of the system through warnings and dashboard lamps.

- ## THE MOTOR:

Given that the plant of interest is an electrified vehicle, the choice of the electric motor used in the vehicle is crucial. (5) (6)With advances in electrical machines and recent control technologies, AC machines have become mainstream (as opposed to DC machines) and now dominated the traction machine market. Both synchronous and asynchronous AC machines are used in commercially available electric-powered vehicles.

However, even though induction machines are lower in cost and easier to control, the rotor conductors increase the copper losses and hence have a higher cooling requirement.

(7)Therefore, Among the electric traction motors, interior permanent magnet (IPM) motors, which include rotors with embedded magnets, are increasingly being used as the driving motors for electric vehicles. Their main advantages are:

- Its wide velocity and torque variation
- High power
- Light weight
- Energy efficiency

Having chosen IPM motor as the driving motor of the vehicle, once the Vehicle Management Unit applies its logic and determines the required torque from the motor, the motor, taking into account the actual battery voltage, produces the torque.

- ## THE TRANSMISSION SYSTEM:

The main difference between the conventional Panda and the electrified Panda is the transmission system which is not exactly like a typical manual transmission system with a clutch nor like an automatic transmission system where the gear shift is done automatically by the vehicle and not according to the driver desire. The new resulting transmission system:

- Has no clutch.
- The transmission to the 3^{rd}, 4^{th} and 5^{th} gear is blocked.
- Only the first and second gear positions are allowed.
- The reverse position is used for parking instead.
- The reverse is, hence, obtained by pushing the reverse push button placed next to the lever for at least 3 seconds.

Given that the driver has either chosen the first or second gear through the shifting lever, the transmission system then adapts the motor output torque to the desired gear by applying the corresponding gear ratio.

- ## THE PLANT DYNAMICS:

Taking the different plant dynamics parameters into consideration, such as the drag force, rolling resistance and other factors as well, the vehicle moves at a certain speed.

- ## THE DASHBOARD:

For the driver to be constantly updated and notified about the vehicle state, multiple lamps are used in the dashboard.

- **P-Lamp:**

  The P-lamp takes up to three states:

  - **On:** In case the vehicle is in the parking state.
  - **Off:** In case the vehicle is not in the parking state.
  - **Flashing:** In case of unsuccessful transition to the parking state or non-standard initial condition.

- **R-Lamp:**

  The R-lamp takes up to two states:

  - **On:** In case the vehicle is in the reverse state.
  - **Off:** In case the vehicle is not in the reverse state.

- **N-Lamp:**

  The N-lamp takes up to three states:

  - **On:** In case the vehicle is in the neutral state.

- **Off:** In case the vehicle is not in the neutral state.
- **Flashing:** In case of unsuccessful transition to the neutral state.

➢ **D-Lamp:**

The D-lamp takes up to for states:

- **On:** In case the vehicle is on one of the drive states (1^{st} or 2^{nd} gear).
- **Off:** In case the vehicle is not on one of the drive states.
- **Flashing:** In case of unsuccessful transition to one of the drive states.

➢ **Gear-Lamp:**

The gear lamp can take up to two states:

- **Red:** In case the first gear is chosen.
- **Green:** In case the second gear is chosen.

- THE FEEDBACK:

According to the actual vehicle speed and the motor speed, the vehicle management unit can keep track of the situation and determine whether the driver desires can be allowed. And in case the actions are not allowed the driver is notified through the dashboard lamps.

For the purpose of developing a logic that could receive the inputs of the driver and act accordingly, a scheme of all the standard and non-standard initial conditions of the vehicle as well as the standard and non-standard driver commands must be designed, so that the system behavior can be monitored in all the cases. Doing that, it can be proved that the designed controller logic is able to accommodate the driver desires safely and accurately.

USER'S OPERATIONS

The main focus of this chapter is to explain the correlation between the PRND operations from the driver point of view and what happens practically from the VMU point of view.

As mentioned in the previous chapter, the different standard and non-standard initial conditions of the vehicle as well as the driver commands must be taken into consideration. This chapter will analyze the scheme of possible situations and conditions.

- ## INITIAL CONDITIONS:

  - **Standard:**

    In a standard initial condition, given that the driver started the vehicle by putting the key and turning it to the first click, the shifting lever is expected to be on the "Parking" state. And only starting from an initial condition, the vehicle can be brought to motion.

  - **Non-Standard:**

    If the shifting lever is put to "Neutral" or one of the two gears, the vehicle is said to be in a non-standard condition. In that case, the driver should be notified that the vehicle is not correctly parked through flashing the P-lamp in the dashboard, so that he can shift the lever back to the parking in order to be able to start driving later.

Flowchart:

In order to determine whether the vehicle is in an initial condition and ready for operation, the following flowchart is followed.

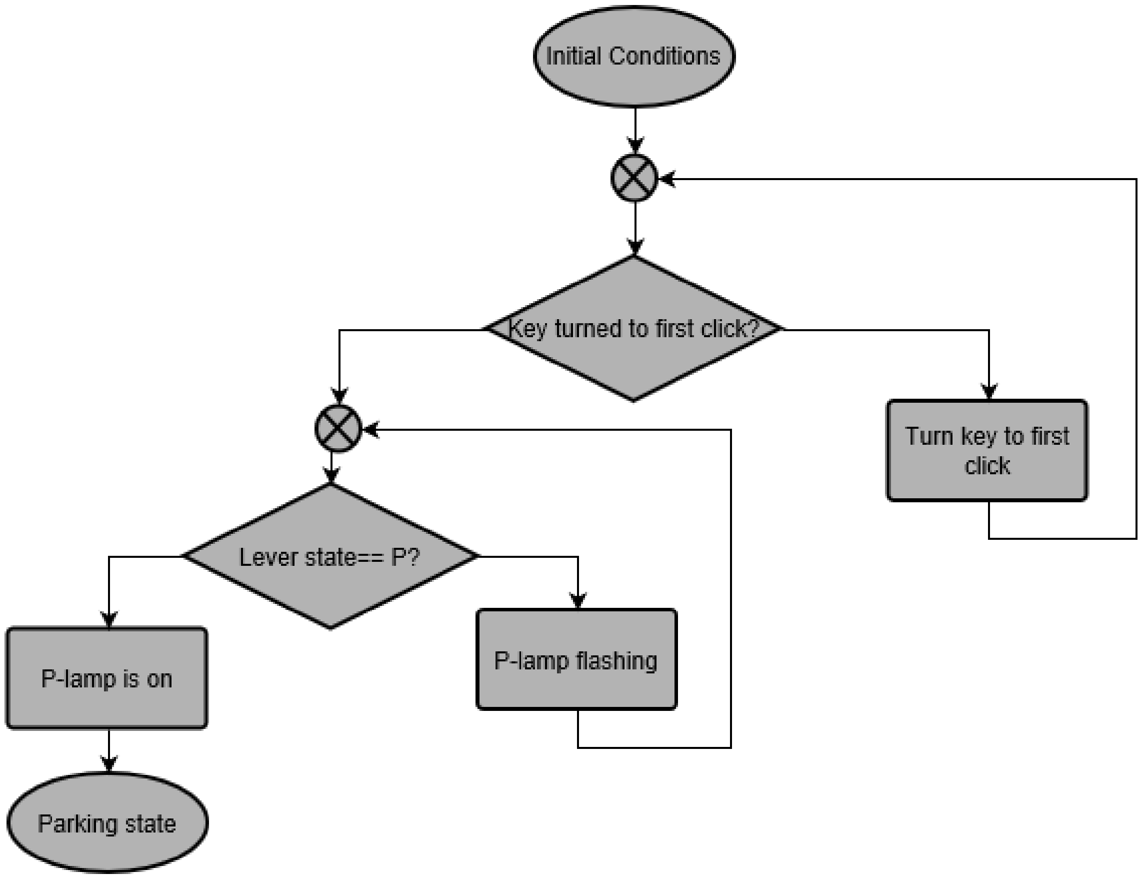


Figure 7 Initial Conditions Flowchart

- MOVING:

Once the vehicle is correctly initialized, in order to allow the forward or backward motion of the vehicle, it must go through a specific procedure for comfort and safety reasons.

➢ **<u>Parking to Neutral transition:</u>**

A common case where the driver would like to go to the neutral state, not just go through it as a transitional to drive, is when the vehicle is to be pulled for instance.

For a successful transition from parking state to neutral state, the brake pedal should be pressed. In case the driver did not press the brake pedal (over 3%), the N-lamp in the dashboard will flash to let him know that the transition to neutral has been unsuccessful. The N-lamp will keep on flashing until the driver goes back to parking and does a correct transition by pressing the brake pedal while shifting the lever from parking to neutral.

Flowchart:

In order to track this process and make sure it happened correctly and that the driver is notified in case of error, two flowcharts describing both procedures are designed as follows:

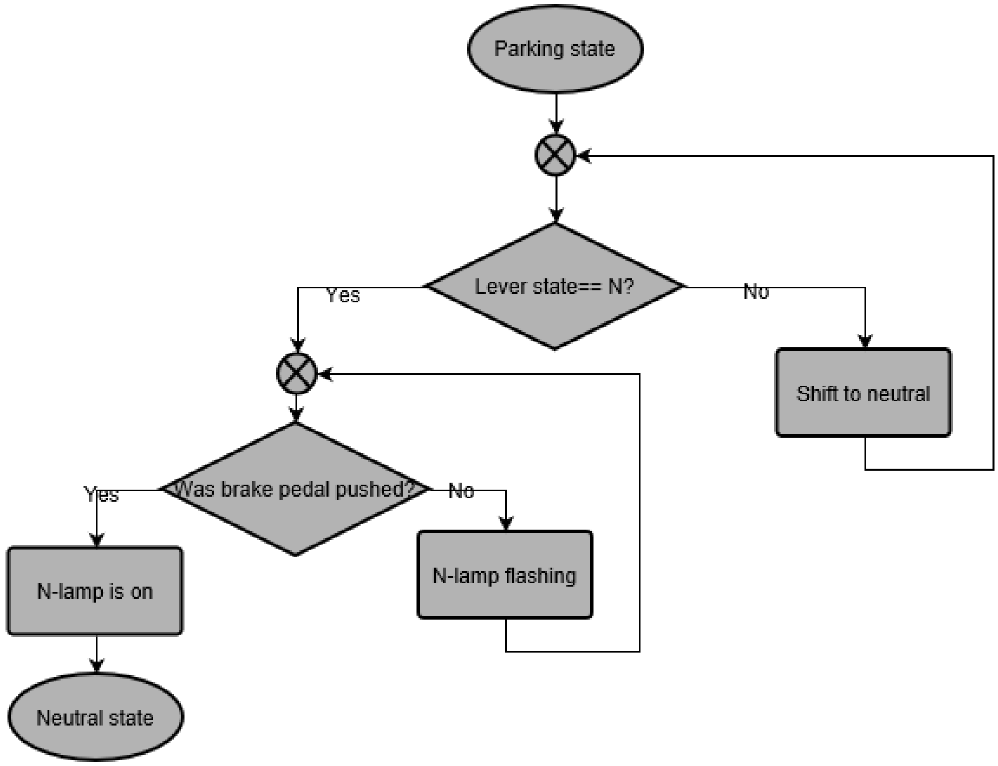


Figure 8 Parking to Neutral Transition Flowchart

Once the transition to one of the neutral state is successfully executed, the driver can, now, move either forward or backward, choosing either the first or the second gear.

- **Neutral to drive transition:**

Just like the transition from parking to neutral, the transition from neutral state to either the first or second gear requires pressing the brake pedal as well. This condition is added to avoid having the acceleration pedal being pressed during this transition, which would cause a jerky motion due to moving from 0 N.m torque to the value of the torque corresponding the position of the acceleration pedal.

In case the driver did not press the brake pedal in this transition, the D-lamp in the dashboard will flash to let the driver know that an unsuccessful transition to one of the drive states (signifying either the first or second gear) has just occurred and that no torque will be generated.

The lamp will keep on flashing until the driver goes back to neutral and does the process correctly by pressing the brake pedal while shifting the lever. Only then, the D-lamp will light up correctly, torque generation will be enabled, and the vehicle will be allowed to either move forward or backward.

- **Gear Determination:**

For the transmission system to determine whether the 1st or 2nd gear lever state is chosen by the driver, a comparison between the wheel speed and the motor speed is done.

At initialization, when the vehicle speed is still zero, the comparison will not help determining which gear was chosen. However, this will only last for a very few seconds until the vehicle speed is around 5 km/hr which is not crucial.

One more point to be taken into consideration is notifying the driver about the currently chosen gear. This is done for safety reasons, so that if, for instance, the driver chooses the 1st gear and pushed the acceleration pedal until the vehicle speed increased to 50 km/hr, pushing the pedal further will not cause the vehicle to accelerate. Therefore, by notifying the driver that he’s currently on the first gear, he will understand that he’s supposed to move to the second gear if he wants to accelerate the vehicle any further.

It’s obvious here that an additional lamp on the dashboard will be needed to show the driver the chosen gear. In case the vehicle is on the first gear, the lamp will be constantly on, while for the second gear the lamp will flash.

- **Moving Forward:**

Given that the vehicle is already in the drive state, either on the first or the second gear, if the reverse button is not pushed, when the driver pushes the accelerator pedal a corresponding torque will be requested from the motor. The transmission system then adapts the output torque of the motor to drive the wheels.

- **Moving Backward:**

If the driver pushes the reverse button while in either of the drive lever states (1^{st} or 2^{nd} gear), the generated motor torque will be in the reverse direction driving the vehicle backward instead.

However, one difference between the forward and backward motion is that in the backward case, a maximum speed constraint is applied.

Furthermore, there is a speed constraint for moving from the driver to the reverse state and vice versa. A speed threshold is set to make sure the vehicle speed is below a certain value before going to reverse from drive and the other way around. In case, for instance, the vehicle speed is over 10 km/hr in the forward direction and, suddenly, the driver requested to move backward, such command should not be allowed and he will have to slow down the vehicle first.

