TAV assignment: Path tracking and Lane Keeping Control

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1. Introduction

This report is intended to evaluate the performances of different controllers to achieve path tracking and lane keeping on a single-track model using MATLAB and Simulink.

2. Model layout

The single-track model is implemented in a state-space form. The state of the system is composed by the lateral deviation and the relative yaw angle and their first derivatives. The control is achieved through the difference between a feedforward and a feedback contribution, the result control input is the steering angle of the vehicle. This input is created to compensate the disturbance input which corresponds to the desired yaw rate. It is noticeable that, since the matrices of the system depend on the velocity of the vehicle, both the feedback and feedforward gains depend on it. This relationship is shown in figure 1 where the control structure has been tuned through a linear quadratic set up.

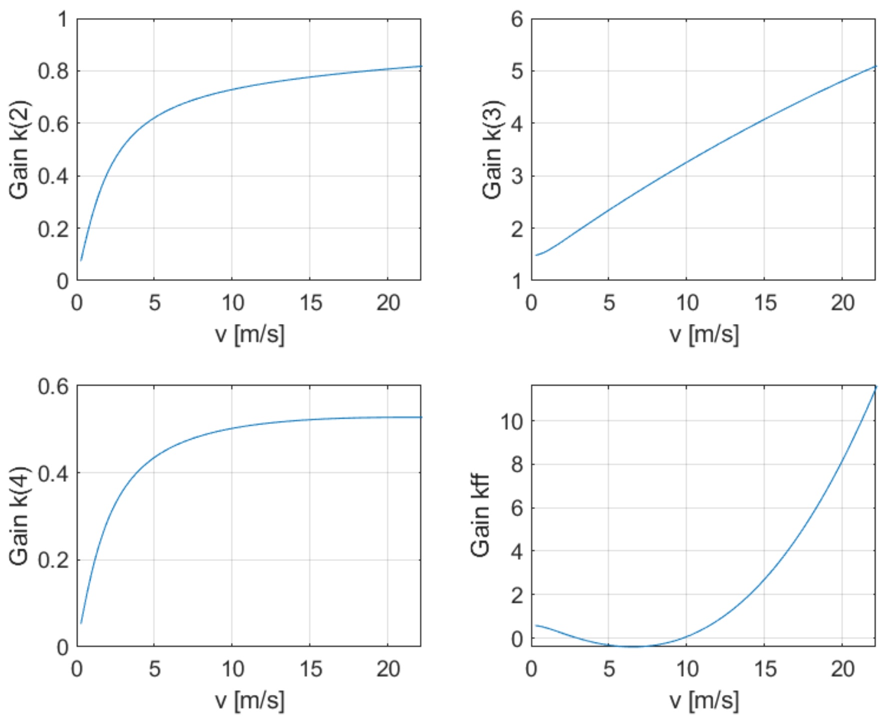

FIGURE 1. Relationship between Gains and velocity

Notice that the first gain of the feedback has not been reported since it's value is consistently around 1.

3. Tuning and performances

In order to evaluate the performances of the control system, various trajectories and speed are considered for tuning. The chosen metrics are the Root Mean Square Error (RMSE) of the lateral deviation and the energy of the control input. Three different configuration of Q and R are chosen such as:

