Control Engineering 2

Problem Based Assignment 1

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1 Simulink model

Given the dynamic laws of the system, it is possible to build a Simulink scheme to simulate the behaviour of the car. The model in Figure 1 allows to perform an open loop simulation or a closed loop by properly enabling cruise control and automatic shift gear. Each block of the scheme is analysed in the next subsections.

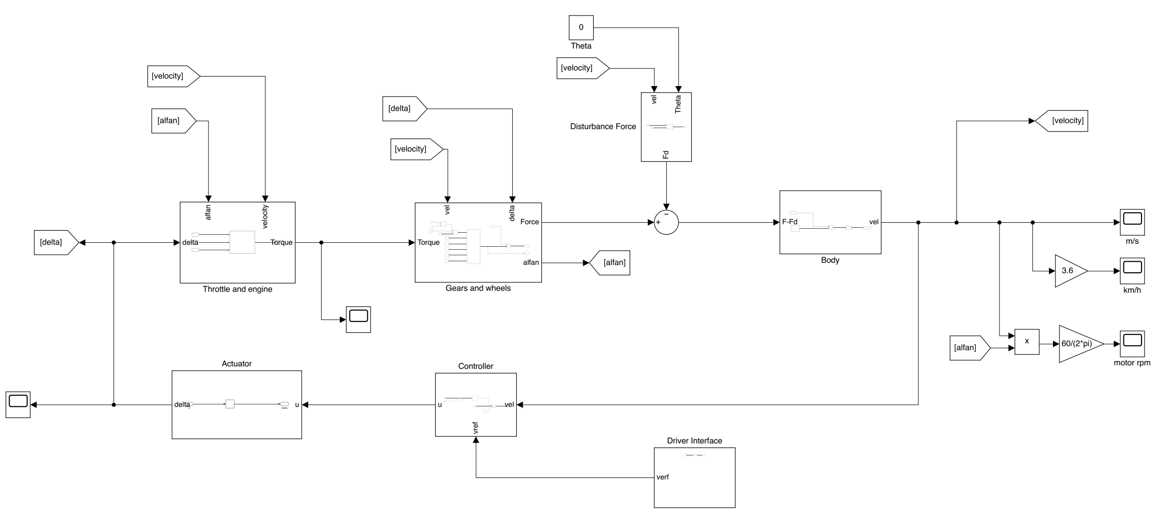


Figure 1: Model overview

1.1 Driver Interface

In this block, Figure 2, it is possible to activate cruise control and set the desired velocity using a slider. This velocity setting is the output of the block. Additionally, the block allows for turning off the cruise control and manually adjusting the throttle aperture as desired. Regarding the transmission, you can choose between automatic or manual with a switch, and shift the gear by using a rotary switch. Finally, the velocity of the vehicle is displayed in km/h.