Flowcharts:

The two previously-explained processes, including the gear determination, are simplified through the following flowchart:

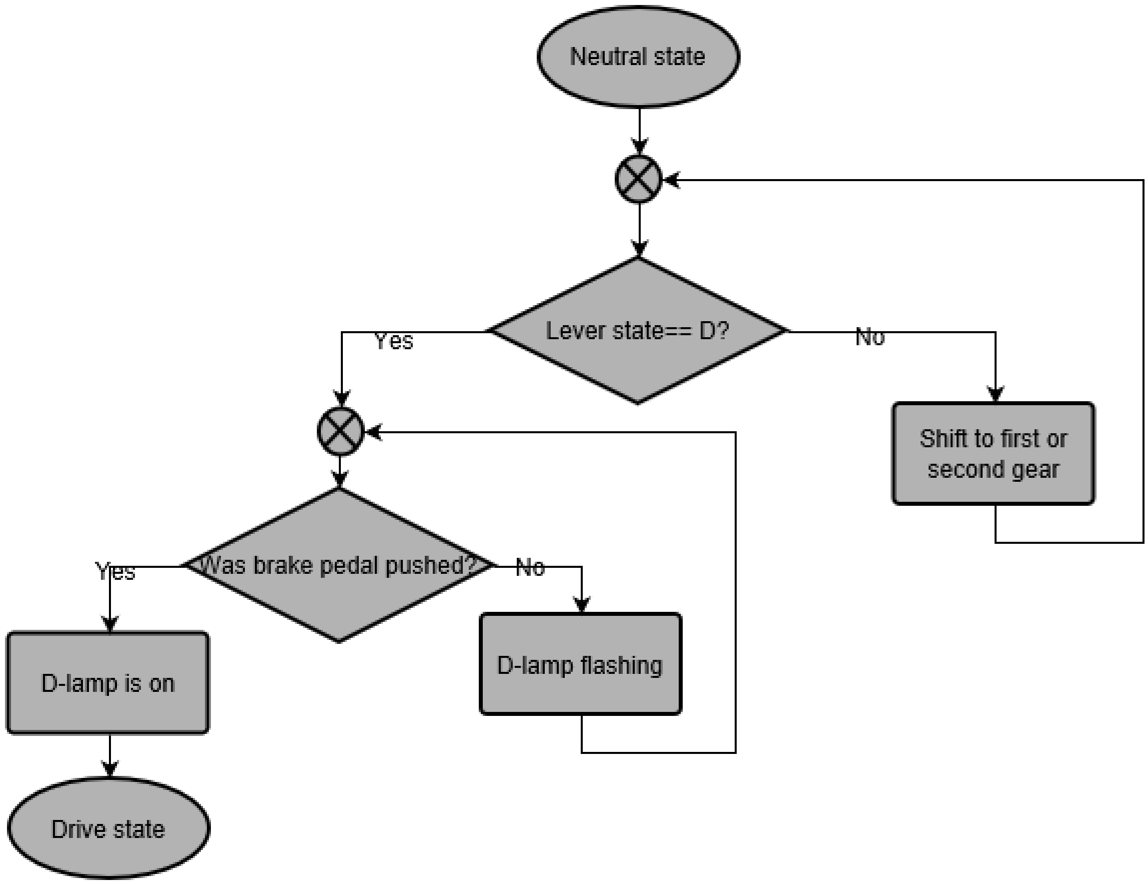


Figure 9 Activating Drive State Flowchart

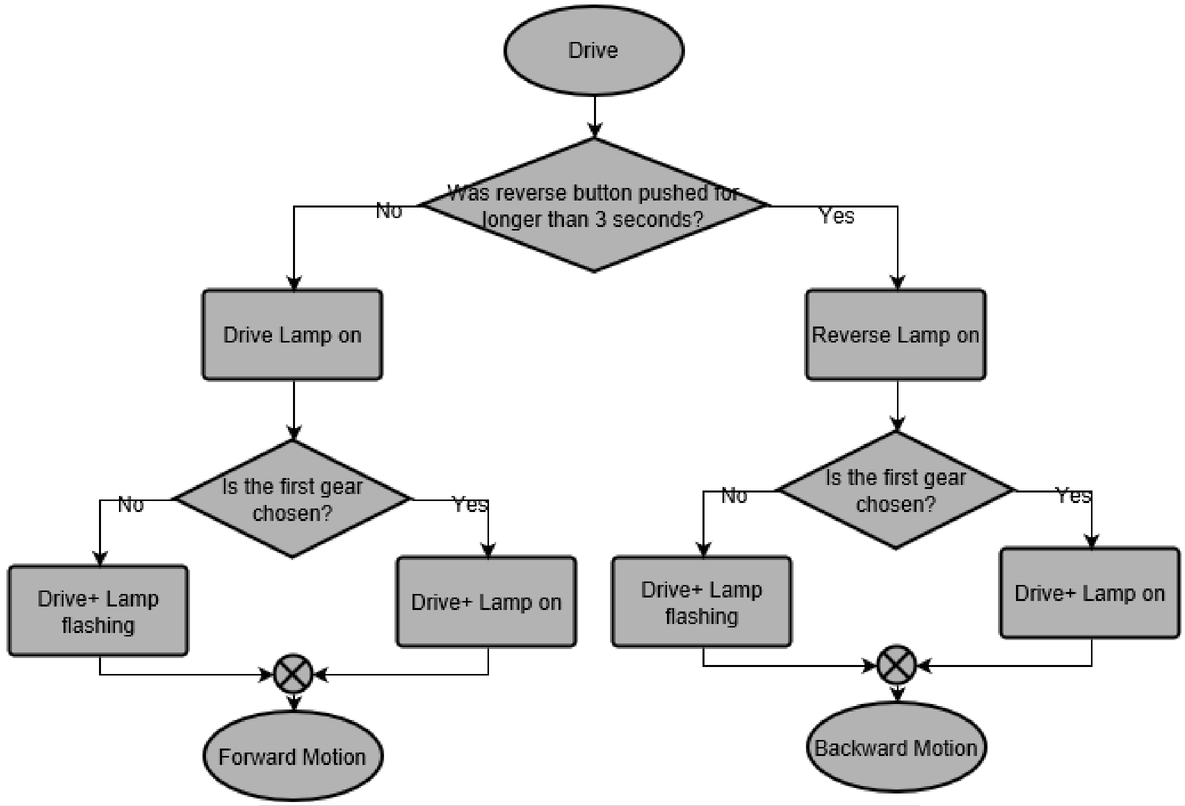


Figure 10 Moving Forward and Backward Flowchart

- GOING TO NEUTRAL FROM DRIVE:

Another standard operation to be evaluated is moving to neutral and/or parking from drive. A regular situation would be stopping in case of traffic or red light. For the driver to bring the vehicle to stop, he’s expected to first slow down the vehicle by removing his foot from the accelerating pedal to decrease the motor torque until the vehicle speed is low enough to shift to neutral where no torque is generated. It could also be possible to move later to the parking state if requested by the driver.

- **Required Action:**

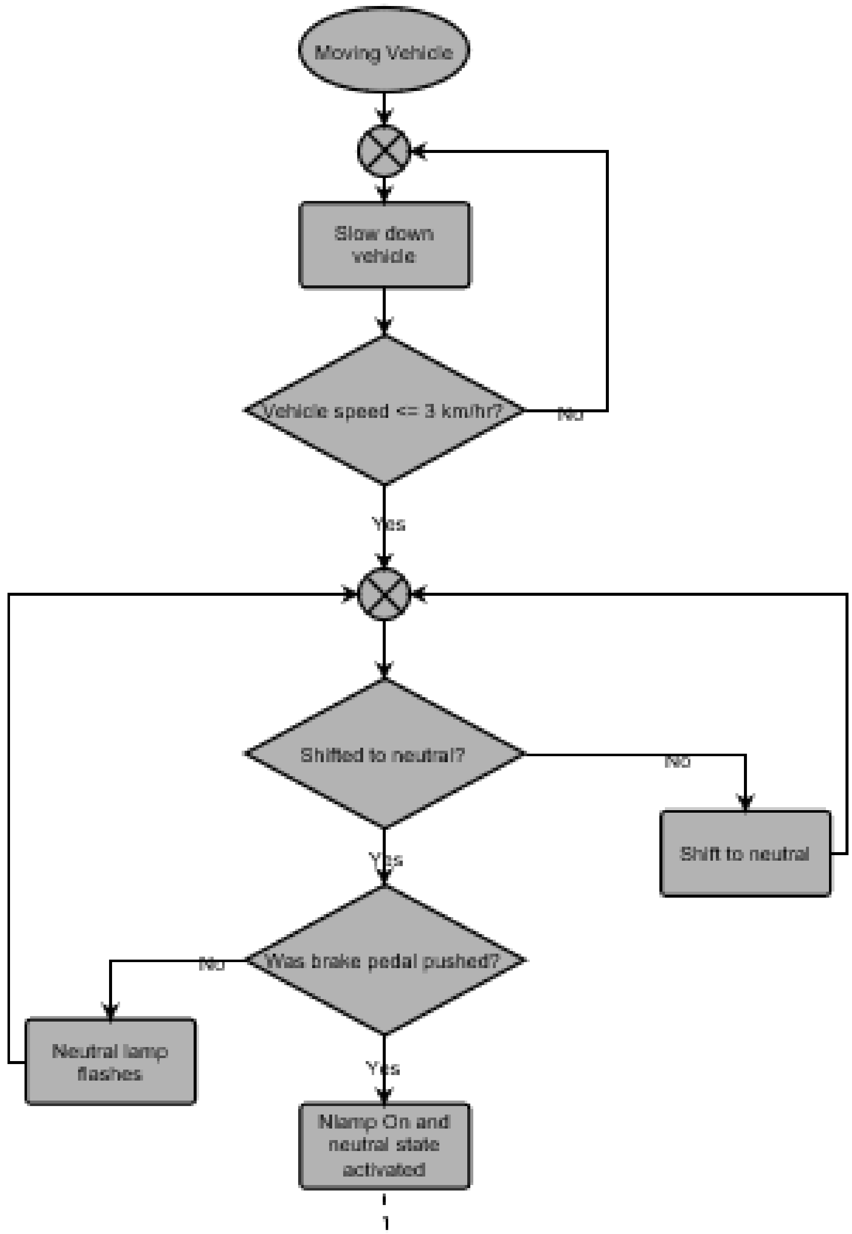
For the transition either from any of the drive states to neutral, or from neutral to parking, the driver must press the brake pedal, however, they don't have to keep pushing the pedal during the neutral or parking state.

- **Incorrect Transition:**

In case they forgot to push the pedal during the transition, the corresponding lamp will flash to remind them to redo the shift correctly for a successful state change.
If the brake pedal is not pushed during the transition from drive to neutral, the neutral lamp will flash signaling an unsuccessful shift. And subsequently, for an unsuccessful transition from neutral to parking, the parking lamp will flash signaling the fault.

Flowchart:

The previous operations are described below through the following flowchart



Moving Vehicle
Slow down vehicle
Vehicle speed <= 3 km/hr?
No
Yes
Shifted to neutral?
No
Shift to neutral
Yes
Was brake pedal pushed?
No
Neutral lamp flashes
Yes
Nlamp On and neutral state activated
1

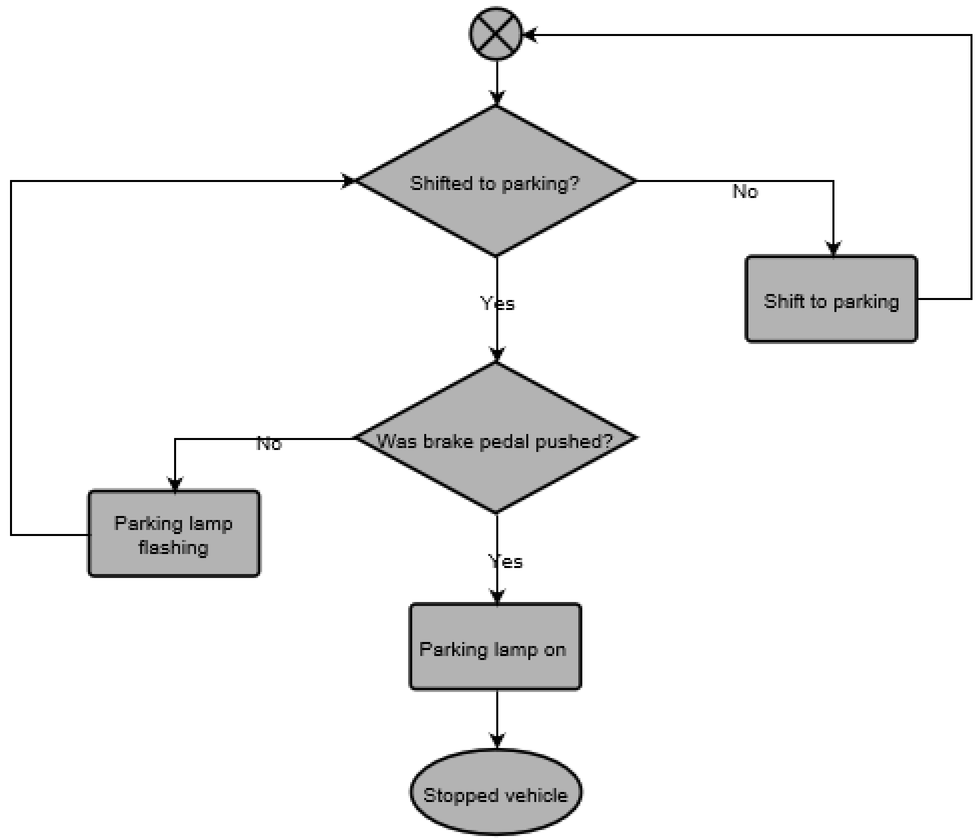


Figure 11 Going to Neutral and Parking from Drive Flowchart

Plant and VMU Modelling

In order to model the previously explained system and design its controller logic, Matlab is the chosen software for this procedure as well as Simulink and Stateflow. And, in this chapter, the modelling procedure is described in detail.

As mentioned in the "Context Description" Chapter, the whole system can be divided into four distinct entities which are:

- The driver
- The driver-vehicle interface.
- The Vehicle Management Unit.
- The vehicle dynamics.

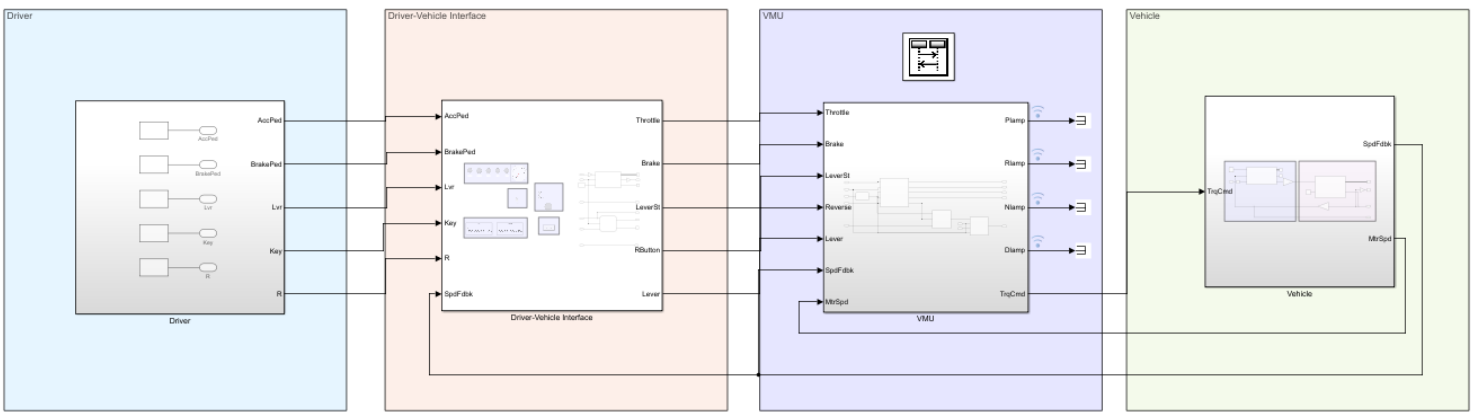


Figure 12 System Scheme on Simulink

Each of these three main entities has a few subsystems that are going to explained and shown in this chapter.

