MBSD Assignment #2 A.Y. 2024/25

Purposes

- Implement the “one pedal controller” as a Simulink model.

To implement the system, follow the description already provided in the Laboratory 1 document considering also eventual assumptions already stated in this latter document.
The safety mechanisms are not required in this laboratory.

The Simulink project has to be split into 3 files:

- **Harness.slx**, containing reference models for the controller and plant and test stimuli generation
- **Controller.slx**, containing the controller (to be developed)
- **Plant.slx**, containing the car longitudinal physical model.

The longitudinal physical model and the test stimuli generators shall demonstrate the effectiveness of the implemented controller with respect to the expected functionalities.
Consider the plant model description as an example of the comments to be inserted in the Controller Software Unit description report.

Templates of these files are available alongside this document.

The deliverable, composed of the 3 Simulink models and a PDF file obtained by filling the following pages of this document (please delete this first page), has to be provided as a .ZIP file up to **May 4th at 23:59 through “Consegna Elaborati” of the Portale della Didattica.** It shall also contain a brief report explaining the design of the controller, using the following template. It is sufficient that only one of the group members uploads it.

Model-Based Software Design, A.Y. 2024/25

Laboratory 2 Report

Components of the working group (max 2 people)

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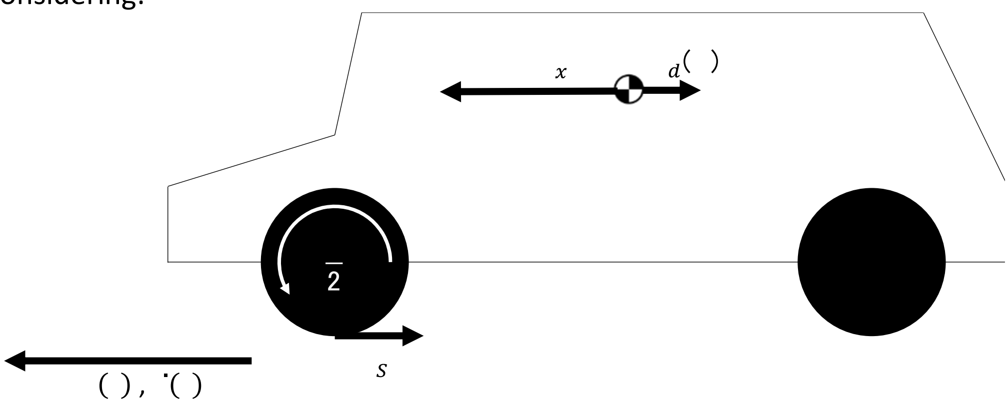
External interfaces of the plant

Name	Direction	Type
`Requested_Torque_Nm`	Input	CAN
`Vehicle_Speed_km_h`	Output	CAN
`Automatic_Transmission_Selector`	Input (from the driver to the controller)	CAN {P, R, N, D, P}
`Selected mode/errors`	Output (to the driver)	CAN

Equations of the plant

The plant considered in this model is the so-called *Vehicle Longitudinal Dynamics*.
Considering:



- $\dot{v}(t)$ the vehicle acceleration, expressed in $[\mathrm{m/s^2}]$
- $v(t)$ the vehicle longitudinal speed, expressed in $[\mathrm{m/s}]$
- m the vehicle mass, expressed in $[\mathrm{kg}]$
- $F_x(t)$ the longitudinal force applied to the vehicle center of gravity, expressed in $[\mathrm{N}]$
- $F_s(t)$ the longitudinal force applied to the wheel on the terrain, expressed in $[\mathrm{N}]$
- $F_d(v)$ the longitudinal force applied to the vehicle center of gravity due to the frictions with air and terrain, expressed in $[\mathrm{N}]$
- I the moment of inertia of each one of the wheels, expressed in $[\mathrm{kg \cdot m^2}]$
- r the radius of the wheel, expressed in $[\mathrm{m}]$
- $\omega(t)$ is the angular speed of the wheel, expressed in $[\mathrm{rad/s}]$
- $\omega_e(t)$ is the angular speed of the engine/electrical motor, expressed in $[\mathrm{rad/s}]$
- $\omega_{e_{RPM}}(t) = \frac{\omega_e(t) \cdot 60}{2\pi}$ is the angular speed of the engine/ electrical motor, expressed in $[\mathrm{revolutions\ per\ minutes}]$
- $\dot{\omega}(t)$ is the angular acceleration of the wheel, expressed in $[\mathrm{rad/s^2}]$
- S is the frontal surface of the car, expressed in $[\mathrm{m^2}]$
- $c_x = 0.3$ is the automobile drag coefficient
- ρ is the average density of air at sea level in standard conditions → $\rho = 1.25\ \mathrm{kg/m^3}$
- i_g is the gearbox reduction ratio
- i_f is the final drive reduction ratio
- $i_t = i_g \cdot i_f$ is the total power train reduction ratio.