$$Q = 100 \cdot \mathcal{I}_{4\times 4} \quad R = 1$$

$$Q = 100 \cdot \mathcal{I}_{4\times 4} \quad R = 10$$

$$Q = 100 \cdot \mathcal{I}_{4\times 4} \quad R = 100$$

Those configurations have been tested on four different paths

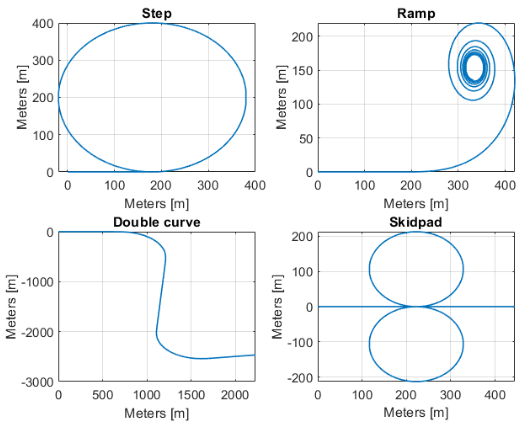

FIGURE 2. Four trajectories

The results are shown below

TABLE 1. Results at 80 km/h

Reference	**Parameters Q**	**R**	**RMSE**	**Feedforward energy**	**Feedback energy**
step	100	1	1.33e-9	1.30	1.18
		10	1.44e-9	0.18	0.14
		100	1.92e-9	0.04	0.02
ramp	100	1	4.04e-7	49.28	44.88
		10	4.23e-7	6.75	5.18
		100	5.39e-7	1.43	0.77
double curve	100	1	5.24e-8	5.20	4.74
		10	5.56e-8	0.71	0.55
		100	7.08e-8	0.15	0.08
skidpad	100	1	2.29e-7	202.24	184.15
		10	2.48e-7	27.70	21.27
		100	3.32e-7	5.89	3.15

TABLE 2. Results at 130 km/h

Reference	**Parameters Q**	**R**	**RMSE**	**Feedforward energy**	**Feedback energy**
step	100	1	5.51e-8	23.42	22.96
		10	6.09e-8	2.72	2.57
		100	8.56e-8	0.41	0.35
ramp	100	1	1.77e-5	887.45	869.86
		10	1.79e-5	103.14	97.27
		100	2.03e-5	15.61	13.39
double curve	100	1	1.13e-6	152.20	149.22
		10	1.16e-6	17.69	16.69
		100	1.48e-6	2.68	2.30
skidpad	100	1	3.84e-6	5917.68	5801.71
		10	4.25e-6	687.78	648.62
		100	6.00e-6	104.12	89.23

It is noticeable that, with both velocities, by increasing R the controller pays more attention to save energy instead of achieving the minimum error possible. However, the RMSE remains small enough, meaning that the configuration is still suitable. Moreover, both the RMSE and the energy increase when the speed increases, as expected. With a speed of 130 km/h, the energy needed with all the configurations is really high, this means that it could be hard to actually realize a controller with these settings. It would be useful to do some more tuning to achieve a good compromise between RMSE and energy.

Because the RMSE doesn't change much, it has been chosen to use the configuration that needed less energy, the one with $Q = 100$ and $R = 100$ at a speed of 80 km/h, for all the next tests.

From these results it also appears that the contribution of the feedforward is always bigger than the feedback one, this last one results to be a corrective contribution, the plot below shows the two contributions.

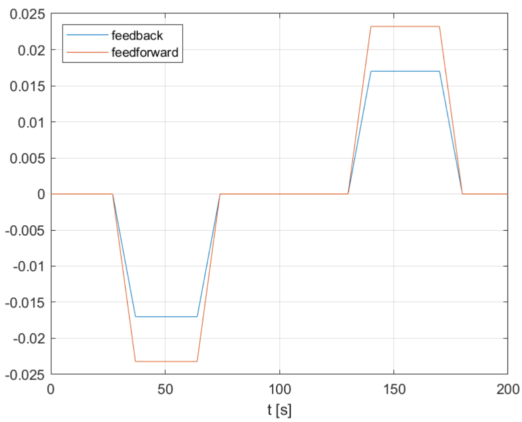

FIGURE 3. Feedback and Feedforward contributions on double curve path

4. Testing

In this paragraph we want to observe in detail the behaviour of the system during the manoeuvres showed before (figure 2). For each path some of the most important variables are shown, in particular:

- delta: the input steering angle;
- beta: vehicle sideslip angle;
- vehicle yaw rate;
- front and rear slip angles;
- lateral error;
- heading angle error;