- ## DRIVER-VEHICLE INTERFACE:

The driver is interacting with the vehicle through inserting some inputs determining his desire to accelerate, decelerate, move forward, move backward…etc. as well as monitoring the dashboard which helps them understand the current vehicle state and whether anything is going wrong.

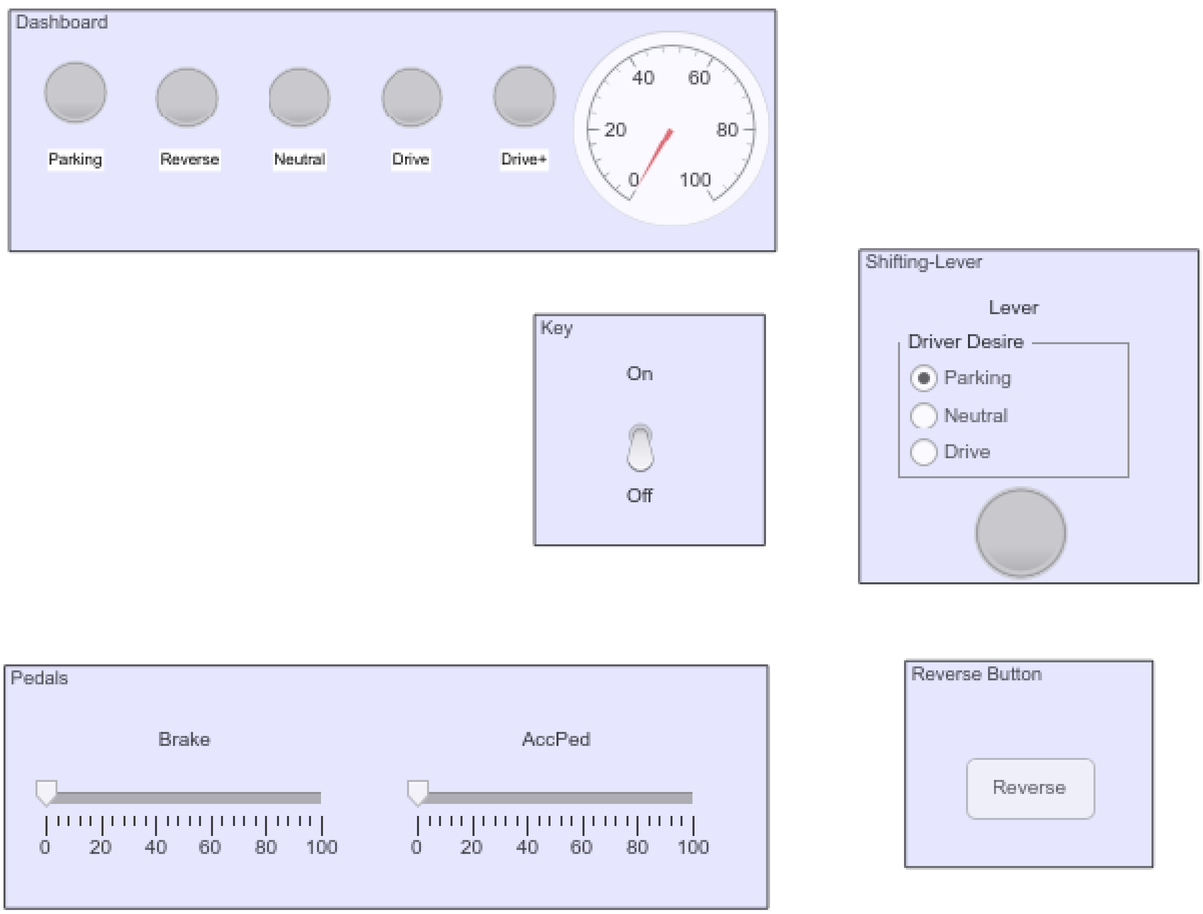


Figure 13 Driver-Vehicle Interface Modelling on Simulink

Therefore, it's convenient to divide the Driver-Vehicle Interface entity into driver inputs and dashboard.

- **Driver Inputs:**

The relevant driver inputs in this control unit (Traction Control) are the brake pedal and the accelerator pedal positions, the key state (as in whether the driver inserted the key and turned the vehicle on or not), the reverse button and the shifting lever state.

- **The Pedals:**

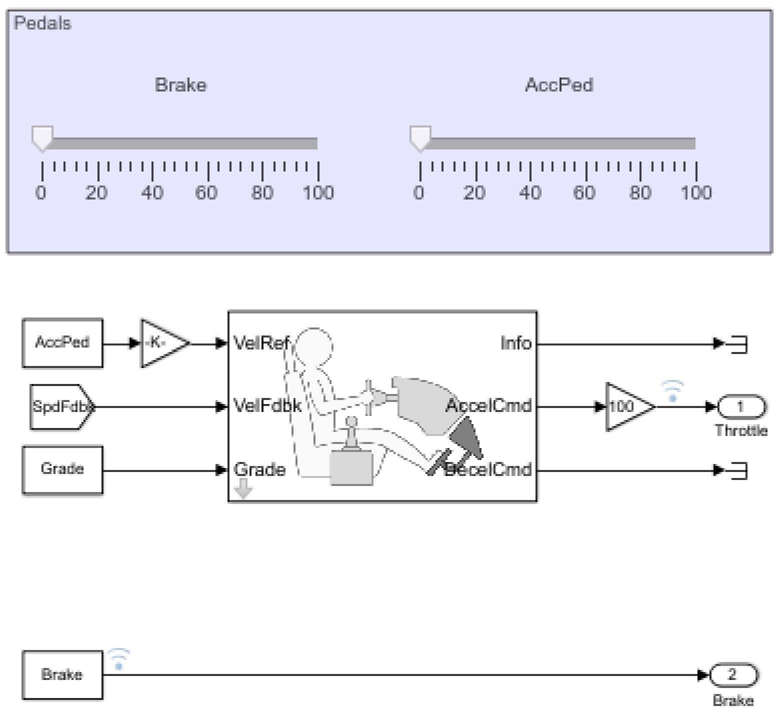


Figure 14 Pedals Modelling in Simulink

- <u>The accelerator pedal</u> is modelled as a slider representing the desired speed of the driver. The output of the accelerator pedal is then affected by many parameters which are represented by the longitudinal driver block.

The exact position of the acceleration pedal is highly relevant for the torque generation algorithm i.e. from 0 to 5 degrees, no torque is generated, while from 5 to 15 degrees, the range is for the regenerative braking…etc.

Given that the slider unit is in Km/hr, a conversion is done through the gain block to make the unit m/s instead. Similarly, since the block output (The acceleration command) takes values from 0 to 1, a gain of 100 is added to make it a percentage.

- The brake pedal is also modelled as a slider; however, the angle is irrelevant to the torque generation algorithm. Therefore, if the percentage is over 3%, the brake command is activated, otherwise, the push is ignored and treated as noise.

Name	Parameter	Unit	Value	Block
AccPed	Acceleration Pedal	Km/hr	From 0 to 100	Acceleration Pedal Constant Block
Conv	Conversion from km/hr to m/s	-	5/18	Gain Block
SpdFdbk	Vehicle Feedback Speed	m/s	27.7	Longitudinal Driver Input
Grade	Road Slope	-	0	Longitudinal Driver Input
Brake	Brake Pedal	-	From 0 to 100	Brake Pedal Constant Pedal
Throttle	Throttle Percentage	-	From 0 to 100	Longitudinal Driver Output
V_max	Nominal Speed	m/s	33.3	Longitudinal Driver
K_p	Proportional Gain	-	15	Longitudinal Driver
K_i	Integral Gain	-	1	Longitudinal Driver
K_aw	Anti-windup	-	0.1	Longitudinal Driver
K_ff	Velocity Feed-Forward	-	0.05	Longitudinal Driver
K_g	Grade Feed-Forward	-	0.01	Longitudinal Driver
Tau_e	Error Filter Time Constant	-	0.03	Longitudinal Driver

Table 1 Driver-Vehicle Interface Parameters

- **The Gear-Shift Lever:**

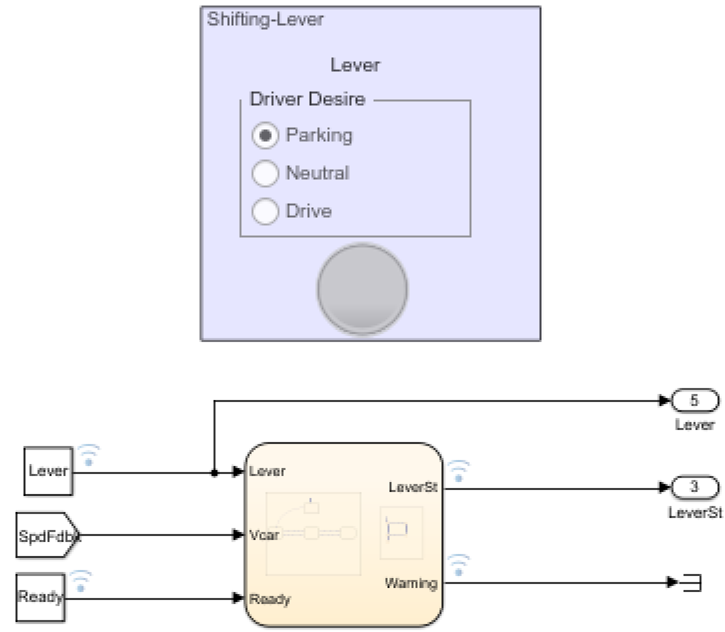


Figure 15 Gear-Shift Lever Modelling in Simulink

The fact that the vehicle of interest is not a regular electric vehicle makes the modelling of the lever different than in an automatic or manual drive vehicle. The lever is the one of a manual drive vehicle i.e. it has 6 possible positions (First, second, third, fourth and fifth gear as well as the neutral and reverse positions). However, there are a few differences:

- ❖ The allowed positions of the lever are only the neutral, first gear, second gear and reverse, while the other positions are mechanically blocked.
- ❖ Furthermore, the reverse position makes the vehicle go to the parking state where the gears are blocked.

The Lever subsystem can be represented through two main charts:

- ❖ <u>Driver Desire:</u>

  The driver desire to move between the different positions of the gear-shift lever is modelled through the following chart.

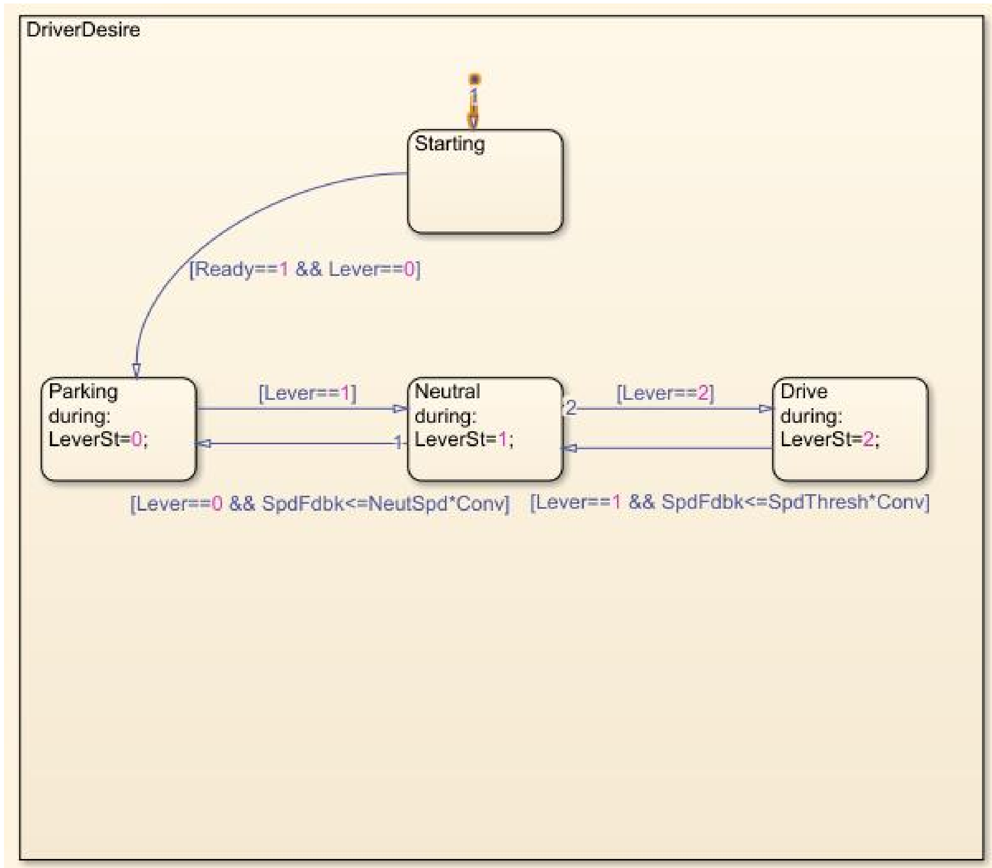


Figure 16 Lever State Machine in Stateflow

- o When the driver starts up the vehicle, the parameter "Ready" is set to 1, and if the gear-shift lever was set to the parking position, that means that the vehicle was correctly parked, and the lever state is "Parking".
- o Otherwise, the dashboard "Plamp" flashes signalling an incorrect initial condition to the driver, and the only way he can go to the "Parking" state is by moving the lever to the parking position first.

- The “Parking” state is also accessible by moving the lever from “Neutral” to “Parking”, given that the current vehicle speed is below 1 km/hr.
- The neutral position is reachable through either moving the lever from parking to neutral, or by moving the lever from drive to neutral given that the speed is below a previously defined threshold (which is, in this case, 3 km/hr).
- The system cannot differentiate between the 1st gear and the 2nd gear positions of the lever, it can only detect that the lever is put to a drive position. The “Drive” state is only accessible from the neutral state by moving the gear-shift lever to either the 1st or the 2nd gear.