An extremely simplified model can be obtained as follow:

$$\dot{v}(t) = \frac{F_x(t) - F_d(v)}{m} \qquad (1)$$

where $\dot{v}(t)$ is the vehicle acceleration, m is its mass, $F_x(t)$ is the longitudinal force applied to its center of gravity by the effects of the torque applied on the wheels, and $F_d(v)$ is the sum of the friction forces on the vehicle due to wheel-terrain and vehicle-air interactions.

Considering that the torque is equally split between the two wheels (valid only on straight tracks)

$$T(t) - 2 \cdot F_s(t) \cdot r = 2I \cdot \dot{\omega}(t) \quad (2)$$

the absence of slipping:

$$\begin{cases} 2 \cdot F_s(t) \cdot r = F_x(t) \\ v(t) = 2\,\pi \cdot r \cdot \ \omega(t) \end{cases}$$

and considering the moment of inertia of the wheels $I = 0$, we can define the following equation, given that $T(t) = 2 \cdot F_s(t) \cdot r \rightarrow F_s(t) = \frac{T(t)}{2 \cdot r}$.

The drag force that limits the maximum speed of the vehicle is equal to:

$$F_d\big(v(t)\big) = X_{air} \cdot \big(v(t)\big)^2 + X_{tyres} \cdot v(t) \quad (3)$$

where:

$$X_{air} = \frac{1}{2} \cdot S \cdot c_x \cdot \rho \quad (4)$$

and, as usually modeled:

$$X_{tyres}\big|_{X_{tyres}\left(50\frac{\mathrm{km}}{\mathrm{h}}\right) = X_{air}\left(50\frac{\mathrm{km}}{\mathrm{h}}\right)} \rightarrow X_{tyres} = \frac{X_{air} \cdot 50}{3.6} \quad (5)$$

By substituting the (2) equation in (1), and by integrating both sides, we obtain:

$$v(t) = \frac{1}{m}\int_0^t F_x(t) - F_d\big(v(t)\big)\,dt = \frac{1}{m}\int_0^t 2 \cdot F_s(t) - F_d\big(v(t)\big)\,dt =$$

$$= \frac{1}{m}\int_0^t \frac{T(t)}{r} - F_d\big(v(t)\big)\,dt \quad (6)$$

and, by substituting (3) in (6):

$$v(t) = \frac{1}{m}\int_0^t \frac{T(t)}{r} - X_{air} \cdot \big(v(t)\big)^2 - X_{tyres} \cdot v(t)\,dt \quad (7)$$

Remember that the integrator block of Simulink requires an initial condition corresponding to the vehicle's longitudinal speed at the beginning of the simulation, $v(0)$. A possible configuration of the integration block is shown in Figure 2.

During the model development, put all the needed gain to obtain as an output of the physical model a speed expressed in km/h.
To simulate the slope θ of the terrain, it is possible to add the gravity force $F_g(\theta)$ as follows:

$$v(t) = \frac{1}{m}\int_0^t \frac{T(t)}{r} - X_{air} \cdot \big(v(t)\big)^2 - X_{tyres} \cdot |v(t)| \cdot dt + m \cdot g \cdot \sin(\theta) \quad (8)$$

With $g = 9.81$ the gravity acceleration on Earth.

Reasonable values for an electric compact car can be:

- $m = 1600$ kg
- $r = 0.3$ m
- The torque T (at the wheel) can vary in the range $[-60; 960]$ Nm
- $S = 3.5\, m^2$
- $c_x = 0.3$