4.1. *Step*

The first one is a simple step

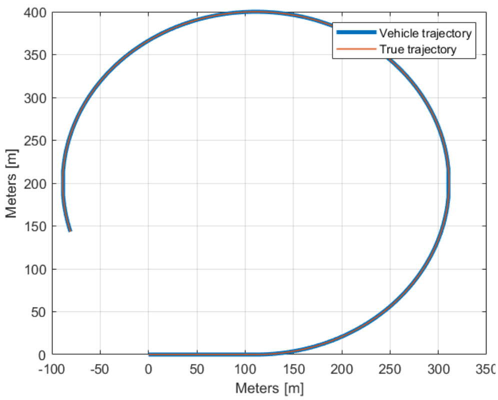

FIGURE 4. Constant steering angle

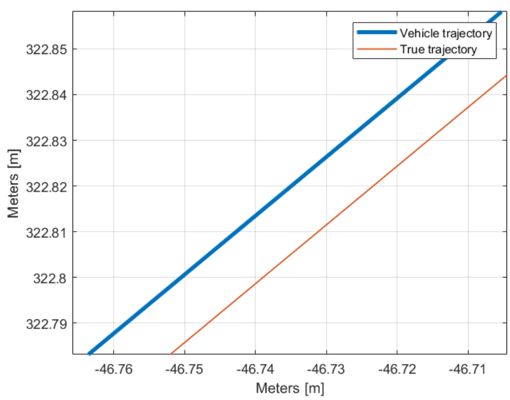

FIGURE 5. Trajectory zoomed

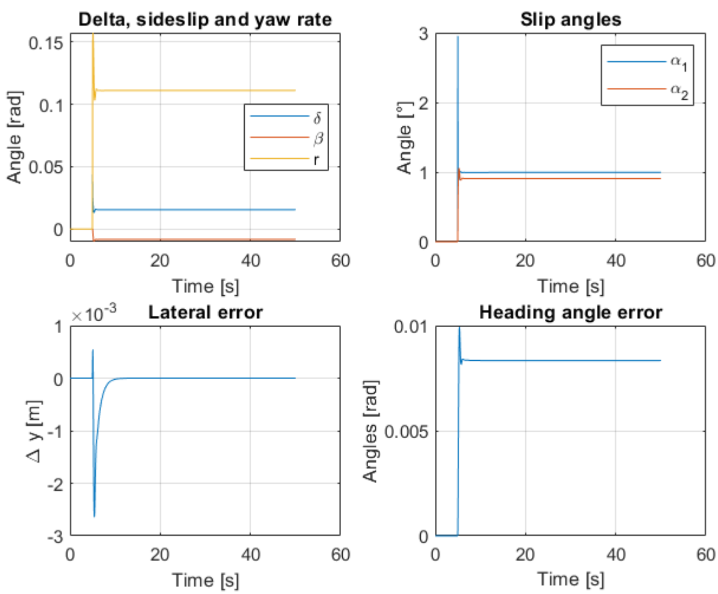

FIGURE 6. System variables

4.2. *Ramp*

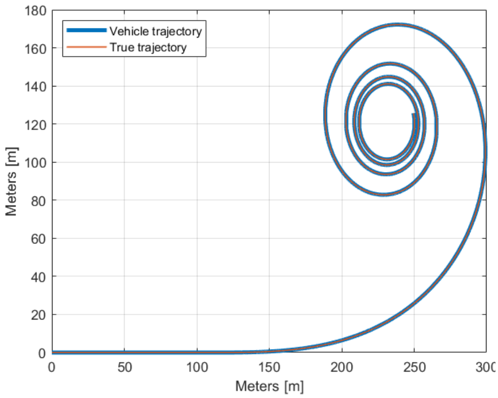

FIGURE 7. Ramp steering angle

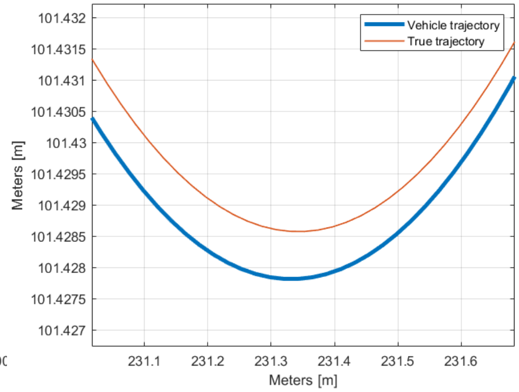

FIGURE 8. Trajectory zoomed