❖ <u>The Failure Warning:</u>

If the driver desire to move from one state to the other was blocked due to the fact that the speed condition was not met, the blocking action must be modelled in the simulation.

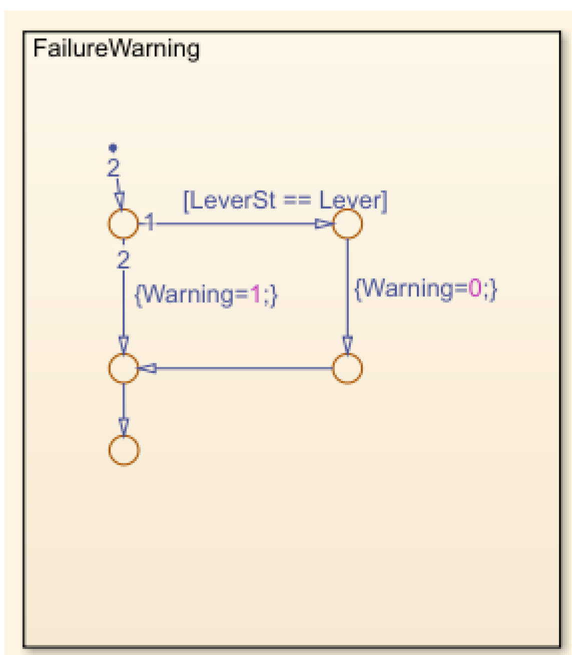


Figure 17 Lever Warning Logic in Stateflow

- If the driver desired lever state is not the same as the output lever state, that means that the action was blocked and, in that case, a warning lamp will take the color red to notify the simulation user that his desired transition was blocked.
- On the other hand, if the transition could be done, both the desired state (represented by the parameter ”Lever”) as well as the current lever state (represented by the parameter “LeverSt”) will be of the same value, hence the warning lamp will take the color green.

Name	Parameter	Unit	Values	Block
Lever	The Driver Desired Lever State	-	From 0 to 2	The Lever Constant Block
SpdFdbk	The Current Vehicle Speed	m/s	From 0 to 27.7	A Stateflow Input
LeverSt	The allowed lever state	-	From 0 to 2	A Stateflow Output
Ready	Turned Vehicle Key	-	0/1	A Stateflow Input
NeutSpd	The threshold speed to move from neutral to parking	Km/hr	1	The Stateflow Chart
SpdThresh	The Threshold to move from drive to neutral	Km/hr	3	The Stateflow Chart
Conv	The conversion from km/hr to m/s	-	5/18	The Stateflow Chart
Warning	The warning lamp signalling a blocked transition	-	0/1	A Stateflow Output (Warning lamp)

Table 2 Gear-Shift Lever Modelling Parameters

- **The Reverse Button:**

  The reverse state can be achieved by pushing a push button right next to the lever in the vehicle. It’s, therefore, modelled as a push button as follows.

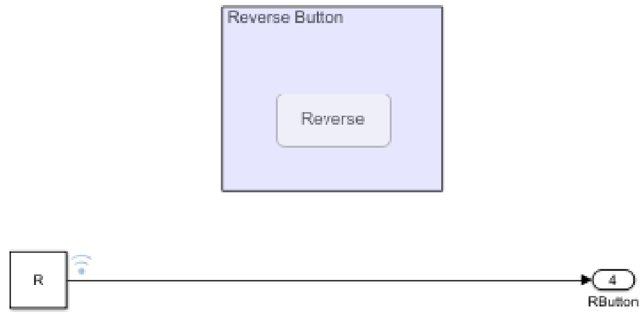


Figure 18 Reverse Button Modelling in Simulink

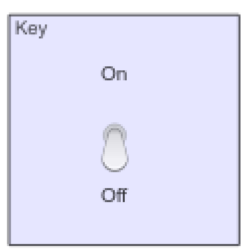
Name	Parameter	Unit	Value	Block
RButton	Reverse	-	0/1	The Reverse Constant Block

Table 3 Reverse Button Modelling Parameters

- **The Key:**

  When the driver starts the vehicle by turning the key to the first click, a parameter “Ready” is used to let the system know it has to start applying the control algorithm.

  A switch is used to model the vehicle key position as follows.



- **<u>The Dashboard:</u>**

  In order to keep the driver notified about the different vehicle states and the possible errors, five dashboard lights are used as well as a speed gauge.

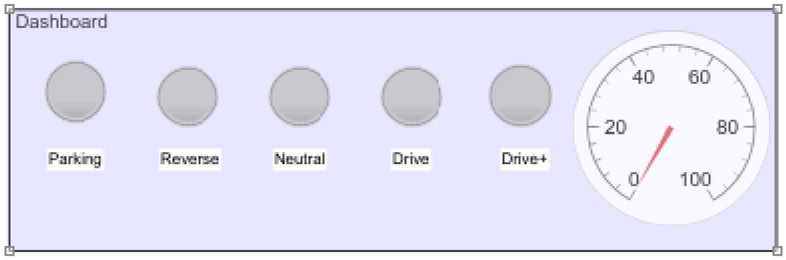


Figure 19 Dashboard Modelling in Simulink

  - **Parking:**

    The Parking lamp takes one of three colors:

    - <u>Red:</u> which means that the lamp is not activated in the dashboard.
    - <u>Green:</u> Which means that the light of the Plamp is on and steady.
    - <u>Blue:</u> Which mean that the light of the Plamp is flashing.

  - **Reverse:**

    The Reverse lamp takes one of three colors:

    - <u>Red:</u> which means that the lamp is not activated in the dashboard.
    - <u>Green:</u> Which means that the light of the Rlamp is on and steady.
    - <u>Blue:</u> Which mean that the light of the Rlamp is flashing.

  - **Neutral:**

    The Neutral lamp takes one of three colors:

    - <u>Red:</u> which means that the lamp is not activated in the dashboard.
    - <u>Green:</u> Which means that the light of the Nlamp is on and steady.
    - <u>Blue:</u> Which mean that the light of the Nlamp is flashing.

- **Drive:**

  The Drive lamp takes one of three colors:

  - Red: which means that the lamp is not activated in the dashboard.
  - Green: Which means that the light of the Dlamp is on and steady.
  - Blue: Which mean that the light of the Dlamp is flashing.

- **Drive+:**

  The Drive+ lamp takes one of two lights notifying the driver whether he's on the first or second gear:

  - Green: Which means that the vehicle is currently on the first gear.
  - Red: Which means that the vehicle is currently on the second gear.

- **The Speed Gauge:**

  The speed gauge shows the driver the current speed of the vehicle in Km/hr.

- THE VEHICLE MANAGEMENT UNIT:

The main aims of this block are to generate the required torque as well as showing the driver which state they are at through giving certain colours to the dashboard lamps. This module can be divided into four main entities as follows:

- The Reverse Logic
- The State Machine.
- The Look-up Table Selection
- The Transmission Ratio

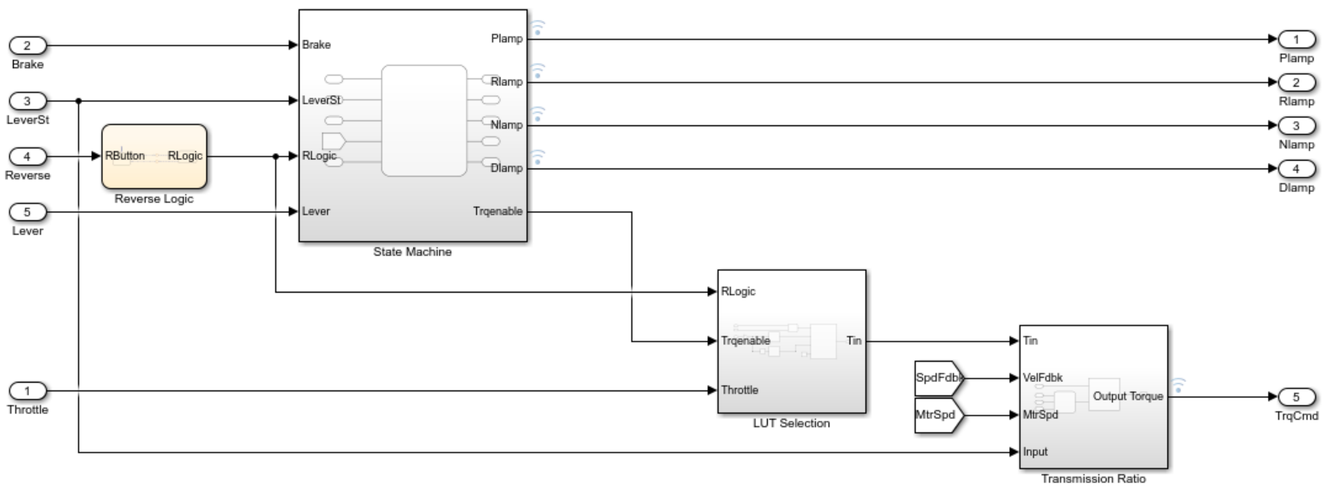


Figure 20 Vehicle Management Unit in Simulink

Each of the four blocks of the Vehicle Management Unit is explained in this subchapter.

➢ **The Reverse Logic:**

Since the reverse motion can be granted by pushing a button right next to the lever, an extra condition has to be added in order to make sure that the driver really intended to push the button and it wasn't just a noise.

The added condition is that the driver has to keep pushing the reverse button for at least three seconds before the reverse command is activated. Otherwise, the push is treated as a noise and nothing happens.

The previously explained procedure is modelled through a Stateflow chart as follows:

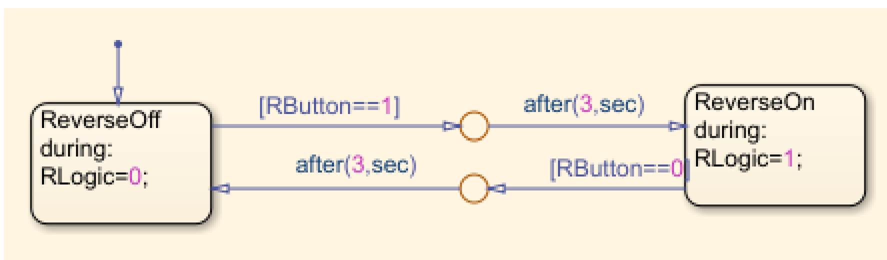


Figure 21 Reverse Logic Modelling in Stateflow

As it can be observed in the chart, there are two states:

- **ReverseOff:**

  Which is the default state entered as soon as the vehicle starts. During this state the reverse logic is set to one.
  This state is also reachable from the ReverseOn state by pushing the reverse button for at least 3 seconds.

- **ReverseOn:**

  The only way to access this state is by pushing the reverse push button for three seconds or more.

Name	Parameter	Unit	Value	Block
RButton	Driver's desire to move backward	-	0/1	The Reverse Logic Stateflow Chart
RLogic	The allowed reverse motion logic	-	0/1	The Reverse Logic Stateflow Chart

➢ **The State Machine:**

This block represents the main subsystem in the Vehicle Management Unit and it puts in action the flowcharts drawn in the "Manager Building" chapter.

In order to have clear states and conditions to move between states, a Stateflow chart is used having six distinct boxes as follows:

- **Initialization:**

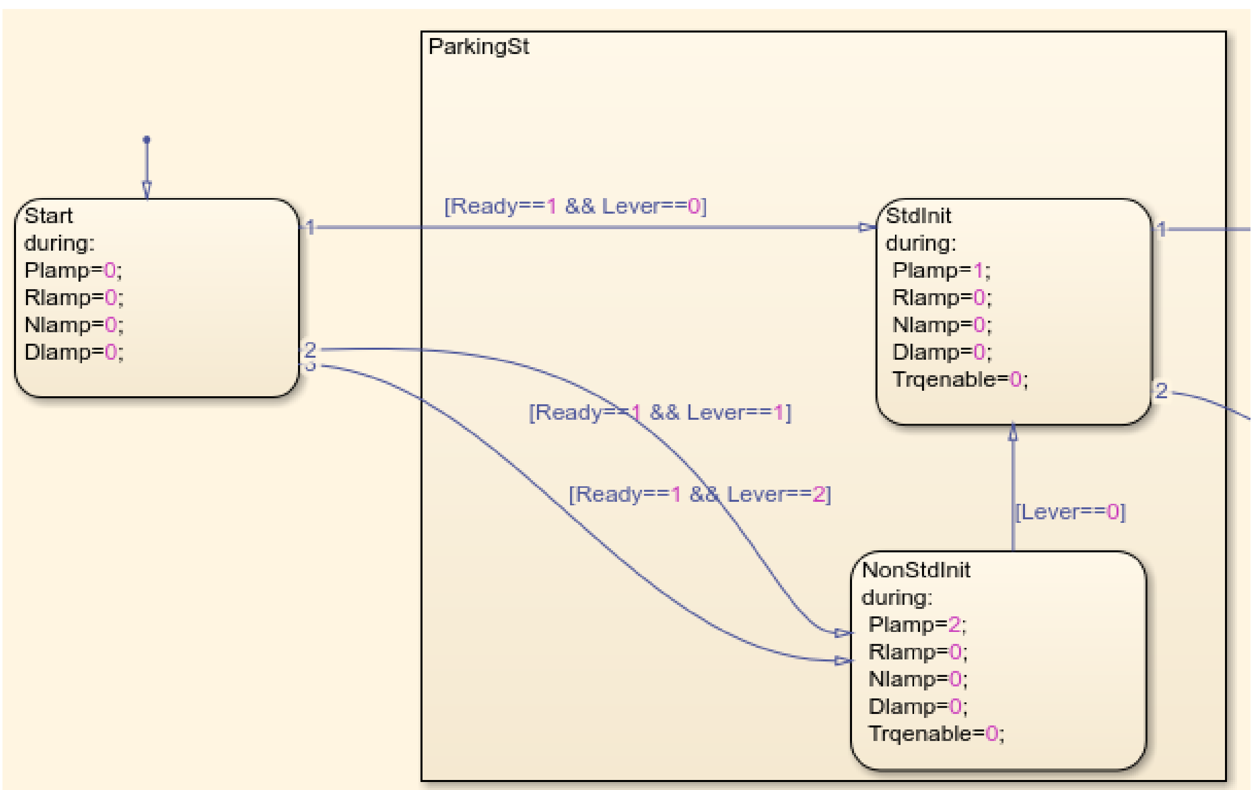


Figure 22 Initial Standard Conditions Logic Modelling in Stateflow

Three distinct states are used to translate the previously drawn chart representing the initial conditions of the vehicle to detect whether the vehicle is starting from a standard initial condition or not:

- Start: It represents the default state the vehicle is at before the driver turns the key to the first click. During this state all the dashboard lights are turned off because the vehicle hasn't started yet.
- StdInit: The first check represented in the flowchart was whether the driver turned the key or not and then if the vehicle is correctly parked. In order to move from "Start" to "StandardInitial" the key must be turned on (Ready=1) and the gear-shift lever must be put to parking. Only if the two conditions are true, the parking light in the dashboard takes a green color signalling a correct initial condition. The driver can then start driving the vehicle normally.
- NonStdInit: On the other hand, if the key is turned but the gear-shift lever was put to neutral, 1^{st} gear or 2^{nd} gear, that means that the vehicle is not in a standard initial condition. In that case the parking light will take the color red signalling a non-standard condition.
  This state can only be exited if the driver moves the gear-shift lever to "Parking", the parking light will then take the color green signifying a standard initial condition.