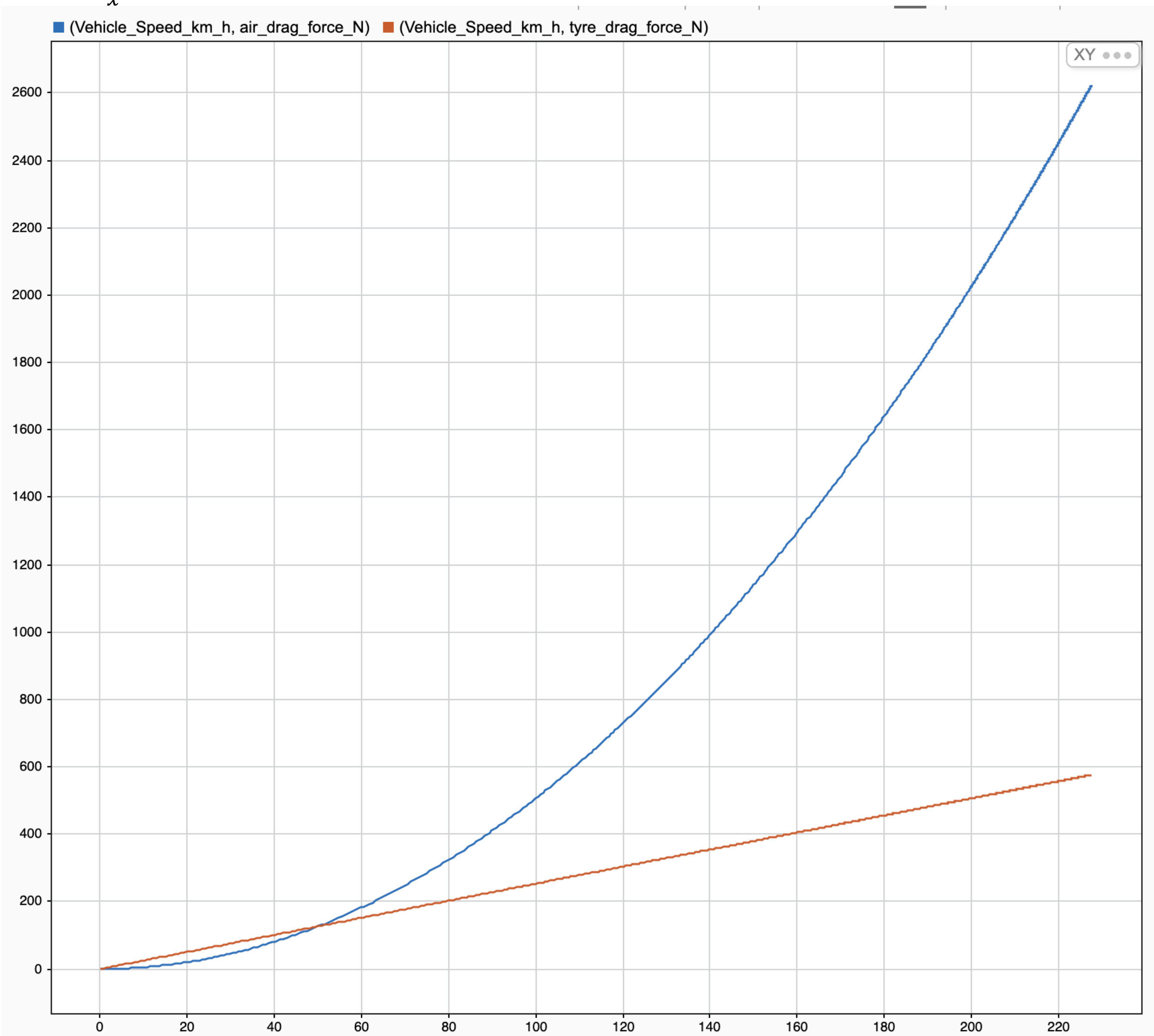


Figure 1 Graph showing drag forces of tires (in orange) and air (in blue) at various speeds. It is possible to observe that, as imposed in equation (5), $X_{tyre} = X_{air}$ at 50 km/h. Below this speed, the tire drag is dominant, after that, the air drag is dominant. Moreover, it is possible to see the top speed of the car (around 230 km/h) when $F_x = \frac{T}{r} = X_{tyre} + X_{air}$, with $F_x = 3200\ N$.

With those values, the top speed on level ground reachable by the car is about 230 km/h, where the drag forces equal the traction force (3200 N).

Considering the reverse direction, the maximum speed reachable with a limitation of -60 Nm is about 45 km/h.

