POLITECNICO DI TORINO

Master of Science Thesis

Automotive Engineering

"Analysis and Comparison of One-Pedal Driving Strategies for Electric Vehicles from Consumption and Comfort Point of View"

Supervisor:

Prof. Stefano Carabelli

Candidate:

Alireza Moayyedi

April 2020

Abstract

One-pedal driving is the idea of applying with the same accelerator pedal both traction and regenerative braking which has emerged thanks to the regeneration capabilities and the potential of implementing complicated control systems in electric vehicles. In this thesis a model-based design approach was used to provide a virtual prototype in MATLAB & Simulink capable of analyzing and comparing different one-pedal driving strategies for electric vehicles. The study was mainly carried out on an electrified old version of Fiat Panda. In the beginning, the vehicle had only a simple on/off regenerative braking with constant level of regeneration which could be activated either by slightly pushing the brake pedal or releasing the accelerator pedal but without any possibility to modulate the magnitude. The first step was to study different levels of regeneration and compare the two modes of activation. 40% regeneration with respect to the maximum regenerative torque was chosen as the trade-off considering both energy recuperation and comfort issues while being able to follow a desired reference cycle. Besides, both activation modes gave the same results. Next, by implementing the real control logic instead of the primarily ideal one in the Simulink model and also tuning some parameters that were initially obtained by calculations, this model was validated with four experimental data sets which were acquired with different regeneration levels. Regarding the consumption values, simulations' errors on average became lower than 6% with respect to the experimental results whereas with ideal control and calculated coefficients they were first in the range of 12% to 37%. Additionally, simulated current and electrical power profiles became much closer to those seen in the real experiments. The following step was to employ this validated model in order to implement, analyze and compare more complicated control strategies that could realize one-pedal driving. Targets to be investigated were mainly energy consumption, comfort issues regarding foot activity between pedals and deceleration profiles while being able to follow precisely a desired reference cycle. Two different strategies which were studies previously done by others and one which was designed and developed during this thesis, in addition to the basic on/off braking were chosen to be investigated, compared and modified if necessary, to be adapted to the aforementioned vehicle. For all of the strategies capable of following some standard reference cycles only using regenerative braking (no exploitation of hydraulic brakes) electrical energy consumption was almost the same. However, regarding comfort huge success was achieved by reducing the number of accelerator pedal releases noticeably e.g. from more than 160 times with the simplest on/off strategy in WLTP Class 3 cycle down to less than 10 times with two of the strategies. Additionally, deceleration profiles were shown to be differently acting on the longitudinal comfort in each strategy. With the basic on/off electric braking repetitive activation of regenerative braking with high deceleration values occurs for most of the velocity range with minimum possibility to modulate it through accelerator pedal positioning. On the other hand, more complicated strategies have maximum deceleration in the mid velocity range and they give more flexibility in modulating the deceleration values with wider exploitation of accelerator pedal positioning.

As I write today these very last lines feeling prouder than ever, I shall never forget all those who never stopped believing in me.

To my father who was a mountain of sacrifice to me dedicating all his life for my future...

To my mother who loved me unconditionally…

To my dear friends who shared with me moments of joy and sadness...

To Anna who never let me feel alone in this path.

Acknowledgments

I would like to mention my deepest appreciation for the kind support I received continuously from Professor Carabelli who mentored me throughout the whole process of this thesis.

I am also grateful to Italtecnica s.r.l. company for providing the data that were essential and extremely useful in developing this thesis.

Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

C0	Ideal control system
C1	On/off regenerative braking with brake pedal activation mode
C2	On/off regenerative braking with accelerator pedal activation mode
C3.1	REDS plus on/off regenerative braking with brake pedal strategy as the supplementary braking source
C3.2	REDS plus on/off regenerative braking with accelerator pedal strategy as the supplementary braking source
C3.3	REDS plus hydraulic braking as the supplementary braking source
S0	Calculated coast-down coefficient set
S1	Tuned coast-down coefficient set
T1	1st experimental test with no regeneration
T2	2nd experimental test with 40% on/off regeneration consisting both activation modes
T3	3rd experimental test with 40% on/off regeneration using brake pedal activation mode
T4	4th experimental test with 20% on/off regeneration using brake pedal activation mode
Cons.	Consumption
EE.	Electrical energy
w/	with
w/o	without
Spec.	specific
Elec.	Electrical
Regen.	Regeneration
Exp.	Experimental
Sim.	Simulated
Rel.	Relative
Coeff.	Coefficient
Ref.	Reference
Abs.	Absolute
Acc.	Acceleration
Vel.	Velocity
F_0	Coast-down coefficient
F_1	Coast-down coefficient
F_2	Coast-down coefficient

1 Chapter I. Introduction

In the recent years the automotive industry has undergone revolutionary advancements. Vehicle electrification has opened the door to a vast field of innovations that could possibly change the core definition of how an automobile is driven. One of the most important features of electric vehicles is their ability to recuperate kinetic energy through regenerative braking that would otherwise get dissipated as in conventional vehicles using friction pads. Many people appreciate the comfortable way of driving provided by automatic transmission as they get rid of the clutch pedal and have to use only the two accelerator and brake pedals. However now with the presence of regenerative braking of electric motors and their potential to employ complex control logics, one may doubt what if the limit is yet pushed further and drivers get rid of using the brake pedals as well. This innovation has the potential to bring along numerous improvements regarding comfort issues and regenerative braking performance.

The concept of one-pedal driving is gaining increasing interest in the area of vehicle electrification, although different commercial names could be used by car manufacturers. For instance, Nissan has the e-Pedal technology that allows the driver to accelerate, decelerate and stop using only the accelerator pedal. Releasing gradually the accelerator pedal, the regenerative motor can produce at maximum 0.2 g deceleration and when the car comes to a full stop hydraulic brakes are automatically activated to maintain the car stopped [1].

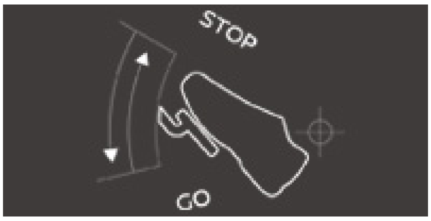


Figure 1. Accelerator pedal functioning of Nissan e-Pedal [1]

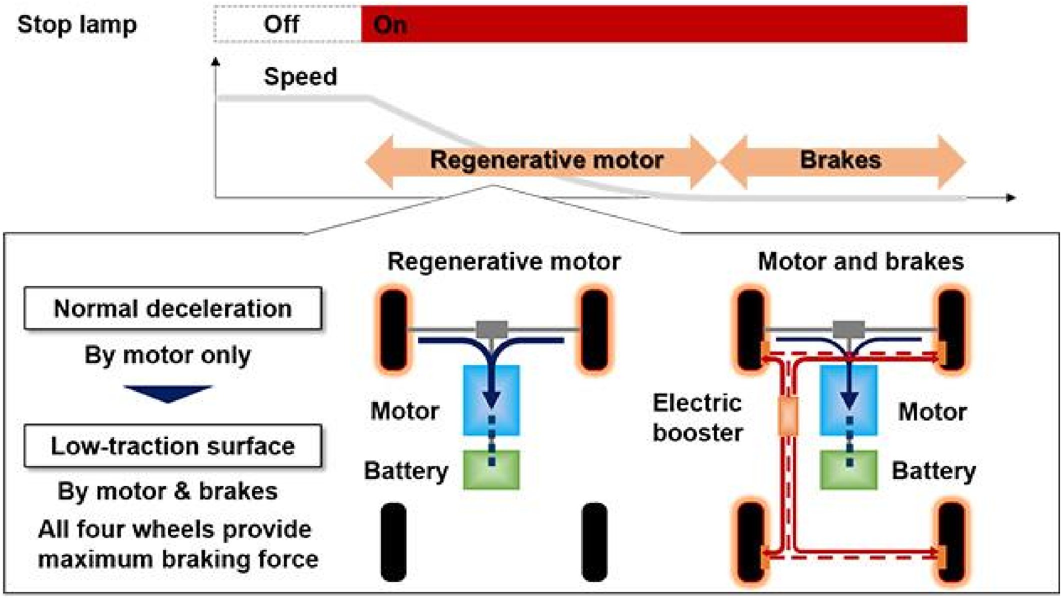


Figure 2. e-Pedal technology of Nissan [1]

For example Nissan Serena e-POWER features one-pedal driving and it claims that brake pedal application is reduced by 70% which causes reduction of wear on friction pads [2].

Figure 3. Nissan Serena e-POWER [2]

In MathWorks Automotive Conference (May 9, 2017) Nathaniel Michaluk from General Motors demonstrated how One-Pedal driving feature was developed for the 2017 Chevrolet Bolt EV using Simulink. It was shown that this feature gives continuous torque modulation without frequent pedal changing. Furthermore, it improved real world EV range as it could enlarge energy recuperation [3].