- **From Parking to Neutral:**

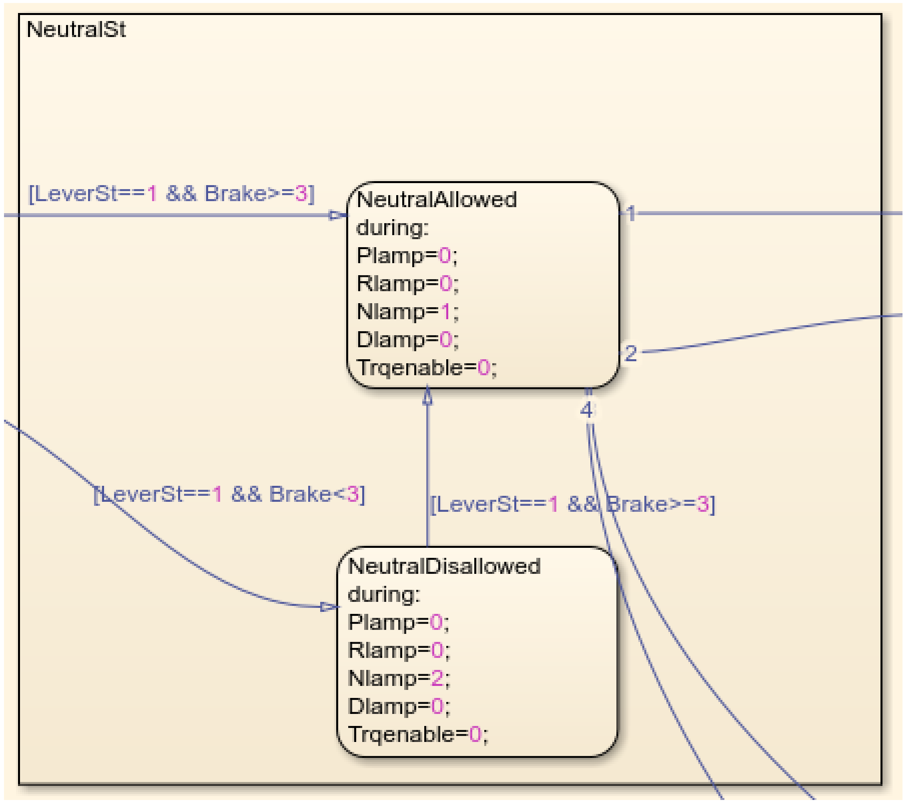


Figure 23 Moving to Neutral Logic Modelling in Stateflow

Once the vehicle is in a standard initial condition, the driver can bring the vehicle to the neutral state by both: moving the gear-shift lever to neutral and pushing the brake pedal at the same time. Also going through the corresponding flowchart, the procedure can be represented in two distinct states:

- NeutralAllowed: In case the driver pushed the brake pedal over 3% (to make sure it wasn't a noise) while changing the gear-shift position from "Parking" to "Neutral", the Nlamp in the dashboard will take the color green telling the driver that the transition was successful.
- NeutralDisallowed: On the other hand, in case the driver forgot to push the brake pedal, the Nlamp will take the color blue to notify the driver that the transition was done incorrectly and that he should do it again while pushing the brake pedal.

If the driver does that, this state is exited, and the vehicle goes to the "Ready" state.

- **Moving Forward and Backward:**

Now, as the driver brought the vehicle successfully to the neutral state, he's able to move either forward or backward according to the flowchart drawn in the "Manager Building" chapter.

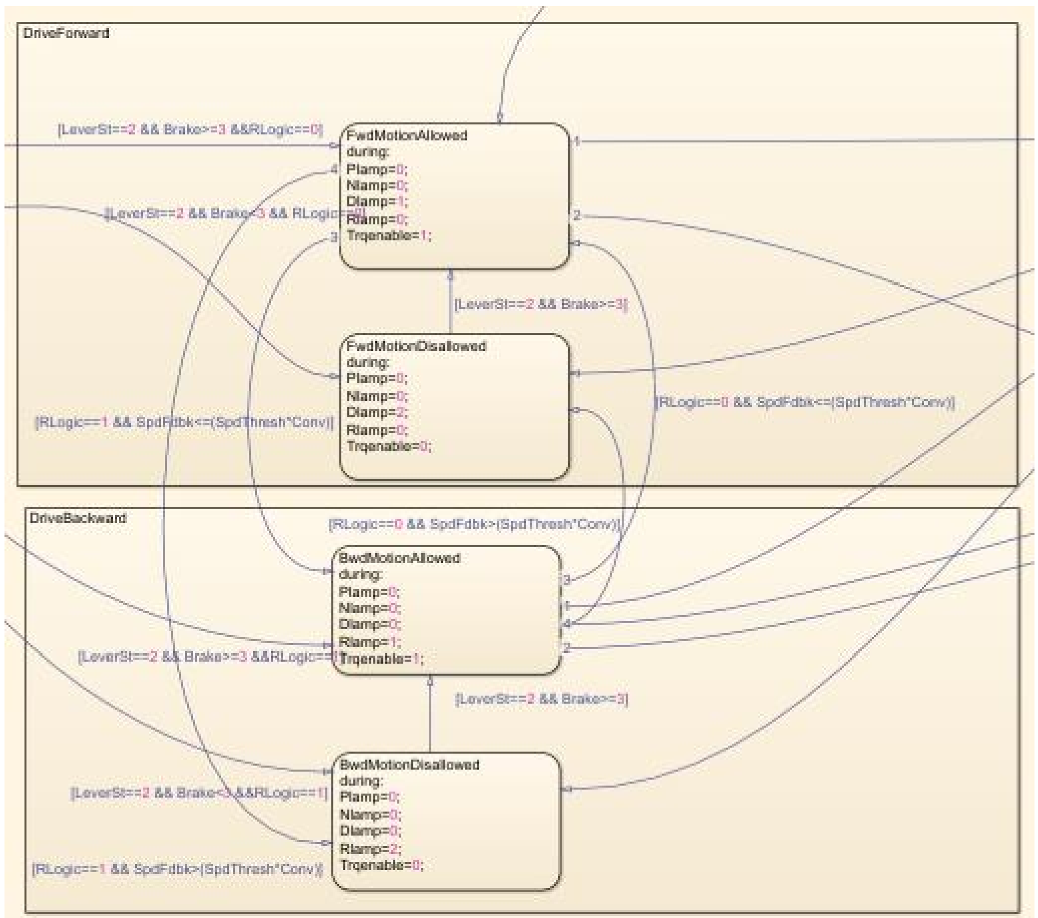


Figure 24 Moving Forward and Backward Logic Modelling in Stateflow

Four distinct states can translate the flowchart:

- FwdMotionAllowed:

  The first check in the flowchart was whether the driver shifted to one of the drive states (1st or 2nd gear) and pushed the brake pedal. In case the driver did this transition correctly, the drive lamp will take the color green and a parameter "Trqenable" is set to one enabling the motor to generate the corresponding torque to the desired speed of the driver.

  This state is also reachable from the "BwdMotionAllowed" state, if the driver pushed the reverse button for at least three seconds.

- FwdMotionDisallowed:

  If the driver did not push the brake pedal while shifting to the drive state, the VMU goes to the "FwdMotionDisallowed" state during which the drive lamp in the dashboard takes the color blue implying an incorrect transition. The "Trqenable" is set to zero in that case and the motor will generate no torque.

  This state will also be adopted by the VMU in case the vehicle was in the "BwdMotionAllowed" state, the speed was above the threshold and the driver requested to move forward. In that case, the driver will have to slow down the vehicle first.

  For the VMU to move to the "FwdMotionAllowed" the driver will have to redo the transition correctly, as in he has to shift the lever again to the drive state while pushing the brake pedal.

- BwdMotionAllowed:

  The procedure to move backwards is similar to the procedure of moving forward starting from the neutral state. The only difference is that, for the backward motion, the driver has to push the reverse button for at least three seconds.

In case this transition is done correctly, the reverse lamp in the dashboard will take the color green and the “Trqenable” will be set to one allowing the motor to generate the required torque.

- <u>BwdMotionDisallowed:</u>

  Similarly, if the brake pedal was not pushed when the shift from neutral to drive was done, the VMU will be in the “BwdMotionDisallowed”. During the mentioned state, the reverse lamp in the dashboard will take the color blue, meaning that the transition was unsuccessful and that no torque will be generated to move the vehicle backwards.

  This state will also be adopted by the VMU in case the vehicle was in the “FwdMotionAllowed” state, the speed was above the threshold and the driver requested to move backward. In that case, the driver will have to slow down the vehicle first.

  The torque will be enabled, and the reverse lamp will light in green only if the driver redoes the shift will pushing the brake pedal.

- **Going to Neutral:**

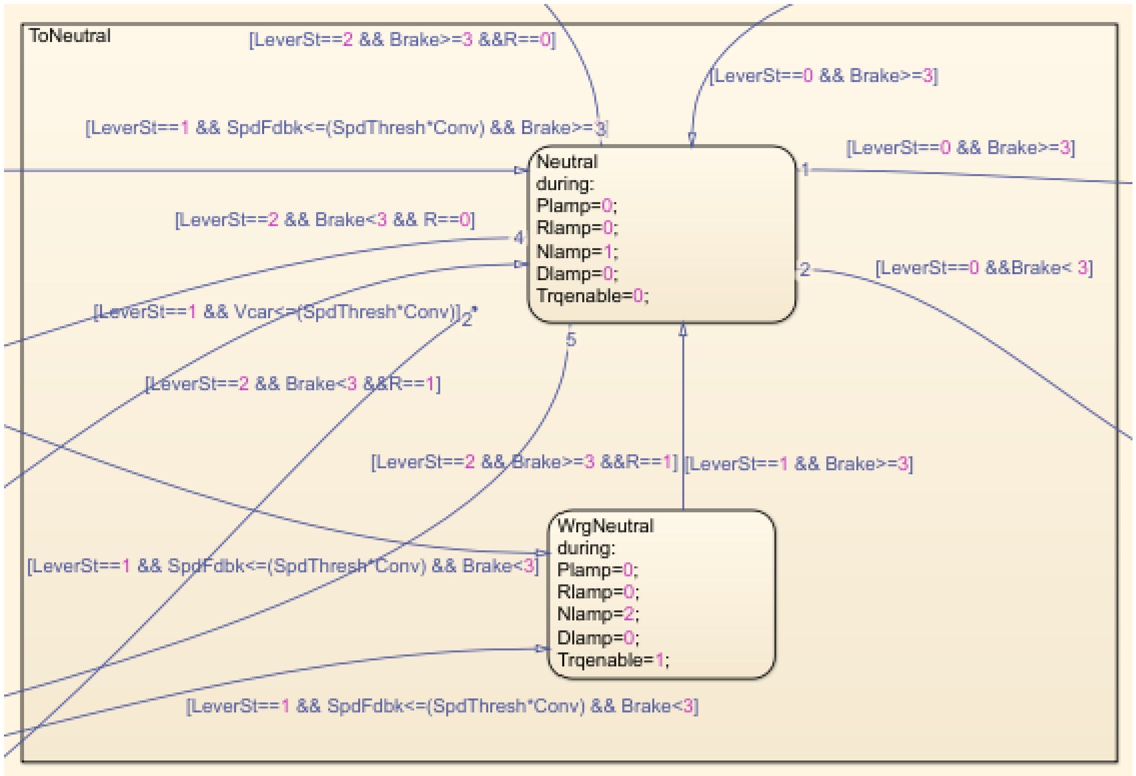


Figure 25 Moving to Neutral from Drive Logic Modelling in Stateflow

For the vehicle to go to the neutral state starting from any of the drive states (either 1st or 2nd gear) whether the vehicle was moving backward or forward, three conditions must be present as shown in these two states:

- Neutral:

  In order to bring the vehicle to the neutral state starting from either the drive state or the reverse state, the vehicle speed must be lower than a specific threshold, which is set in this case to 3 km/hr. The driver must also move the gear-shift lever to neutral while pushing the brake pedal.

During this state, the neutral lamp in the dashboard takes the color green implying that the neutral state is activated correctly and that now no torque will be generated.

- <u>WrgNeutral:</u>

  In case the driver did not push the brake pedal while doing the shift, the neutral lamp in the dashboard will light in blue signalling an incorrect transition.

  The motor will still be enabled to generate torque until the driver redoes the shift successfully.

- **Go to Parking:**

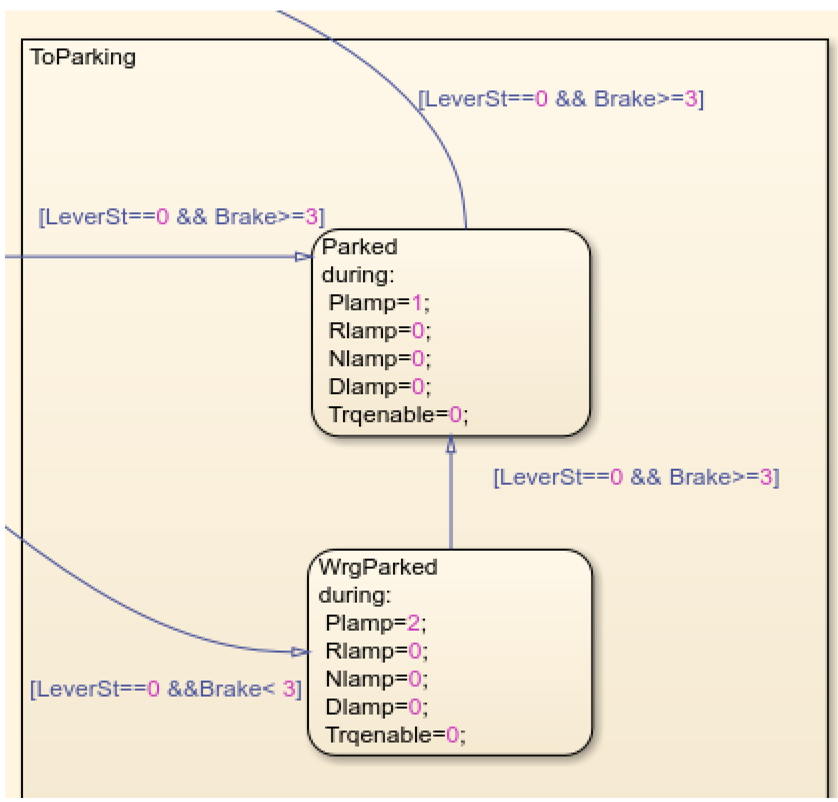


Figure 26 Moving from Neutral to Parking Logic Modelling in Stateflow

Once the driver brought the vehicle to the neutral state successfully, he can also go to parking if he desires following the procedure explained in the corresponding flowchart in the “Manager Building” chapter.