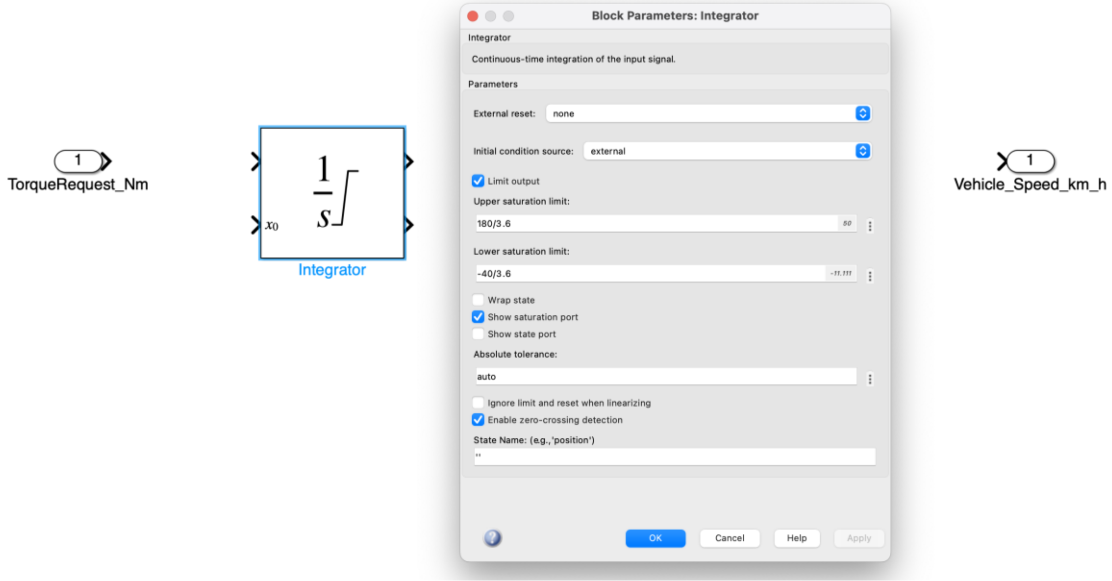


Figure 2 Settings window for the Integrator block of Simulink

Use these values (with a certain tolerance, for example, 10 %) to saturate the integrator block.

To make the model more realistic, it is possible to compute the torque request at the engine/motor. A typical ratio value for transmission of an electric car with a single gear can be around $i_t = 12$[1].

All the initialization parameters of the model are automatically loaded model by a callback of the function **init_fn** as shown in Figure 3.

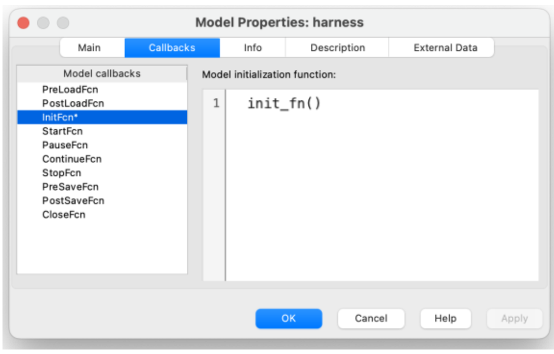


Figure 3 init_fn callback configuration in the harness model properties.

[1] Usually, the first gear of a car has a transmission ratio about $i_g = 3$, hence the engine makes 3 complete rotations very single rotation of the pinion gear of the differential. In the differential (final drive), the pinion gear makes about $i_f = 4$ revolutions for every revolution of the axle shafts. From here, the typical ratio of $i_t = 12$ between the torque at the wheel and the torque at the engine/electrical motor.

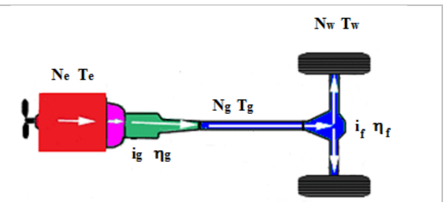


Figure from http://www.thecartech.com/subjects/auto_eng/Gearbox_ratios3.htm

Description of the whole system

Draw the I/O block diagram of the plant and the controller, showing how they interact.

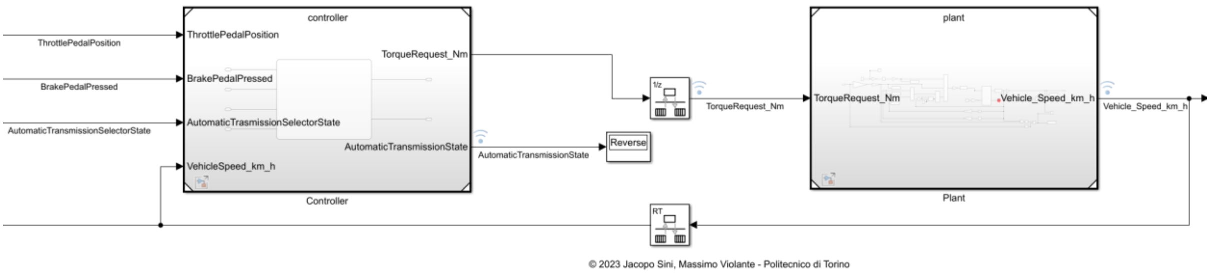


Figure 4 Simulink block diagram of the plant and the controller and their I/O.

As can be seen in figure 4, the plant required the signal *TorqueRequest_Nm* as the control input driving the dynamic of the vehicle. This signal is produced as the output of the controller and is provided to the plant through CAN communication. The controller, in turn, requires 4 input, three of which are communicated through CAN and one is provided by an analog signal. The three signal transmitted through CAN are: *BrakePedalPressed*, a binary data, *AutomaticTransmissionoSelectorState* – including data regarding the driving modes of the vehicle chosen by the driver through the *Automatic Transmission Selector*, and *VehicleSpeed_km_h*. The analogue signal required is *ThrottlePedalPosition*, which has a value between 0 and 1. The output of the controllers are communicated through CAN. These outputs are *TorqueRequest_NM*, driving the plant, *and AutomaticTransmissionState,* which is supposed to be represented to the driver through instrument cluster.