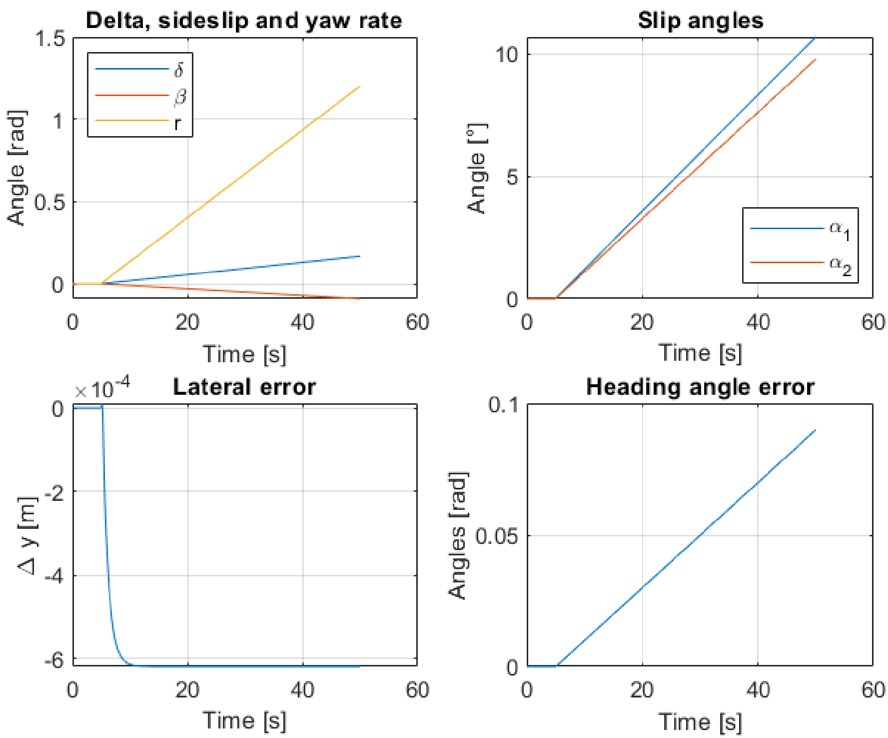

FIGURE 9. System variables

4.3. *Double curve*

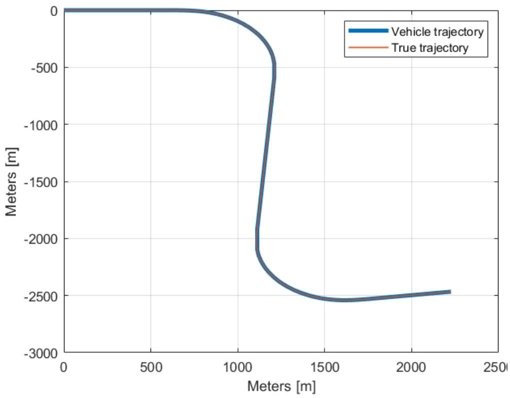

FIGURE 10. Double curve path

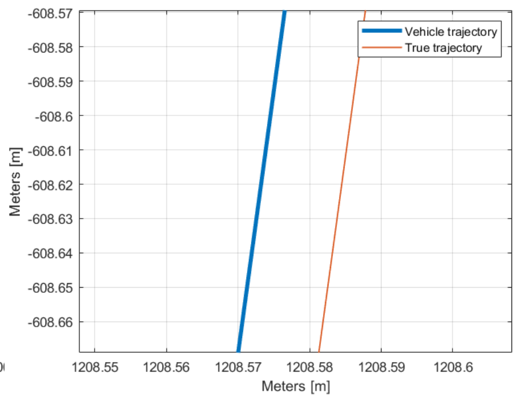

FIGURE 11. Trajectory zoomed

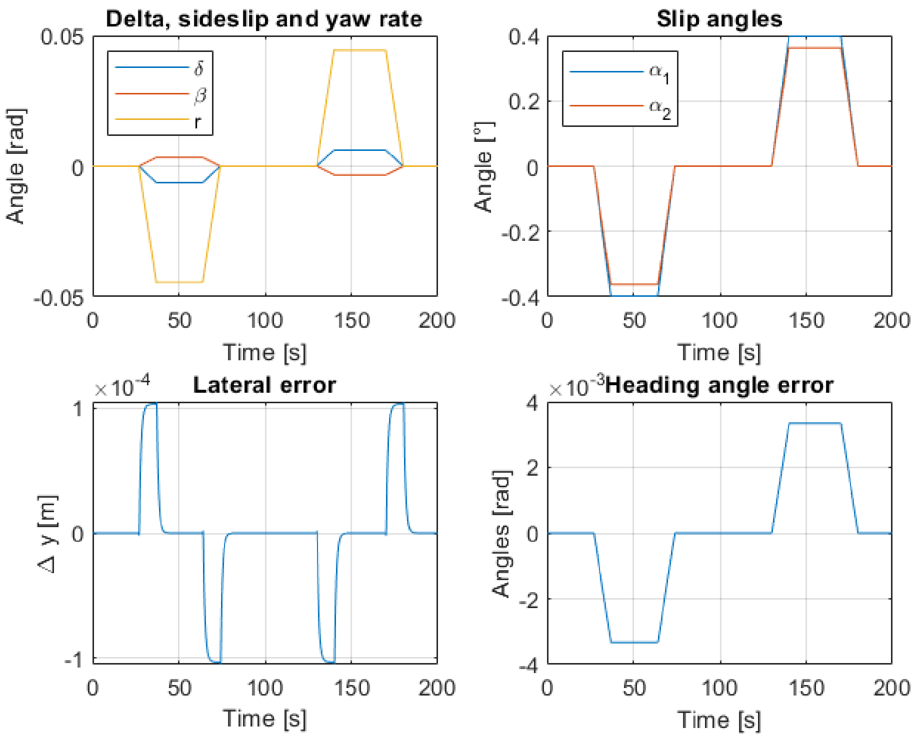

FIGURE 12. System variables

4.4. *Skidpad*

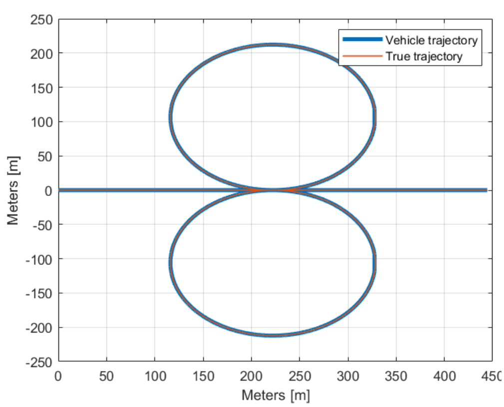

FIGURE 13. Skidpad circuit

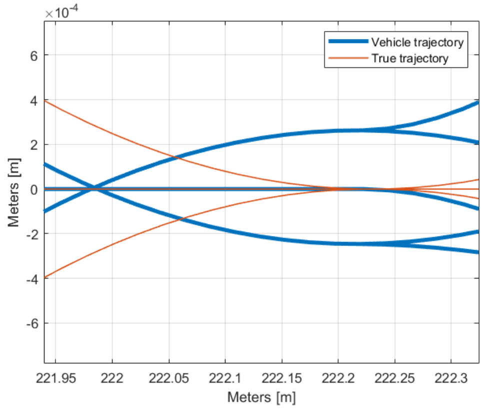

FIGURE 14. Trajectory zoomed