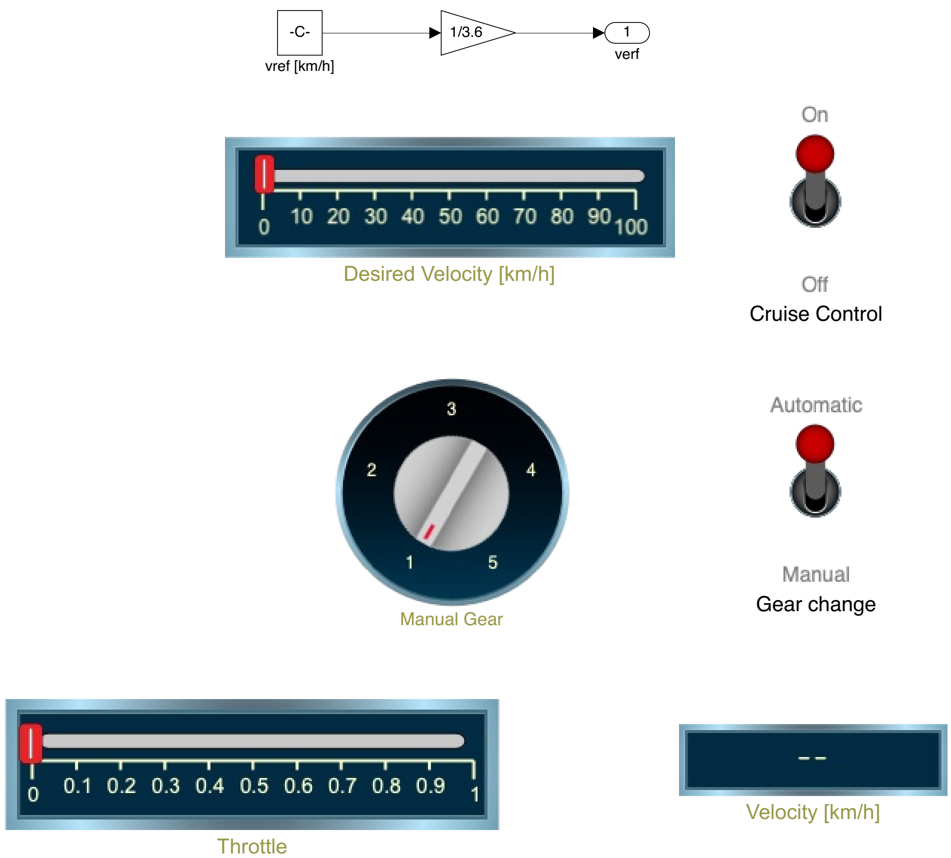


Figure 2: Driver interface

1.2 Controller

The controller block, Figure 3, has as inputs the velocity of the car, vel, and the desired velocity from the driver interface, $vref$. Here, the error is computed as $vref - vel$ and given as input to the PI controller. Details about the parameters chosen for the PI are in 3. The output of the PI is the aperture of the throttle. Finally, there is a switch that allows choosing between the throttle aperture computed by the PI controller and the one manually selected through the driver interface. This switch is also controlled via the driver interface. The output of the block is the aperture of the throttle, denoted as u.

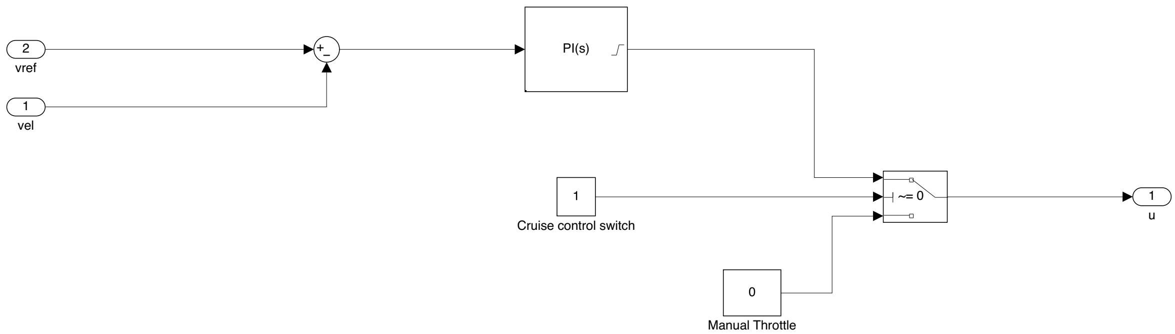


Figure 3: Controller block

1.3 Actuator

This block depicted in Figure 4 is simply a saturation block. It could be avoided since this saturation is already present in the PI controller and the manual throttle is number between 0 and 1.

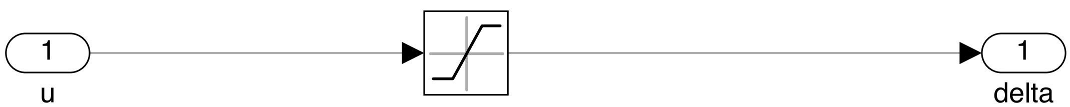


Figure 4: Actuator block

1.4 Throttle and engine

The Throttle and engine block, in Figure 5, has as input the throttle aperture *delta*, the velocity of the car *velocity* and the effective wheel radius $alfan$ of the inserted gear n. These three values are indeed necessary to compute the torque. This computation is performed by means of a MATLAB function block depicted in Figure 6.

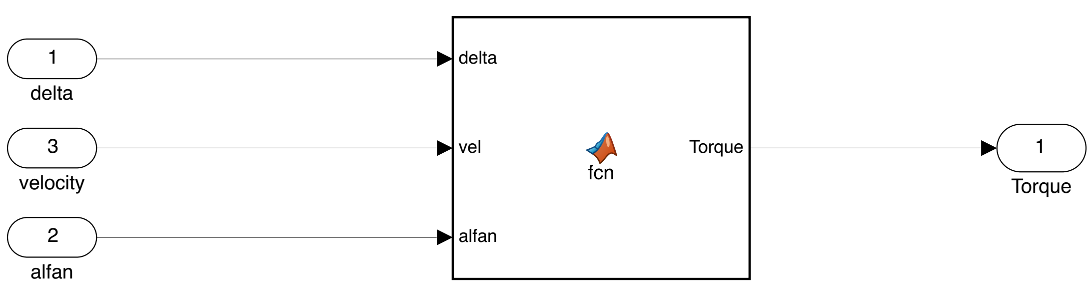


Figure 5: Throttle and engine block

```
function Torque = fcn(delta,vel,alfan)
% Parametrs

Tm      =   200;      % Nm
wm      =   450;      % rad/s
beta    =   0.35;


w=vel*alfan;


Torque = delta*Tm*(1-beta*(w/wm-1)^2);
```

Figure 6: Engine software

1.5 Gears and wheels

This block, depicted in Figure 7, computes the force applied to the vehicle. To do so, a gear has to be selected. The inputs *delta* and *vel* are used by the Automatic change State flow block in order to compute automatically a proper gear. More details about the StateFlow chart are in section 4.1. The automatic gear change can be disabled in favor of the manual one through a switch that is controlled in the driver interface. Notice that the gear simply selects the proper effective wheel radius which is then multiplied to the Torque to compute the Force.