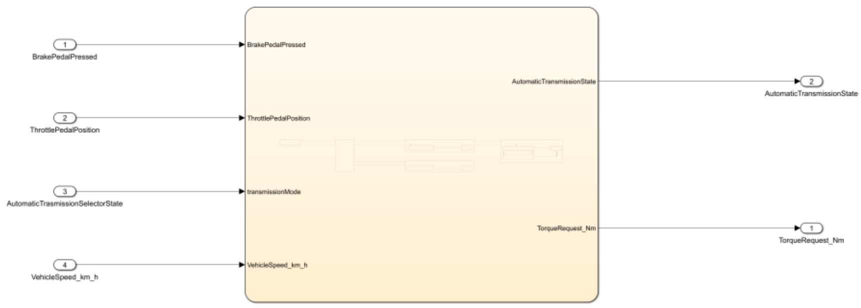


Figure 5 the controller chart I/O.

Controller SW Unit specifications

Provide a brief description of the Controller functionalities and its interfaces.

Receiving *BrakePedalPressed, ThrottlePedalPosition, AutomaticTransmissionSelectorState,* and *VehicleSpeed_km_h*, the controller is responsible for choosing the correct transmission modes and, corresponding to that, requesting torque from the plant. The input, output, and parameters used in the controller finite state machine are described in the following table.

Interfaces

Name	Unit	Type[2]	Data Type[3]	Dimension	Min	Max
`MAX_TORQUE`	Nm	Parameter	Single	1*1	80	80
`MAX_TORQUE_REVERSE`	Nm	Parameter	Single	1*1	40	40
`MAX_RDB_ENGAGE_SPEED`	Km/h	Parameter	Single	1*1	0.5	0.5
`BrakePedalPressed`	-	Input	Boolean	1*1	0	1
`ThrottlePedalPosition`	-	Input		1*1	0	1
`AutomaticTransmissionSelectorState`	-	Input	Enum: TransmissionState	1*1	0	4
`VehicleSpeed_km_h`	km/h	Input	Single	1*1	-60	240
`TorqueRequest`	Nm	Output	Single	1*1	-40	80
`AutomaticTransmissionState`	-	Output	Enum: TransmissionStaet	1*1	0	4

A brief description of the parameters and variables:

- MAX_TORQUE: the maximum value of the torque that the controller can produce as its output while the vehicle is in Drive or Brake mode.

- MAX_TORQUE_REVERSE: the value of the maximum negative torque that the controller can request while the vehicle is driving in Reverse mode.

- MAX_RDB_ENGAGE_SPEED: maximum readable engage speed is a value used in order to prevent the vehicle to move in the opposite direction while the transmission mode is Brake.

- BrakePedalPressed: if the pedal is pressed, 1; otherwise, 0.

- ThrottlePedalPosition: It can assume a value single type value between 0 and 1, depending on the course of the throttle pedal.

- AutomaticTransmissionSelectorState and `AutomaticTransmissionState`: it can have integer between 0 and 4, where:
    - 0: Park
    - 1: Reverse
    - 2: Neutral

[2] Input, Output, Local, Global, Volatile

[3] Struct, Double, Integer, Enum, Boolean, etc…

- ○ 3: Drive
- ○ 4: Brake

- VehicleSpeed_km_h: the speed of the vehicle, that is limited between -60 and 240 in the plant.
- TorqueRequest: which can have values between +80 and -40 N.m.

Draw the Finite State Machine (FSM) representing the controller logic

The top-level Finite State Machine of the controller by which the transmission modes are selected according to the input data can be seen in the following figure.

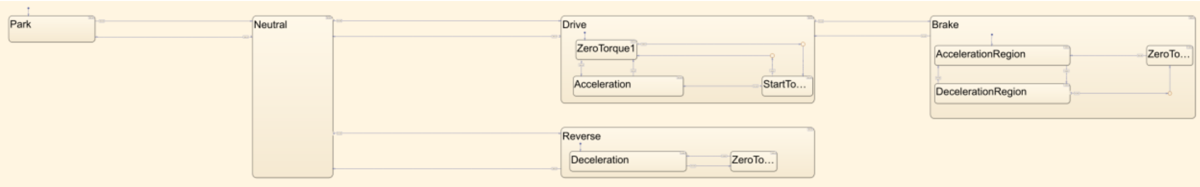


Figure 6 Top view of the state machine implemented in the controller.