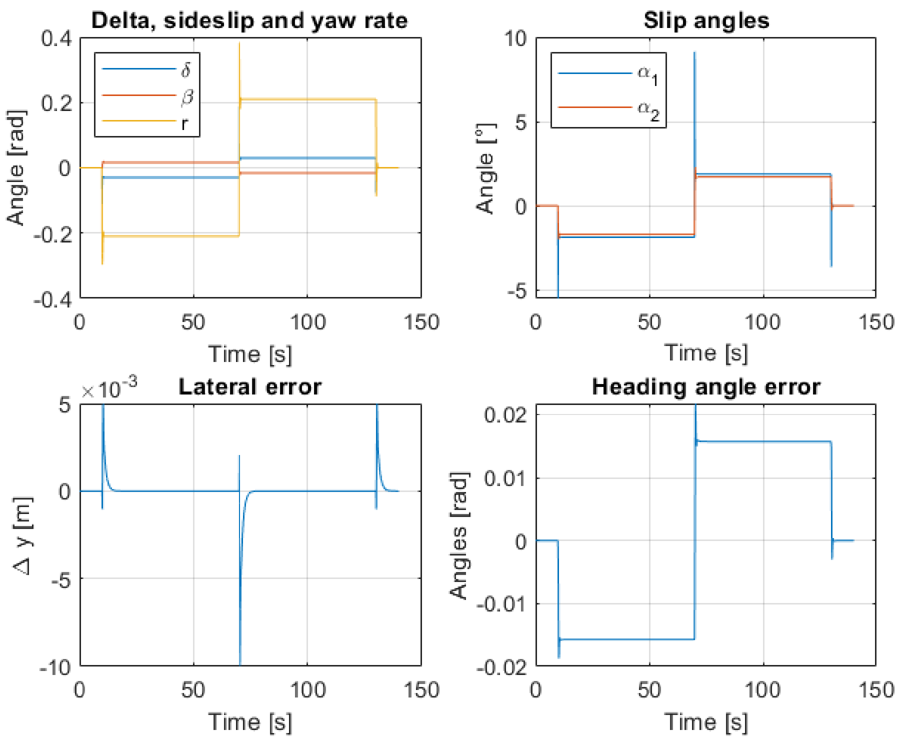

FIGURE 15. System variables

4.5. *Considerations*

The graphs before show that the controller is very strong and follows all the paths with a small lateral error, the main criticality is the response to a step command, as we can see, the response is characterized by an high overshoot that can be problematic in real application. This problem could be resolved with a better tuning or changing the curvature path.

5. Additional considerations

5.1. *Integral control contribution*

The presented control structure works well enough but can be further improved with the implementation of an integral contribution. This is achieved by adding a state that corresponds to the integral of the lateral deviation. This leads to a change in the feedback gain and improves the lateral deviation, even though it includes a small oscillation.

