Politecnico di Torino

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Master degree in Automotive Engineering

Driver Assistance System Design

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Project 1

Adaptive cruise control

1.1 Propedeutic exercise 1: ACC design of the single lead vehicle (simplified vehicle model)

The goal of the first propedeutic exercise is to build a constant time gap ACC controller and then tune all the parameters needed to improve the vehicle response to the single lead vehicle's speed profile.

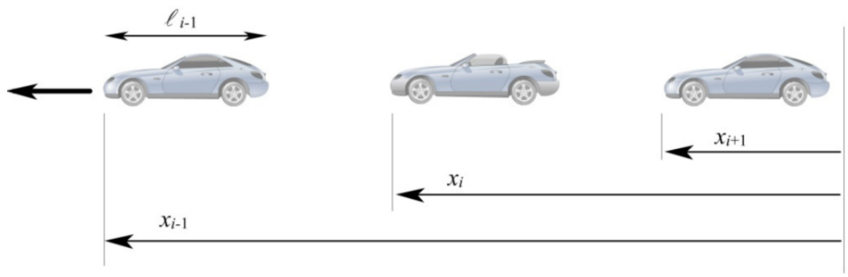


Figure 1.1: Leading and following vehicles

The equation 1.1 describes how the commanded acceleration changes with the respect to the parameters applied.

$$a_i = -\frac{1}{h} \cdot (\lambda \delta_i + \dot{\varepsilon}_i) \tag{1.1}$$

where δ_i is the spacing error and can be compute as $\delta_i \doteq \varepsilon_i + L_{des}$, $L_{des} = h \cdot \dot{x}_i$ is the desired distance between the two vehicles and $\varepsilon_i \doteq x_i - x_{i-1}$ is the actual relative distance between the two vehicles (x_i is the ego vehicle longitudinal position in an inertial reference frame). The parameters λ and h are the value to tune, where:

- λ defines the aggressiveness of the controller;
- h is the desired time gap.

1.1.1 CTG controller built on Simulink

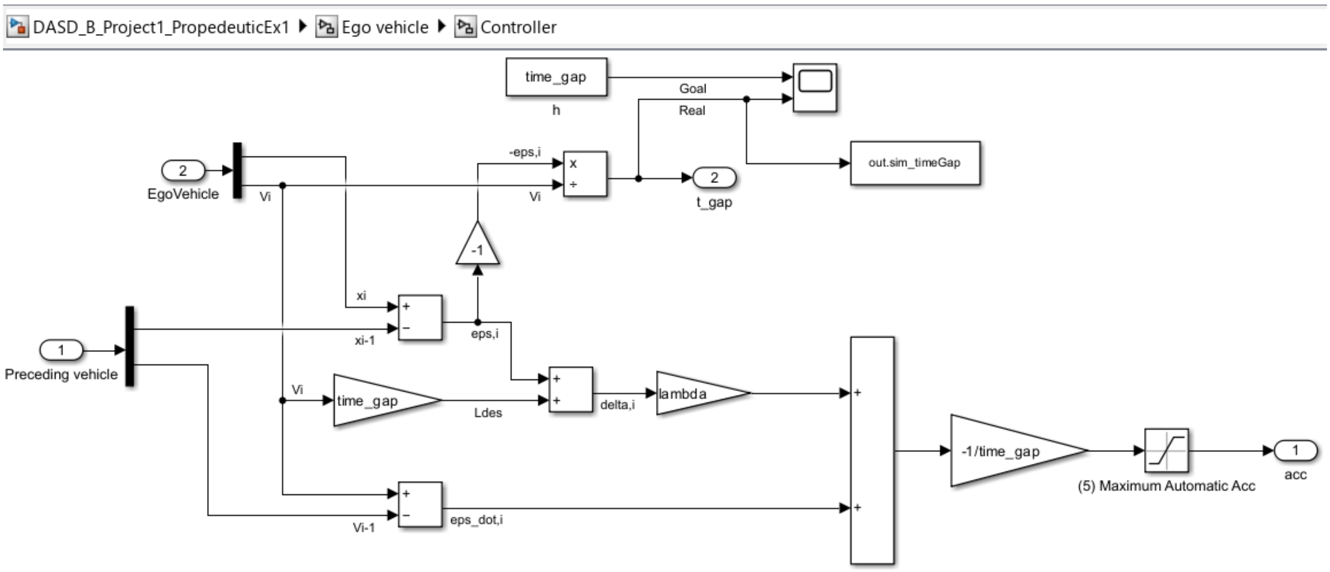


Figure 1.2: CTG controller

Some key performance indicators (KPI) from ISO 15622:2018 are additionally **monitored** in order to guarantee the correct functioning of the controller.

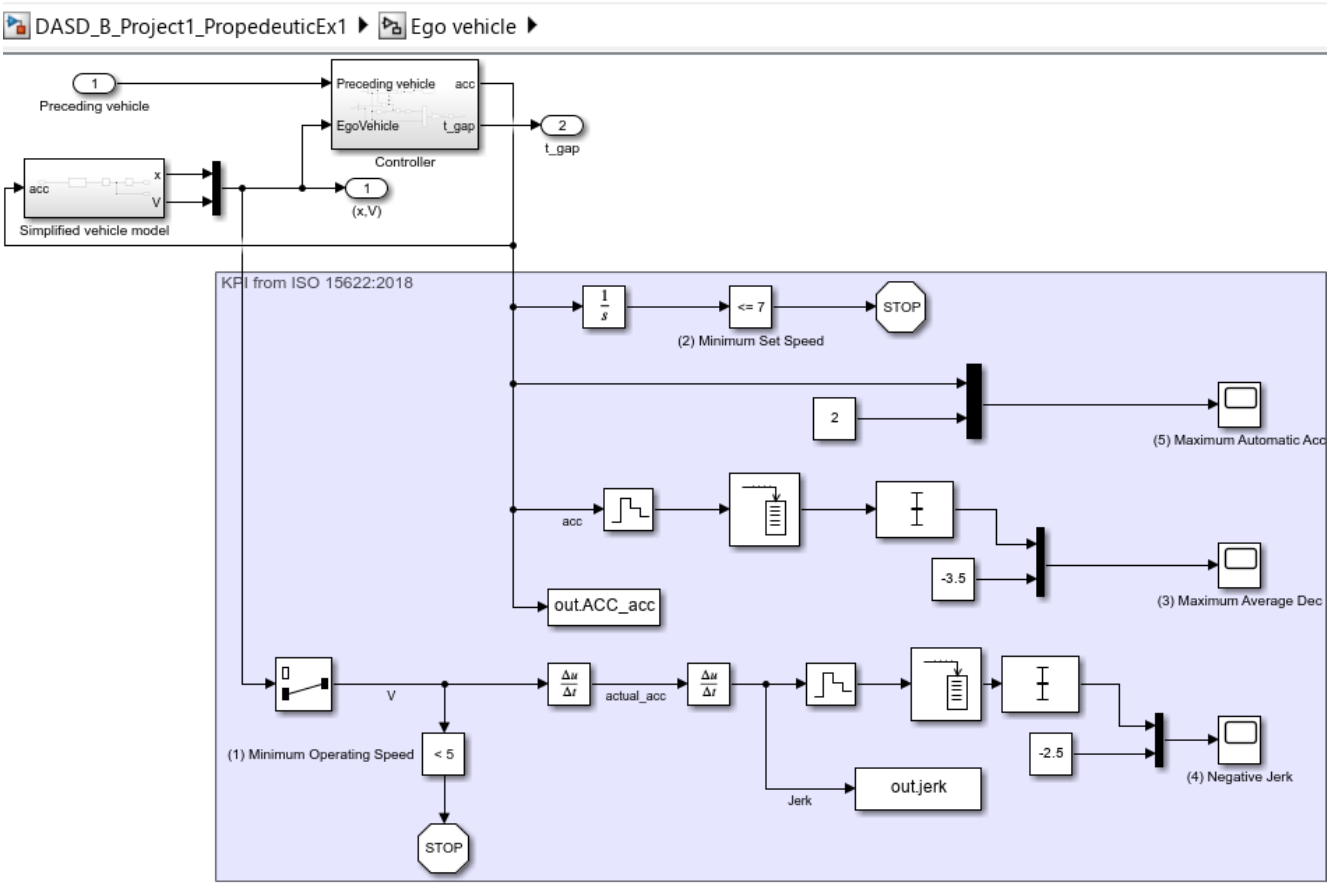


Figure 1.3: KPI related to Ego Vehicle behavior

The model on which simulation are performed is the compact one, with an initial speed of 15 m/s.

The leading vehicle (x_{i-1} in 1.1) at time t = $0s$ has a distance of $3000m$ from the origin of the reference frame while the ego vehicle (x_i in 1.1) has a distance of $2900m$ from that same spot. The resulting distance between the two cars at the beginning of the simulation is $100m$: in this way it surely is in the detection range of the long radar which is implemented on the x_i car.

In order to evaluate all the different scenarios (including the possibility that the ego vehicle struggles to catch up the leading one at high speed) a saturation has been set on the maximum speed of the ego vehicle at $25m/s$.

These settings have been adopted for all the exercises of project 1.

1.1.2 Tuning of λ and time gap h to improve vehicle response to lead vehicle's speed profile

The tuning of λ and time gap h led to an optimal ego vehicle response to lead vehicle speed profiles for the following values:

Parameter	**Value**
λ	0.4
h	$2s$

Table 1.1: Summary of the ACC parameters

1.1.3 Discussion of the safety implications of relevant parameters

In this section, some key performance indicators are shown in order to guarantee that the behavior of the car, while the ACC is operating, respects the safety criteria of ISO 15622:2018. For each KPI, the dotted lines remark the limits of the normative.

It is possible to observe that the system's average automatic deceleration does not exceed 3.5 m/s^2 if averaged over 2 seconds (exception made a couple of peaks).

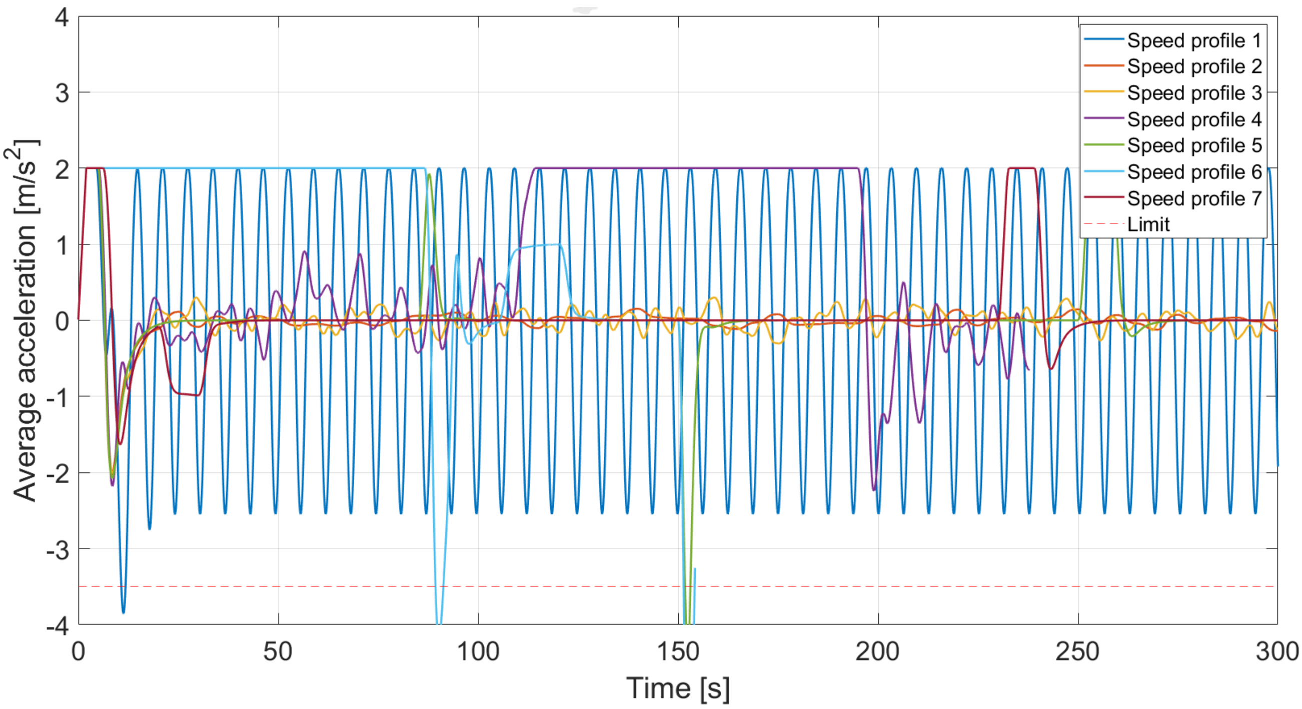


Figure 1.4: KPI: Maximum Average Deceleration

The system's maximum deceleration rate (negative jerk) that describes the average rate at which deceleration increases, does not exceed 2.5 m/s^3 if averaged over 1 second (only the sinusoidal speed profile stresses the negative jerk in a considerable way: being on the limit with the design of λ, a possible way to attenuate it could be through the reduction of the aggressiveness of the controller).

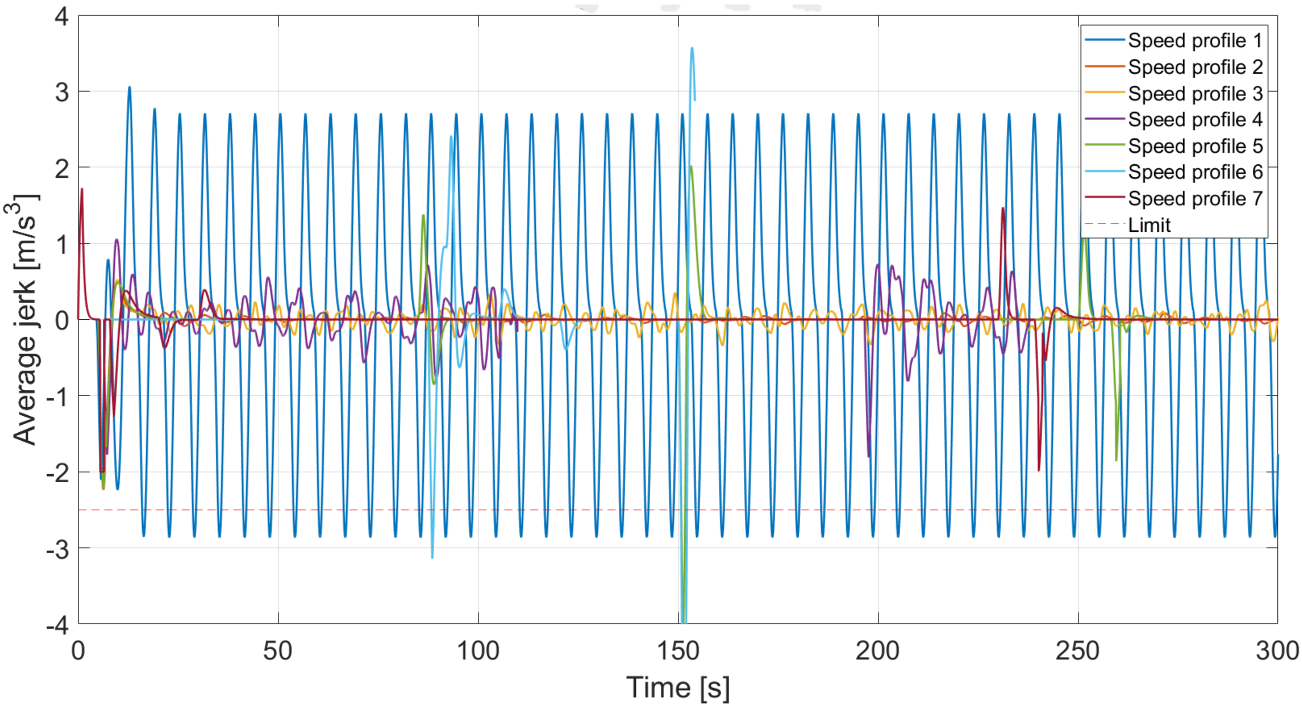


Figure 1.5: KPI: Negative Jerk

The maximum automatic acceleration does not exceed 2 m/s^2 since the controller saturates the automatic acceleration before sending it inside the simplified vehicle model.

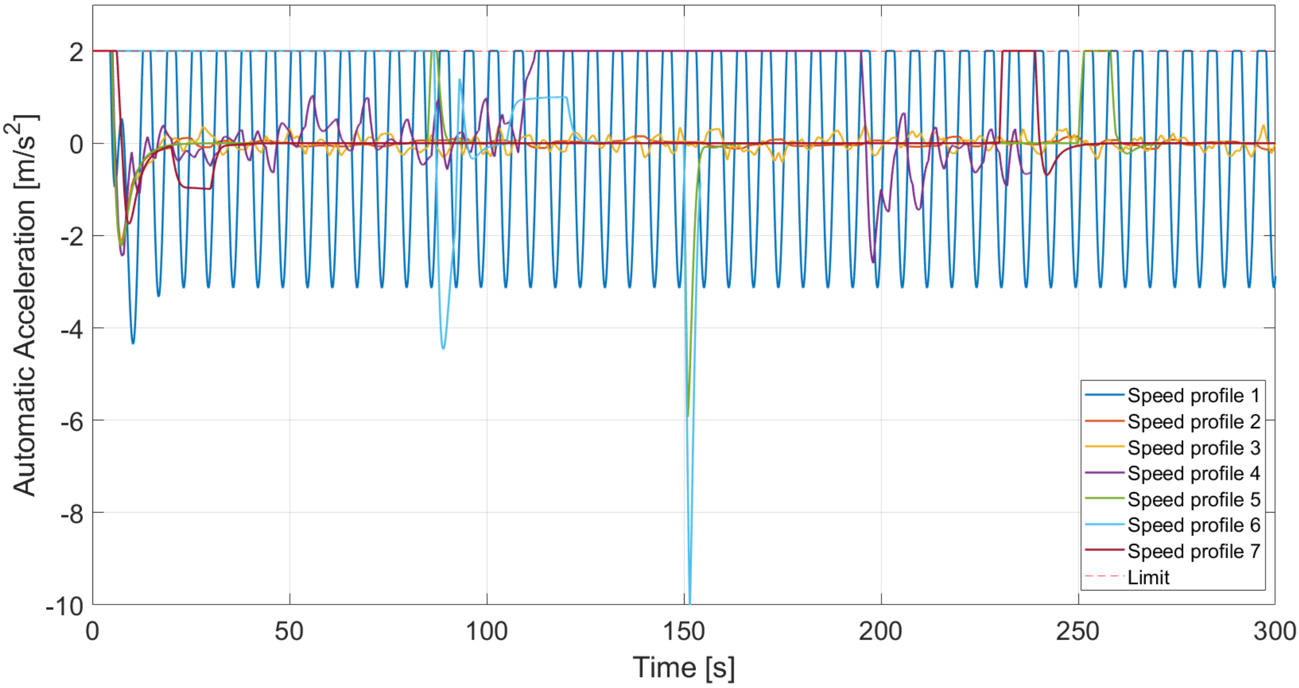


Figure 1.6: KPI: Maximum Automatic Acceleration

1.1.4 Limits on the values of λ and h for safety reasons

For safety reasons the desired time gap must be set in a range between 1.5 to 3 seconds, in order to follow the preceding vehicle without being too close to it: for this reason h is set at 2 seconds.