The default state, as can be seen in the figure, is *Park* mode. The conditions for changing the states are as follows:

1) Park => Neutral:
   (Brake pedal is pressed) AND (any transmission mode other than Park is chosen by the transmission selector)
2) Neutral => Park:
   (Brake pedal is pressed) AND (value of the velocity is less than 5Km/h) AND (Park is chosen by the transmission selector)

While in these two state, no torque is requested by the controller.

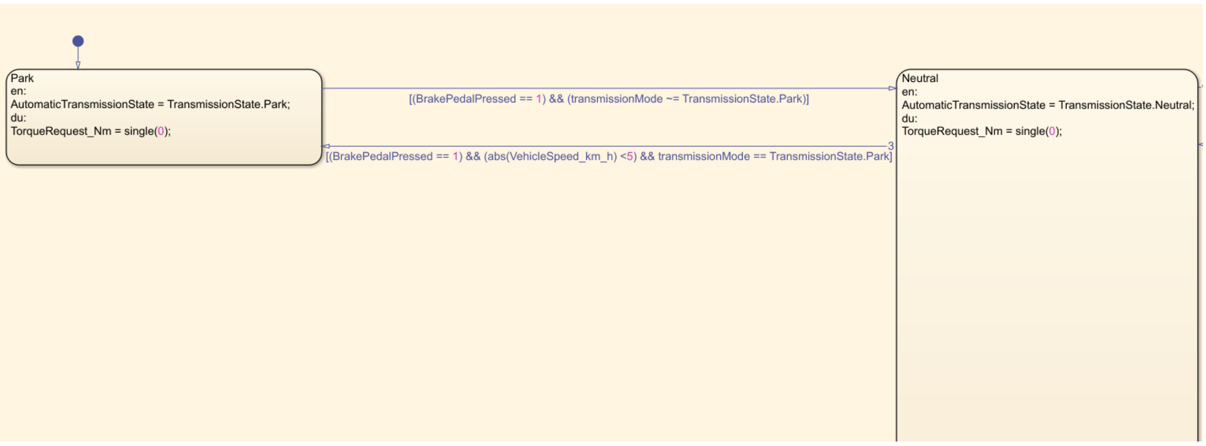


Figure 7 Conditions for transition between the state between Neutral and Park

3) Reverse => Neutral:
   (any transmission mode other than Reverse is chosen by the transmission selector)

4) Neutral => Reverse:
   (Brake pedal is pressed) AND (value of the velocity is less than 5Km/h) AND (Reverse is chosen by the transmission selector)

5) Neutral => Drive:
   (Brake pedal is pressed) AND (value of the velocity is more than -5Km/h) AND (Drive OR Brake is chosen by the transmission selector)

6) Drive => Neutral
   (any transmission mode other than Brake AND Driver is chosen by the transmission selector)

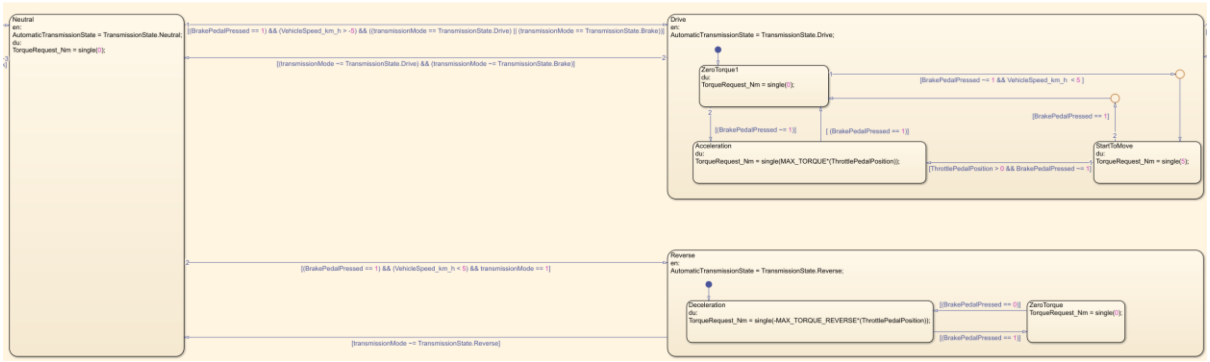


Figure 8 Conditions for transition between the state between Neutral and Drive, as well as Neutral and Reverse

7) Drive => Brake:
   (The throttle pedal position is larger than 1/3, corresponding to the acceleration region of its course) AND (Brake is chosen by the transmission selector)

8) Brake => Drive
   (any transmission mode other than Brake is chosen by the transmission selector)