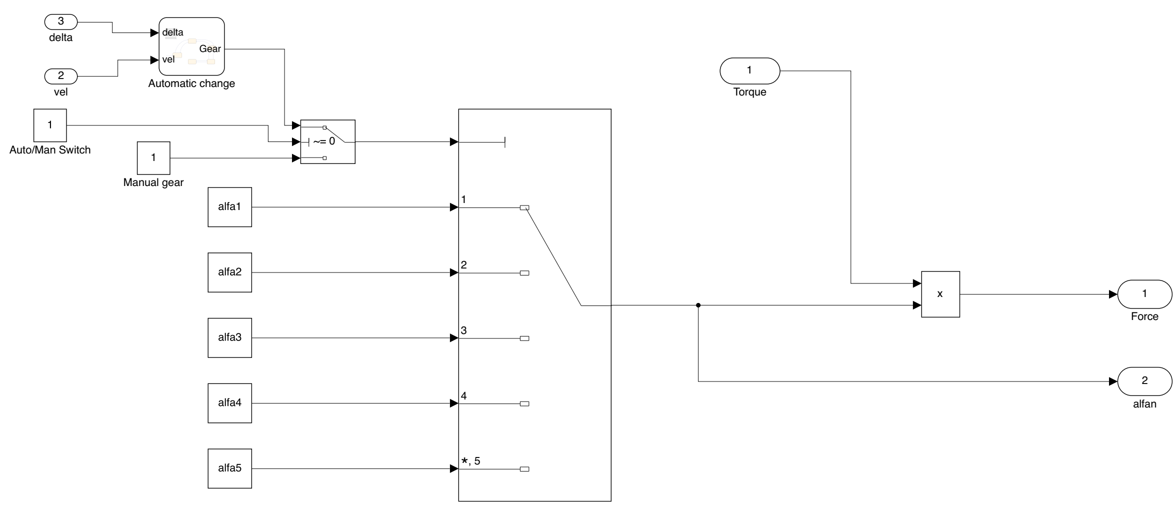


Figure 7: Gears and wheels block

1.6 Disturbance force

In Figure 8, the Disturbance Force block is represented. The inputs are the slope of the road *Theta* and the velocity of the car. In the MATLAB function block, Figure 9, the gravity load force, rolling friction force and aerodynamic force are computed and summed. These three components form the total disturbance force which is the output of the block.

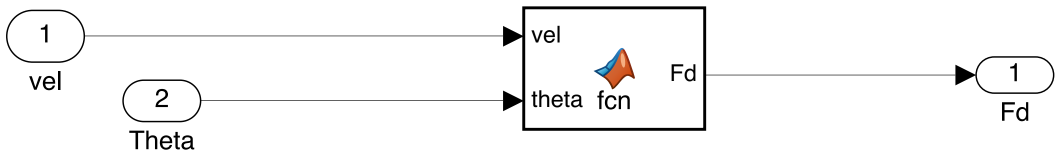


Figure 8: Disturbance force block

```
function Fd = fcn(vel,theta)

% Parametrs

m       =   1200;    % Kg
g       =   9.81;    % m/s^2
Cr      =   0.01;
rho     =   1.3;     % kg/m^2
Cd      =   0.36;
A       =   2.2;     % m^2

% Forces


Fd1 =   m*g*sin(theta);

Fd2 =   m*g*Cr*cos(theta)*sign(vel);

Fd3 =   1/2*rho*Cd*A*vel^2;



Fd = Fd1+Fd2+Fd3;
```

Figure 9: Disturbance force software

1.7 Body

The Body block, in Figure 10, takes as input the difference between the force generated by the engine F and the disturbance force Fd. This difference is then divided by the mass of the vehicle to compute the acceleration. The integrator block is then used to obtain the velocity value from the acceleration. Notice that, by properly setting the integrator block is possible to enforce the initial velocity of the system.