For the tuning of λ, it must be taken into account that reasonable values for the aggressiveness of the controller are in a range between 0.1 and 2.5. In order to be compliant with safety implication on KPI from ISO 15622:2018, the value of $\lambda = 0.4$ is the one that better fits the desired limits.

1.1.5 Analysis of different lead vehicle speed profiles

The following vehicle speed profiles are the ones on which the controller is tuned: on these profiles the controller is capable of imposing a stable time gap after a transient evolution from the initial conditions.

It can be observed that for speed profiles 2, 3, 5 and 7 the stability is asymptotical while speed profile 1 the evolution of the time gap suggest a marginal stability (also due to the oscillatory behavior of the leading vehicle speed profile).

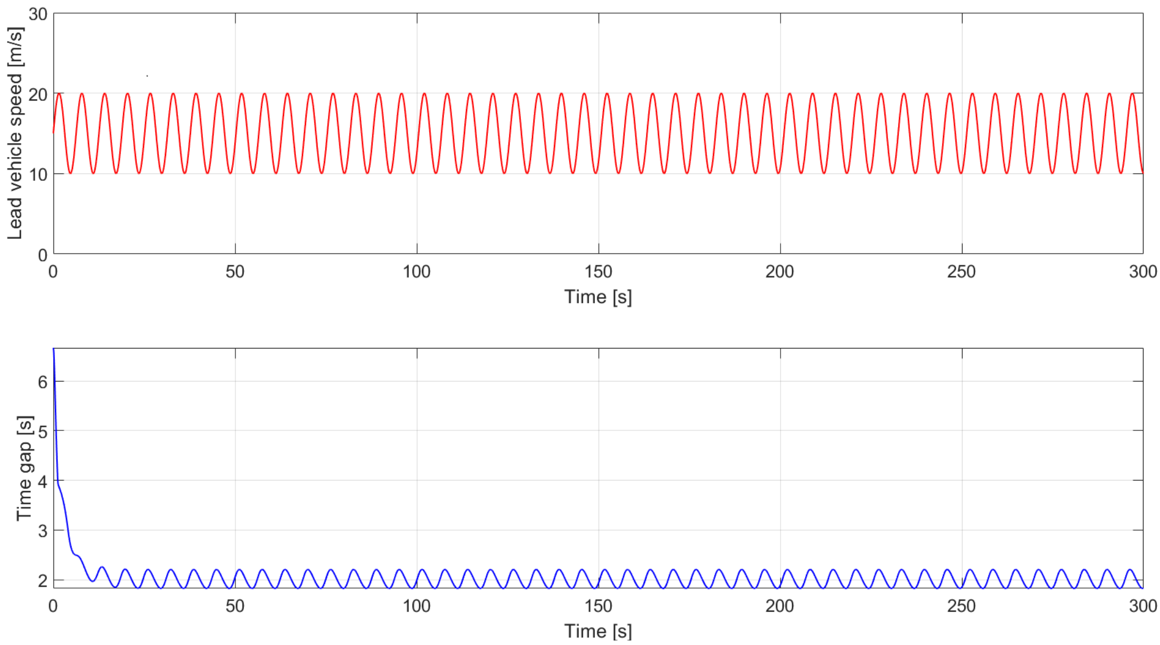


Figure 1.7: time gap evolution with leading vehicle speed profile 1

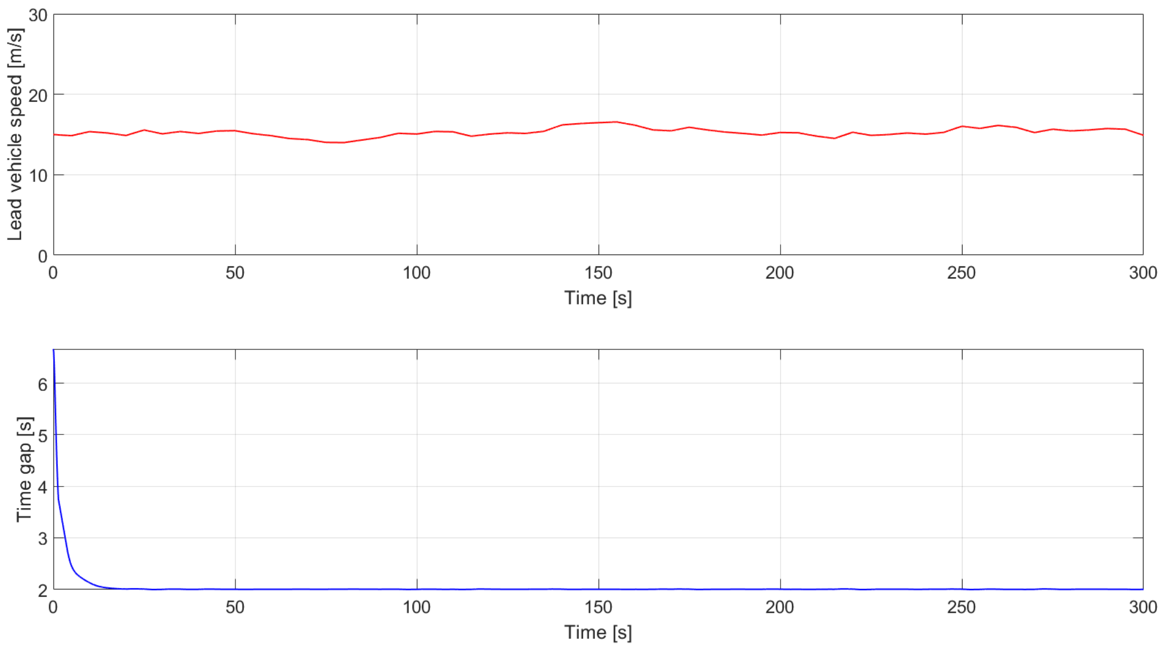


Figure 1.8: time gap evolution with leading vehicle speed profile 2

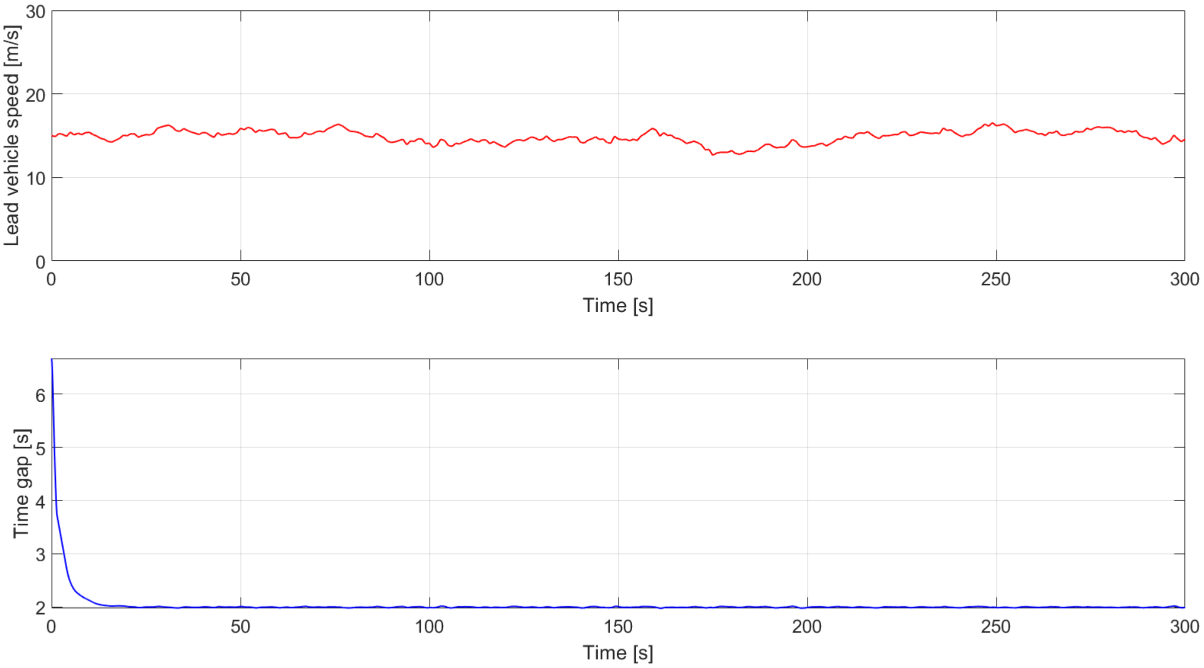


Figure 1.9: time gap evolution with leading vehicle speed profile 3

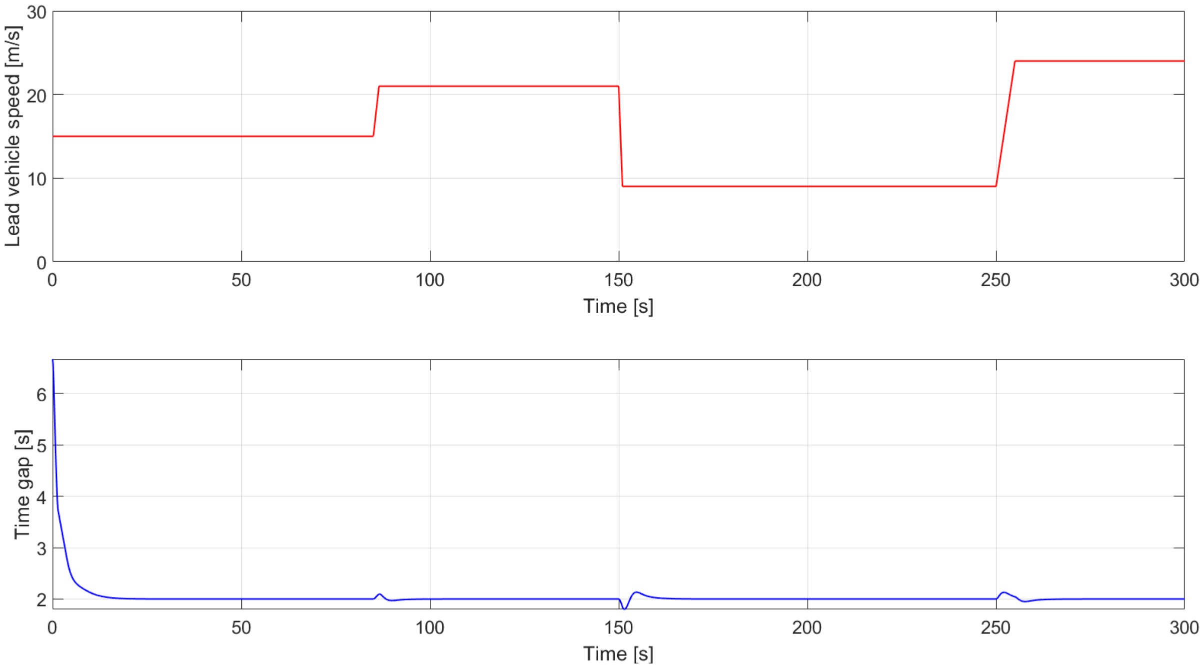


Figure 1.10: time gap evolution with leading vehicle speed profile 5

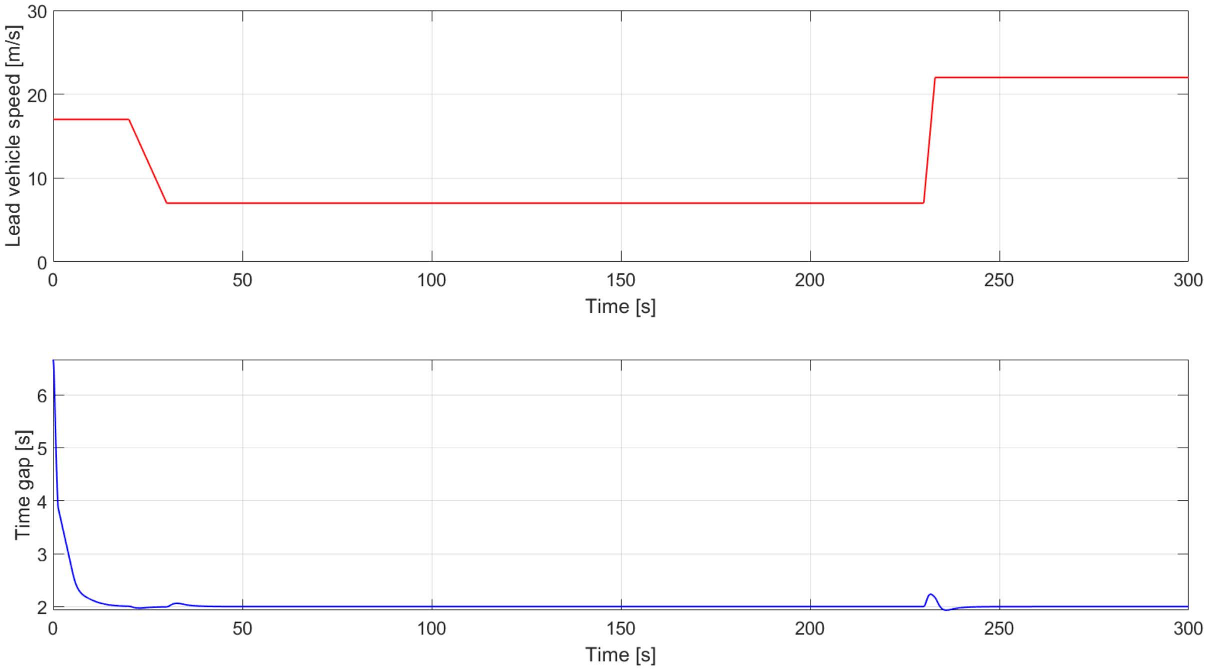


Figure 1.11: time gap evolution with leading vehicle speed profile 7

It is also possible to observe that, due to the fact that the ego vehicle speed is saturated at 25 m/s, when the leading vehicle reaches speeds higher than 25 m/s (like it happens for speed profile 4) the following one is not capable to keep the desired and constant time gap. Since the minimum operating speed for ACC positive acceleration is 5 m/s, when extremely low speeds are reached the ACC stops working as imposed.

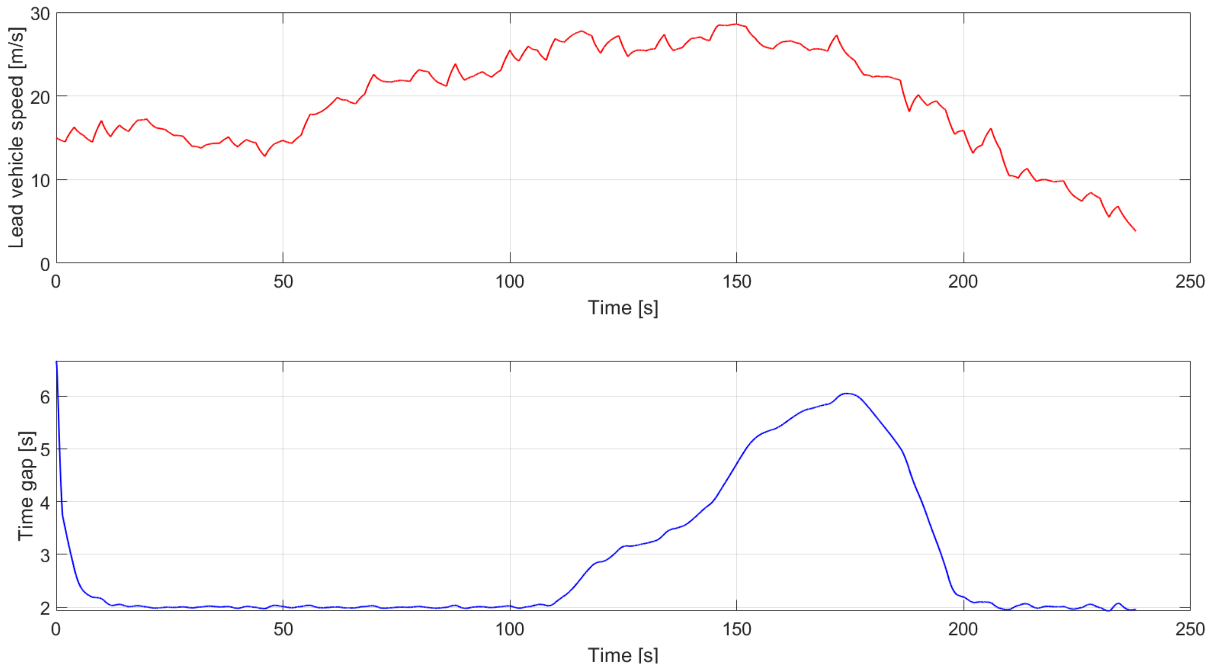


Figure 1.12: time gap evolution with leading vehicle speed profile 4

What has been described for speed profile 4 happens also in case of speed profile 6, with ACC breaking out from his functioning due to low speeds of the leading vehicle.