Two distinct states are used to translate the flowchart:

- Parked:
  This state is only reachable from the neutral state, by shifting the gear-shift lever to parking while pushing the brake pedal, given that the vehicle speed is below a specific threshold which is set in this case to 1 km/hr.
  The Plamp in the dashboard will light in green implying a correct transition.

- WrgParked:

  In case the driver did not push the brake pedal while doing the shift of the lever, the transition will be unsuccessful and the Plamp will light in blue until the driver does the shift correctly while pushing the pedal.

Name	Parameter	Unit	Value	Block
LeverSt	Allowed gear-shift lever state	-	From 0 to 2	Stateflow Chart Input
Conv	Conversion from km/hr to m/s	-	5/18	Stateflow Chart Constant
SpdFdbk	Vehicle Feedback Speed	m/s	27.7	Stateflow Chart Input
Trqenable	Allowing motor to generate torque	-	0/1	Stateflow Chart Output
Brake	Brake Pedal	-	From 0 to 100	Stateflow Chart Input
Plamp	Plamp logic	-	From 0 to 2	Stateflow Chart Output
Rlamp	Rlamp logic	-	From 0 to 2	Stateflow Chart Output
Nlamp	Nlamp logic	-	From 0 to 2	Stateflow Chart Output
Dlamp	Dlamp logic	-	From 0 to 2	Stateflow Chart Output
Lever	Gear-shift lever initial state	-	From 0 to 2	Stateflow Chart Input
SpdThresh	Max speed to shift from drive to neutral	km/hr	3	Stateflow Chart Constant
Rlogic	Reverse button logic	-	0/1	Stateflow Chart Input
Ready	Vehicle key logic	-	0/1	Stateflow Chart Constant

Table 4 VMU State Machine Parameters

➢ The Look-up Table Selection:

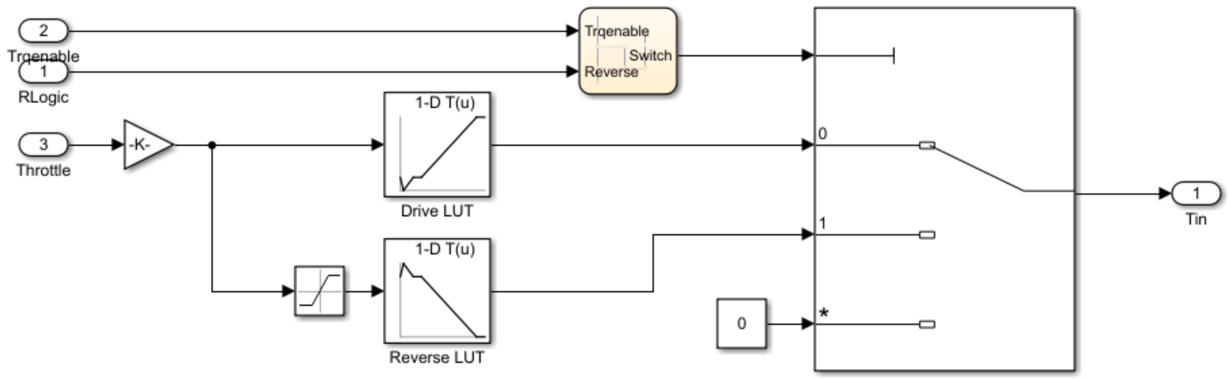


Figure 27 Look-up Table Selection Modelling in Simulink

In order to put in action the decisions made in the “State Machine” Stateflow chart, a multiport switch is used to decide which lookup table will be used in case a torque is to be generated. At first, a Stateflow chart is given the “Trqenable” and “RLogic” as inputs:

- In case either the first or second gear is chosen while the reverse button is not activated, the first lookup table is used to choose the torque corresponding to the throttle percentage.
- While in case the reverse button is pressed and either the first or second gear is chosen, the second lookup table will be used (corresponding to the second port). However, one main difference between the forward and backward motion is that, in the backward motion, there is a limit on the maximum achievable speed which is set here to 10 km/hr.
- Otherwise, no torque will be generated (neutral and parking states), and the selected port is the third one.

The previously explained logic is realized through an if-Elseif pattern in Stateflow as shown below:

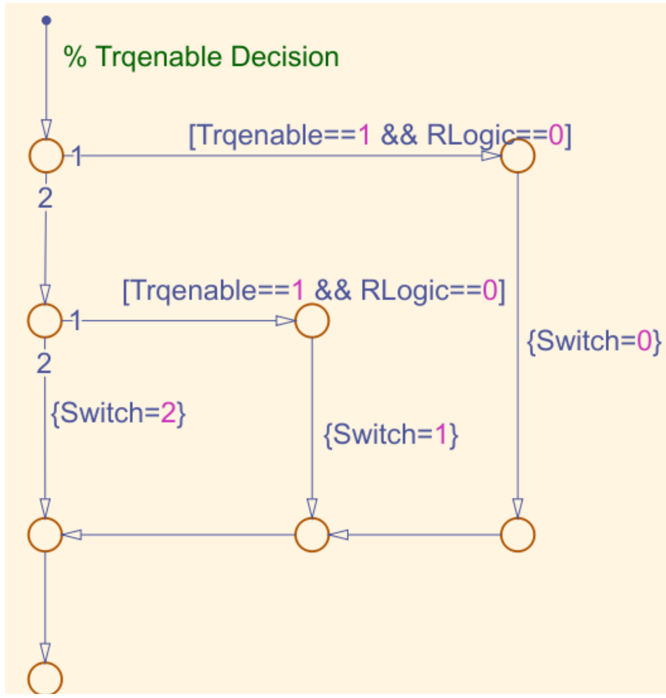


Figure 28 Look-up Table Selection Logic in Stateflow

Name	Parameter	Unit	Values	Block
RLogic	The reverse button state	-	0/1	LUT logic subsystem i/p
LeverSt	The allowed lever state	-	From 0 to 2	LUT logic subsystem i/p
Trqenable	Enabling the torque generation	-	0/1	LUT logic subsystem i/p
Switch	The multiport switch input	-	From 0 to 2	Stateflow chart o/p
Tin	The i/p torque to transmission system	N.m	From -30 to 144	LUT logic subsystem o/p
Bwdmax	Maximum backward speed	Km/hr	10	Saturation Block

Table 5 Look-up Table Logic Parameters

- **The Transmission Ratio:**

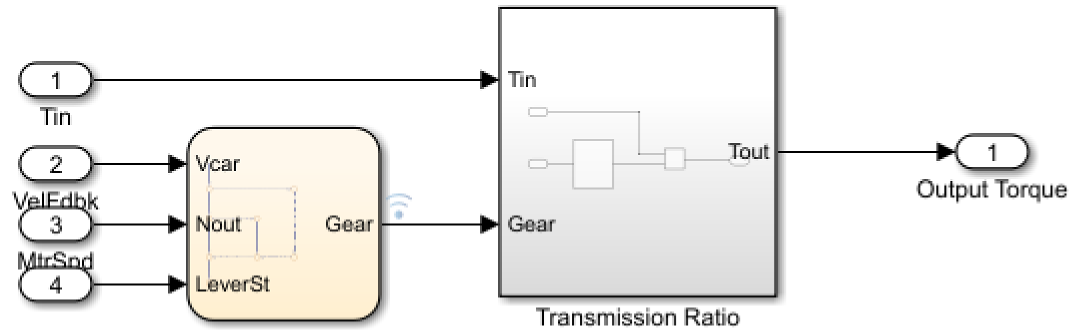


Figure 29 Gear Detection Modelling in Simulink

The transmission ratio subsystem aims at applying the gear ratio corresponding to the chosen gear by the driver to generate the output torque sent to the wheels.

The neutral and the parking states can be easily detected, while for the first and second gear, it can only be known that the vehicle in the drive state. Therefore, in order to know the exact gear, a comparison of the vehicle speed and the motor speed is done as follows.

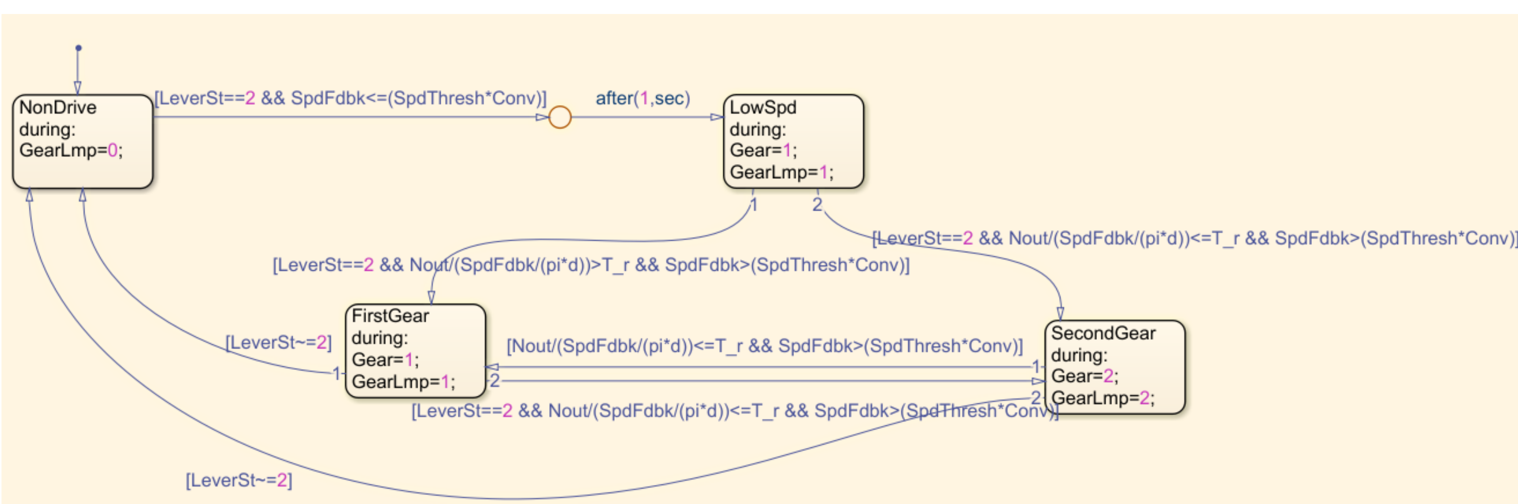


Figure 30 Gear Detection Logic Modelling in Stateflow

When the vehicle state has just changed from neutral to either of the drive states, the feedback speed of the vehicle is zero, therefore, the comparison is that case is pointless because it will yield zero. Hence, when the vehicle speed is below a certain threshold (it’s set to 3 km/hr in this case), the used gear ratio is the one of the first gear, because the gear ratio does not make a significant difference in such low speeds.

Given the transmission system of the Fiat Panda, the ratio of the first gear is 16.5 while the second gear is 8.6.
In case the ratio between the motor speed to the wheel speed is less than or equal to 8.6, that means that the transmission system is at the second gear. Otherwise, it’s the first gear.

For converting the vehicle speed in km/hr to the wheel speed in rpm the following equation is used

$$Nout = \frac{\mathrm{SpdFdbk} * 50}{3 * \pi * \mathrm{d}}$$

Equation 1: The speed conversion equation

Where: Nout is the wheel speed in rpm

d is the tyre diameter (set to 0.61 m)

Once the gear has been detected, the torque is multiplied by the gear ratio to give the output torque to the wheels as follows.

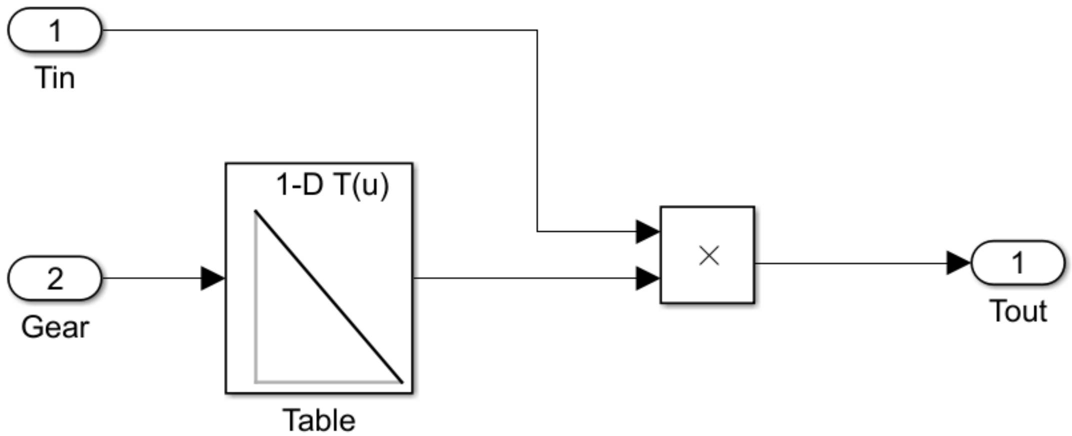


Figure 31 Transmission Ratio Selection

Name	Parameter	Unit	Values	Block
Tin	The input torque to transmission system	N.m	From -144 to 144	The transmission ratio susbsystem i/p
SpdFdbk	The vehicle feedback speed	Km/hr	From 0 to 100	The gear detection Stateflow chart i/p
Nout	The motor speed	rpm	-----	The gear detection Stateflow chart i/p
Gear	The chosen gear	-	1 or 2	The gear detection Stateflow chart o/p
d	The tyre diameter	m	0.61	The gear detection Stateflow chart constant
Tout	The torque command to the motor.	N.m	-------	The transmission ratio susbsystem o/p
Conv	Conversion from Km/hr to m/s	-	5/18	The gear detection Stateflow chart constant
SpdThresh	Speed threshold	Km/hr	3	The gear detection Stateflow chart constant
T_r	Transmission Ratio	-	8.67	The gear detection Stateflow chart contant

Table 6 Gear Detection Parameters

- THE VEHICLE :

Once both the driver-vehicle interface and the VMU have been modelled, the torque command must be sent to the motor to generate the corresponding torque. It's also important to take the vehicle dynamics into consideration to check the behavior of the whole system.