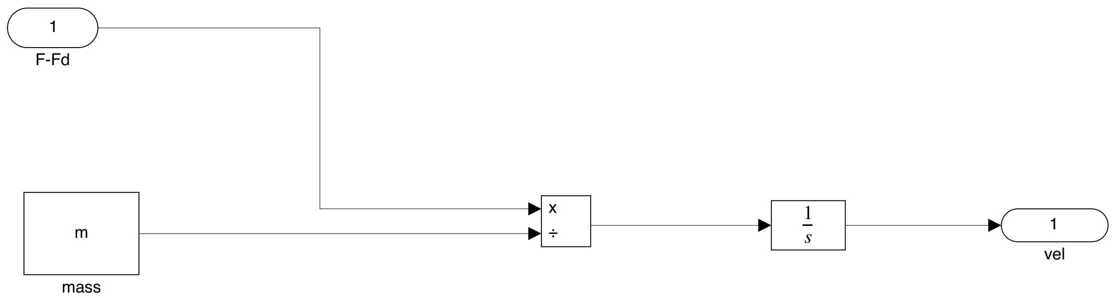


Figure 10: Body block

2 Open loop response

The first task to carry out is an open loop simulation where the throttle aperture performs a step from 0 to 0.5 with first gear and flat road. To do so, the cruise control and automatic shift are switched off. In Figure 11, the response of the system is depicted showing a rise time of 12.27 seconds. This time is computed as the time between 5% and 95% of the final value which is equal to 28.89 m/s (104.33 km/h).

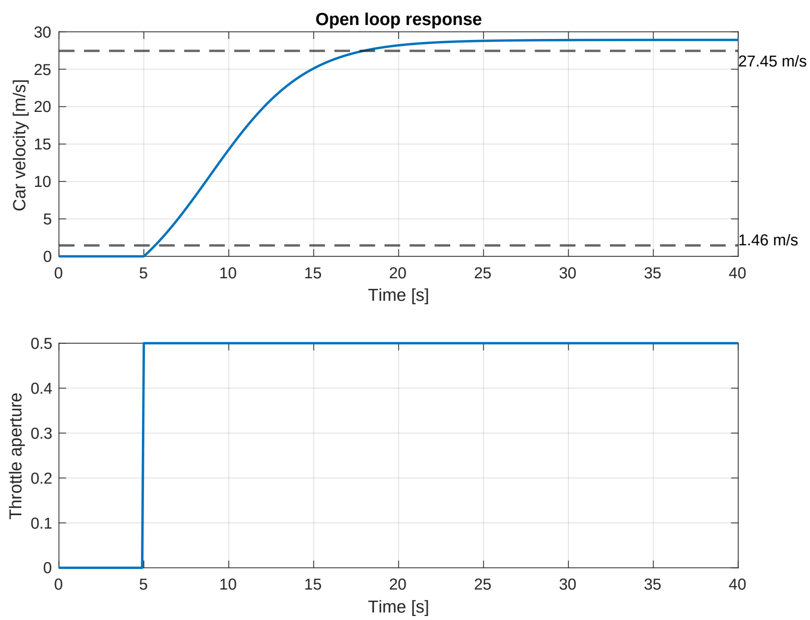


Figure 11: Open loop step response

3 Closed loop response

The second task is to use the cruise to control to bring the car from 20 m/s to 30 m/s in third gear and flat ground. Hence, the cruise control is activated and the third gear is fixed.

To perform the control of the system a PI controller is employed. The following equation is representative of the control input computations.

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)\, d\tau \tag{1}$$

Where $e(t)$ is the velocity error and $u(t)$ is the output of the controller. The proportional parameter is $k_p = 1.8$ and the integral $k_i = 0.7$. These parameters have been chosen with a trial and error procedure aiming to reach a good performance in tracking the reference and wise use of the input. In addition, due to the saturation of the input, the windup phenomenon occurs resulting in a deterioration of the performance. To cope with this issue, a clamping anti-windup method is set in the PI block.

The results of the control are portrayed in Figure 12. The car starts at 20 m/s and reaches perfectly the desired velocity of 30 m/s in around 5 seconds. The initial velocity of the car of 20 m/s is enforced through the integrator in the Body block (10). Notice that the system is in perfect equilibrium at 20 m/s since the controller finds in few time instants the input associated with that equilibrium.