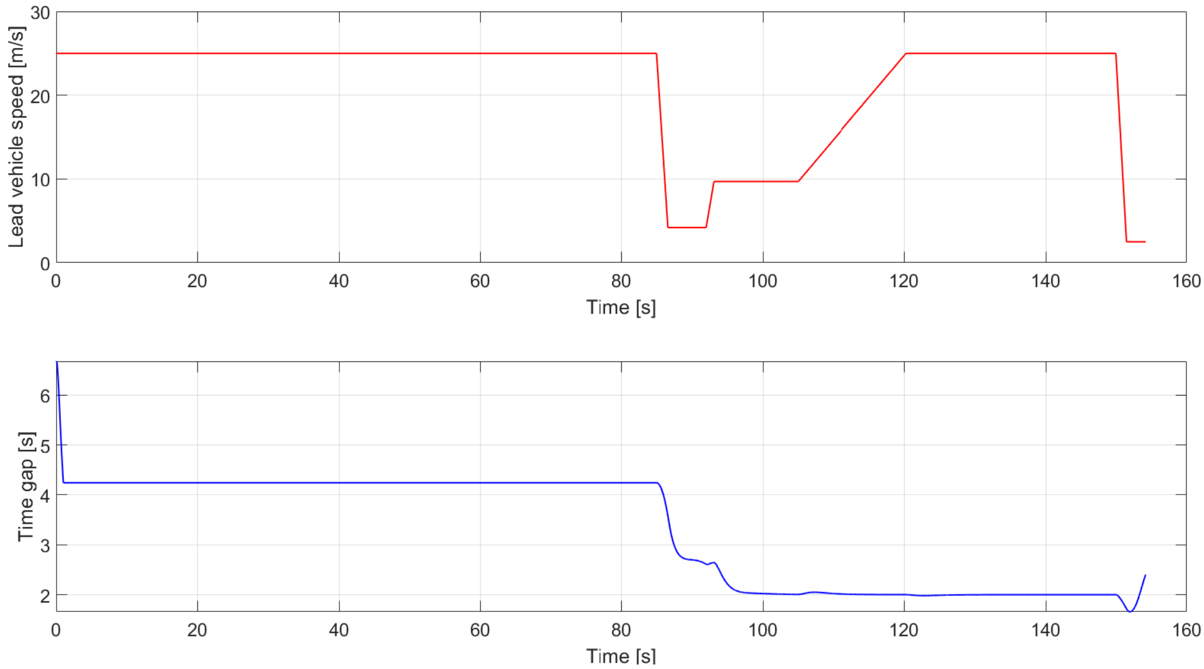


Figure 1.13: time gap evolution with leading vehicle speed profile 6

1.1.6 Feasibility of the controller in real life

A CTG that uses a simplified vehicle model represented by the transfer function:

$$tf(s) = \frac{1}{\tau s + 1} \tag{1.2}$$

is sufficient for designing simple controllers in low-dynamic contexts, such as highway driving with constant traffic flow or vehicle platooning scenarios but with major practical limitations:

- the model does not include braking dynamics, so it cannot respond properly to sudden changes, such as an obstacle or a sharply braking vehicle;
- the model does not account for real-world nonlinearities: real vehicle dynamics (like tire friction, actuator delays, loading, road slopes, etc.) are not modeled.

1.2 Exercise 1: ACC design of the single lead vehicle (complete vehicle model)

1.2.1 CTG + PI controller

Starting from the ACC developed in the the previous chapter, the implementation is improved using a complete vehicle model rather than a simplified one. The reference acceleration, given as output of ACC, is converted in accelerator (h_a) and brake command (h_b) thanks to an additional controller that is placed between the ACC and vehicle model as can be seen in the following figure.

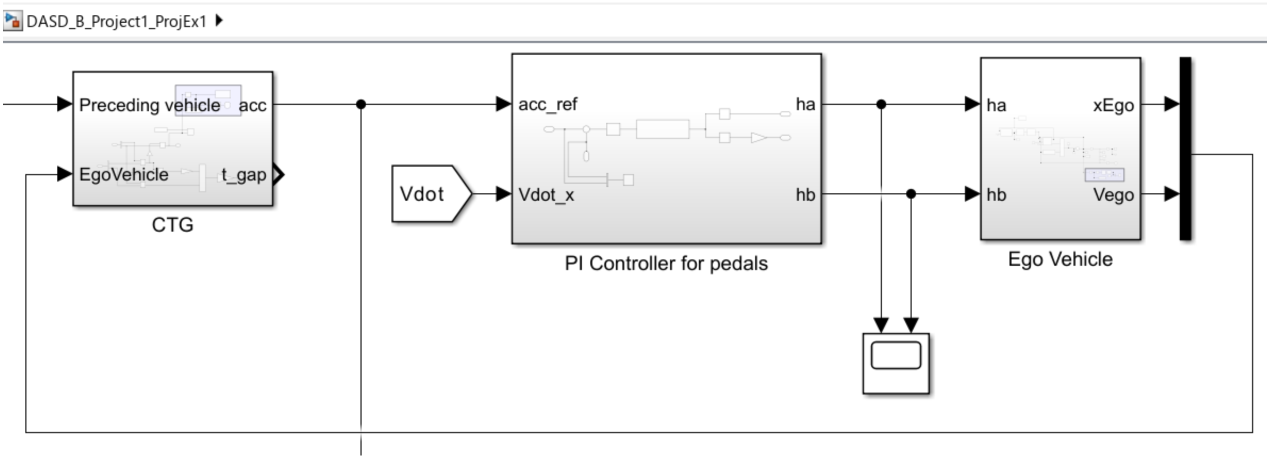


Figure 1.14: Simulink model of the project 1

CTG is the control time gap controller already implemented in propedeutic 1.

Going deep on the brake and accelerator pedal PI controller:

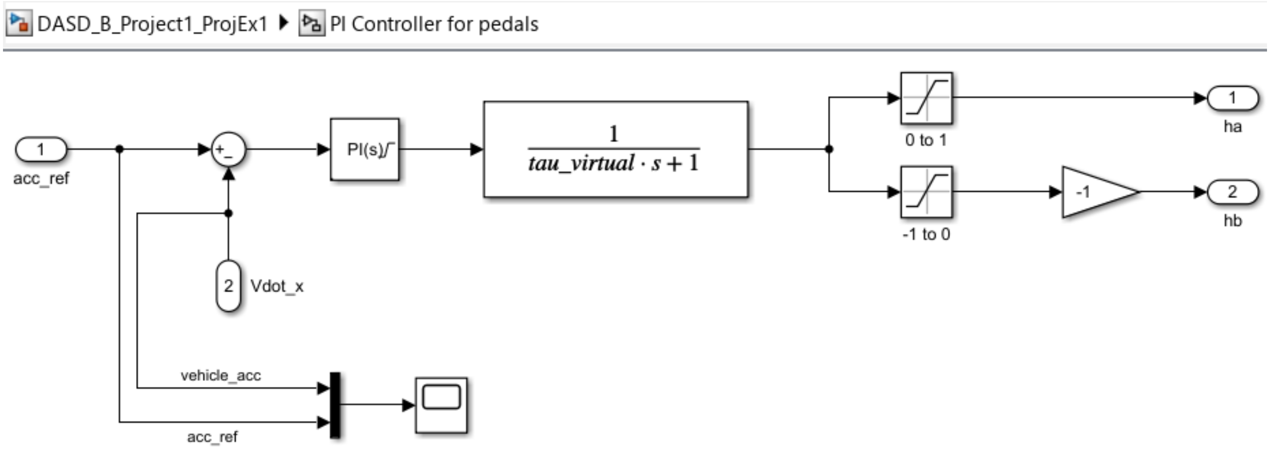


Figure 1.15: PI controller for pedals

To achieve the desired control behavior, a PI controller is used. It takes as input the acceleration error, defined as $e = a_{\text{ref}} - a_{\text{ego}}$. The output of the PI controller is passed through a first-order transfer function:

$$H(s) = \frac{1}{\tau_{\text{virtual}} \cdot s + 1} \tag{1.3}$$

This block acts as a low-pass filter, introducing a delay that mimics the response dynamics of a human driver. Proper selection of the parameter τ_{virtual} is essential for achieving a good trade-off between responsiveness and stability in the system dynamics.

The output of the transfer function can be ether positive and negative therefore two saturation block are used to decompose that output into accelerator and brake command.

- The first block determines the **throttle command** (h_a). The saturation limits are set between 0 and 1. When the output of the transfer function is positive, it is assigned to h_a and limited to a maximum value of 1.
- The second block determines the **brake command** (h_b). Similarly, the saturation limits are set between 0 and 1. When the output of the transfer function is negative, it is multiplied by -1 to make it positive, then assigned to h_b and saturated at 1.

Effective tuning of the controller requires careful consideration of the loop transfer function. The system is composed of two key elements:

$$\text{PI Controller:} \quad tf(s) = K_P + \frac{K_I}{s} = \frac{K_P \cdot s + K_I}{s} \tag{1.4}$$

$$\text{Low-Pass Filter:} \quad H(s) = \frac{1}{\tau_{virtual} \cdot s + 1} \tag{1.5}$$

The low-pass filter introduces a pole at:

$$s = -\frac{1}{\tau_{virtual}} \tag{1.6}$$

Meanwhile, the PI controller introduces a zero at:

$$s = -\frac{K_I}{K_P} \tag{1.7}$$

To achieve zero-pole cancellation, the zero introduced by the PI controller must coincide with the pole introduced by the low-pass filter. This condition leads to the following relationship:

$$\frac{1}{\tau_{virtual}} = \frac{K_I}{K_P} \quad \Rightarrow \quad K_I = \frac{K_P}{\tau_{virtual}} \tag{1.8}$$

Zero-pole cancellation helps improve the system response, making it both faster and smoother.

The proportional gain K_P is selected to ensure full throttle ($h_a = 1$) is applied when the maximum acceleration is requested. Assuming the maximum required acceleration is 3 $\mathrm{m/s^2}$, the gain is calculated as:

$$K_P = \frac{\text{Full throttle } (h_a = 1)}{\text{Maximum acceleration}} = \frac{1}{3} = 0.33 \tag{1.9}$$

1.2.2 Tuning of λ and time gap h to improve vehicle response to lead vehicle's speed profile

The tuning of λ and time gap h led to an optimal ego vehicle response to lead vehicle speed profiles for the following values:

Parameter	**Value**
λ	0.4
h	1.8
$\tau_{virtual}$	0.2
K_P	0.33
K_I	$\frac{K_P}{\tau_{virtual}} = 1.65$

Table 1.2: Summary of the PI controller and ACC parameters

1.2.3 Discussion of the safety implications of relevant parameters

In this section, some key performance indicators are shown in order to guarantee that the behavior of the car, while the ACC is operating, respects the safety criteria of ISO 15622:2018. For each KPI, the dotted lines remark the limits of the normative.

It is possible to observe that the system's average automatic deceleration does not exceed 3.5 m/s^2 if averaged over 2 seconds (exception made a couple of peaks).

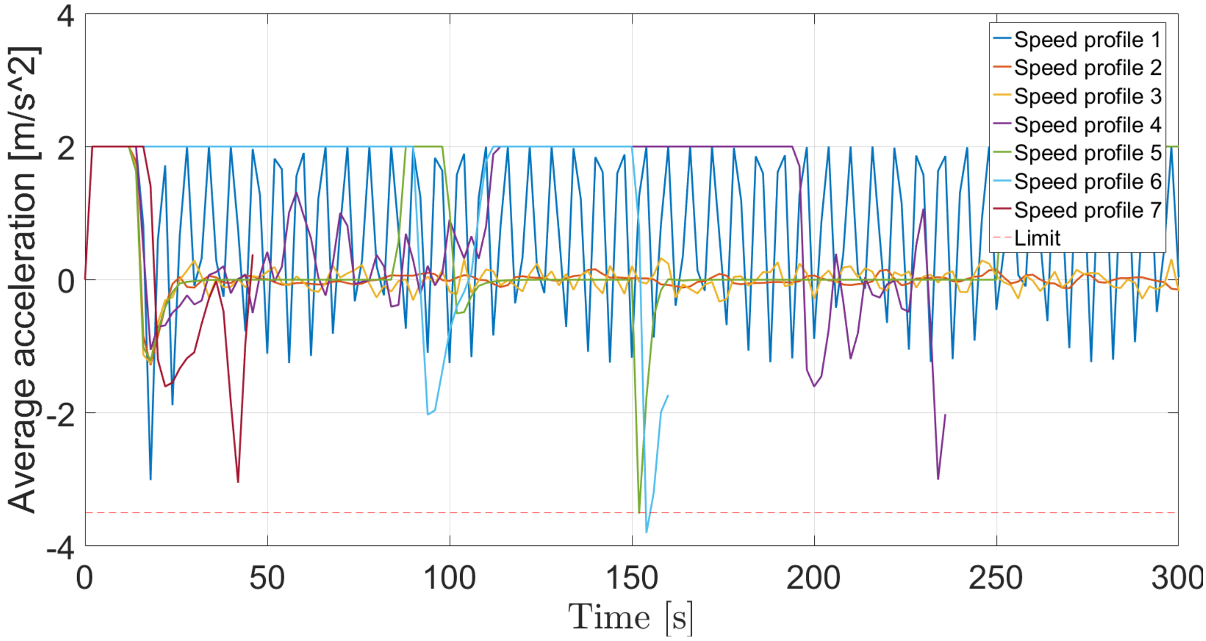


Figure 1.16: KPI: Maximum Average Deceleration

The system's maximum deceleration rate (negative jerk) that describes the average rate at which deceleration increases, does not exceed 2.5 m/s^3 if averaged over 1 second. Only the sinusoidal speed profile stresses the negative jerk in an appreciable way, otherwise the limit is exceeded only in few countable local points. A possible way to attenuate it could be through the reduction of the aggressiveness of the controller.

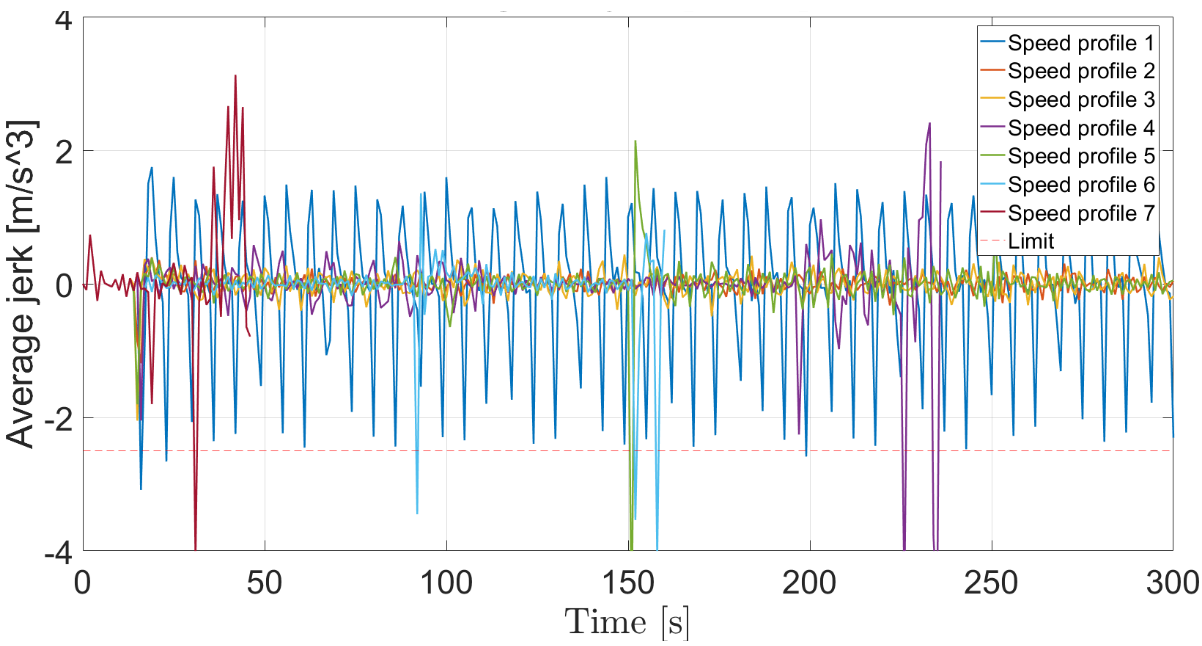


Figure 1.17: KPI: Negative Jerk

The maximum automatic acceleration does not exceed 2 m/s^2 since the controller saturates the automatic acceleration before sending it inside the simplified vehicle model.

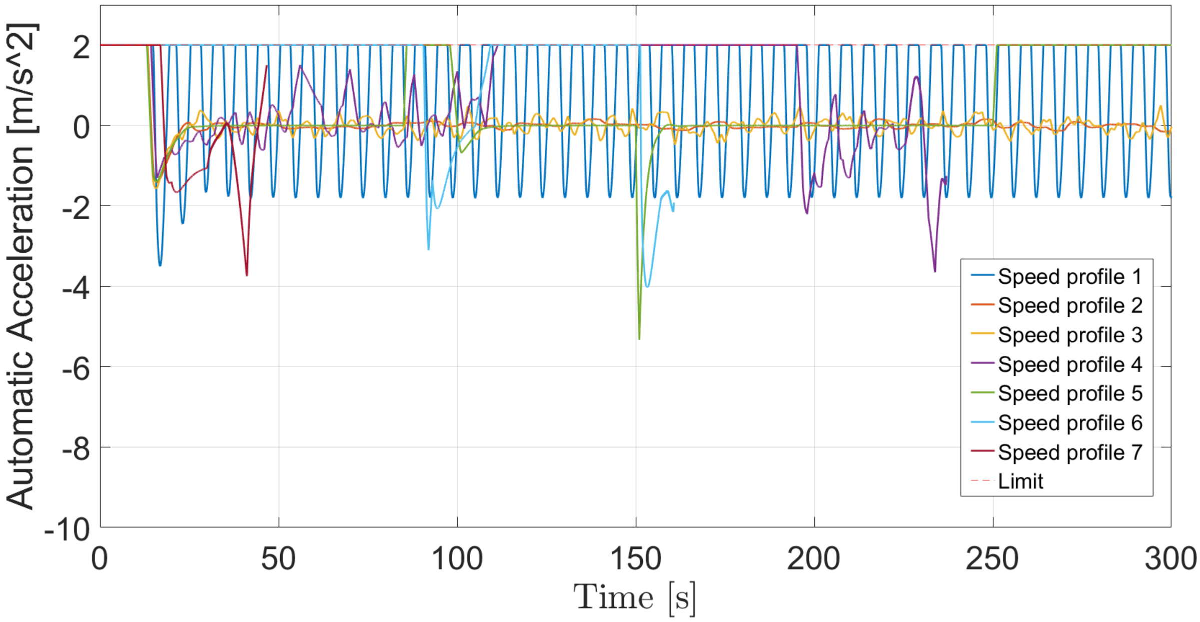


Figure 1.18: KPI: Maximum Automatic Acceleration

1.2.4 Analysis of different lead vehicle speed profiles

The following vehicle speed profiles are the ones on which the controller is tuned: on these profiles the controller is capable of imposing a stable time gap after a transient evolution from the initial conditions.
It can be observed that for speed profiles 2, 3 and 5 the time gap is stable on the desired value while for speed profile 1 the evolution of the time gap suggest a marginal stability (due to the oscillatory behavior of the leading vehicle speed profile).