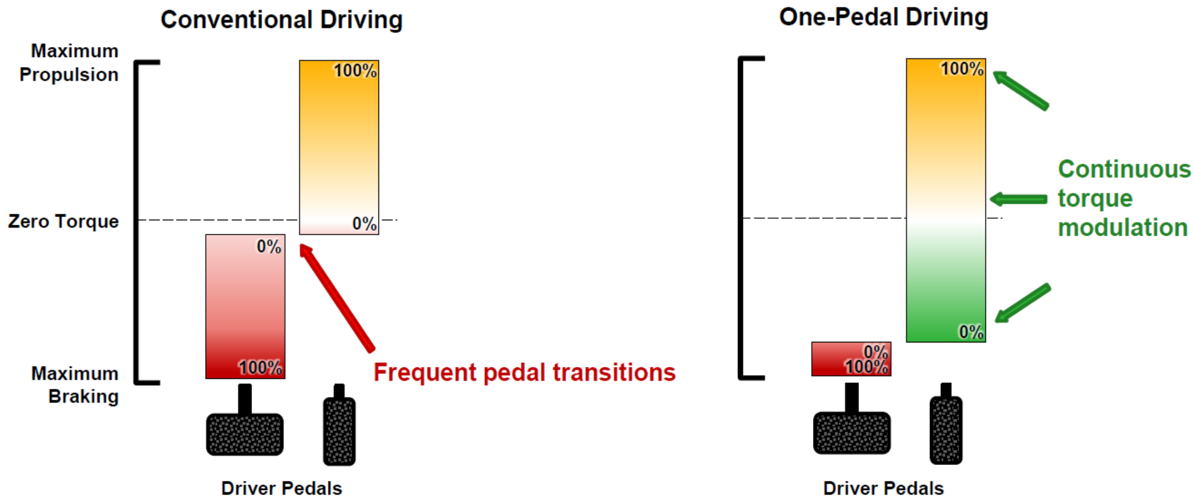


Figure 4. One-Pedal Driving's comfort benefit as represented in [3]

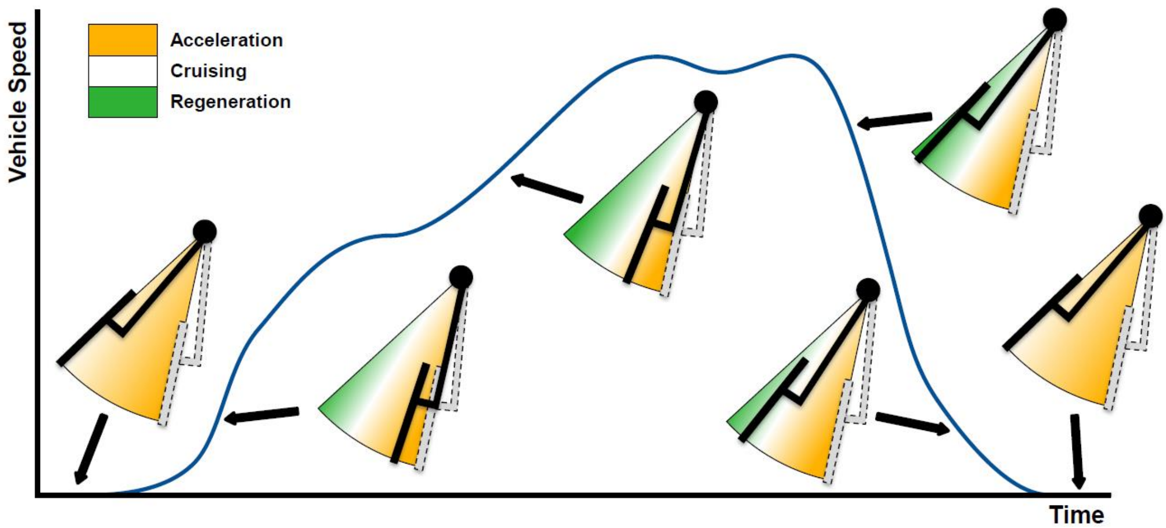


Figure 5. One-Pedal Driving strategy represented in [3]

Figure 6. Chevrolet Bolt EV [3]

A study that aimed to optimize energy consumption of electric vehicles depicted that energy recovery technology could play an important role in reducing consumption and extending driving range. The vehicle investigated in this paper was a Changan EV sedan that featured the innovative I-Pedal mode technology. It was seen that compared to traditional regenerative braking systems with I-Pedal 3% reduction in energy consumption was achieved [4].

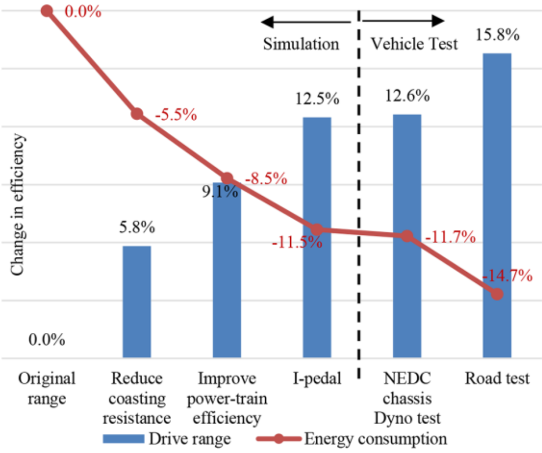


Figure 7.Road map of energy consumption and drive range changes obtained in [4]

Apart from those mentioned so far, there are many other electric vehicles that include one-pedal driving feature such as Tesla Model S, BMW i3, Nissan Leaf etc.

However, realizing one-pedal driving has its own challenges. It depends on many aspects of the vehicle e.g. vehicle characteristics, electrical systems, battery specifications, vehicle electronics and so on. Furthermore, not using the friction brakes in electric vehicles as frequent as in conventional gasoline or diesel vehicles creates its own problems such as creep groan noise [5].

The goal of this thesis is to develop a reliable virtual prototype in MATLAB/Simulink that is capable of developing and implementing different one-pedal driving control strategies for electric vehicles and perform comparison and analysis on the simulation results regarding energy consumption and comfort issues. The study is carried out for a retrofitted old version of Fiat Panda which its conventional powertrain was replaced with an electric one with the purpose of electrifying it. But it should be mentioned that the procedure could be done for any electric vehicle that has the possibility to employ one-pedal driving and to use it in urban or suburban environment.

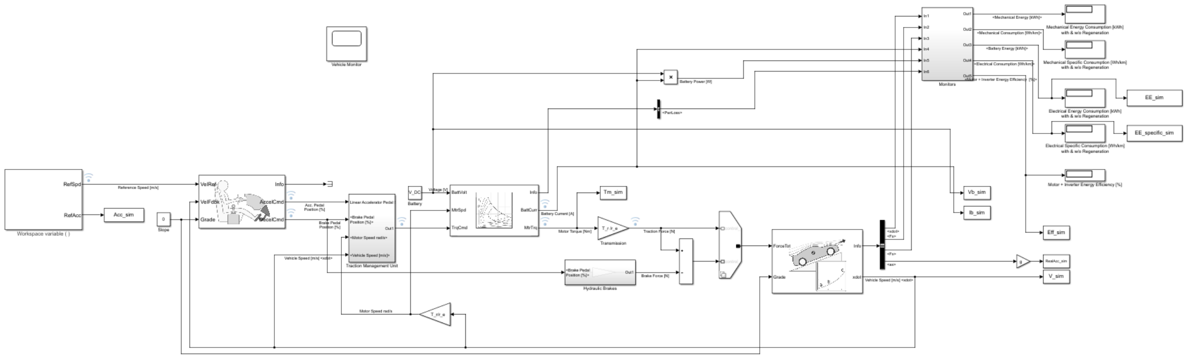


Figure 8. Simulink model

The final virtual product of this thesis exploits the Simulink model as depicted in figure 8 which will be addressed continuously throughout this thesis. This Simulink model is made of mainly Vehicle Dynamics Blockset. The input is the desired reference cycle; longitudinal driver is modeled as a PI controller; powertrain is a mapped electric motor parametrized by maximum power and torque; battery is considered as a simple constant voltage source. By default, it also employs an ideal traction control system and uses 1 DOF rigid vehicle model parametrized by coast-down coefficients. However, the coast-down coefficients of the vehicle under study in this thesis, were not obtained through standard procedures but rather simply calculated considering aerodynamic and rolling resistances. Furthermore, the regeneration control system implemented in the real vehicle is not ideal. As it will be shown later these two parts of the model, traction control and rigid vehicle model, will be mostly focused on to be further developed in order to improve simulation results and implement one-pedal driving strategies.

The electrified vehicle under study by default employs a simple on/off regenerative braking with constant level of regeneration. In this system whenever driver slightly pushes the brake pedal regeneration gets activated but with (selectable) constant level of regenerative torque with respect to the maximum regenerative torque available. Optionally this fixed level regeneration could be also set to be activated whenever driver releases the accelerator pedal which in this case it could be considered as the simplest one-pedal driving strategy for this vehicle. In the second chapter accelerator pedal mapping is introduced and it will be shown how a simple mapping could change foot activity on the pedal. Then, on/off regenerative braking is studied to analyze different regeneration levels and to find the tradeoff value considering deceleration capabilities, energy recuperation and longitudinal comfort. In the next step experimental data that have been acquired with the aforementioned vehicle in real world tests, will be used to validate the Simulink model. Following the model validation, it will be possible to implement more sophisticated one-pedal driving strategies and compare the results with the simplest one already available in the real vehicle to see what happens from energy consumption and comfort point of view.

2 Chapter II. Accelerator Pedal Mapping

2.1 Introduction

The purpose of this chapter is to study how accelerator pedal mapping could cause any difference in driving the vehicle. The plan is to change the accelerator pedal map from the default linear mode to somewhat more sportive and aggressive one. First the chosen mapping strategy is shown and then the consequent effects on the driver's behavior regarding his action on the accelerator pedal along with the performance of the traction unit is addressed. Finally, the effect on the electrical energy consumption is analyzed. Different reference cycles including WLTP Class 1, WLTP Class 3, NEDC, FTP72 and US06 are chosen for simulations. It should be mentioned that for this analysis the model with the ideal control system is used.