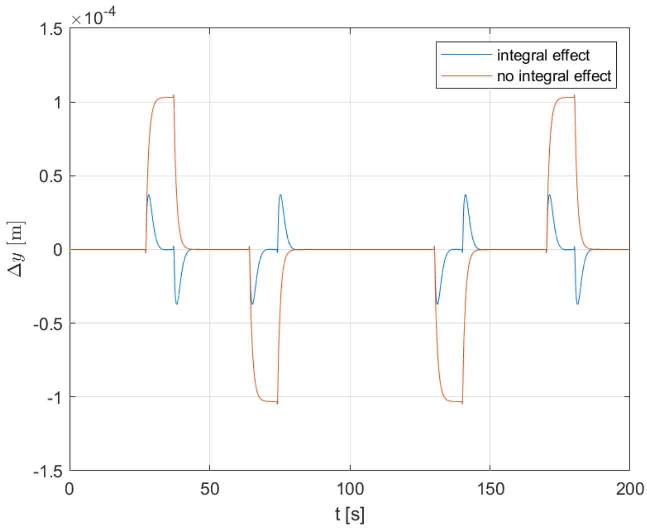

FIGURE 16. Effect of integral contribution on lateral deviation

5.2. *Understeer, oversteer and neutral control*

All the previous test have been carried out in an understeer condition. However, cars might also be affected by oversteering or being in neutral conditions. Therefore, this could change the values of the command input and the lateral deviation, as shown in the following images.

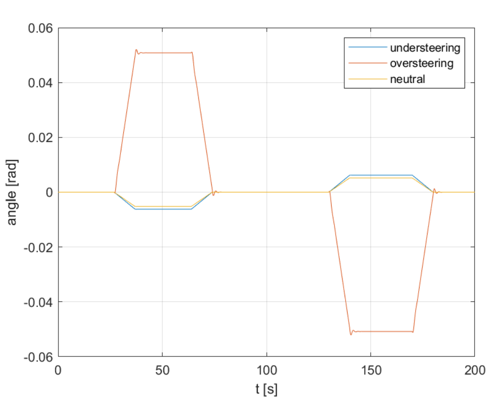

FIGURE 17. Steering angle in understeering, oversteering and neutral conditions

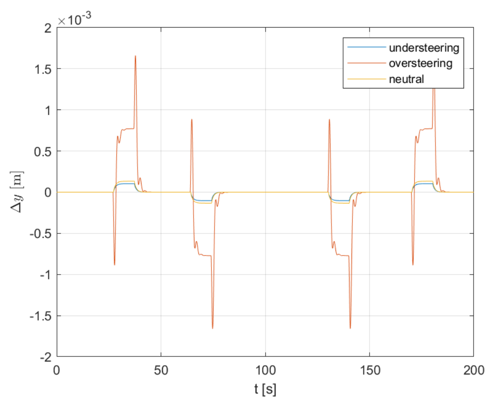

FIGURE 18. Lateral deviation in understeering, oversteering and neutral conditions

5.3. ***Feedforward generation with delay***

It is then considered the effect of a pure time delay on the feedforward generation. Intuitively, the delay in the input steering angle is not perceived because the yaw rate, which is not delayed, start to correct the vehicle trajectory before the application of the steering angle. Therefore, it is expected that the lateral deviation increases, as proven in the following figure.

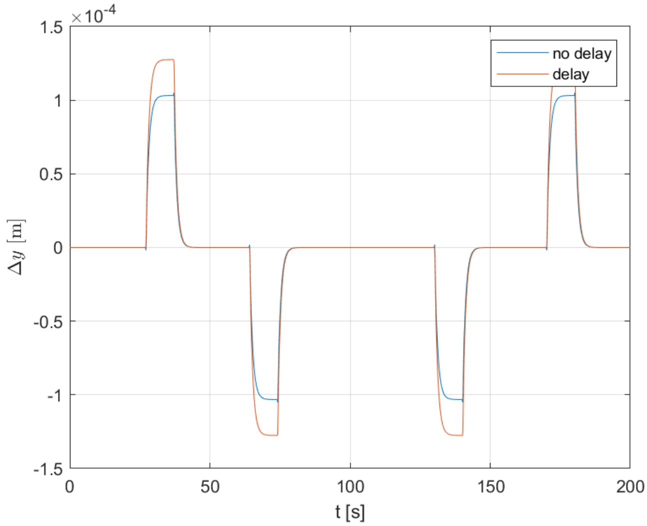

FIGURE 19. Effect of a pure time delay