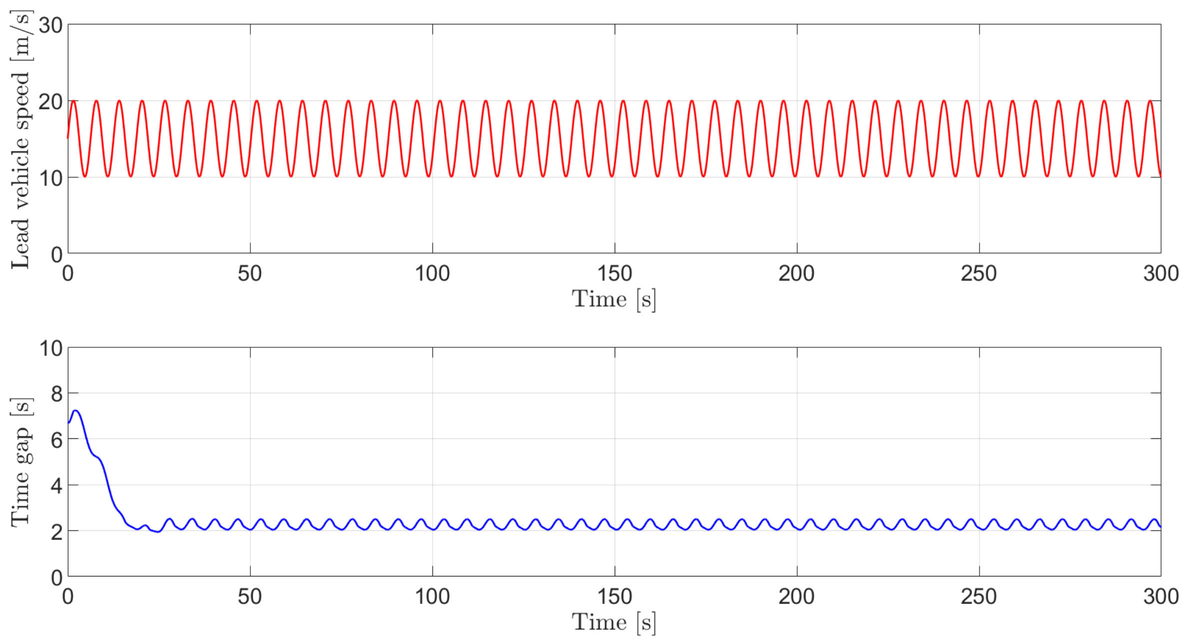


Figure 1.19: Time gap evolution with leading vehicle speed profile 1

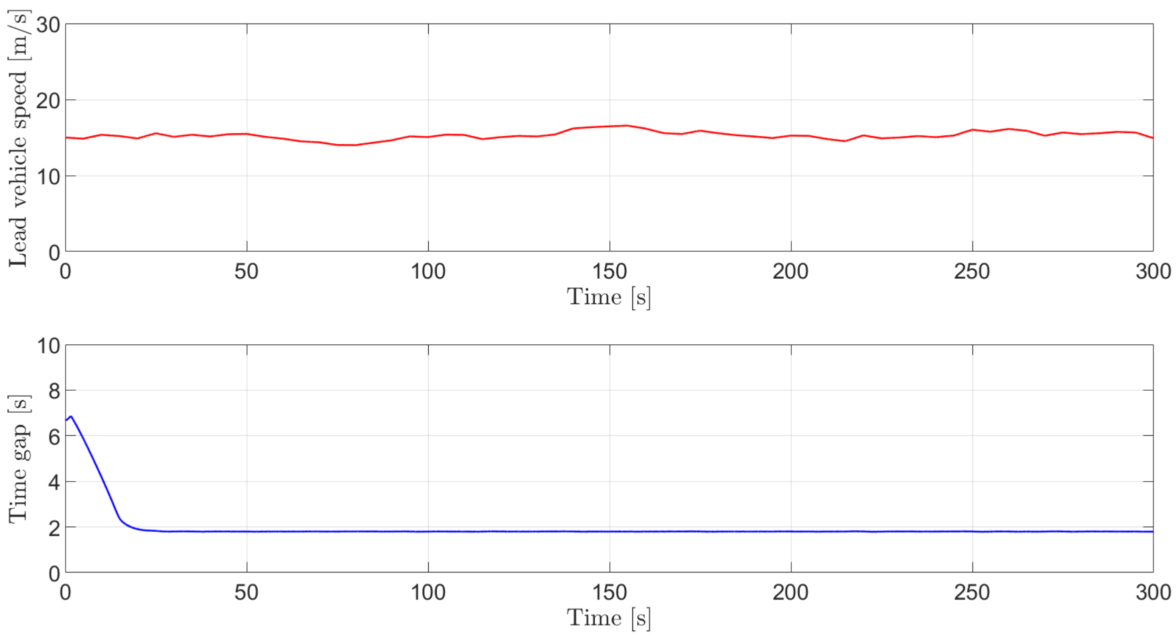


Figure 1.20: Time gap evolution with leading vehicle speed profile 2

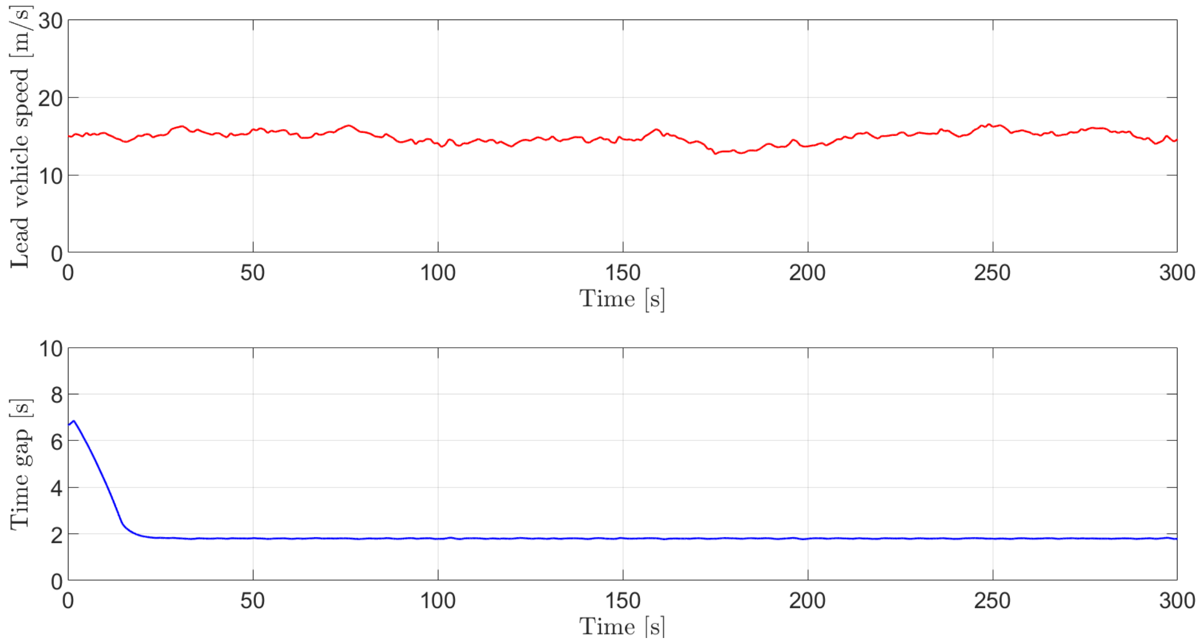


Figure 1.21: Time gap evolution with leading vehicle speed profile 3

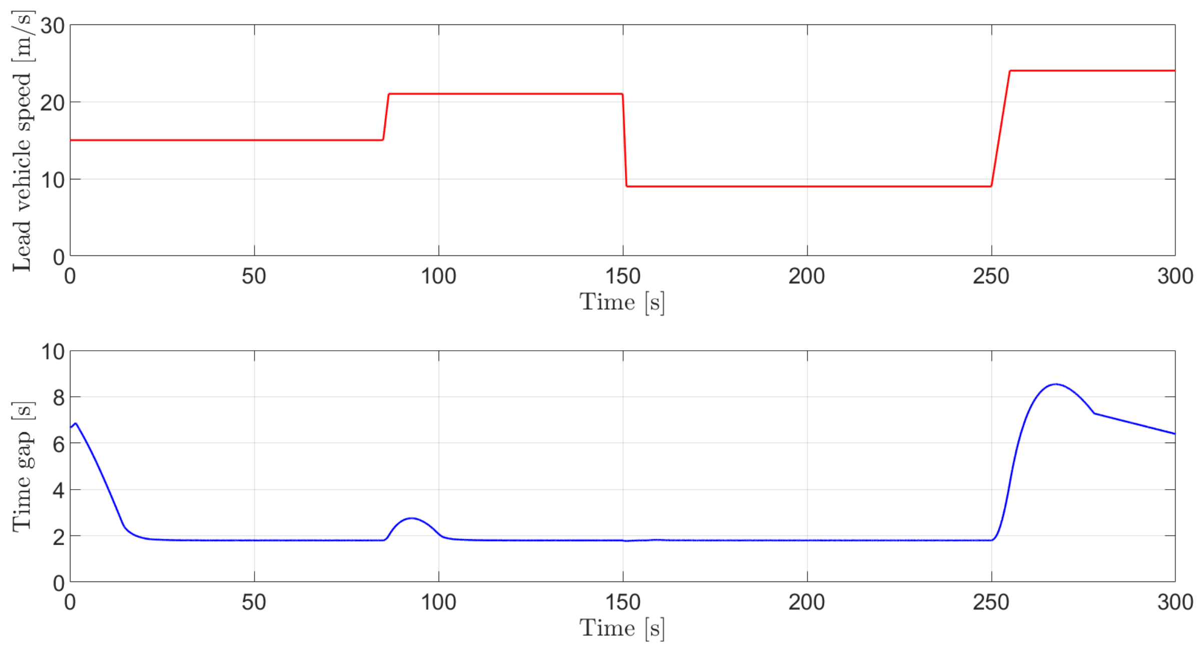


Figure 1.22: Time gap evolution with leading vehicle speed profile 5

It is also possible to observe that, due to the fact that the ego vehicle speed is saturated at 25 m/s, when the leading vehicle reaches speeds higher than 25 m/s (like it happens in speed profile 4) the following one is not capable to keep the desired and constant time gap. Since the minimum operating speed for ACC positive acceleration is 5 m/s, when extremely low speeds are reached the ACC stops working as imposed.

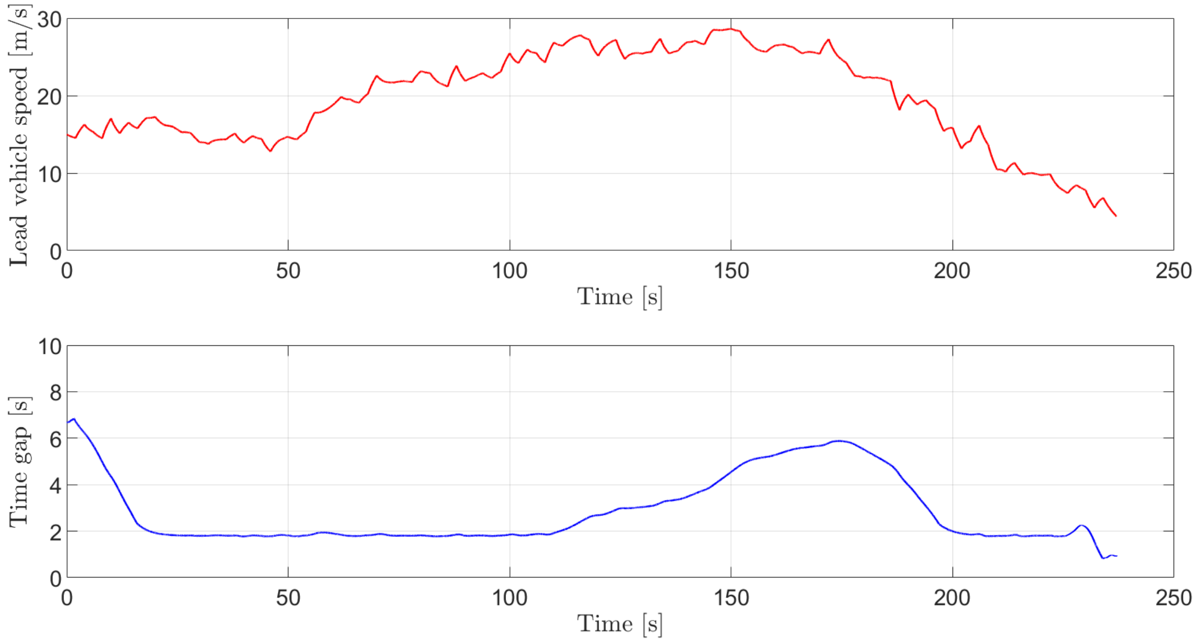


Figure 1.23: Time gap evolution with leading vehicle speed profile 4

What has been described for speed profile 4 happens also in case of speed profile 6, with ACC breaking out from his functioning due to low speeds of the leading vehicle. At the beginning of the simulation, it is additionally noticeable that the following vehicle is struggling to close the gap due to the saturation imposed on the maximum speed.

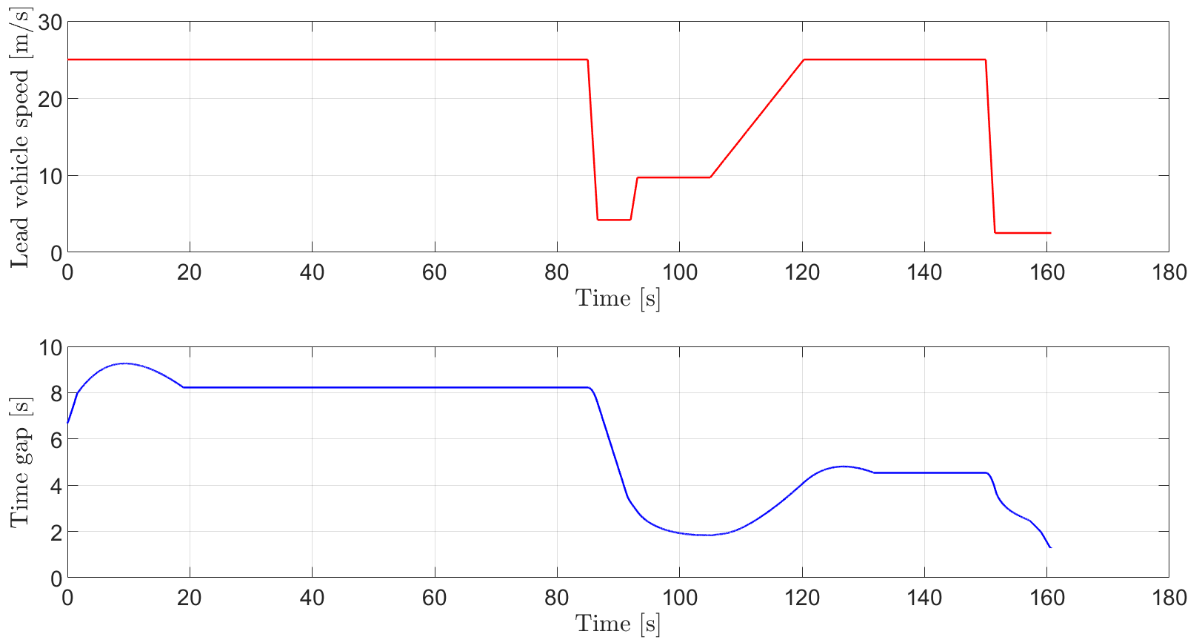


Figure 1.24: Time gap evolution with leading vehicle speed profile 6

1.2.5 Limits on the values of λ and h for safety reasons

For safety reasons the desired time gap must be set in a range between 1.5 to 3 seconds, in order to follow the preceding vehicle without being too close to it: in order to slightly improve the traffic capability with respect to the propedeutic exercise, h is set to 1.8 s.

For the tuning of λ, it must be taken into account that reasonable values for the aggressiveness of the controller are in a range between 0.1 and 2.5. In order to be compliant with safety implication on KPI from ISO 15622:2018, the value of $\lambda = 0.4$ is the one that better fits the desired limits.

1.2.6 Feasibility of the controller in real life

Differently from what has been previously mentioned in propedeutic exercise, the ACC controller implemented for exercise 1 is undoubtedly more feasible in real life with respect to the simple CTG.

The main reason is that, for this exercise, the CTG has been implemented with a compete vehicle model and an accelerator controller (PI) in the middle.

More precisely:

- The complete vehicle model model can account for real vehicle dynamics, involving actuator delays, gearbox logic, differential, clutch that are now modeled inside the Ego Vehicle subsystem.
- The accelerator controller is able to guarantee a fast enough acceleration behavior in closed-loop.