2.2 Defining the accelerator pedal map

First, a look up table which intends to enhance the behavior of accelerator pedal's response with respect to the driver's foot movement is created. As seen the first 5 percentages define a dead band which actually represents the imperfection of the accelerator pedal functionality specially in the real vehicle which is an old one. Afterwards up to 30% of the pedal movement there is a steep response in order to create a tractive sensation for the driver. Followingly the response's intensity decreases.

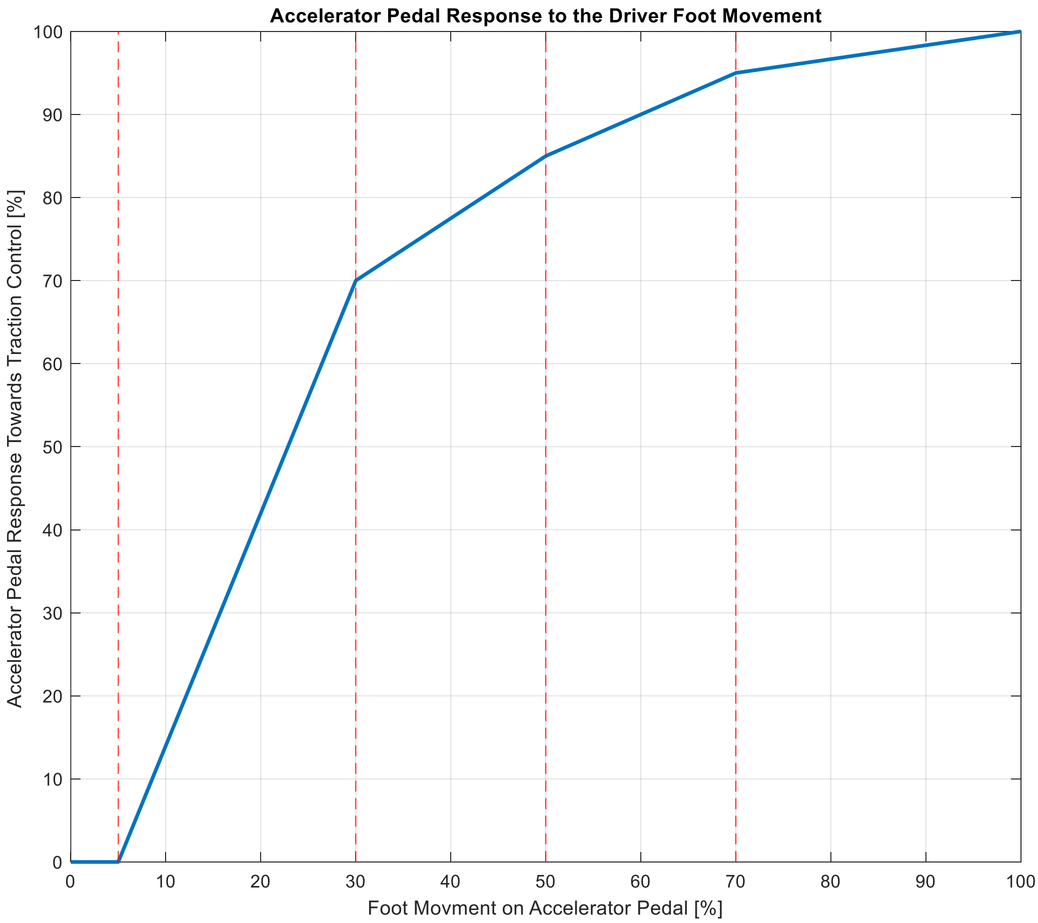


Figure 9. A simple sportive accelerator pedal mapping for an electric vehicle

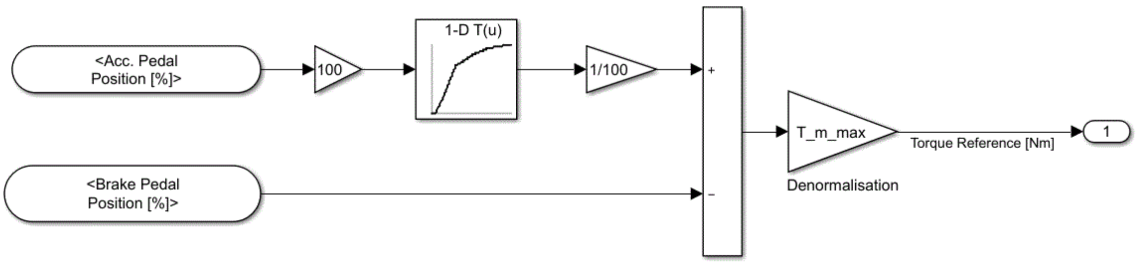


Figure 10. Simulink implementation of the accelerator pedal map

2.3 Comparing linear and mapped accelerator pedal

In the following some comparative figures are plotted to study what happens in case of a mapped accelerator pedal with respect to the linear one. These plots include vehicle velocity over the cycle, accelerator and brake pedal positions and their corresponding histograms, torque reference and consequent motor torque values and finally electrical energy consumption with and without regeneration.

2.3.1 Analysis on WLTP Class 1 driving cycle

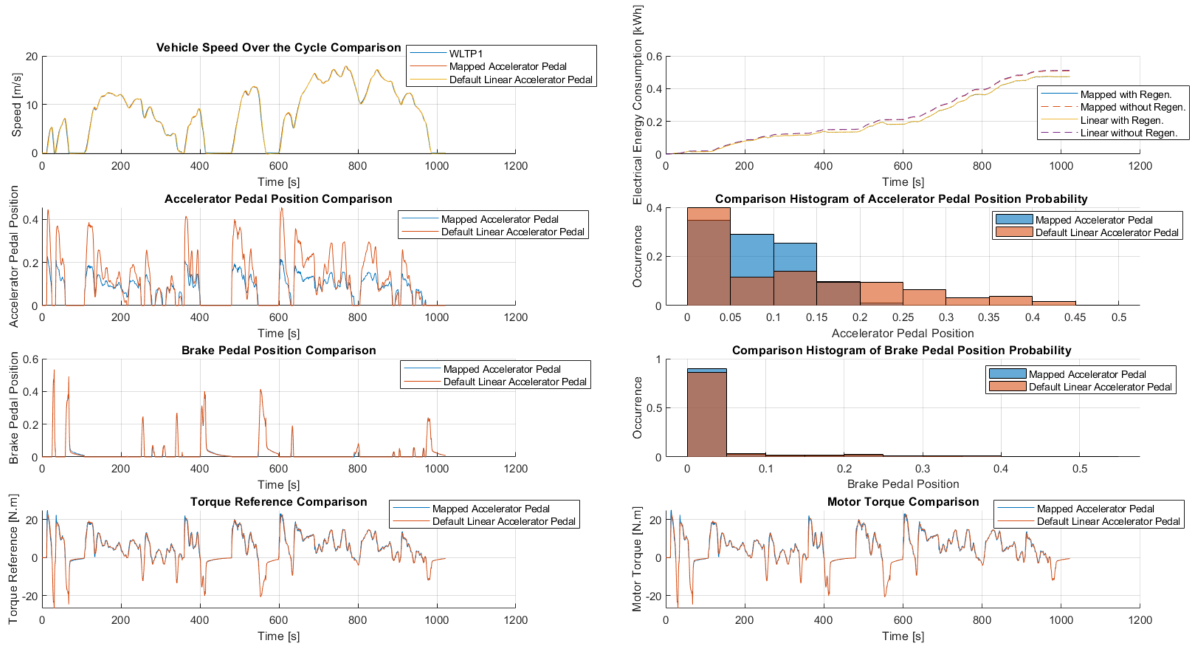


Figure 11. WLTP Class 1 results

It is interesting to see how the pedal mapping can affect the electrical energy consumption and whether the effect would differ with regeneration or without it.

Electrical energy consumption comparison:

- Electrical Energy Consumed with Mapped Accelerator Pedal and Regeneration= 0.47302 [kWh]
- Electrical Energy Consumed with Mapped Accelerator Pedal but without Regeneration= 0.50819 [kWh]

- Electrical Energy Consumed with Linear Accelerator Pedal and Regeneration= 0.47403 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal but without Regeneration= 0.51212 [kWh]
- Electrical Energy Saved with Mapped Accelerator Pedal and Regeneration= 0.21208 [%]
- Electrical Energy Saved with Mapped Accelerator Pedal but without Regeneration= 0.7668 [%]

Surprisingly it can be seen that only with a simple accelerator mapping the electrical energy consumption can change about 0.75% in case of no regeneration.