As shown in the scheme of the whole system in the "Context Description" chapter, the vehicle section is divided into three main entities:

- The motor.
- The transmission
- The vehicle dynamics

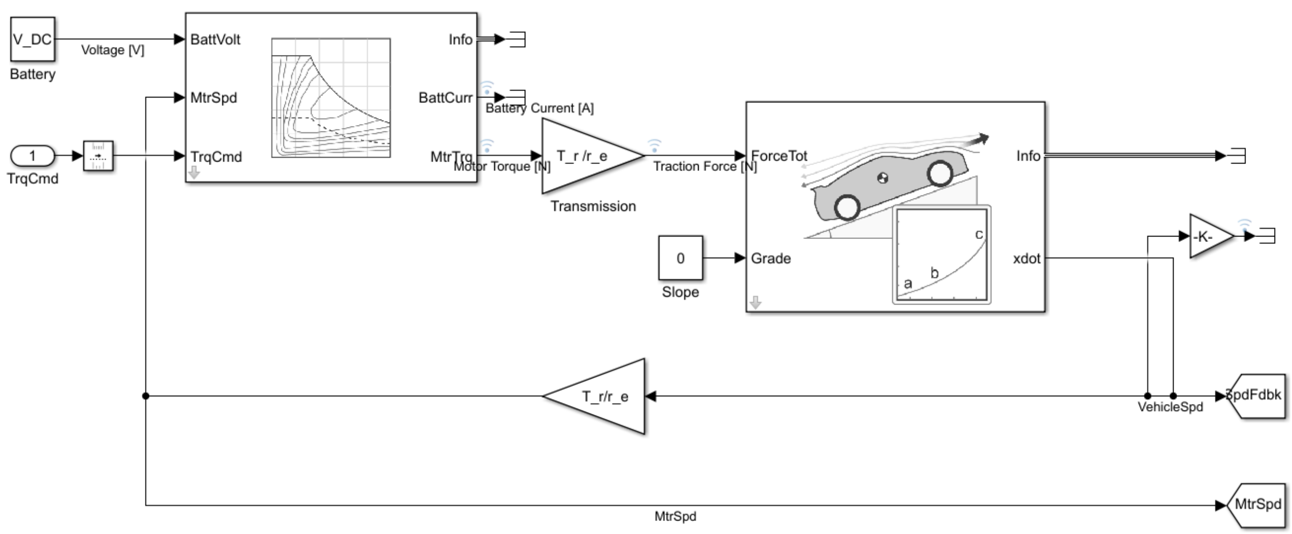


Figure 32 Vehicle Dynamics Modelling in Simulink

- **<u>The Motor:</u>**

Now that the VMU has decided the exact torque to be generated by the motor, taking into consideration the current battery voltage as well as the vehicle speed and based on some calculations, the motor decides whether it's possible to generate the required torque.

In order to calculate the overall efficiency of the motor and drive, both the nominal speed and the nominal torque are to be computed.

Given a nominal motor speed of 2895 rpm, the equivalent in radians/second will be:

$$W\_n = \frac{2895}{2\Pi * 60}$$

Where: W_n is the nominal speed in rad/s

For a nominal torque of 40 N.m, the overall motor and drive efficiency will be:

$$eta_n = 83\%$$

Since the maximum power is required in the modelling phase, it's to be calculated as follows:

$$P_{m_{max}} = W_n * T_{m_{max}} * 1.1$$

Where: T_{mmax} is the maximum motor torque in N.m

One major topic to be taken into consideration as well is the losses in the motor, either the fixed losses, the iron losses or the copper losses.

For the motor used in the plant:

$$Pl_{iron} = 0$$
$$Pl_{eln} = 100$$
$$tau\_m = 0.02$$

Where: Pl_{iron} is the iron power loss in Watt.

Pl_{eln} is the fixed power loss independently from the torque and speed in Watt.

Tau_m is the torque control time constant in seconds.

- **<u>The Transmission:</u>**

Once the motor generated the torque corresponding to the desired speed, the transmission ratio is applied to step up the torque before it’s sent to the vehicle dynamics block. This is modelled through a simple gain block.

- **<u>The Vehicle Dynamics:</u>**

There are many factors that could affect the speed of the vehicle making it higher or lower than the desired speed by the driver such as the rolling resistance, the drag force, the road slope…etc. Many of these factors are taken into consideration in the vehicle dynamics block to simulate more or less the expected output speed.

Name	Parameter	Unit	Values	Block
V_DC	Battery Voltage	V	96	Battery voltage constant block
Trqcmd	Torque command sent from VMU to motor	N.m	66	Mapped motor block input

T_m_max	Maximum generated torque by the motor	N.m	66	Mapped motor block constant
P_m_max	Maximum generated power by the motor	W	$2.201*10^4$	Mapped motor block constant
Tau_m	Torque control time constant	s	0.02	Mapped motor block constant
Eta_n	Motor and drive overall efficiency	%	83	Mapped motor block constant
W_n	Nominal speed	Rad/s	7.67	Mapped motor block constant
T_m_n	Nominal motor torque	N.m	40	Mapped motor block constant
Pl_iron	Iron losses	W	0	Mapped motor block constant
Pl_eln	Fixed losses	W	100	Mapped motor block constant
T_r	Transmission ratio	-	8.67	Transmission gain
m_e	Vehicle mass	Kg	$1.0359*10^3$	Vehicle body total road load
c_0	Rolling resistance coefficient	-	145.0911	Vehicle body total road load
c_1	Rolling and driveline resistance coefficient	-	0	Vehicle body total road load
c_2	Aerodynamic drag coefficient	-	0.4764	Vehicle body total road load
g	Gravitational constant	m/s^2	9.81	Vehicle body total road load

MODEL-IN-THE-LOOP TESTING

Before moving to any further steps in the process such as the code generation or integrating the different parts of the system, the behaviour of the designed VMU must be tested first.

Having already modelled the plant and taken into account most of the factors that are relevant to the traction control unit, and using Simulink as the desktop environment, the dynamics of the designed system can be observed and then the model can be refined if necessary.

The test procedure will use as a script the flowcharts shown in the “Manager Building” Chapter. Therefore, starting from the very first state, every branch will be tried to check whether the system will behave as expected.

- ## THE INITIAL CONDITIONS:

  According to what’s mentioned in the “Manager Building” chapter, two checks must be done at first to decide whether the vehicle is starting from standard initial conditions, as in if it was correctly parked, or not. In case the vehicle is starting from non-standard initial conditions, the driver is notified through the dashboard lamps to put the car into the correct starting state to be able to move to other states and drive the vehicle.

These two checks are:

➢ **<u>If the key is turned to the first click:</u>**

When the key is not turned to the first click all the dashboard lamps will be off as shown below and the speed gauge is pointing to zero. Everything will remain the same until the second check is done.

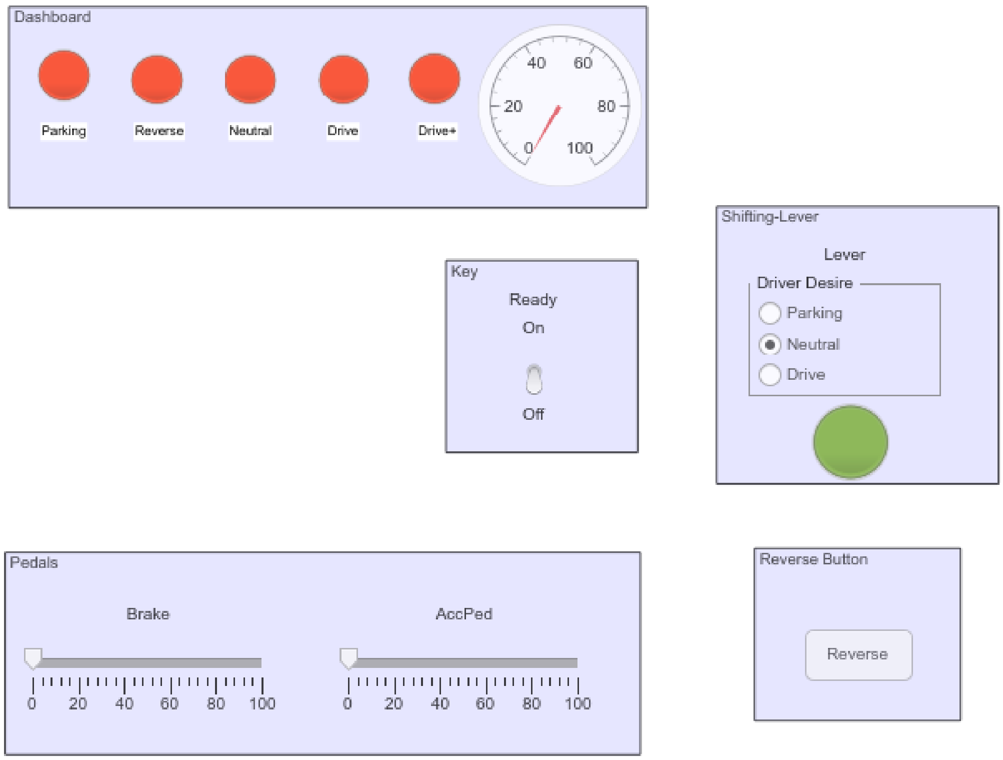


Figure 33 MIL: Before Turning the Key

➢ **<u>If the vehicle was correctly parked:</u>**

Once the driver has turned the key, The VMU checks whether the gear-shift lever was initially put to parking or not.

In case the vehicle was not correctly parked the expected behaviour is having the parking lamp lighting in blue. Checking the simulation, the parking lamp does turn into blue signalling an incorrect initial condition.

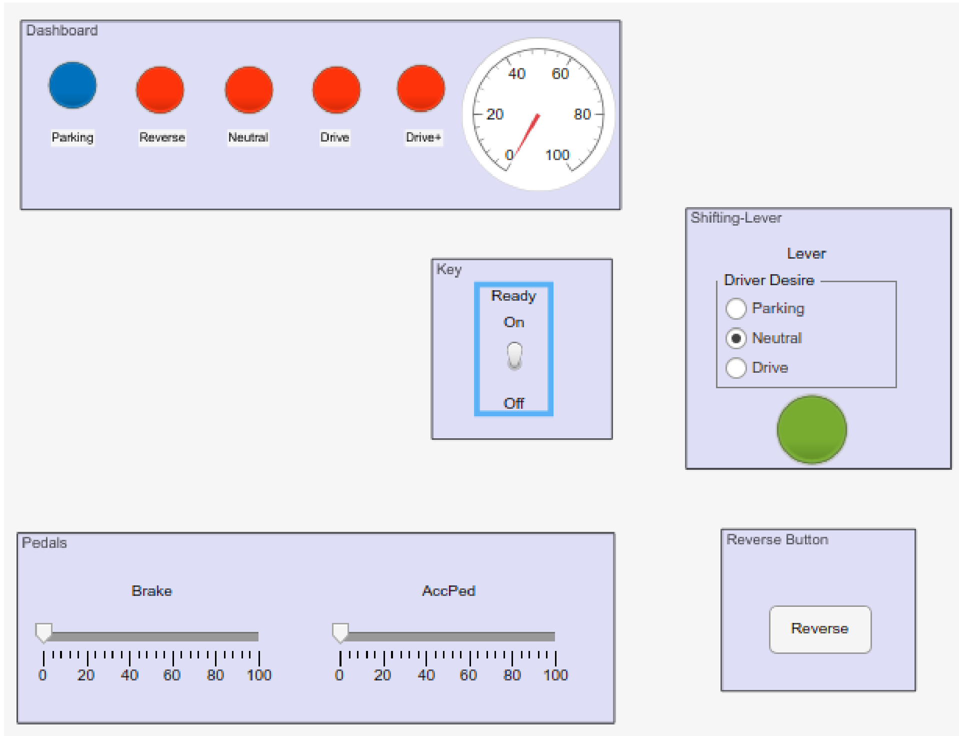


Figure 34 MIL: Non-standard Initial Conditions

As soon as the driver puts the lever into the parking state the Plamp color changes into green as shown below and as expected already.

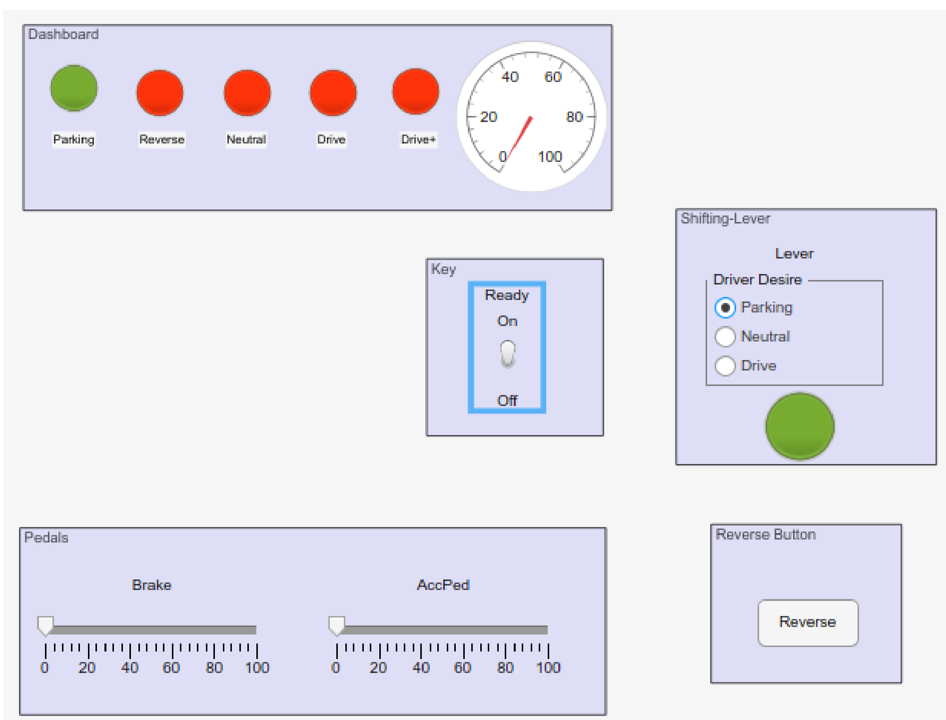


Figure 35 MIL: Standard Initial Conditions

- ## FROM PARKING TO NEUTRAL:

Once the VMU made sure the vehicle started from standard initial conditions, the driver is able to move to the neutral state and, subsequently, to the drive state. As explained previously, the driver needs to push the brake pedal while doing the shift. In case he forgets to push the pedal, the Nlamp is expected to light in blue.