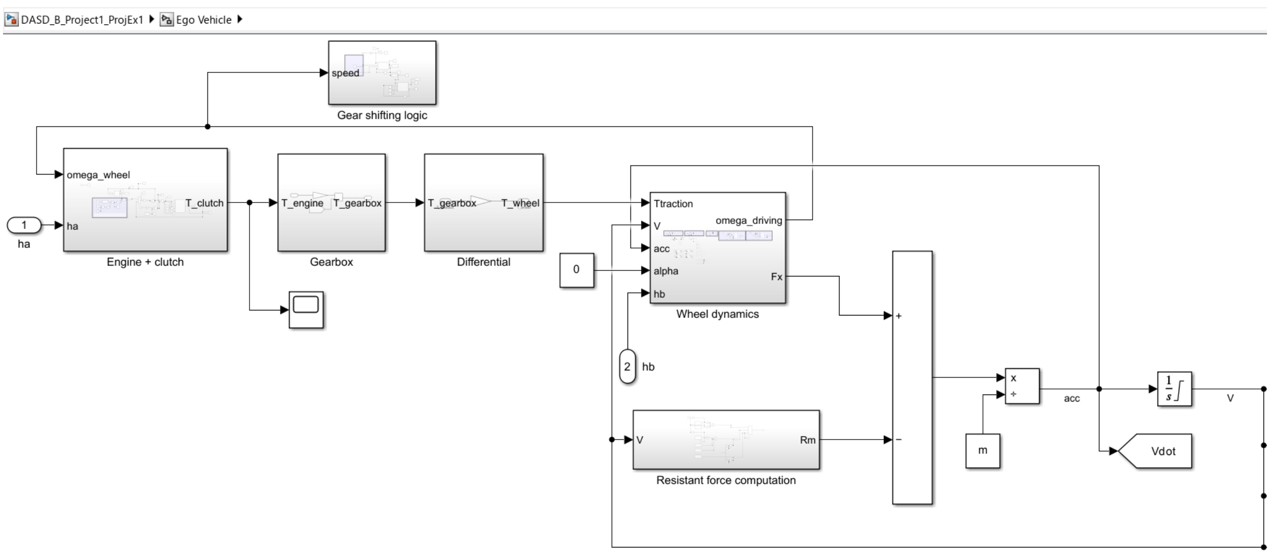


Figure 1.25: Ego Vehicle complete model

1.2.7 Ego Vehicle stability in different road conditions

The driving cycle simulated from the leading vehicle is the "Artemis motorway 130 kph driving cycle" in a **wet road** scenario while the Ego Vehicle model is a BEV.

Saturation is applied on the speed profile of the driving cycle in order to account for several aspects:

- below certain speeds there is no interest in testing the ACC behavior.

  $\Longrightarrow$ Lower saturation $= 10\ m/s$

- The design parameters of the CTG ($\lambda = 0.4$ and $h = 1.8$) are compliant with an increased traffic capacity. In this context, lower maximum speeds are consequently reached, especially in wet road conditions.

  $\Longrightarrow$ Upper saturation $= 22\ m/s$ which had to be specifically lower than the value of upper saturation imposed to the Ego Vehicle.

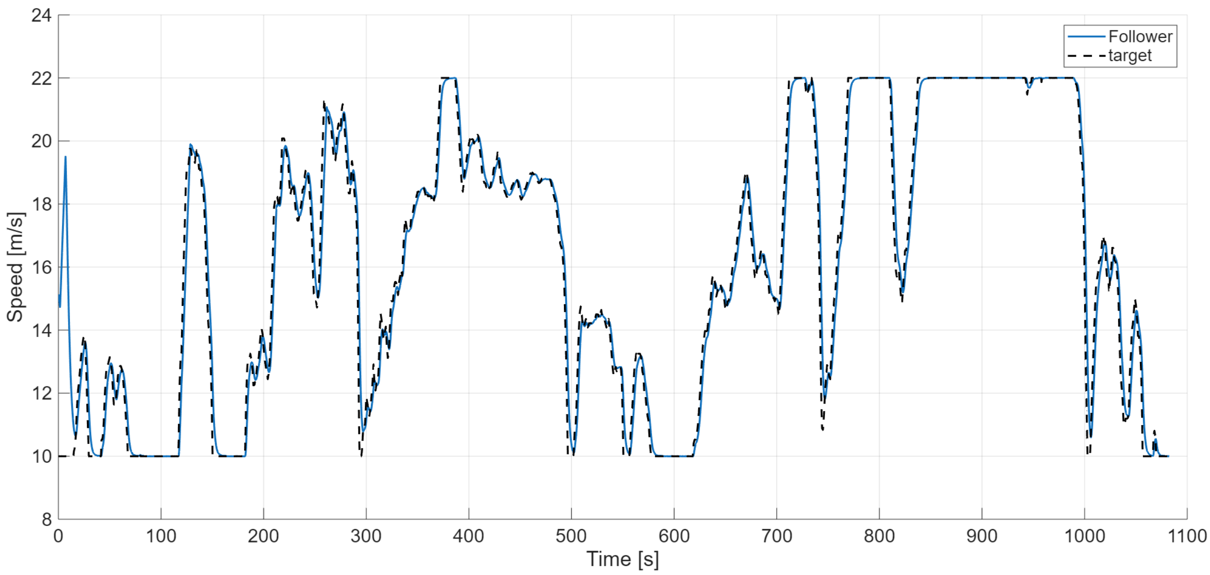


Figure 1.26: Artemis saturated speed profile

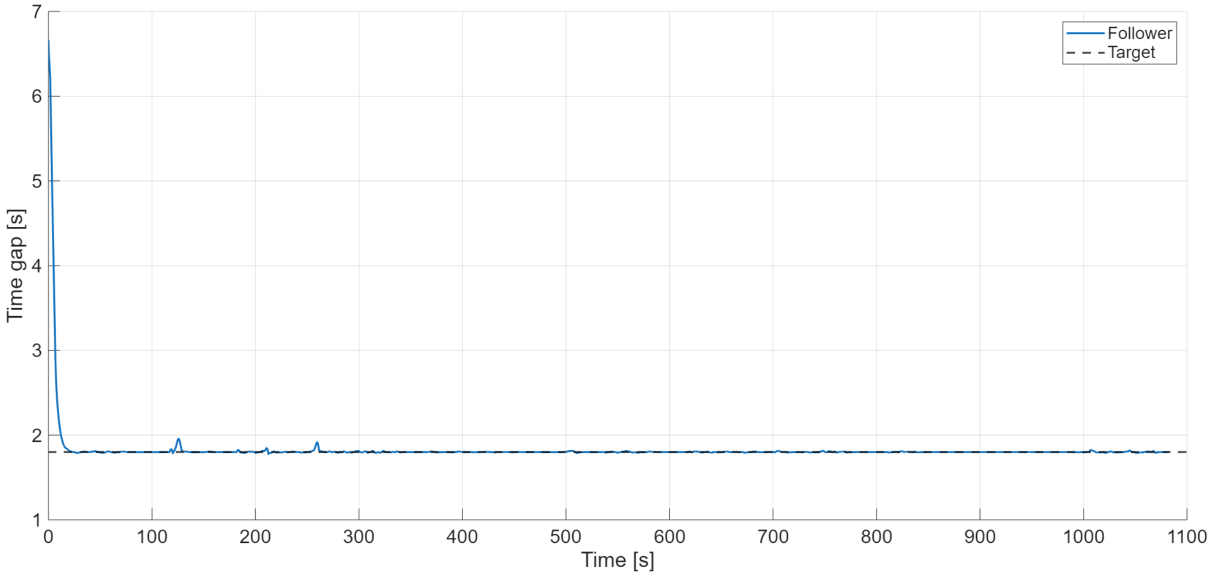


Figure 1.27: Time gap profile

It can be observed that even imposing wet road condition (setting μ_{wet} on the Matlab script), the Ego Vehicle is able to properly adapt his speed profile to the desired time gap from the leader. After some seconds of initial evolution (which is mainly relatable to the different initial conditions in terms of position and velocity) the Ego vehicle reaches the stability.

Additionally, also the safety constraints are respected: system's average automatic deceleration does not exceed 3.5 m/s^2 if averaged over 2 seconds and system's maximum deceleration rate (negative jerk) does not exceed 2.5 m/s^3 if averaged over 1 second.

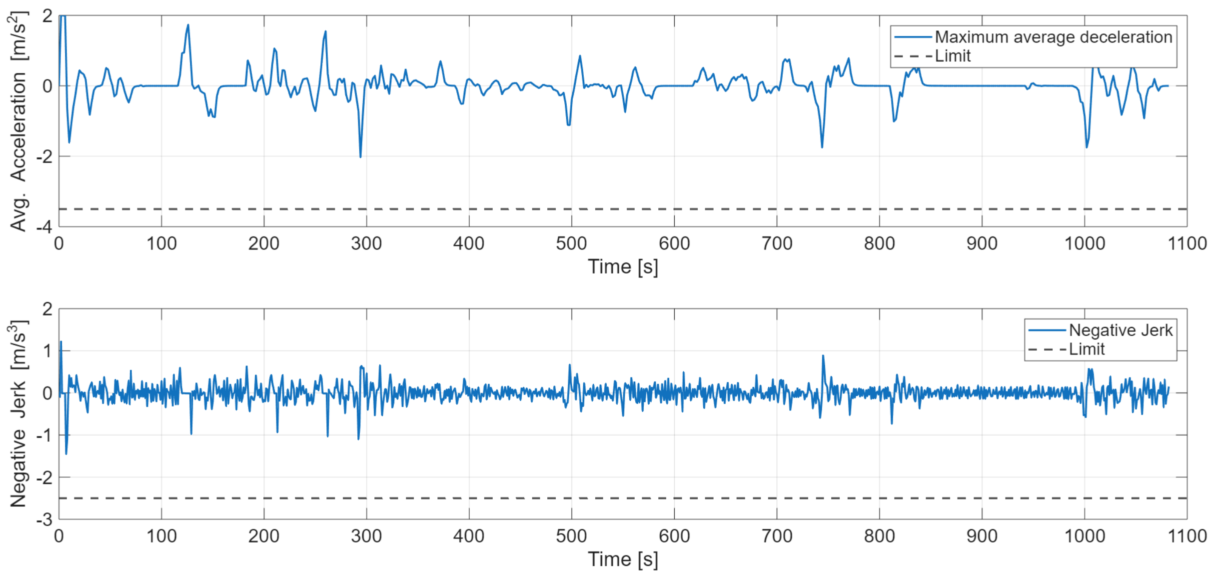


Figure 1.28: Safety constraints

1.3 Propedeutic exercise 2: platoon stability

The goal of the second propedeutic exercise is to study the stability of a platoon of vehicles.

1.3.1 Explanation of why the controller achieves platoon

Theorem: considering the string of vehicles, if the following conditions are assumed:

1. $h \geq 2\tau$
2. $g(t) = \mathcal{L}^{-1}\{G(s)\}$ has the same sign $\forall t \geq 0$

then, a value of λ exists such that the CTG controller ensures string stability.

Having a realistic value of $\tau = 0.5s$, a lower boundary of the time gap $h \geq 1$ must be ensured to prevent string instability. For this reason $h = 1.8s$ has been chosen, allowing an increased traffic capacity. The choice on $\lambda = 0.4$ is not critical and it has been performed by trial-and-error.

$$\lambda = 0.4 \quad h = 1.8s$$

Table 1.3: Summary of the ACC parameters

For a string of vehicles, the transfer function from δ_{i-1} to δ_i is obtained linearizing this model and applying the Laplace transform.

$$G(s) = \frac{s+\lambda}{\tau h s^3 + h s^2 + (\lambda h + 1)s + \lambda} = \frac{s+0.4}{0.9s^3 + 1.8s^2 + 1.72s + 0.4}$$

Using Matlab commands *hinfnorm* and *impulse*, it was possible to verified that :

$$\|G(s)\|_\infty \approx 1 \quad \text{and} \quad g(t) \geq 0 \quad \forall t \geq 0$$

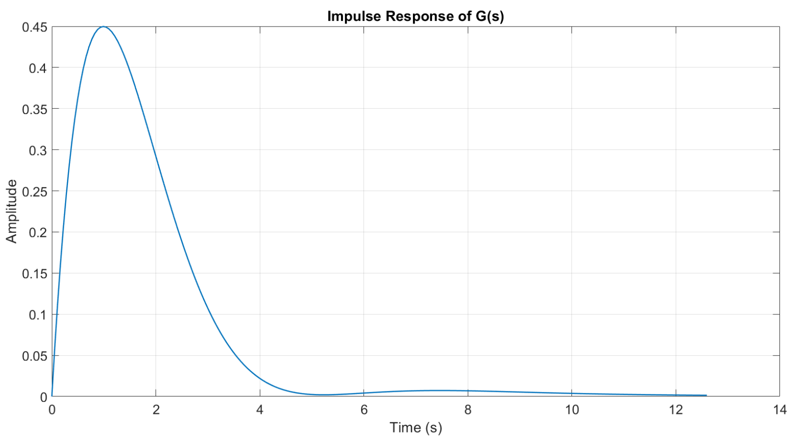


Figure 1.29: 2^{nd} condition of the theorem

1.3.2 Case 1

It is possible to provide an explanation about case 1 on the reason why time distance between the 1^{st} and 2^{nd} vehicle has more fluctuation than other vehicles.

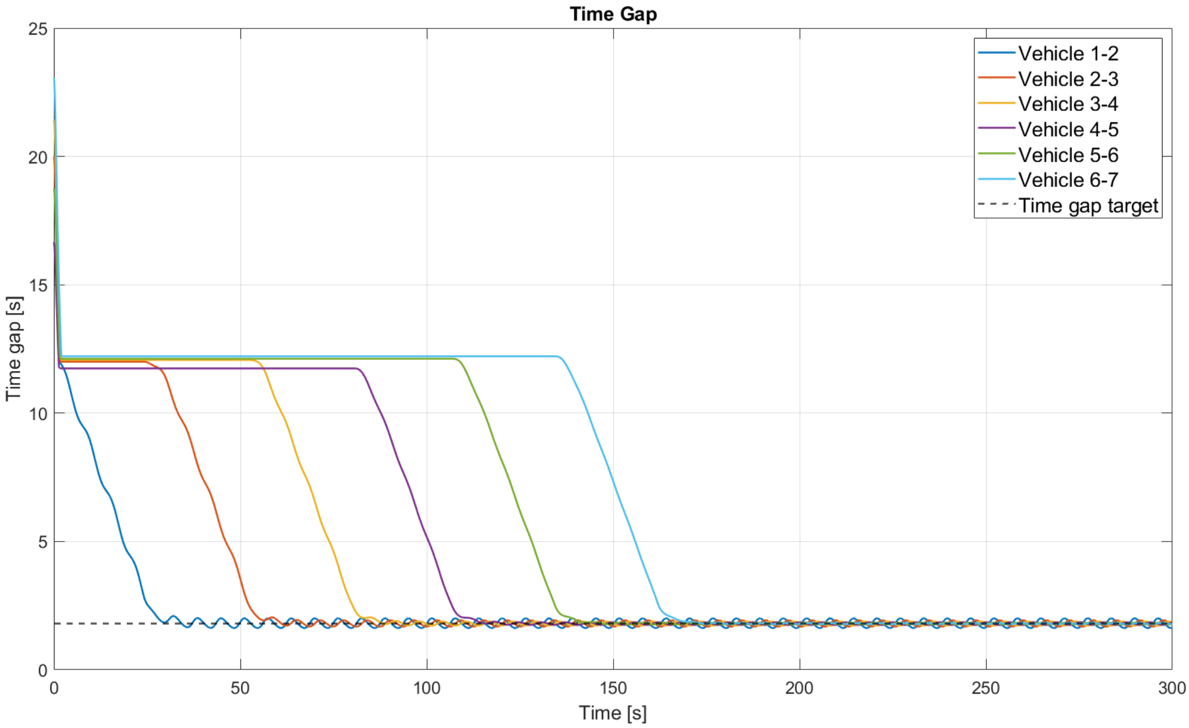


Figure 1.30: Time gap evolution for speed profile 1

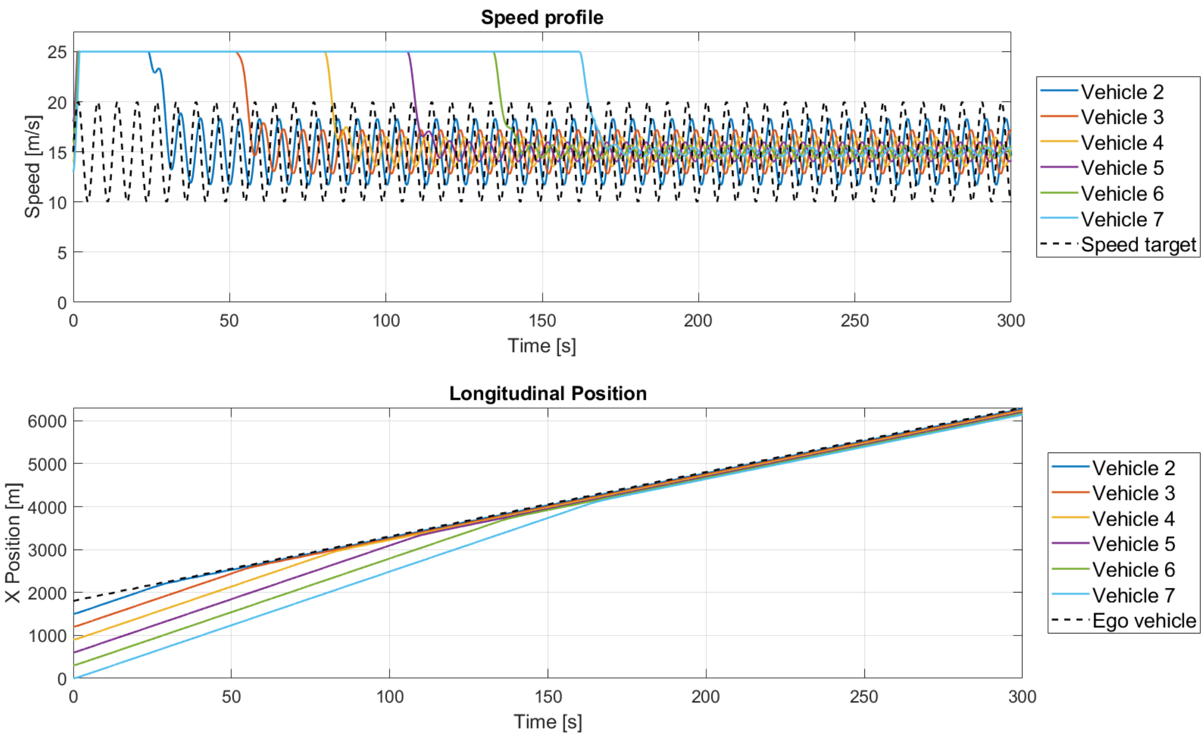


Figure 1.31: Speed and position of each vehicle of the string

In order to accomplish string stability, the spacing error δ_i should decrease with the number of vehicles in the platoon. δ_i is related to the actual distance between two vehicles ϵ_i which, in case of CTG policy, is equivalently expressed as time distance. Being the speed profile a sinusoidal one, the fact that the spacing error has the highest fluctuation for the first couple of vehicle reflects also on the time distance fluctuations.