2.3.2 Analysis on WLTP Class 3 driving cycle

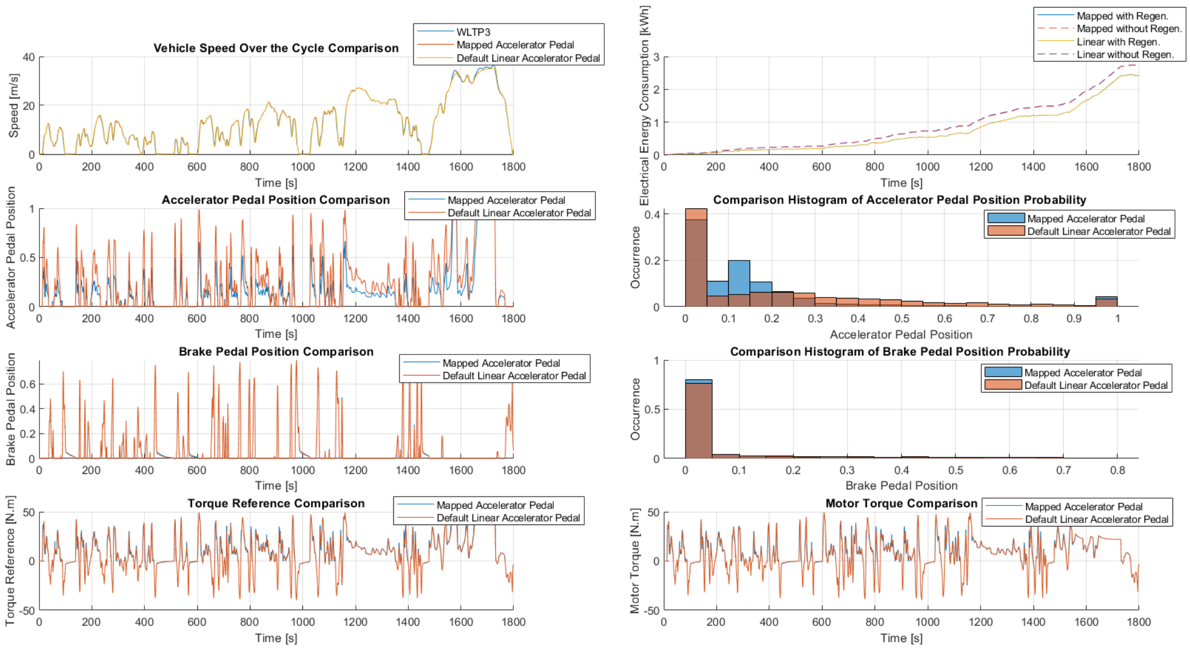


Figure 12. WLTP Class 3 results

Electrical energy consumption comparison:

- Electrical Energy Consumed with Mapped Accelerator Pedal and Regeneration= 2.4189 [kWh]
- Electrical Energy Consumed with Mapped Accelerator Pedal but without Regeneration= 2.7345 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal and Regeneration= 2.4152 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal but without Regeneration= 2.7424 [kWh]
- Electrical Energy Saved with Mapped Accelerator Pedal and Regeneration= -0.15326 [%]
- Electrical Energy Saved with Mapped Accelerator Pedal but without Regeneration= 0.28714 [%]

Again, it can be seen that only with a simple accelerator mapping the electrical energy consumption can reduce about 0.28% in case of no regeneration but at the same time increasing about 0.15% with regeneration.

2.3.3 Analysis on NEDC driving cycle

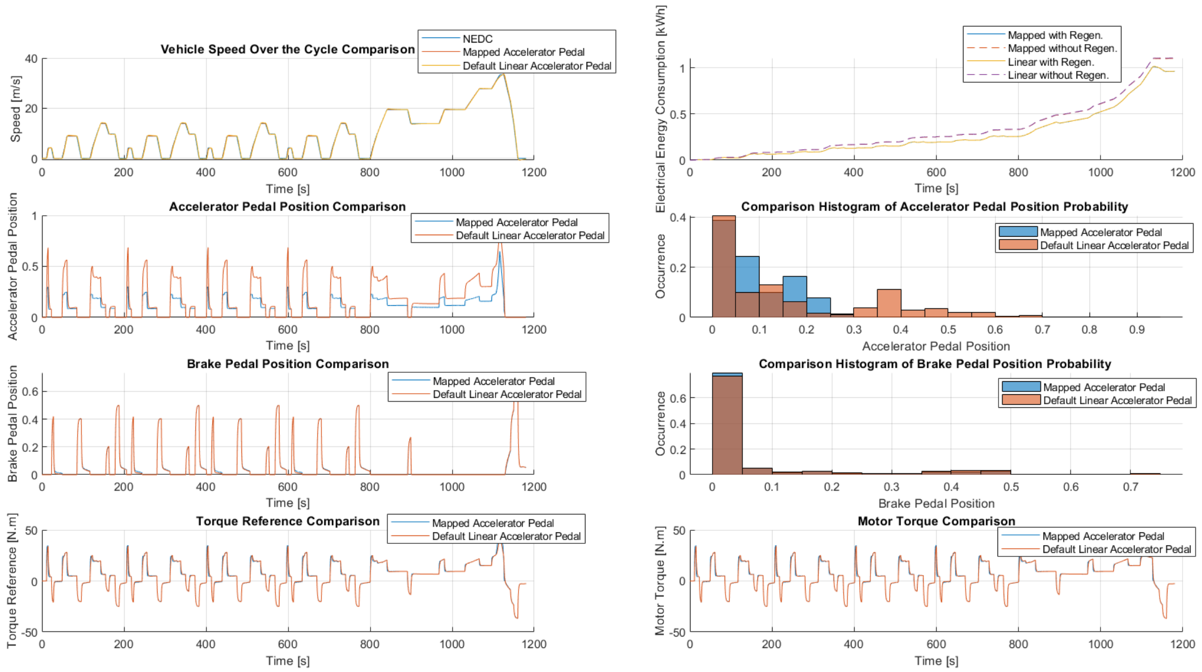


Figure 13. NEDC results

Electrical energy consumption comparison:

- Electrical Energy Consumed with Mapped Accelerator Pedal and Regeneration= 0.95962 [kWh]
- Electrical Energy Consumed with Mapped Accelerator Pedal but without Regeneration= 1.0994 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal and Regeneration= 0.96074 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal but without Regeneration= 1.1044 [kWh]
- Electrical Energy Saved with Mapped Accelerator Pedal and Regeneration= 0.1156 [%]
- Electrical Energy Saved with Mapped Accelerator Pedal but without Regeneration= 0.45158 [%]

In case of NEDC cycle there is a small percentage of energy saving for both with regeneration and without it.

2.3.4 Analysis on FTP72 driving cycle

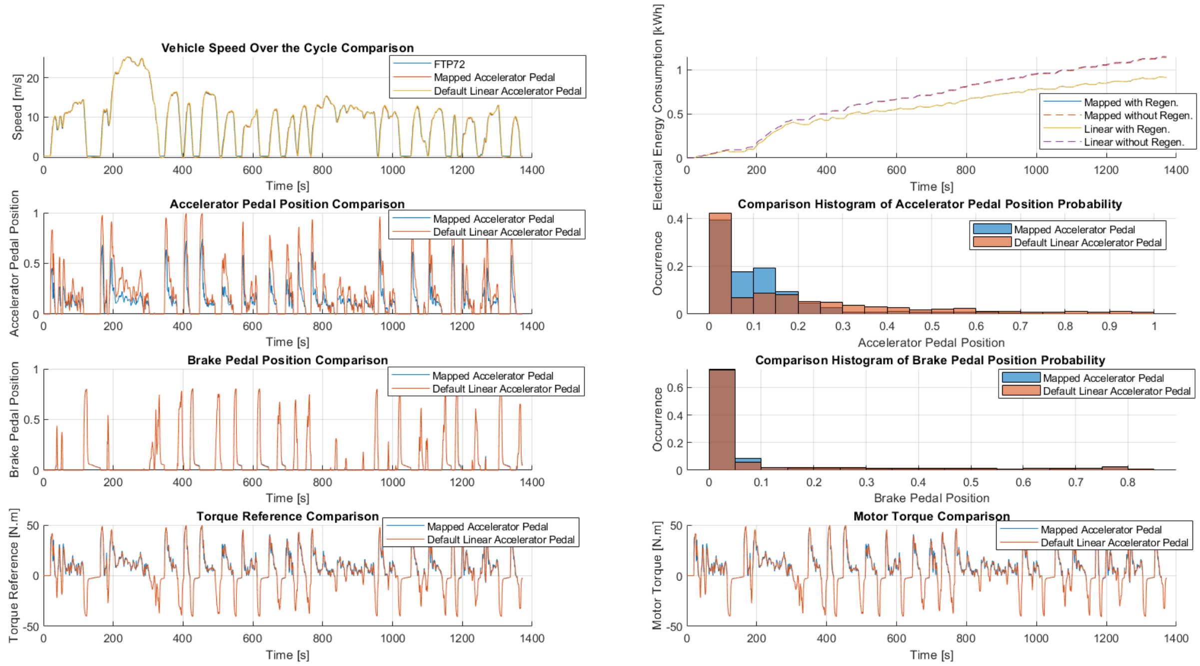


Figure 14. FTP72 results

Electrical energy consumption comparison:

- Electrical Energy Consumed with Mapped Accelerator Pedal and Regeneration= 0.91479 [kWh]
- Electrical Energy Consumed with Mapped Accelerator Pedal but without Regeneration= 1.1413 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal and Regeneration= 0.9154 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal but without Regeneration= 1.1506 [kWh]
- Electrical Energy Saved with Mapped Accelerator Pedal and Regeneration= 0.067398 [%]
- Electrical Energy Saved with Mapped Accelerator Pedal but without Regeneration= 0.80566 [%]

Also, FTP72 cycle shows that in the case of mapped accelerator pedal there is small amount of energy saving.