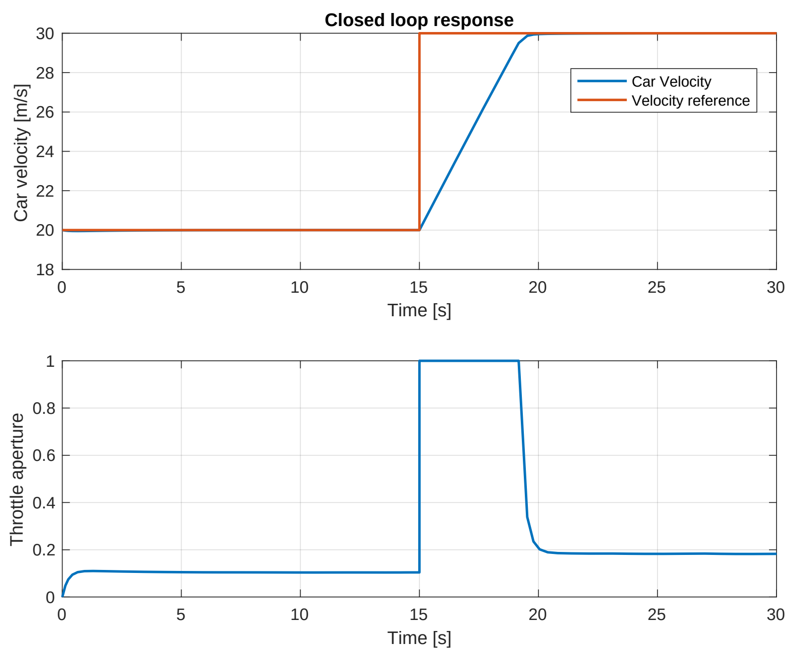


Figure 12: Closed loop 20 m/s to 30 m/s step response

4 Acceleration from 0 to 100 km/h with Automatic Gear Shift

The final goal is to accelerate the vehicle from 0 to 100 km/h at full throttle using the cruise control and automatic shift. The characteristics of the motor are displayed in Figure 13. Here, it is clear that the maximum available torque is equal to 200 Nm and the maximum power is around 126.8 kW. It is noticeable also that the maximum power of the motor is at a higher regime with respect to the maximum torque. Indeed the maximum power is reached around 7300 rpm instead the maximum torque around 4300 rpm.

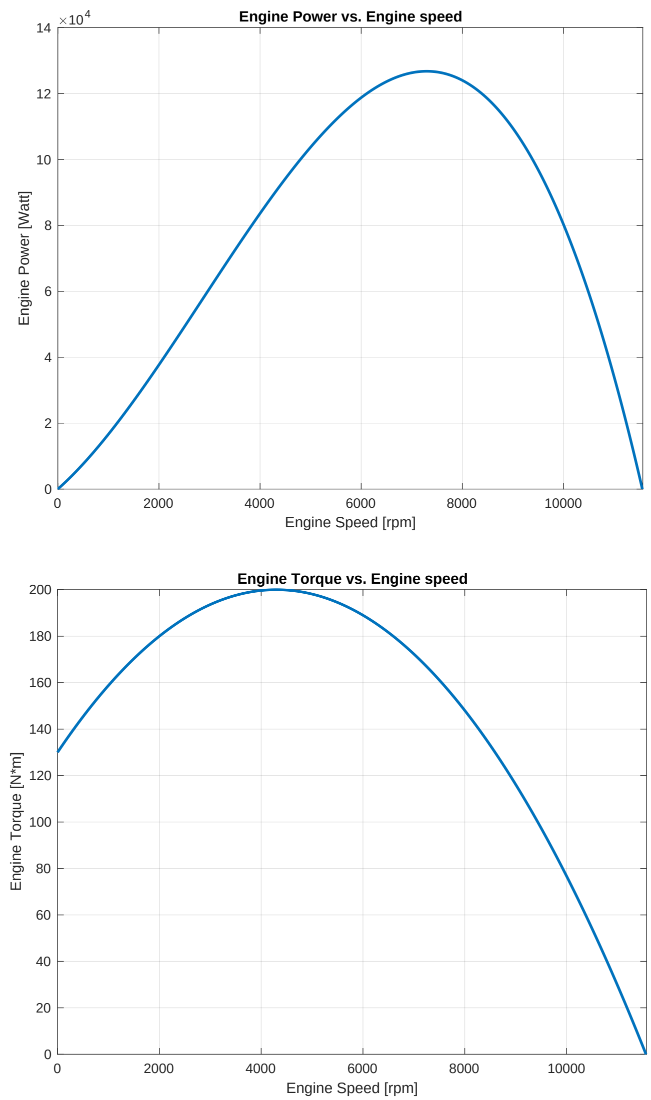


Figure 13: Motor characteristics

4.1 Automatic gear shift

A method of changing gears would be the one that maximises the motor's power and, consequently, the force that moves the vehicle. The shortest amount of time to go from 0 to 100 km/h would be achieved in this manner, yielding the highest performance. However, the issue with this approach is that, regardless of the driver's input, the vehicle would shift gears at extremely high speeds.

A better strategy, which is the one used in the industry, is to determine when to transfer gears based on the car's speed as well as the throttle aperture.

Hence, as observable in the Gears and Wheels block, the automatic gear shift takes as inputs both the velocity of the car and the throttle aperture.
In the StateFlow chart in Figure 14 it is visible that the thresholds on the car velocity (t1,t2,t3,t4) are a function of the throttle aperture denoted as delta.