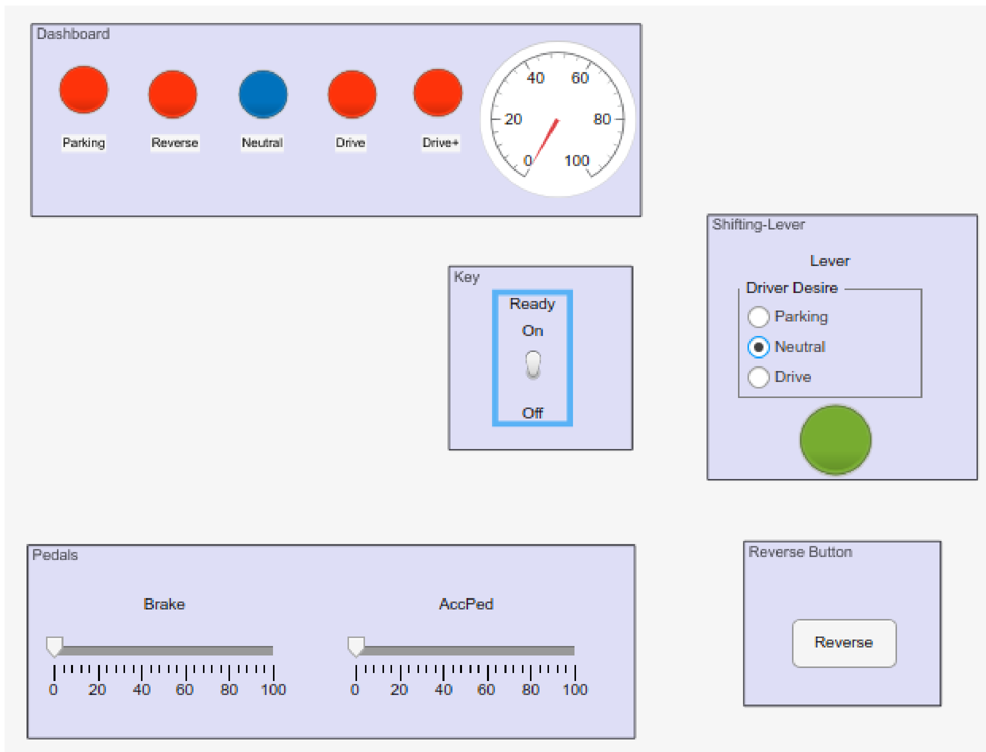


Figure 36 MIL: Incorrect Transition to Neutral

However, as soon as the driver redoes the transition pushing the brake pedal, the Nlamp will light in green signalling the activation of the neutral state.

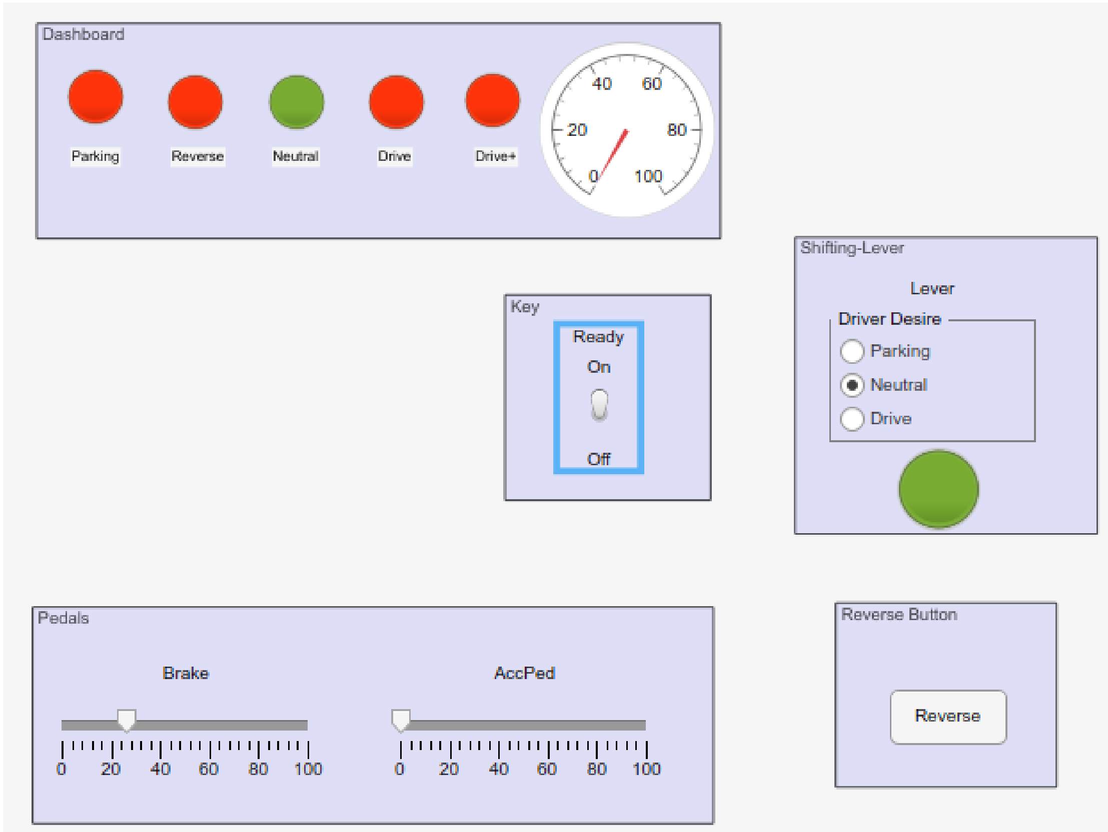


Figure 37 MIL: Activation of Neutral State

- MOVING:

Now the driver can bring the vehicle to move either forward or backward, on the first or the second gear, by following the flowchart drawn before.

➢ **<u>Transitioning from neutral to drive</u>**

As explained before, if the driver forgot to push the brake pedal during the lever shift from neutral to drive, the drive lamp is expected to light in blue implying an unsuccessful transition to drive. In that case, the torque is not generated and hence, the vehicle speed must be still zero even if the accelerator pedal is pushed.

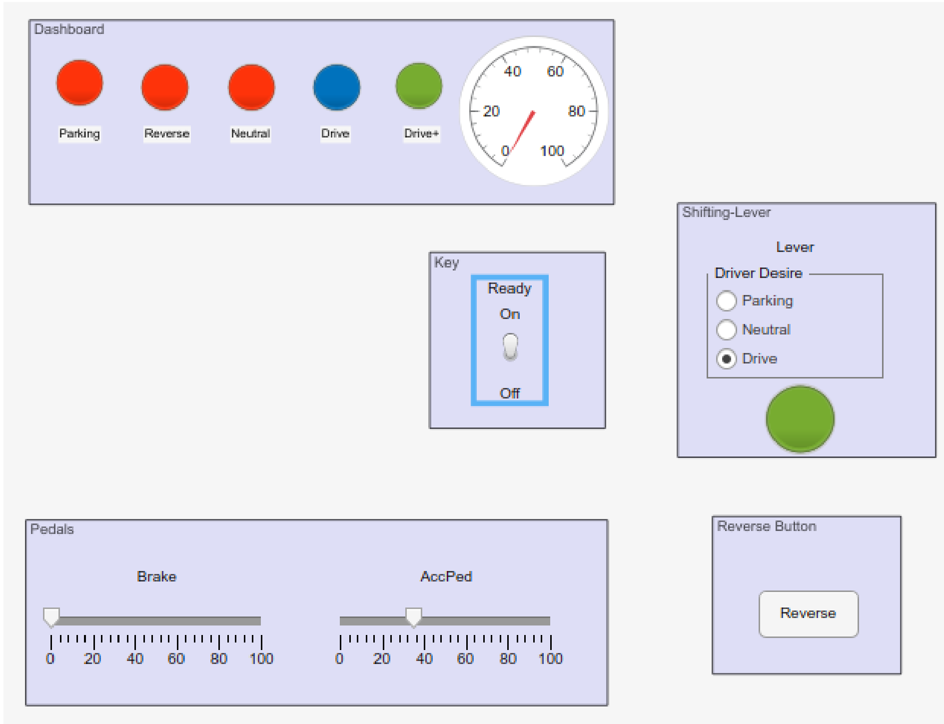


Figure 38 MIL: Unsuccessful Transition from Neutral to Drive

As soon as the driver pushes the brake pedal while doing the transition, the Dlamp will take the color green, and the torque corresponding to the desired speed by the driver can be generated.

Figure 39 MIL: Successful Transition from Neutral to Drive

➢ Moving Forward:

Once the Vehicle has entered the drive state, the VMU first checks whether the reverse button is pushed or not to act accordingly. In case it's not pushed, that means that the driver wants to move forward.

The VMU also compared the vehicle speed feedback with the motor speed to understand which gear the driver chose and hence gives the Drive+ lamp the color corresponding to the gear.

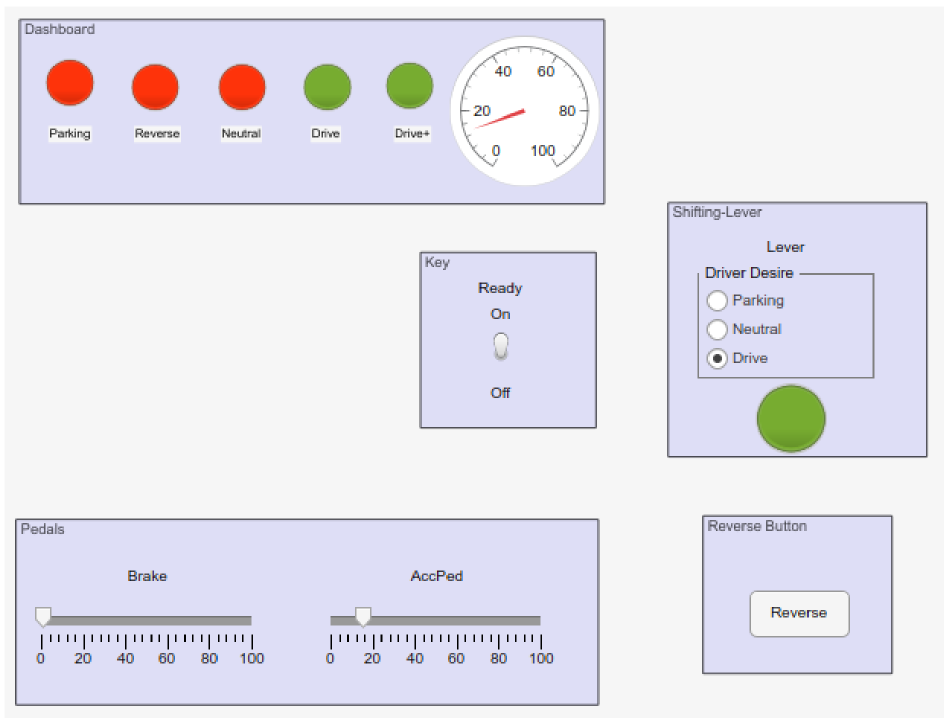


Figure 40 MIL: Vehicle Moving Forward

➢ Moving Backward:

For the VMU to activate the reverse state, the driver has to push the reverse push button for at least 3 seconds. If not, the push is ignored. Also, there is a limitation on the reverse speed of the vehicle i.e. even if the vehicle is on the second gear and the driver is pushing the accelerator pedal hard, a maximum backward speed of 10 km/hr can be achieved.

Figure 41 MIL: Backward Driving

- ## GOING TO NEUTRAL FROM DRIVE:

If the driver decided to bring the vehicle to neutral, he's supposed to slow down the vehicle first. In case the vehicle's speed was above a certain threshold (which is 3 km/hr in that case), the transition is blocked mechanically, and disallowed in the simulation as well.

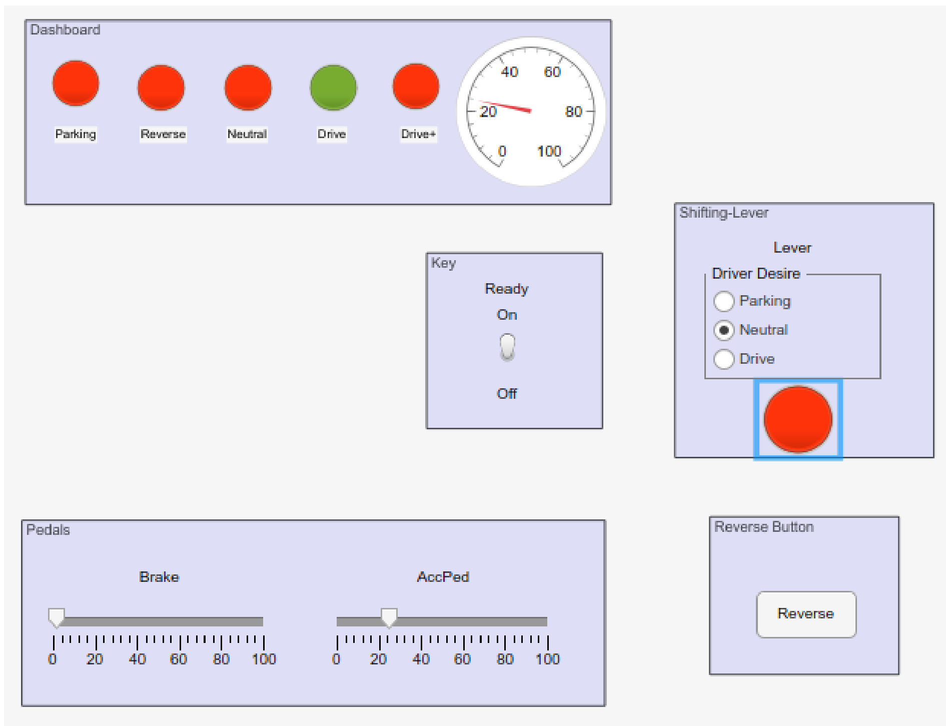


Figure 42 MIL: Disallowed Shift to Neutral

When the vehicle speed goes below the threshold, the transition to neutral is allowed. The brake push is also necessary for a successful transition.

REFERENCES

1. **Britannica, Encyclopædia.** *Electric Automobiles.* 2014.

2. **Agency, International Energy.** *Global EV Outlook.* 2018.

3. **W. Brennan, John and E. Barder, Timothy.** *Battery Electric Vehicles vs. Internal Combustion Engine Vehicles.* s.l. : Arthur D Little, 2016.

4. **Lowry, John and Larminie, James.** *Electric vehicle technology explained.* 2012.

5. **Yang, Y., et al.** *State-of-the-art electrified powertrains: Hybrid, plug-in.* 2016.

6. **Wang, A., et al.** *Influence of skewed and segmented magnet rotor on IPM machine.* 2019.

7. **Yang, Y., Schofield, N. and Emadi, A.** *Integrated Electro-Mechanical Double-Rotor Compound Hybrid Electric Vehicles.* 2016.