2.3.5 Analysis on US06 driving cycle

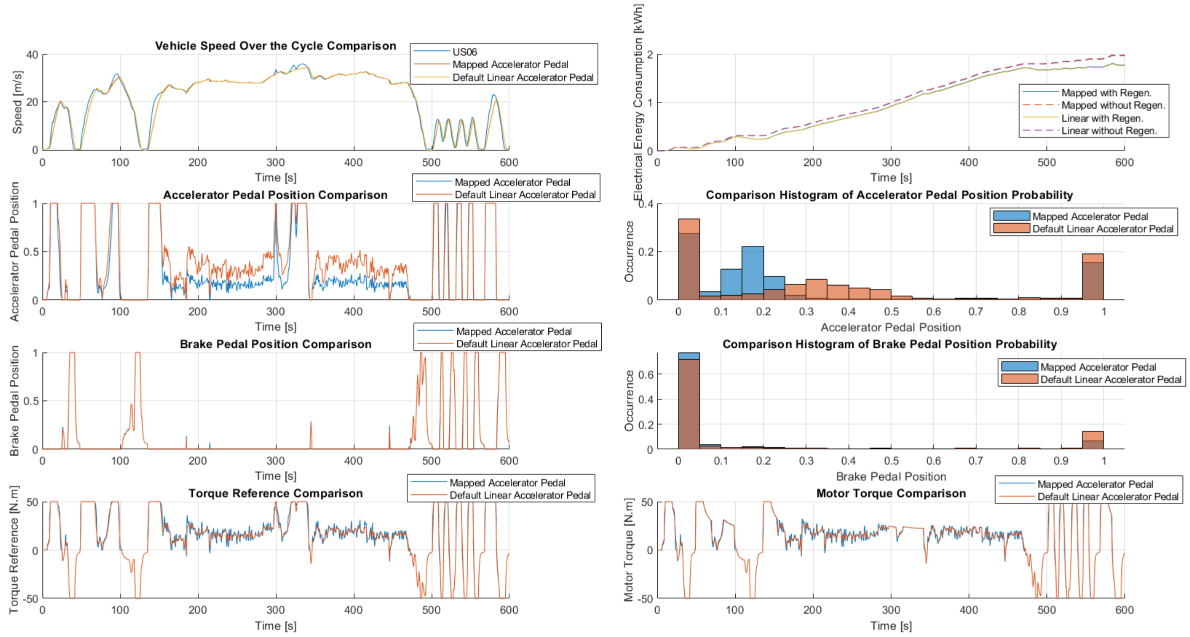


Figure 15. US06 results

Electrical energy consumption comparison:

- Electrical Energy Consumed with Mapped Accelerator Pedal and Regeneration= 1.772 [kWh]
- Electrical Energy Consumed with Mapped Accelerator Pedal but without Regeneration= 1.9809 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal and Regeneration= 1.7626 [kWh]
- Electrical Energy Consumed with Linear Accelerator Pedal but without Regeneration= 1.9661 [kWh]
- Electrical Energy Saved with Mapped Accelerator Pedal and Regeneration= -0.53469 [%]
- Electrical Energy Saved with Mapped Accelerator Pedal but without Regeneration= -0.74958 [%]

In the case of US06, the amount of energy saving does not follow the trends previously observed. It is shown that in this case more electrical energy is consumed with a mapped accelerator pedal.

2.4 Conclusions

By comparing the two cases of linear and mapped accelerator pedal in 5 different driving cycles, it has been observed that foot activity from the driver greatly reduces to lower pedal positions while the behavior of speed profiles or motor torque along the cycle remain quite the same.

Another unexpected issue observed is the electrical energy consumption difference that occurs in the two cases. Looking at different reference cycles it was seen that for NEDC and WLTP

Class 1 and FTP72 a small amount of energy saving occurred while for more aggressive cycles being WLTP Class 3 or US06 the situation was different. It was seen that in WLTP3 although consumption without regeneration was reduced but it was instead increased with regeneration. In US06 for both conditions it increased.

Although more trials are required to confirm such conclusion, but it may be justifiable to express that based on the observations in this section, applying a mapped accelerator pedal in smooth driving cycles may help slightly in energy saving.

3 Chapter III. On/Off Regenerative Braking

3.1 Introduction

As mentioned previously the vehicle under study has a simple on/off regenerative braking system. This means that regenerative braking gets activated with constant regeneration level through either slightly pushing the brake pedal or completely releasing the accelerator pedal. Regeneration level and activation strategies could be optionally chosen through vehicle electronics. The main problem with this sort of regenerative braking is that it can cause repetitive braking with high levels of deceleration that can result in discomfort for the passengers and also damage the vehicle itself. Hence a tradeoff should be chosen in the level of regeneration regarding the aforementioned issues. The aim of this chapter is to study application of on/off electric braking on the vehicle's longitudinal performance and its regeneration capabilities. This study is performed for both strategies: activating the electric braking by the information coming from brake pedal's signal and activating by the information coming from accelerator pedal's signal. Furthermore, different regeneration levels with respect to the maximum regenerative torque of the electric motor are simulated to better observe the differences in the final result.

3.2 Fixed level regenerative braking - activation through brake pedal signal

In this case whenever the brake pedal is moved, no matter its position, a constant regenerative torque is applied. Furthermore different regeneration levels: 100%, 80%, 60%, 40%, 30%, 20% and 0% with respect to the maximum regenerative torque of the electric motor are applied to see the vehicle's performance and to find the limiting degradation level that allows the vehicle follow the desired driving cycle.

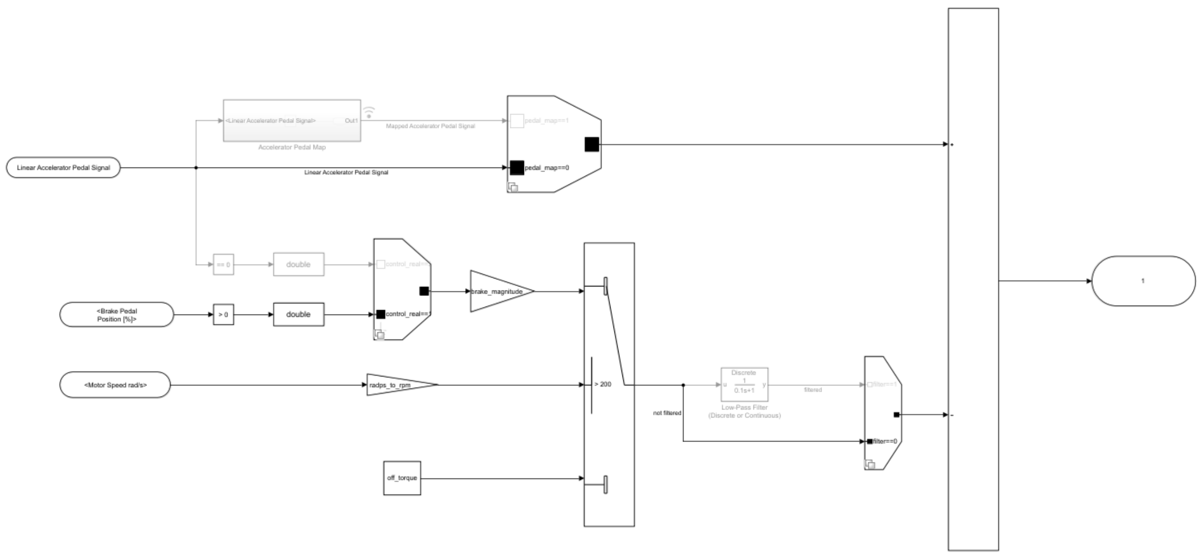


Figure 16. Simulink implementation of on/off regenerative braking with brake pedal strategy

It is also important to mention that in order to avoid unwanted actuation of the electric motor at low vehicle speeds, regenerative braking deactivates as the motor speed decreases lower than 200 rpm. Otherwise the vehicle may even start moving backwards unwantedly.

3.3 Fixed level regenerative braking - activation through accelerator pedal signal

In this mode instead of brake pedal signal, the accelerator pedal's signal is exploited to activate the regenerative braking. The strategy is to activate it whenever the driver releases the accelerator pedal completely.

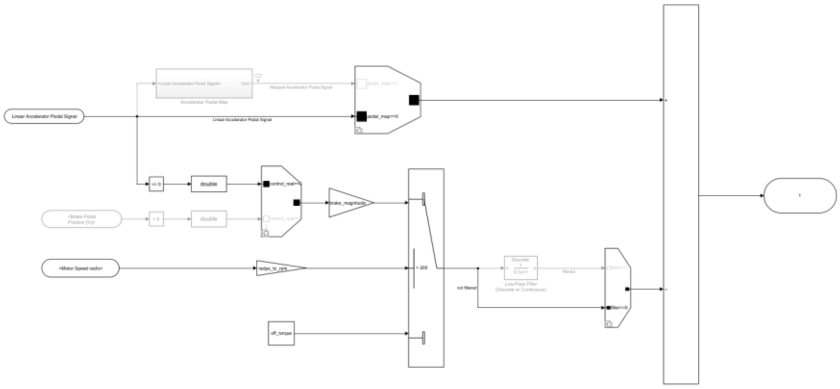


Figure 17. Simulink implementation of on/off regenerative braking with accelerator pedal strategy

It is important to mention that in the Simulink model, brake pedal's signal is not being used at all here.

Also, in this case the system will stop working if the motor speed drops below 200 rpm.

3.4 Comparing activation through accelerator pedal signal and brake pedal signal

Although the final strategy is to apply one pedal driving which means in the end the acceleration pedal's signal is going to be used as the regenerative braking activator, it is still important to study if there is any difference between using brake pedal or accelerator pedal's signal. Thus, the two strategies with equal levels of regeneration are simulated for NEDC and WLTP Class 3 cycles. Results are plotted in the same figures to find out whether they differ or not.

3.4.1 Quantifying the accuracy of following the reference speed cycle

Calculating the error of a simulated profile with respect to its reference is an important measurement that gives a clear understanding of how accurate simulated profiles are and it gives the possibility of comparing different models. In this thesis numerous times simulated profiles are compared with their reference ones such as standard driving cycles or the experimental ones that were carried out in experimental tests e.g. current profiles acquired in a real vehicle.

For this purpose, the squared error at each time instant of these profiles is calculated and then integrated over time and finally divided by the time length of the profile.

$$E_{12} = \int_0^{t_{end}} error^2(t)dt$$

$$P_{12} = \frac{E_{12}}{t_{end}}$$

In this way it can be understood for example which constant braking level allows the least error in following the reference speed cycle or when the error increases noticeably which shows the limiting degradation level of regenerative braking.