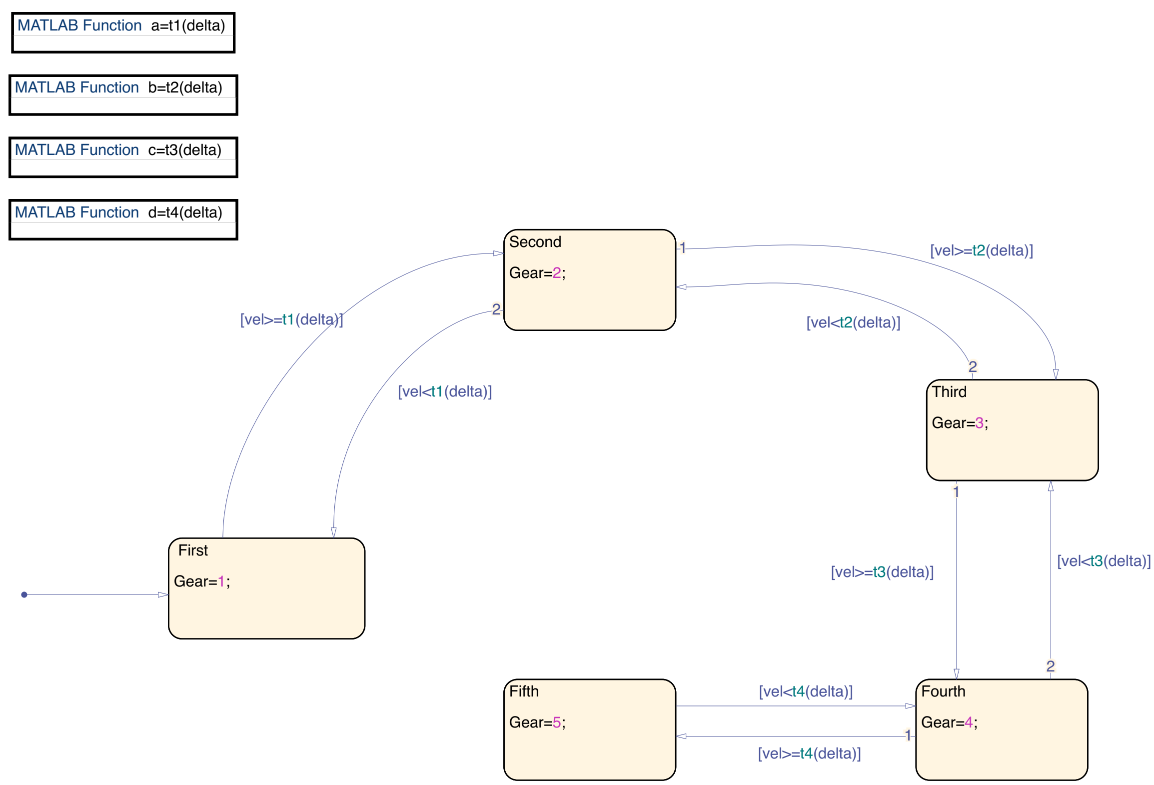


Figure 14: Automatic gear shift

To compute these functions, the values of the thresholds have been computed for delta equal to 1, 0.8, 0.4 and 0 following this reasoning:

- For delta=1, the controller, or the driver, wants to exploit all the available engine's power resulting in an aggressive drive style. Hence, the velocities on which the gears are changed are the ones that keep the highest possible power as visible in Figure 15.
- For delta=0.8, a reasonable regime of shifting the gear has been considered to be 5000 rpm which corresponds to 103.78 kW.
- For delta=0.4, a regime to shift the gear has been considered to be around 2000 rpm corresponding to roughly 39kW.
- For delta=0, the thresholds have been considered to be just slightly lower than the ones for delta=0.4 to keep them roughly constant between delta equal 0.4 and 0.

Following, the functions t1,t2,t3 and t4 have been fitted on these points by using the MATLAB function $polyfit(x, y, 3)$, where 3 is the grade of the polynomial that fits the points. In this way, all the values of the throttle aperture have a corresponding threshold on the car's velocity on which the gear is shifted. These functions are displayed in the Appendix in Figures 17, 18,19 and 20.