1.3.3 Case 5

Also for case 5, as the simulation goes forward each vehicle decreases its own gap until the desired one ($h = 1.8s$) is reached. It can be seen from the graph that platoon stability is accomplished after a considerable amount of time: until last vehicle of the string reaches the platoon, few minutes are needed to close the initial distance gap.

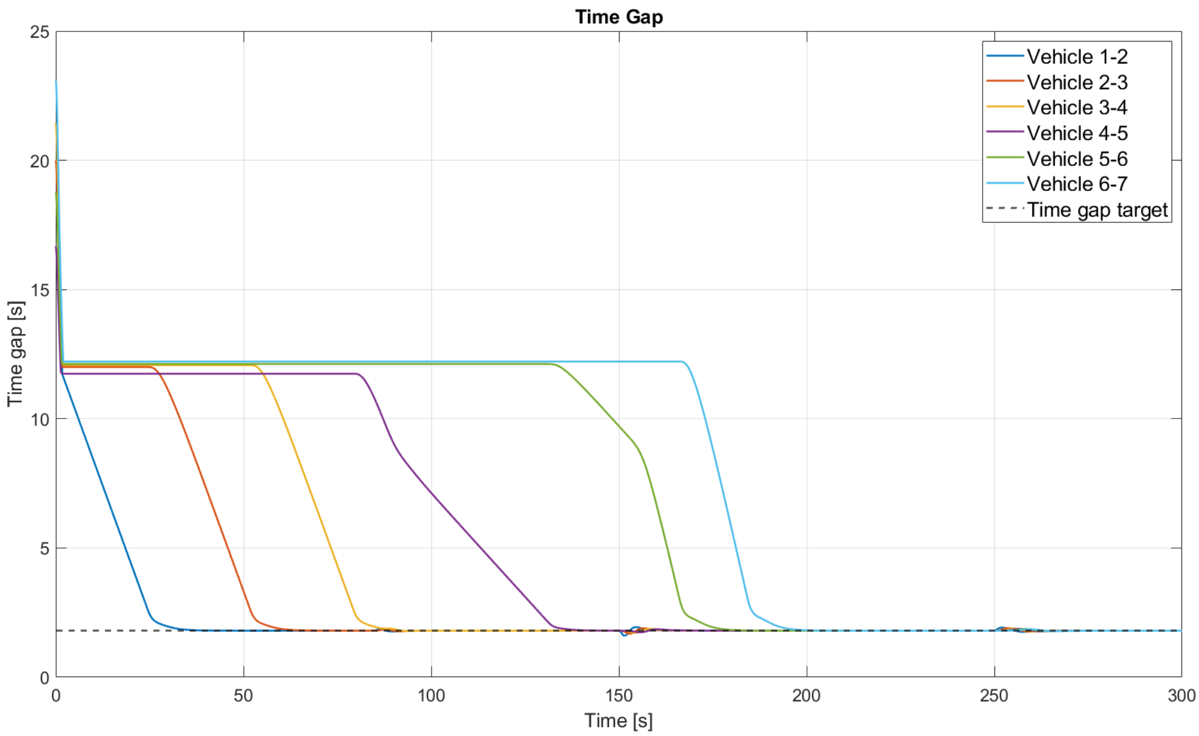
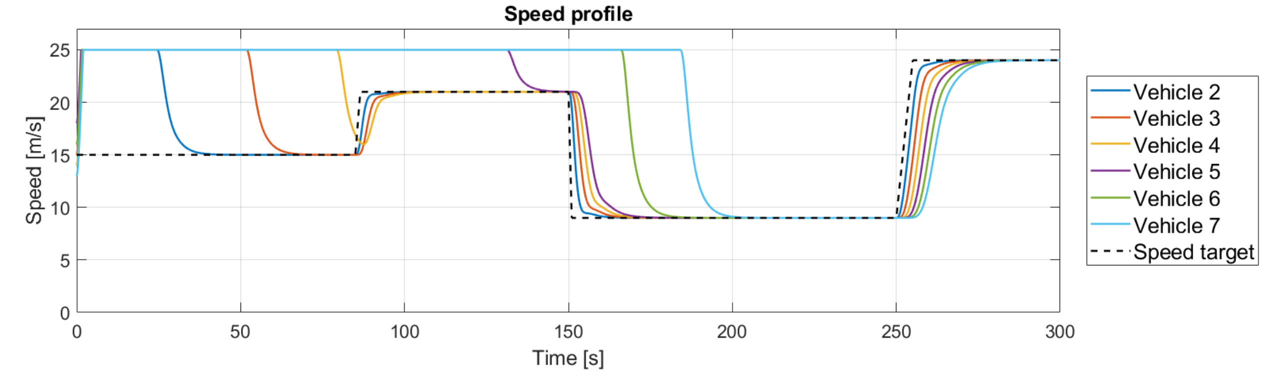


Figure 1.32: Time gap evolution for speed profile 5

Once the platoon is reached (after 200 s) the vehicles follow the speed profile of the leading vehicle with good precision. From the longitudinal position graph it is noticeable that all the vehicles converge to similar distances at the desired time gap.



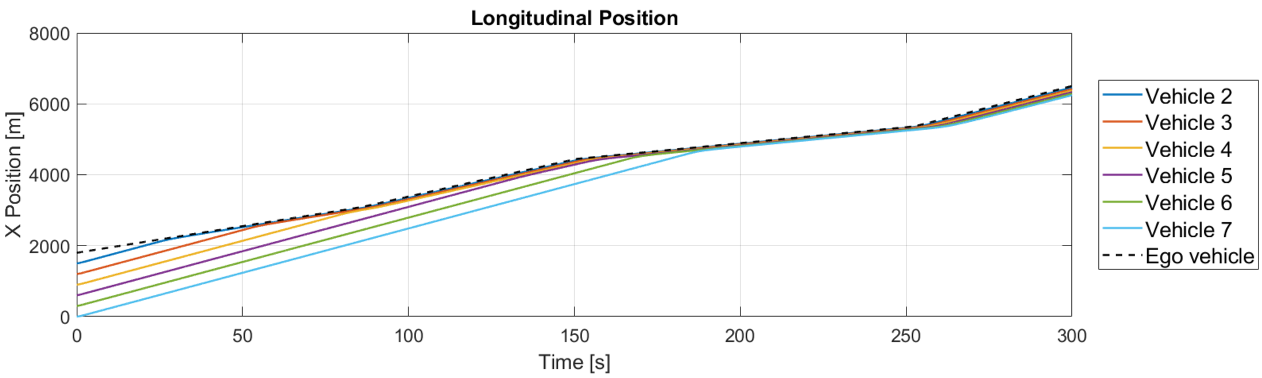


Figure 1.33: Speed and position of each vehicle of the string

1.3.4 Case 6

From the plot below it is observable that the controller fails but only for the 1^{st} vehicle.

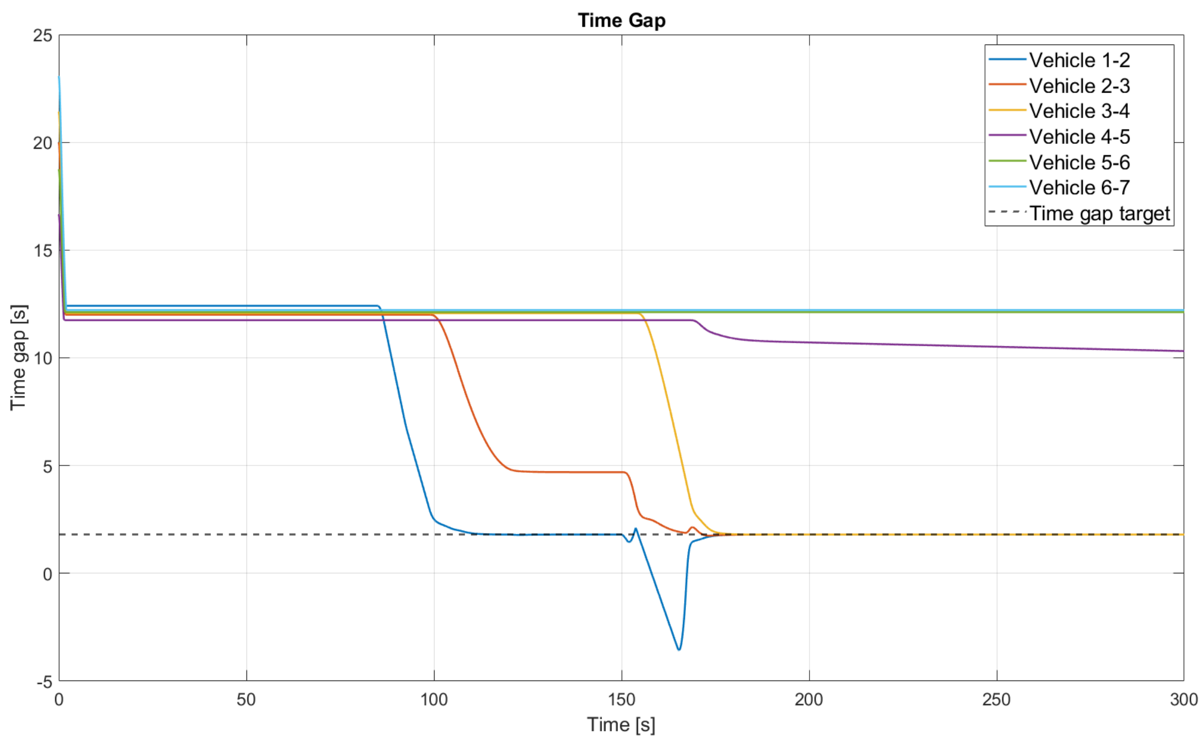


Figure 1.34: Time gap evolution for speed profile 6

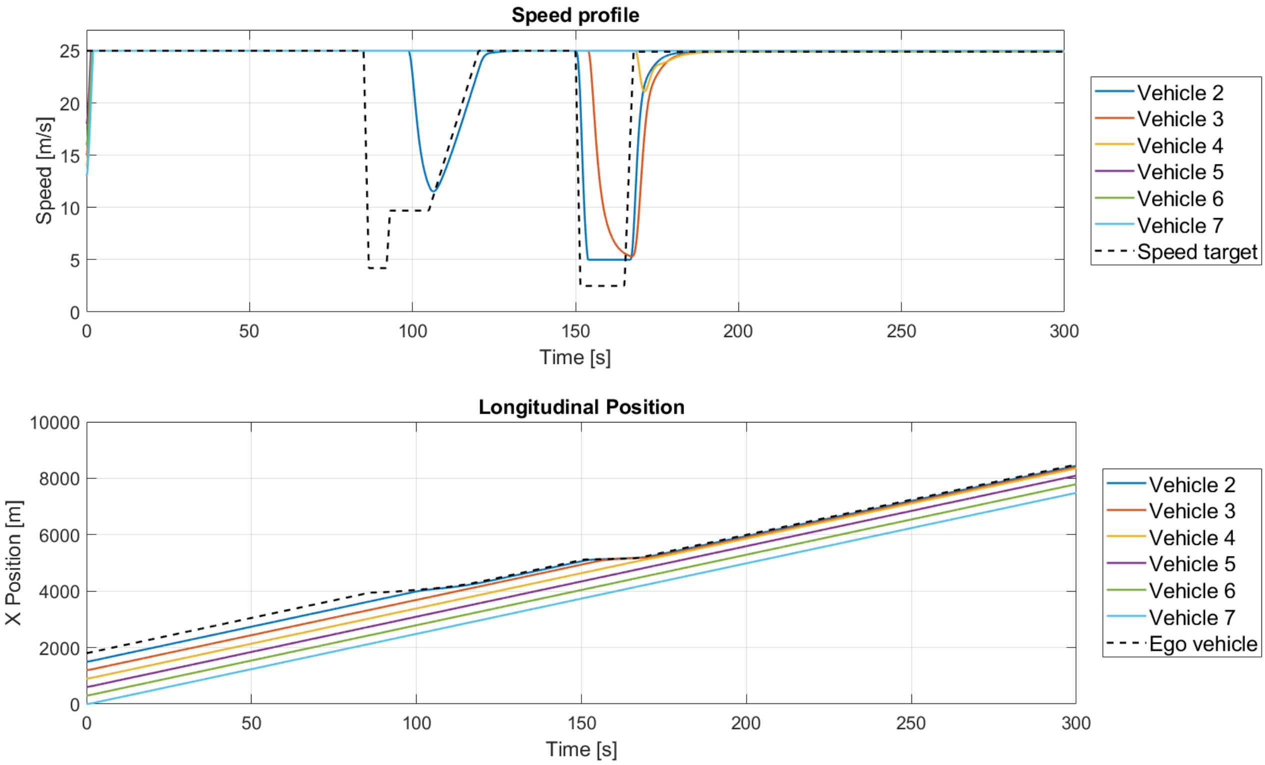


Figure 1.35: Speed and position of each vehicle of the string

As it is observable from the speed profiles, the controller fails only for the first following vehicle because it is the one that is called to a strong breaking maneuver below a speed of 5 m/s. The ACC cannot set an operating speed below a certain minimum threshold and, as a consequence, if not deactivated it set a minimum operating speed of 5 m/s (which is not enough to avoid the collision). Other following vehicles (having the same constraints of the vehicle 2) can avoid the impact reducing their speed up to that same threshold of the one in front, as it can be seen from the speed profile of vehicle 3.

1.3.5 Case 7

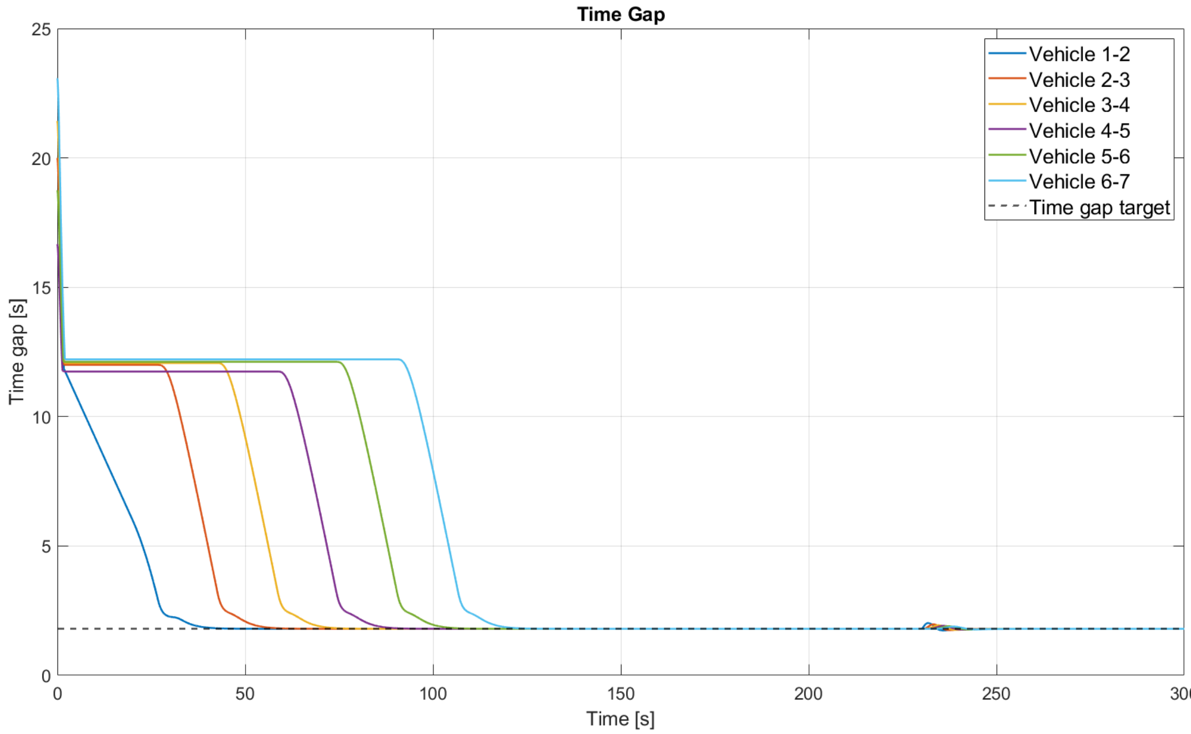


Figure 1.36: Time gap evolution for speed profile 7

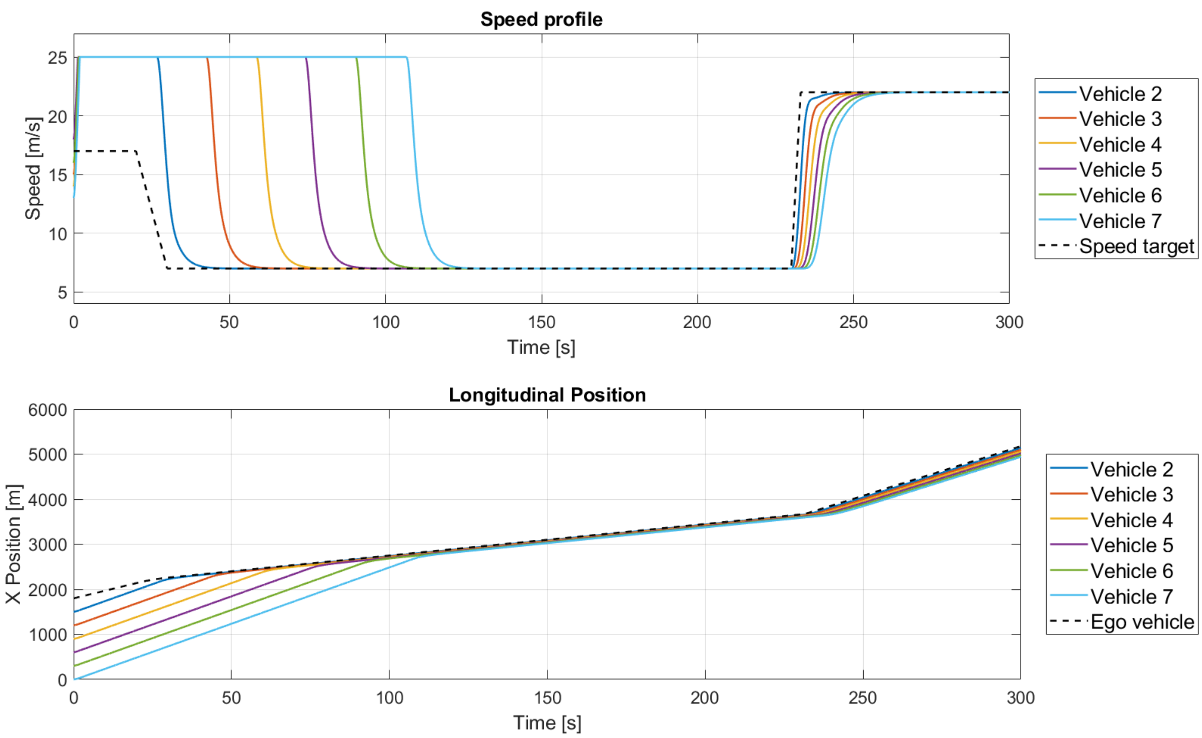


Figure 1.37: Speed and position of each vehicle of the string

Looking at the speed profiles, it is possible to observe that the response to the first step (leading vehicle strongly decelerating) is clearly slower than the second one (about 200s after the simulation is started): this happen because while the leading vehicle is strongly braking, the following ones are still trying to catch him. For this reason they remain at their maximum speed, postponing the braking action in order to close that pre-existent gap.