3.4.2 NEDC results

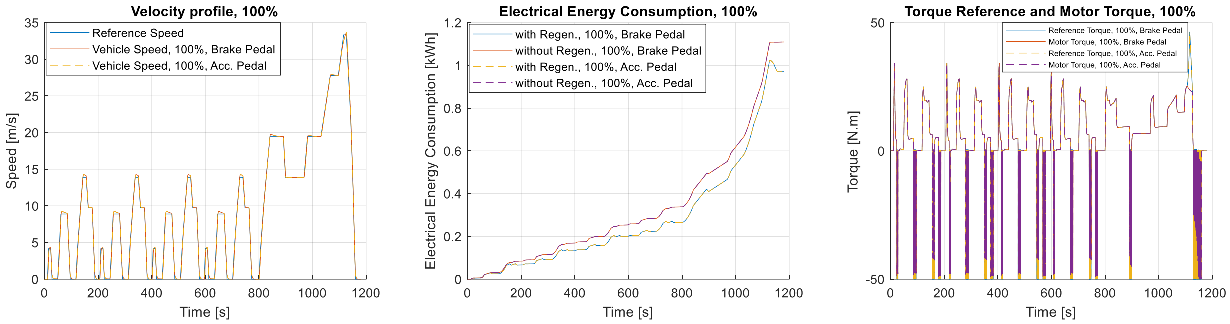


Figure 18. 100% on/off regenerative braking with both pedal strategy - NEDC cycle