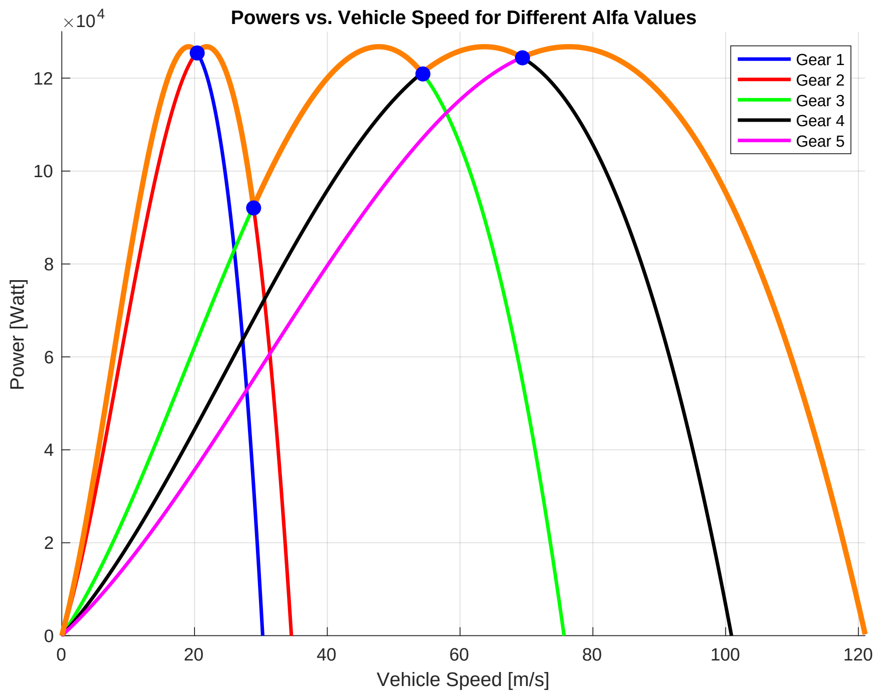


Figure 15: Automatic gear shift that maximizes the power from the engine. The blue dots represent the velocities on which the gears are shifted. The orange curve is the resulting power

4.2 Results

Finally, a step velocity reference from 0 to 100 km/h has been applied by employing the PI controller for the cruise control and the aforementioned algorithm to shift the gears.

The response of the closed loop, the dynamic of the throttle aperture, gears and engine speed are visible in Figure 16. When the reference goes to 100 km/h, the throttle aperture achieves 1 until the car reaches that velocity. This leads the automatic gear to exploit all the available power as seen in Figure 15. Hence, the vehicle reaches 100 km/h in around 5.5 seconds and second gear, achieving the lowest possible time.
Once the vehicle is almost at 100 km/h, the controller lowers delta to keep the car at that velocity. When delta decreases the automatic transmission changes the gears reaching rapidly the fifth one since is the most efficient. This is visible also from the engine velocity plot where high values are reached until the car does not achieve 100 km/h. Subsequently, the engine speed converges between 2000 rpm and 3000 rpm in fifth gear thanks to the auto gear shift in function of the throttle aperture.