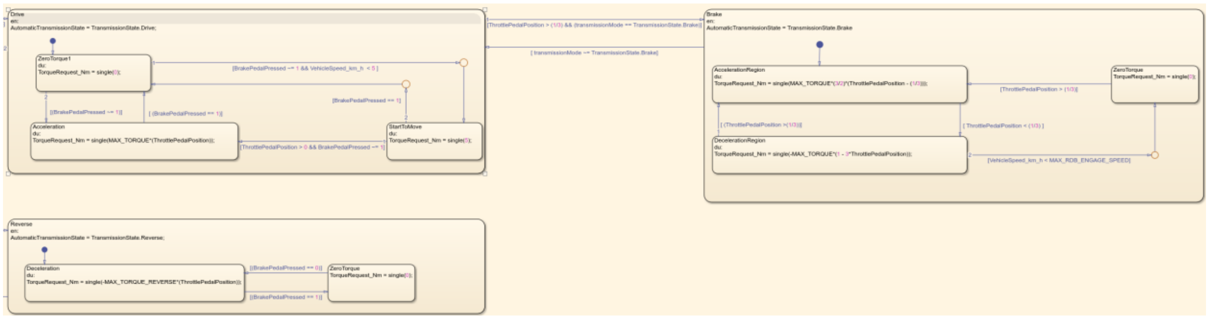


Figure 9 Conditions for transition between the state between Drive and Brake; the substates of Drive, Reverse, and Brake state can be seen in this figure.

The internal states of the controller are described, hereunder:

Reverse substates:

The default substate of this state is called Deceleration, where a torque between 0 and –MAX_TORQUE_REVERSE is requested according to the position of the throttle pedal. The substate goes to ZeroTorque substate in case the brake pedal is pressed.

Drive substates:

The default substate of this state is called ZeroTorque, where no torque is requested. When the driver stops pressing the brake pedal, we expect that the vehicle starts to move at low velocities, without pressing the throttle pedal; therefore, a constant torque of 5 N.m is requested when throttle pedal is not pressed and the velocity is low, and the driver stops pressing the brake pedal. Then, when the throttle pedal is pressed substates transits to Acceleration substate, where a torque between 0 and MAX_TORQUE is requested according to the position of the throttle pedal. The substate goes to ZeroTorque substate in case the brake pedal is pressed.

Brake substastes:
The State changes to Brake state when the throttle pedal is in its acceleration region, after 1/3 of its course. Therefore, it is logical that the default substate of this state is AccelerationRegion. A positive torque is requested according to the (2) in the following relationship.

$$\begin{cases} \tau_r = -\max(\tau_a) \cdot (1 - 3p), \quad \text{when } 0 < p \leq \frac{1}{3} \text{ (braking region)}. \quad (1) \\ \tau_r = \max(\tau_a) \cdot \frac{3}{2} \cdot \left(p - \frac{1}{3}\right) \;, \quad \text{when } \frac{1}{3} < p \leq 1 \text{ (acceleration region)}. \quad (2) \end{cases}$$

If the position of the throttler pedal enters the first 1/3 of its course, the substate transits to DecelerationRegion substate, where the negative torque is calculated according to (1).
In order for the vehicle no to move in the reverse direction, if its velocity becomes lower than MAX_RDB_ENGAGE_SPEED, which in this case is 0.5 Km/h, the current substate becomes ZeroTorque – where no torque is requested until the throttle pedal enters in the last 2/3 of its course and a transition from ZeroTorque .

Comment on the design choices of the FSM, which are not trivial to be understood just by analyzing the controller logic.

In the transition from Neutral to Park the velocity of the vehicle should be lower than 5 km/h, where the vehicle is low enough that by pressing the brake pedal to change the mode, the vehicle stops.

From Neutral to Drive, one condition is that the velocity is more than – 5 km/h. While one changes the transmission mode from Reverse to Drive, the vehicle should be almost stopped so that no train is imposed on the Motor and the gearbox.

The transmission to Brake is passing from Drive, to make sure that the throttle pedal is in the acceleration region of its course, preventing the controller to be in a state that generates a torque that causes moving in the reverse direction. Also, for this transition, it is not required to press the brake pedal, since the vehicle is already moving and it would be inconvenient to press the brake pedal for this transition.

In the Driver and Reverse States, there exist one Substate called ZeroTorque, which is activated when the brake pedal is pressed. The reason is that the controller shall not ask for torque, while the driver intends to stop the vehicle. In addition, ZeroTorque in Brake mode, prevents the

Comment with plots of the results obtained from the test cases (it is suggested to use the Data Inspector)