Differently, at the second speed step, all the vehicles are already aligned on the desired time gap, so the step action on the accelerator pedal from the controller is more immediate since there is not an exceeding gap that requires to be closed.

1.4 Exercise 2: ACC design and tuning of the platoon stability

For this exercise, the same control structure designed in Project exercise 1 is implemented for each vehicle which is part of the string: all the following vehicles are characterized by a CTG, a PI controller for pedals and the model of the vehicle with the same structure discussed in figure 1.15.

The design parameter of the CTG and PI controller are the same discussed for exercise 1 in table 2.1.

1.4.1 Case 1

Since the lead vehicle follows a sinusoidal speed profile, it introduces a continuous oscillation in speed. Vehicle 2, being the first in line behind the leader, is directly exposed to these fluctuations without any damping or filtering from other vehicles. It attempts to track the leader's speed closely, causing its time gap to fluctuate significantly in response to the sinusoidal changes.

Subsequent vehicles (Vehicles 3, 4, etc.) follow a vehicle that is already responding to the leader's oscillations. This response acts like a low-pass filter, smoothing out the fluctuations. Thus, Vehicle 3 experiences less fluctuation than Vehicle 2, and so on. This is often referred to as string stability, where perturbations diminish down the vehicle string if the system is designed properly.

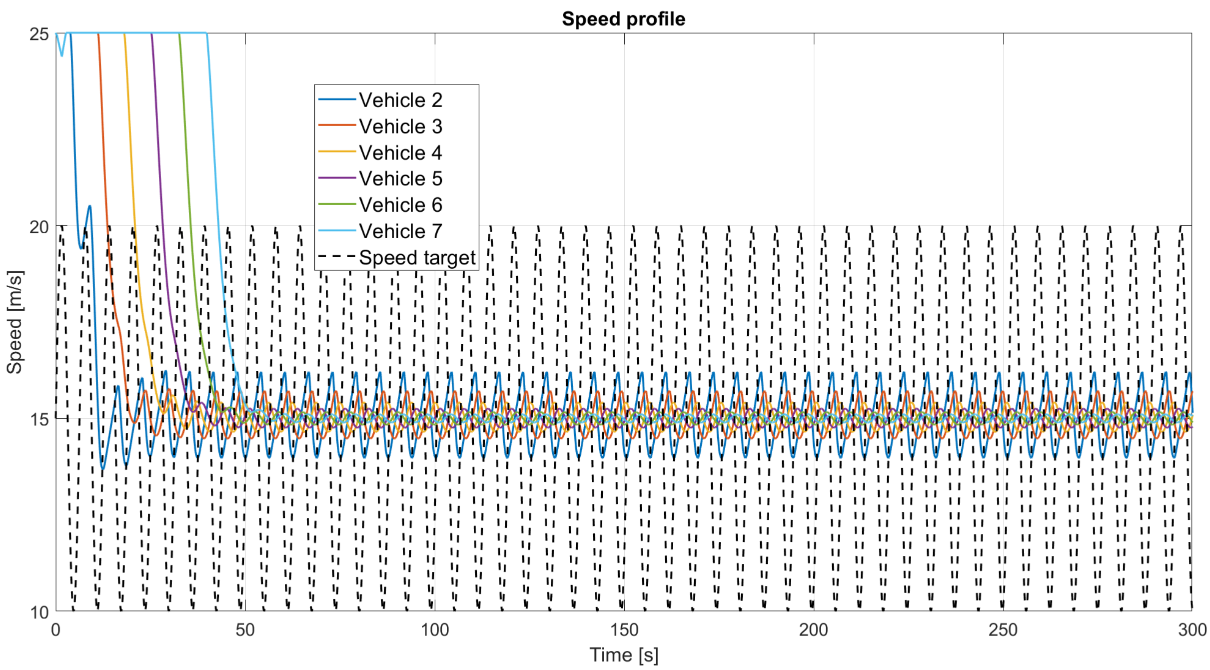


Figure 1.38: Speed and position of each vehicle of the string

It is possible to observe (as it was previously discussed in case 1 for propedeutic exercise) that time distance between the leading and first following vehicle has more fluctuation than other vehicles. Differently from chapter 1.3.2, the following vehicles reach faster the desired time gap, proving that the implementation is improved using a complete vehicle model rather than a simplified one.

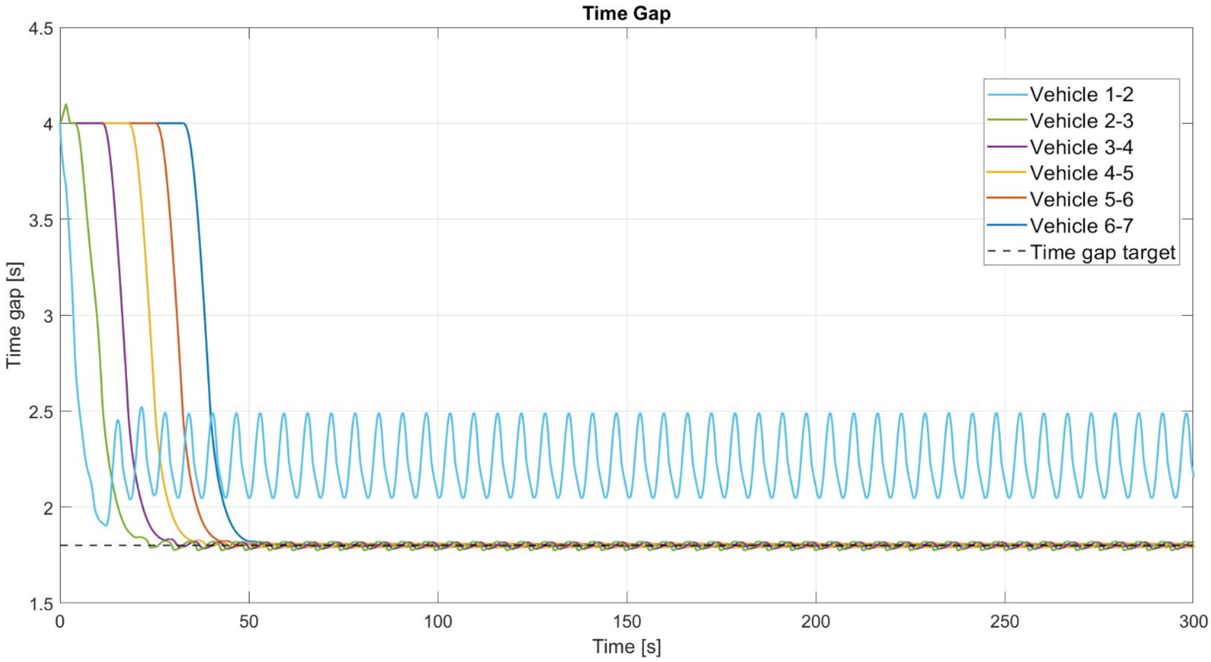


Figure 1.39: Time gap evolution for speed profile 1

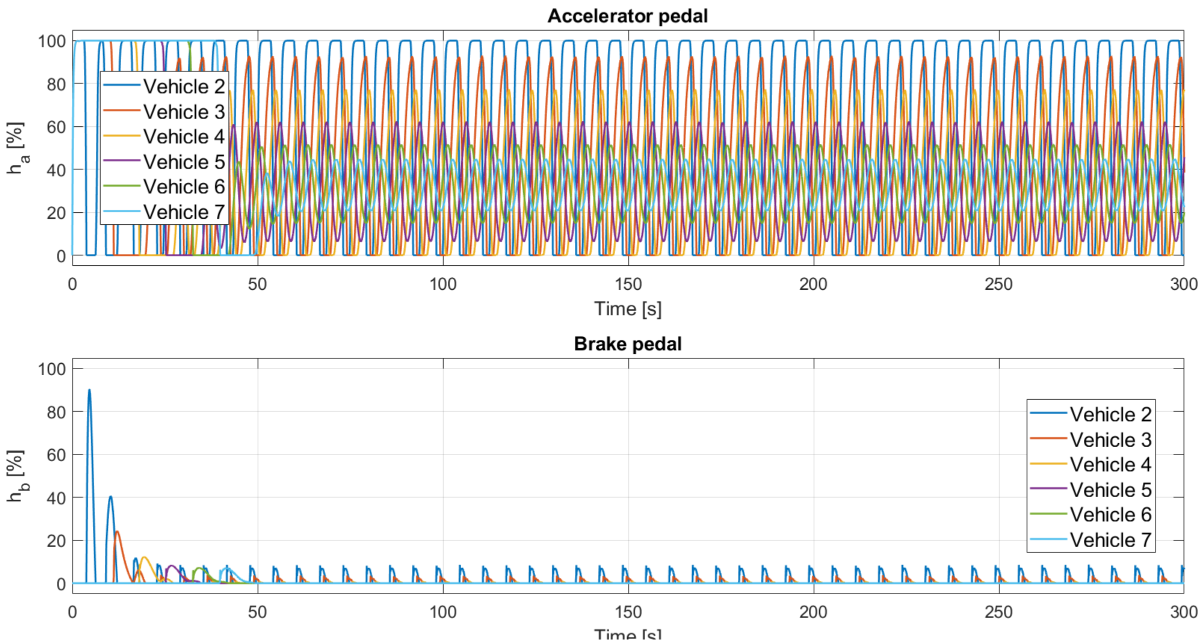


Figure 1.40: Pedals commands for the mission

1.4.2 Case 5

The speed profile 5 is characterized by step variations.

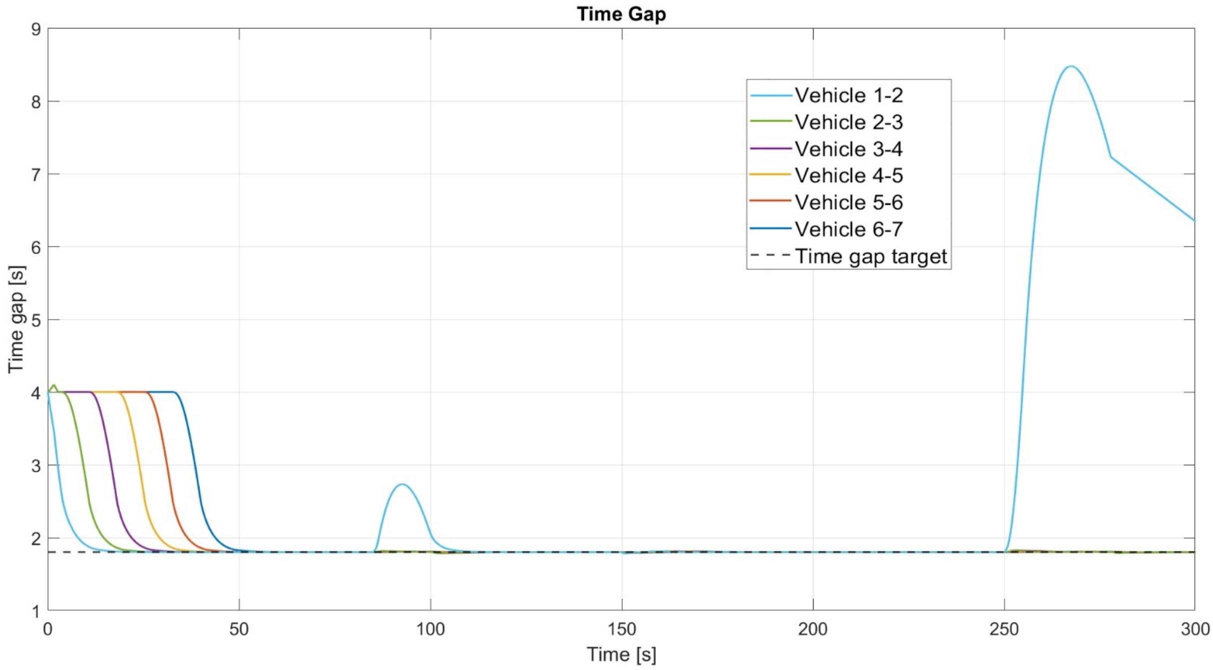


Figure 1.41: Time gap evolution for speed profile 5

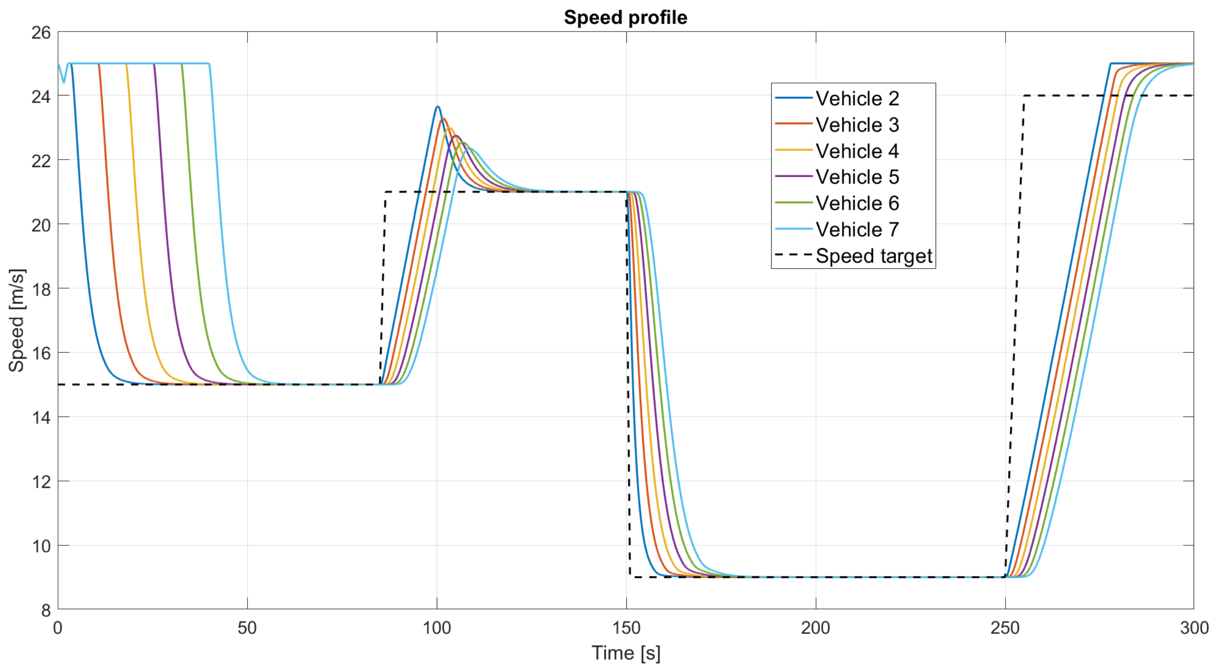


Figure 1.42: Speed and position of each vehicle of the string

Comparing the plots with the one obtained from case 5 of propedeutic exercise 2, it is correct to assume that the response of the following vehicles to the step variations of speed of the leading one is strongly dependent from the dynamic of the vehicle: for our simulations, the compact vehicle has been chosen.

This configuration makes it evident, as illustrated in the graph below, that although the response to speed changes is immediate (confirmed by the prompt reaction of the pedal commands, which demonstrates the controller's effectiveness) the following vehicles are unable to match the acceleration profile of the leader. This is indicated by a trajectory slope that deviates considerably from the near-vertical line followed by the leading vehicle.

This is also an explanation on why the time gap between leading vehicle and first one following considerably increases at the steps (especially last one at time = 250 s) while the others behind are able to keep the same pace of the one in front since it is characterized by the same dynamics (all of them are different from the leading one).