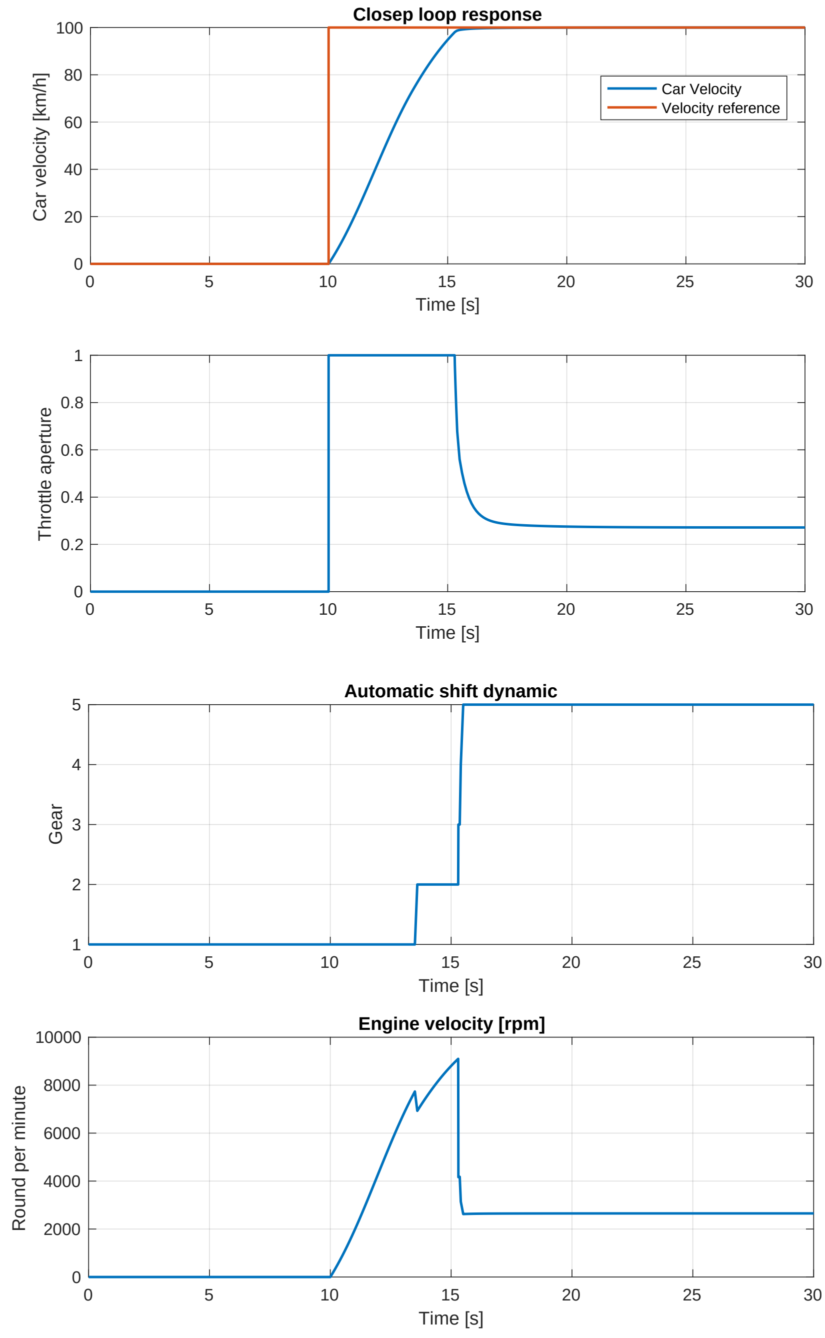


Figure 16: Closed loop 0 to 100 km/h step response

4.3 Appendix

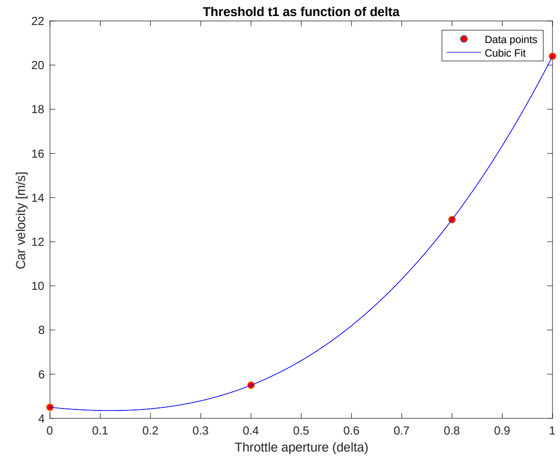
```
function a=t1(delta)

% UP1/DOWN2

a=10.1042*delta^3+8.1875*delta^2-2.3917*delta+4.5;


end
```

(a) t1 function



(b) t1 plot with fitted points

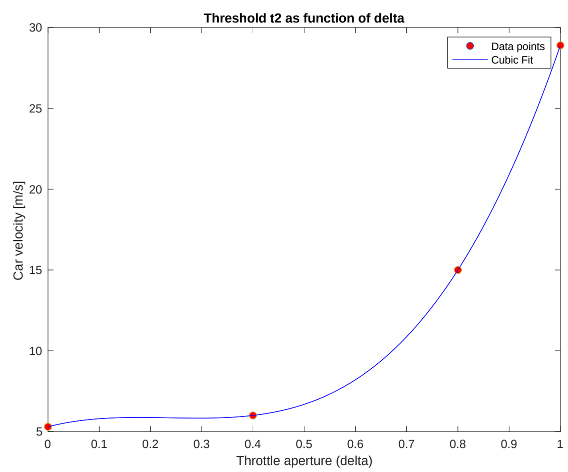
Figure 17

```
function b=t2(delta)
% UP2/DOWN3

b=52.3958*delta^3-36.9375*delta^2+8.1417*delta+5.3;

end
```

(a) t2 function



(b) t2 plot with fitted points

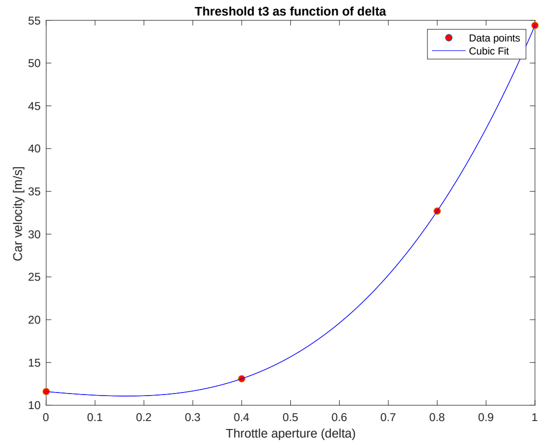
Figure 18

```
function c=t3(delta)
% UP3/DOWN4

c=42.6042*delta^3+5.4375*delta^2-5.2417*delta+11.6;

end
```

(a) t3 function



(b) t3 plot with fitted points

Figure 19

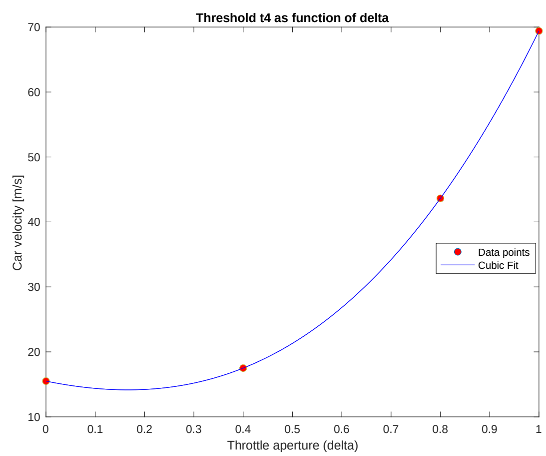
```
function d=t4(delta)

% UP4/DOWN5

d=30.4687*delta^3+38.8438*delta^2-15.4125*delta+15.5;

end
```

(a) t4 function



(b) t4 plot with fitted points

Figure 20