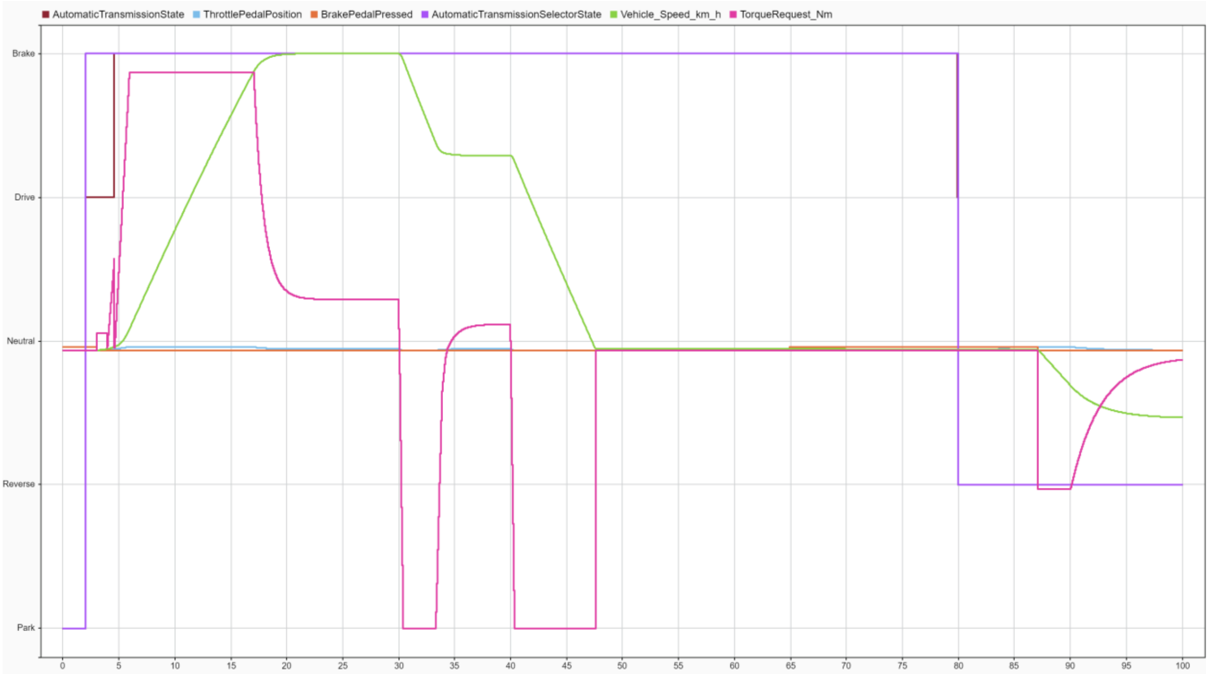


Figure 10 The result of the test, using the controller.

The figure above, generated with the Simulink Data Inspector tool, displays the time evolution of all the system's data variables, offering a comprehensive view of the simulation and confirming the proper operation of the state machine. Key observations and additional details are as follows:

1. **Initial Conditions and "Park" State:**
   - The simulation starts with the vehicle in the "Park" state. At this point, the brake pedal is engaged, which is reflected by the corresponding data trace, and the vehicle's speed is maintained at 0 km/h. This indicates that the system initializes correctly with safety and stationary conditions.
2. **Transition to "Brake" Mode and Acceleration Phase:**
   - When the driver switches to "Brake" mode, the AutomaticTransmissionState change to drive first, and the transition to brake does not happen while the ThrottlePedalPostion does not exceed 1/3 of its course.
   - At first the driver does not press the throttle pedal for some seconds, but in the mean while the BrakePedalPressed becomes 0. In this situation, we expect that the vehicle gradually starts to move, which is the case since the controller request a constant 5 N.m torque.
   - When the throttle pedal passed 1/3, it can be seen that the state transfers to Brake state.
3. **Torque Saturation and Regenerative Braking:**
   - The torque request is properly saturated at +80 Nm when the throttle pedal is fully pressed. When the vehicle reaches a velocity around 85 km/h the gas pedal is released a bit to maintain this velocity.

- Conversely, when the throttle pedal is fully released in the regenerative braking state, the torque request is limited to -80 Nm. This controlled deceleration is crucial for safety and energy recovery, and it prevents abrupt changes in vehicle dynamics.

4. **Stopping at Zero Speed and Prevention of Reverse Motion:**
    - Approximately 48 seconds into the simulation, the vehicle's speed reaches 0 km/h even though the throttle pedal remains fully released in Brake mode. At this juncture, the controller transitions to the "ZeroTorque" substate.
    - In the "ZeroTroque" substate, the torque request is set to zero. This is an important safety measure as it prevents any inadvertent movement of the vehicle in the reverse direction when it is meant to be stationary.
5. **Transition to "Reverse" Mode and Reverse Torque Application:**
    - The simulation concludes with a transition to the "Reverse" state at around 80 seconds. During this phase, the reverse torque request saturates at -40 Nm, and at the end of the simulation, the velocity reaches -20 km/h.

In summary, the expanded analysis of the signals confirms that the system behaves as intended and complies with its input requirements. The detailed traces and state transitions validate the effectiveness of the controller.