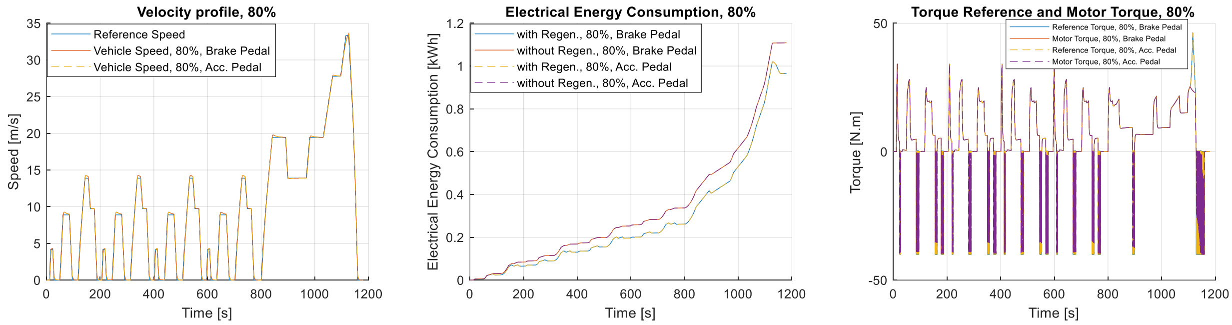


Figure 19. 80% on/off regenerative braking with both pedal strategy - NEDC cycle

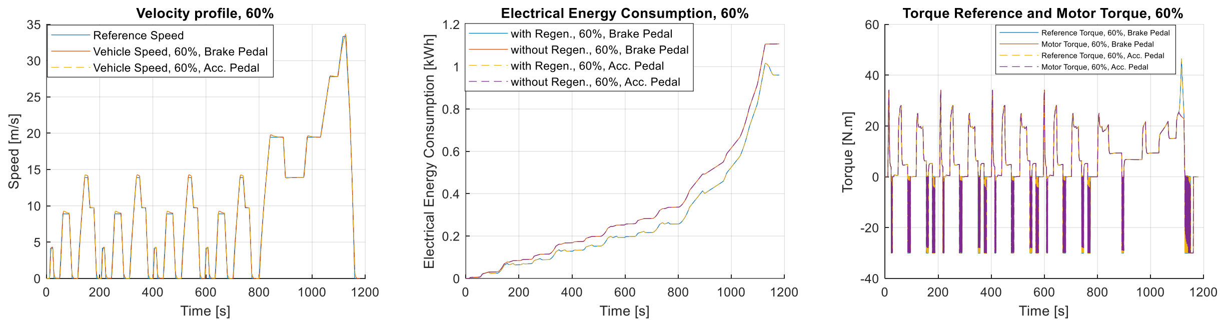


Figure 20. 60% on/off regenerative braking with both pedal strategy - NEDC cycle

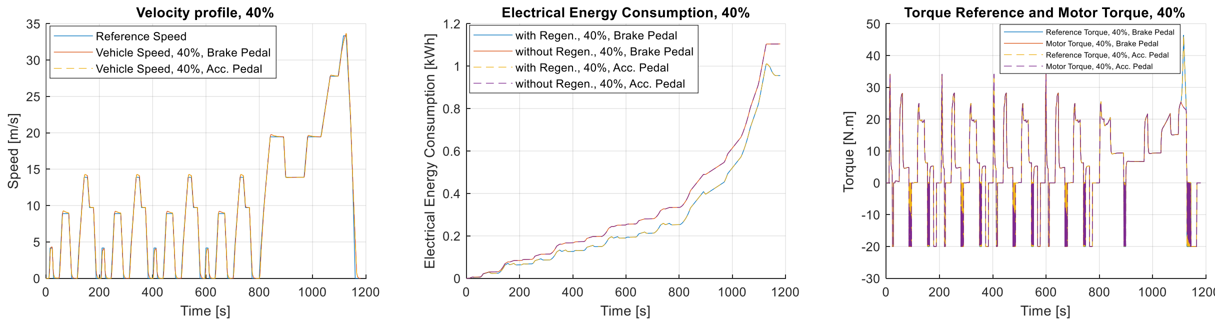


Figure 21. 40% on/off regenerative braking with both pedal strategy - NEDC cycle

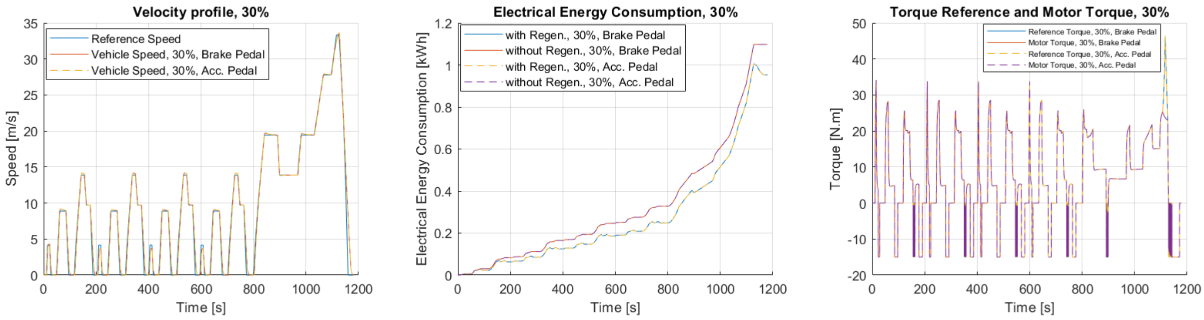


Figure 22. 30% on/off regenerative braking with both pedal strategy - NEDC cycle

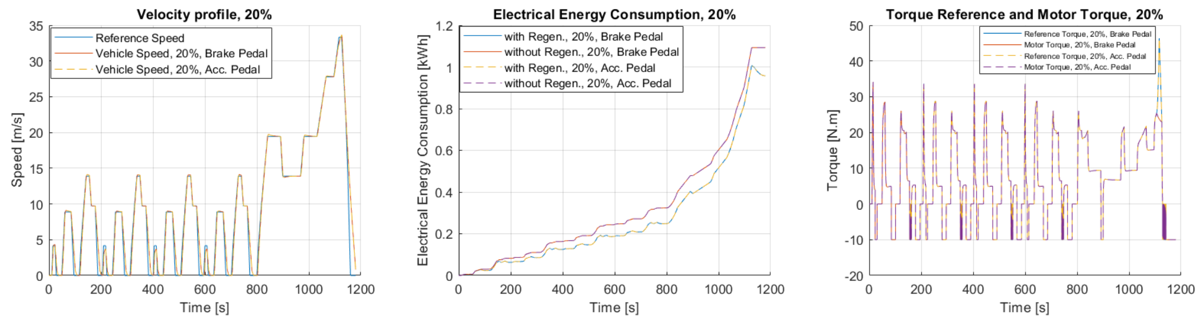


Figure 23. 20% on/off regenerative braking with both pedal strategy - NEDC cycle

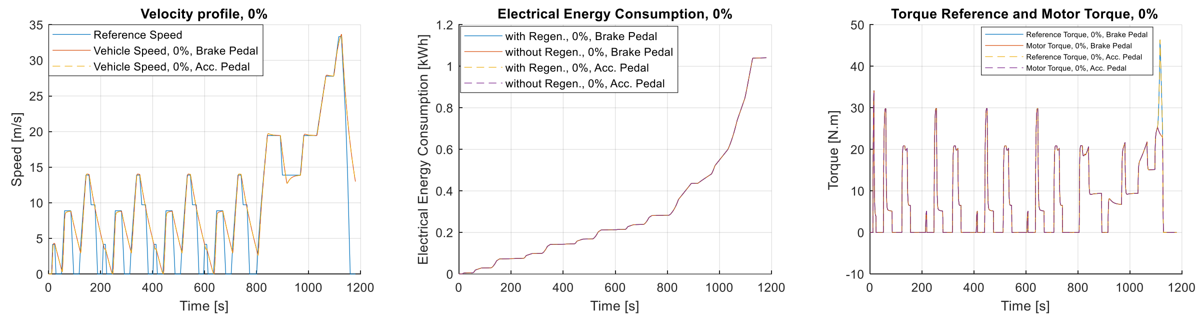


Figure 24. 0% on/off regenerative braking with both pedal strategy - NEDC cycle

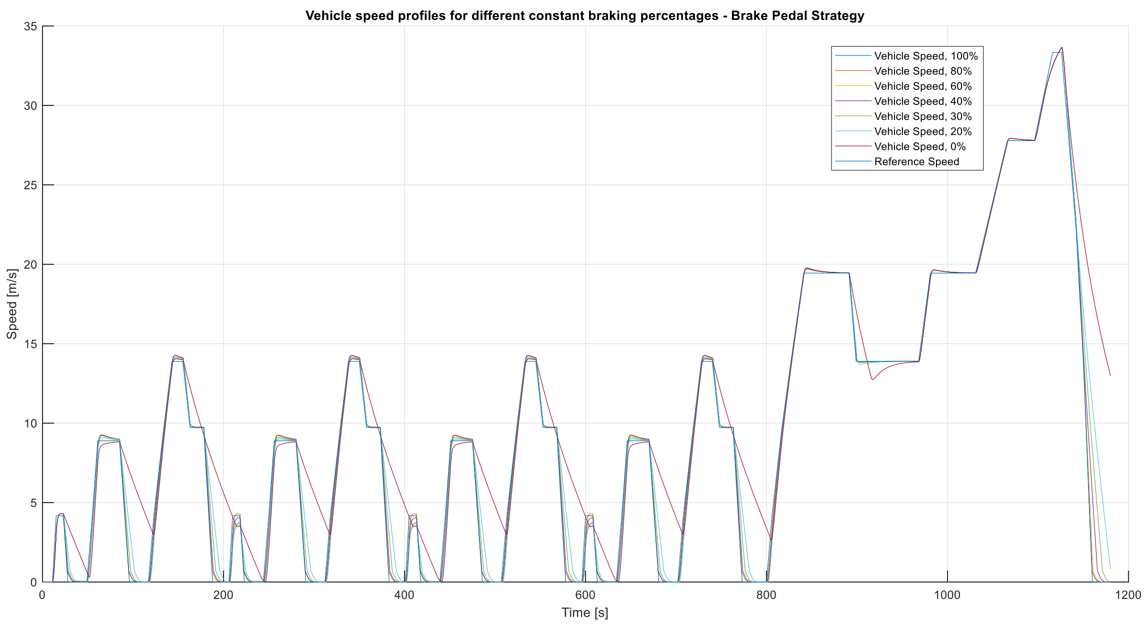


Figure 25. All the velocity profiles simulated with brake pedal strategy - NEDC cycle

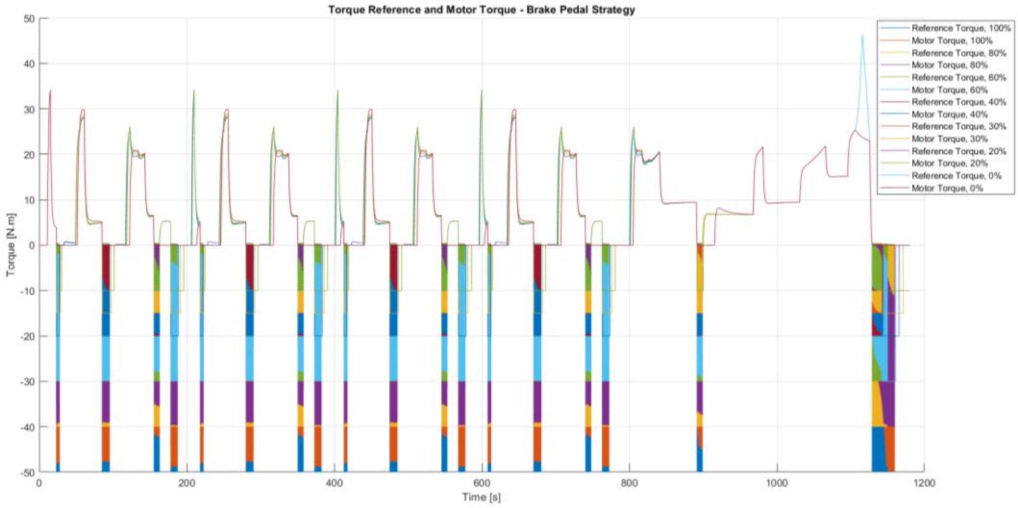


Figure 26. All the torque profiles simulated with brake pedal strategy – NEDC cycle

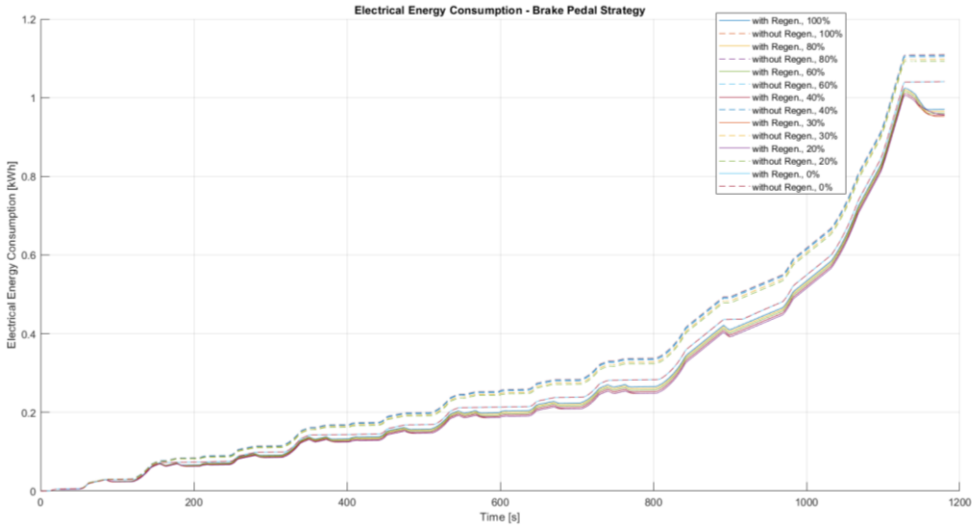


Figure 27. All the electrical energy consumption profiles simulated with brake pedal strategy – NEDC cycle

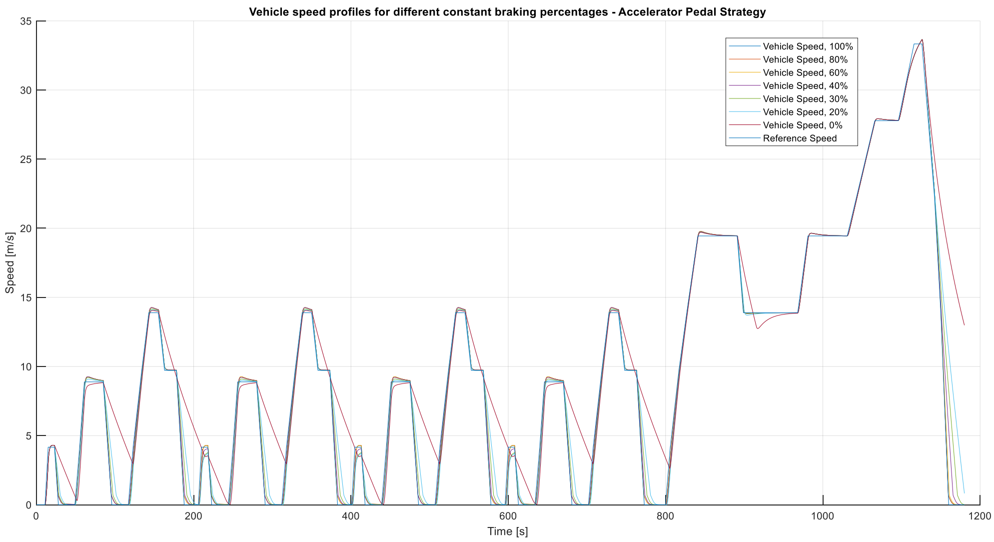


Figure 28. All the velocity profiles simulated with accelerator pedal strategy - NEDC cycle

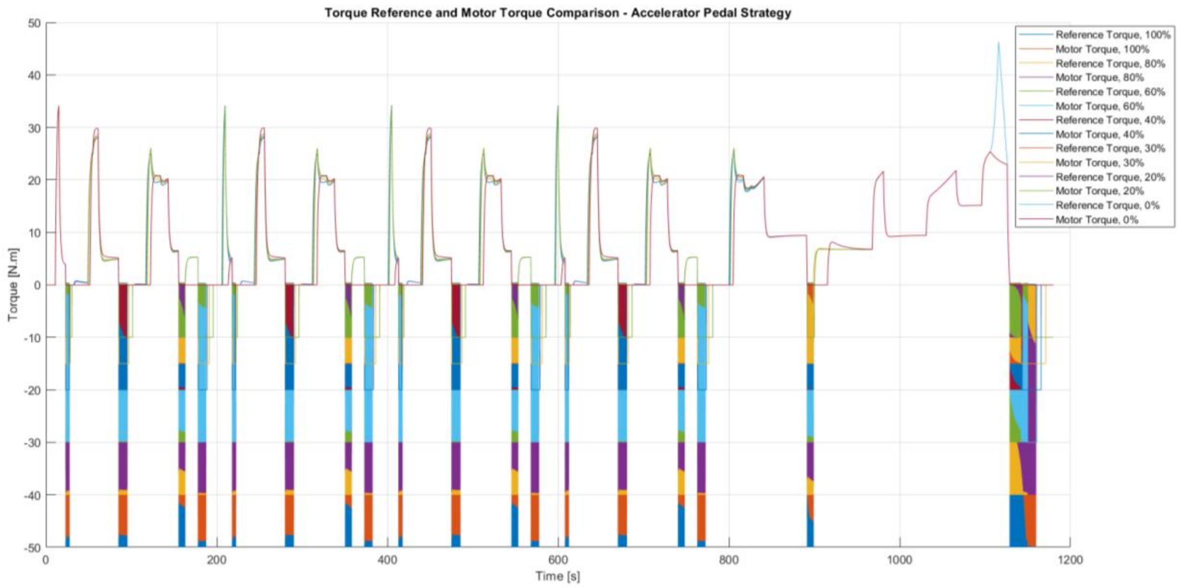


Figure 29. All the torque profiles simulated with accelerator pedal strategy – NEDC cycle