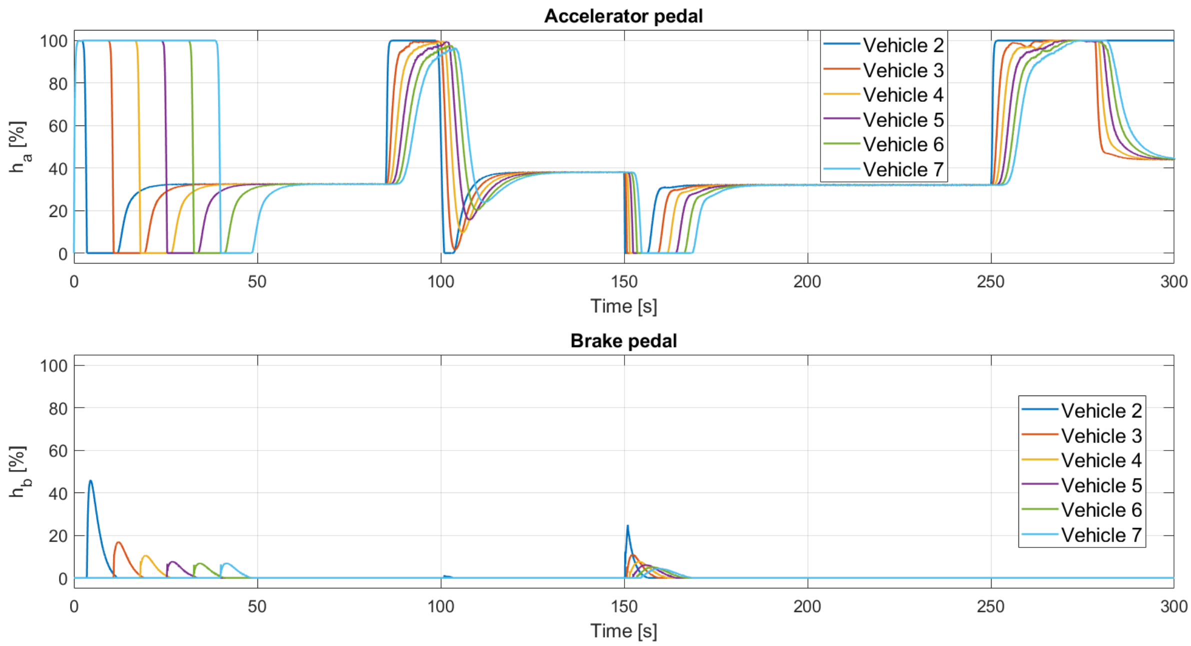


Figure 1.43: Pedals commands for the mission

1.4.3 Case 6

As it was discussed in propedeutic exercise 2, this speed profile is characterized by the failure of the controller: it fails only for the first following vehicle which is the one called to a strong breaking maneuver, below a speed of 5 m/s to avoid the crash.

The ACC cannot set an operating speed below a certain minimum threshold and, as a consequence, if not deactivated it set a minimum operating speed of 5 m/s (which is not enough to avoid the collision). Other following vehicles (having the same constraints of the vehicle 2) can avoid the impact reducing their speed up to that same threshold of the one in front, as it can be seen from the speed profile of vehicle 3.

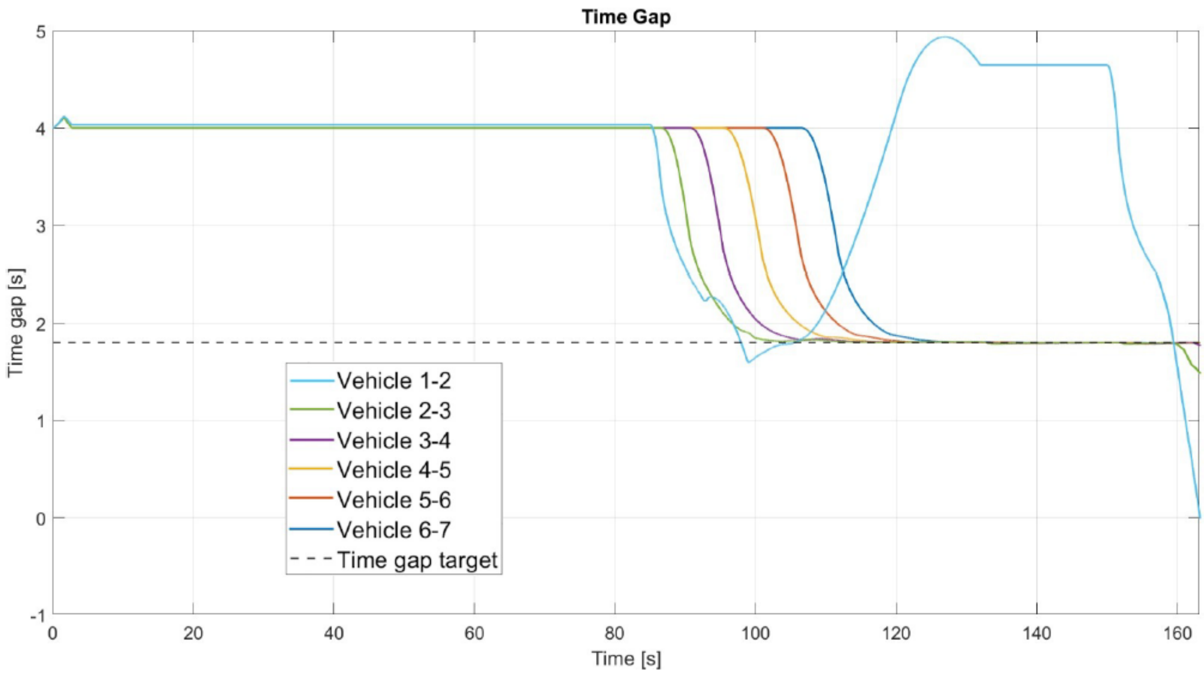


Figure 1.44: Time gap evolution for speed profile 6

Differently from propedeutic exercise 2, a complete vehicle model + PI controller for pedal commands allows to achieve a better response to step variations looking at the speed profiles.

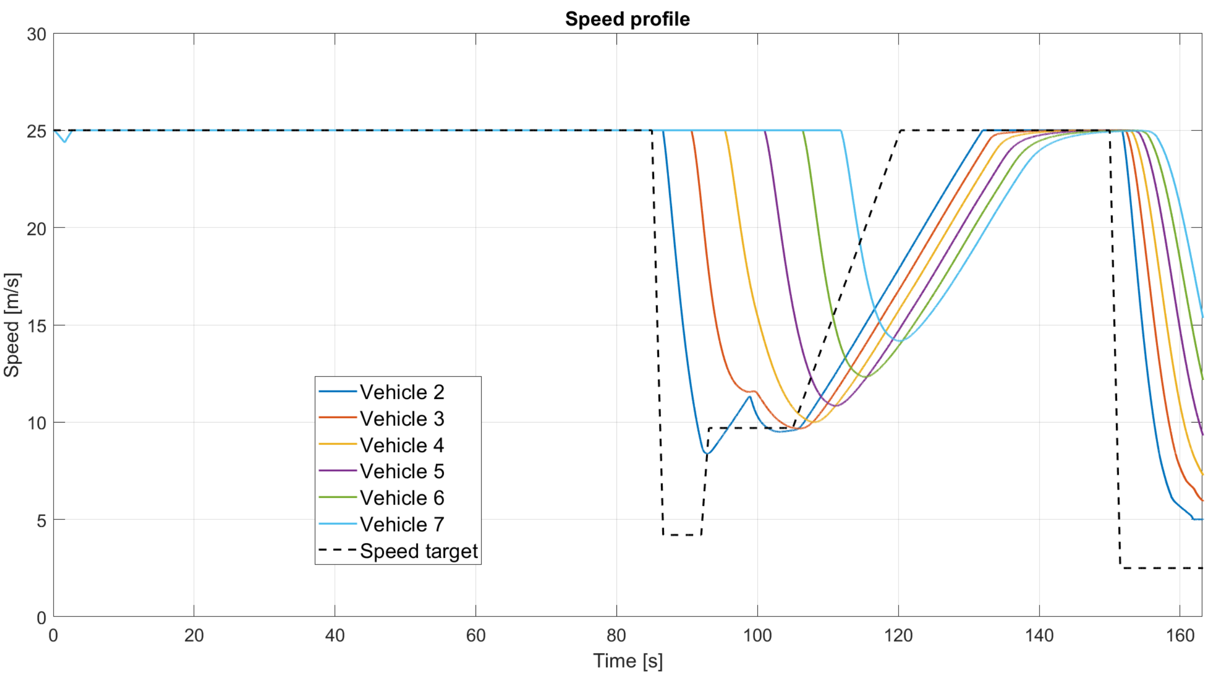


Figure 1.45: Speed and position of each vehicle of the string

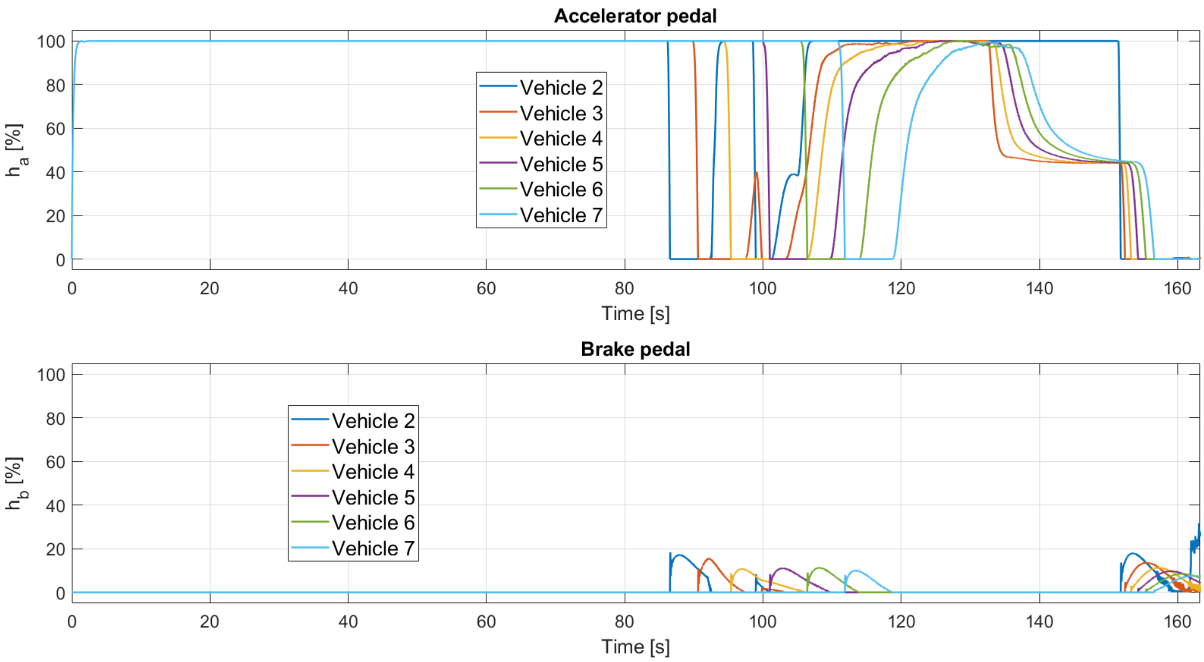


Figure 1.46: Pedals commands for the mission

1.4.4 ACC testing without speed constraints on Ego Vehicle speed

The driving cycle chosen for the simulation is the "Artemis motorway 130 kph driving cycle". In order to allow the controller to work properly, only a lower boundary saturation is imposed: this is also due to the fact that below certain speeds there is no interest in testing the ACC. The upper constraints are removed because the aim is to test the ACC at every possible speed of the driving cycle as requested.

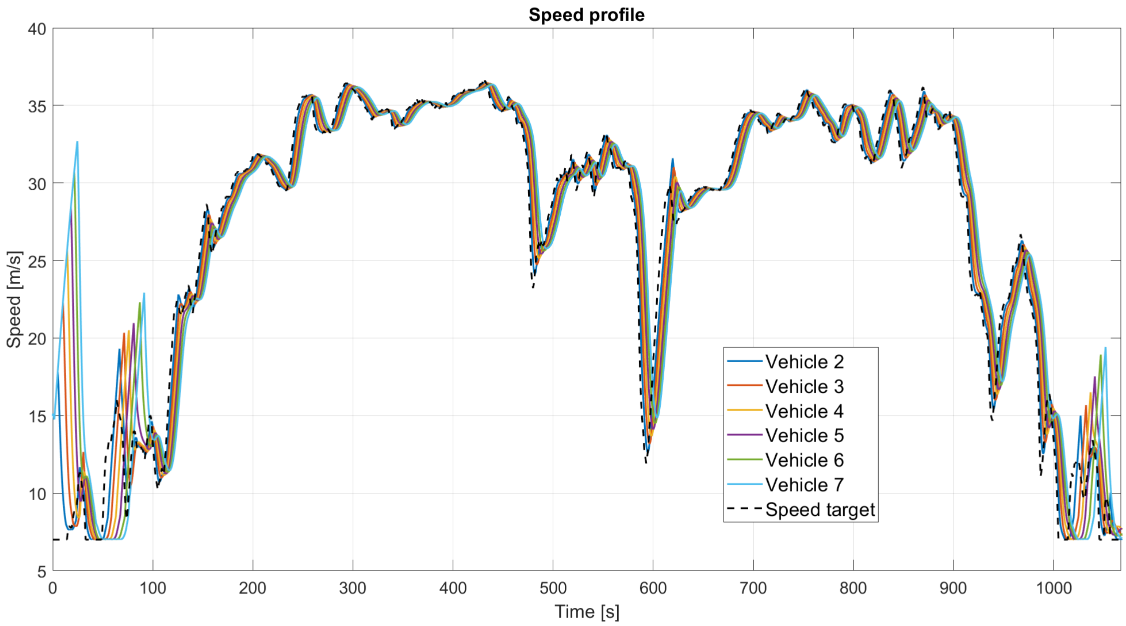


Figure 1.47: Speed profile

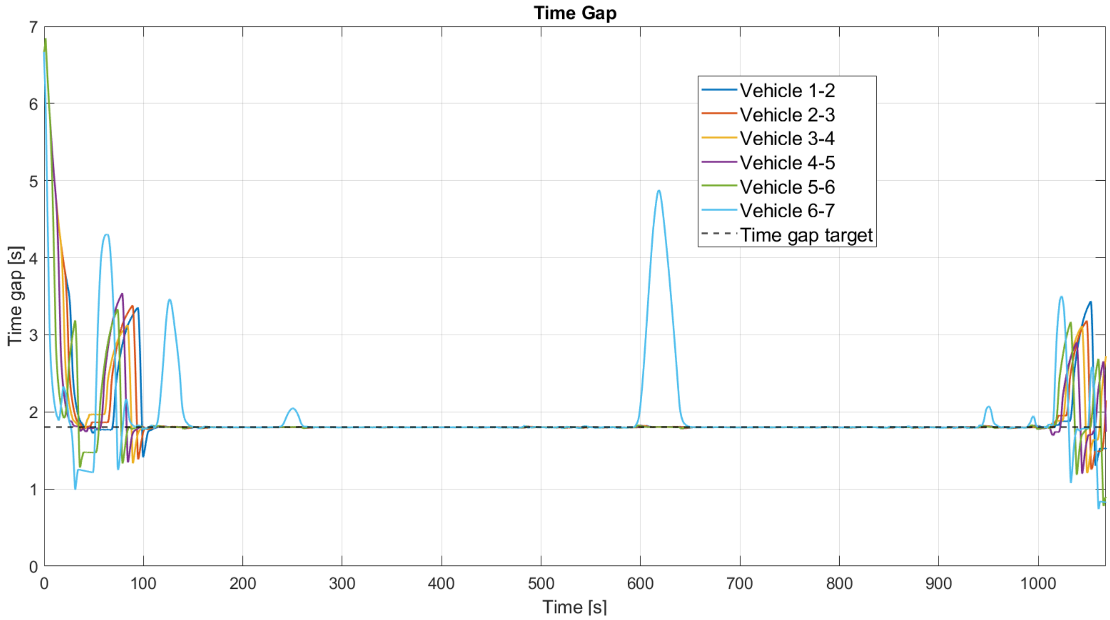


Figure 1.48: Time gap evolution

It can be noticed that the Ego Vehicles successfully adjusts their speeds to maintain the target time gap with the leading vehicle. Following a brief initial phase, primarily due to differences in starting position and speed, the Ego Vehicles achieve stability.

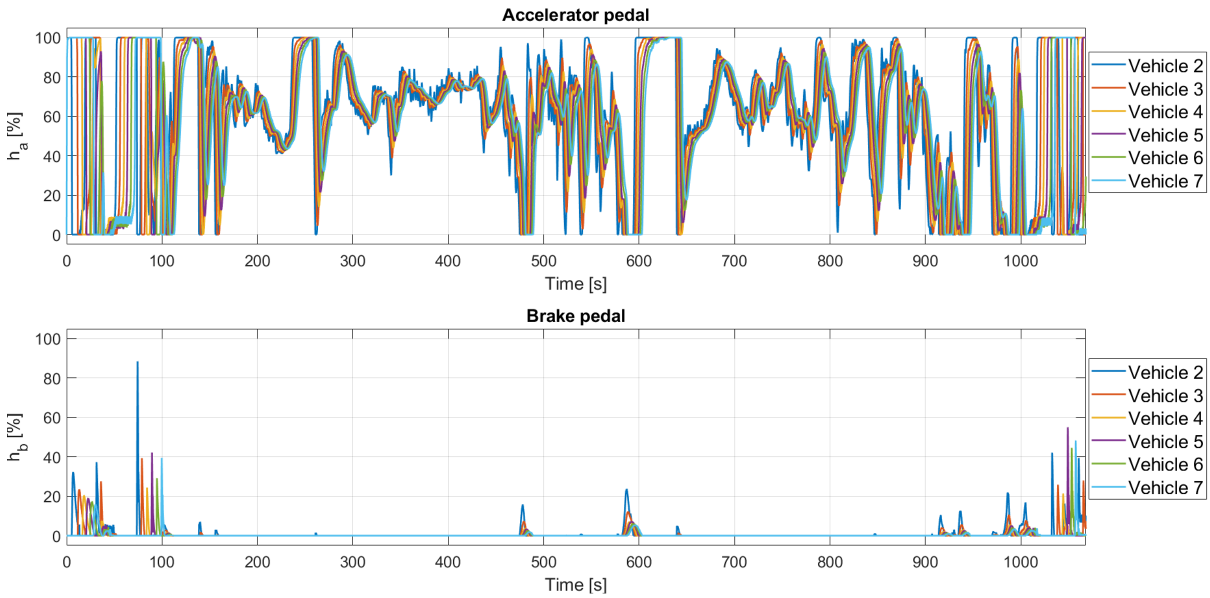


Figure 1.49: Pedals commands for the mission