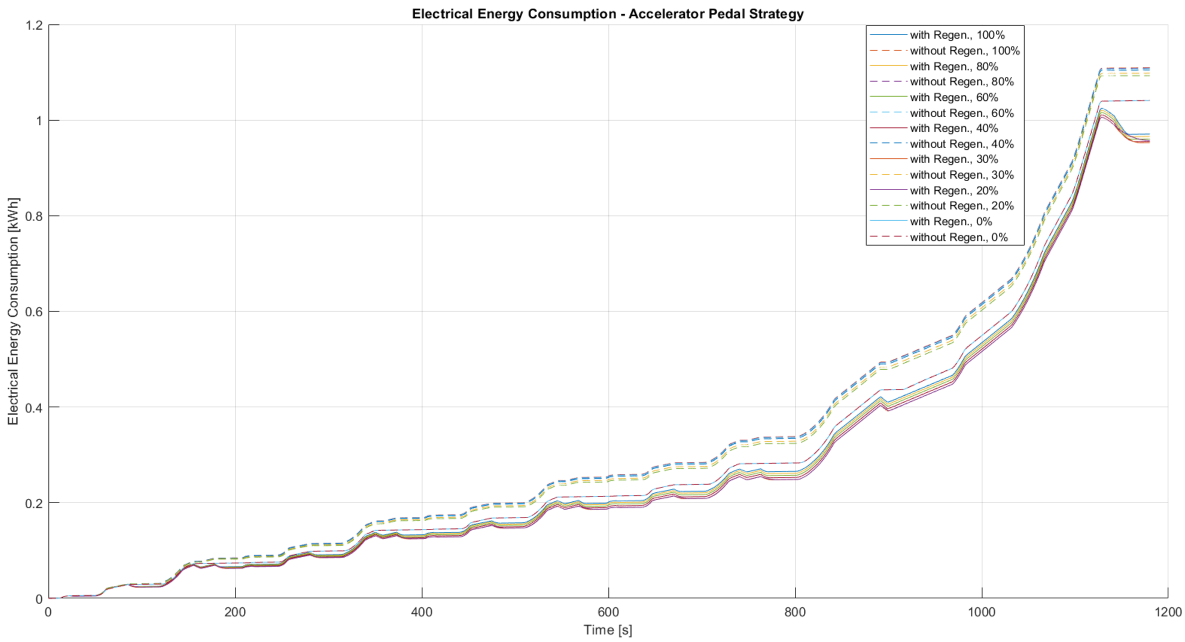


Figure 30. All the electrical energy consumption profiles simulated with accelerator pedal strategy – NEDC cycle

After performing the simulations, a summary table of key parameters that define the behavior of the vehicle for what regards its electrical energy consumption either with regeneration or without, the consequent energy saving with regeneration and also the ability of the vehicle to follow the desired speed cycle is presented.

Followingly, it can be seen which braking level in each case gives the minimum electrical energy consumption, maximum energy saving through regeneration and the most accurate vehicle speed profile.

Reg. level [%]	EE w/ regen [kWh] - Brake pedal signal	EE w/ regen [kWh] - Acc. pedal signal
100	0.970526606	0.970639209
80	0.965694688	0.965712848
60	0.960479065	0.960435013
40	0.95540832	0.955300624
30	0.952844538	0.95273496
20	0.957451989	0.957366285
0	1.040909775	1.040897581

Reg. level [%]	EE w/o regen [kWh] - Brake pedal signal	EE w/o regen [kWh] - Acc. pedal signal
100	1.109373584	1.109492162
80	1.10860867	1.108629682
60	1.107636409	1.107601193
40	1.104650998	1.104558247
30	1.097854635	1.097976446
20	1.092592562	1.0925867
0	1.040909775	1.040897581

Reg. level [%]	Saved energy [kWh] - Brake pedal signal	Saved energy [kWh] - Acc. pedal signal
100	0.138846978	0.138852953
80	0.142913982	0.142916834
60	0.147157344	0.14716618
40	0.149242678	0.149257623
30	0.145010097	0.145241486
20	0.135140573	0.135220415
0	0	0

Reg. level [%]	Velocity error [(m/s) ^2] - Brake pedal signal	Velocity error [(m/s) ^2] - Acc. pedal signal
100	0.105337865	0.105314751
80	0.105408042	0.105409556
60	0.115747226	0.115764297
40	0.294008274	0.293885984
30	0.88104446	0.879309496
20	2.226647438	2.226118832
0	12.48442165	12.48183727

Table 1. Summary table displayed as in form of heatmaps to better visualize the comparisons - NEDC cycle

- Minimum electrical energy consumed with brake pedal signal strategy and regeneration= 0.95284 [kWh] with 30% braking
- Minimum electrical energy consumed with accelerator pedal signal strategy and regeneration= 0.95273 [kWh] with 30% braking
- Considering both acceleration and brake pedal signal cases with regeneration the minimum electrical energy consumed happens with Accelerator Pedal strategy and 30% braking
- Minimum electrical energy consumed with brake pedal signal strategy but without regeneration= 1.0409 [kWh] with 0% braking
- Minimum electrical energy consumed with accelerator pedal signal strategy but without regeneration= 1.0409 [kWh] with 0% braking
- Considering both acceleration and brake pedal signal cases without regeneration the minimum electrical energy consumed happens with accelerator pedal strategy and 0% braking

- Maximum electrical energy saved with brake pedal signal strategy through regeneration= 0.14924 [kWh] with 40% braking
- Maximum electrical energy saved with accelerator pedal signal strategy through regeneration= 0.14926 [kWh] with 40% braking
- Considering both acceleration and brake pedal signal cases with regeneration the maximum electrical energy saving happens with accelerator pedal strategy and 40% braking
- Minimum error following the reference speed cycle with brake pedal signal strategy happens with 100% braking
- Minimum error following the reference speed cycle with accelerator pedal signal strategy happens with 100% braking
- Considering both acceleration and brake pedal signal strategies the best case following the reference cycle that leads to least error happens with accelerator pedal strategy and 100% braking

3.4.3 WLTP Class 3 cycle

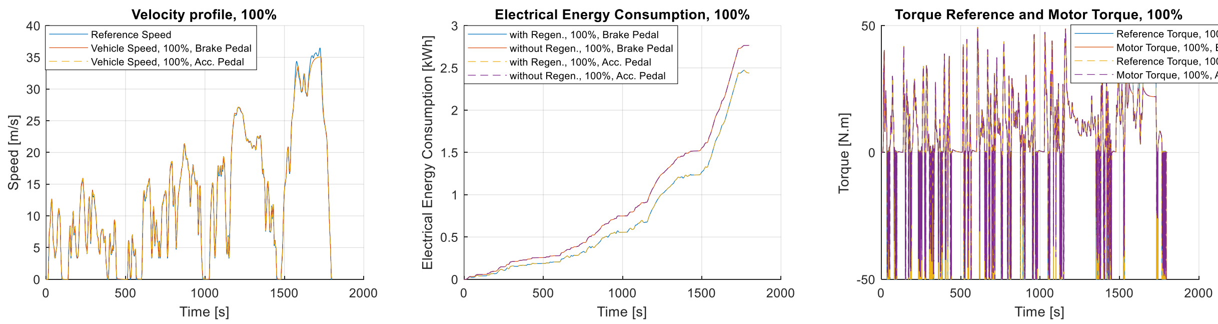


Figure 31. 100% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

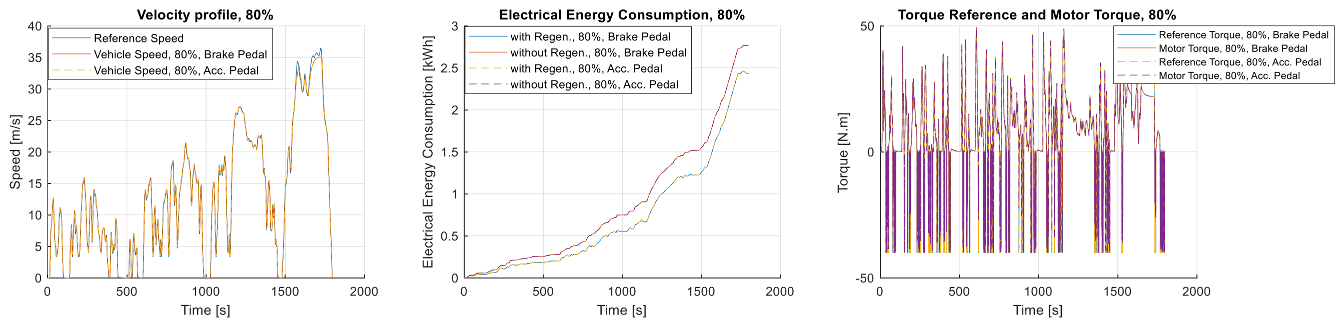


Figure 32. 80% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

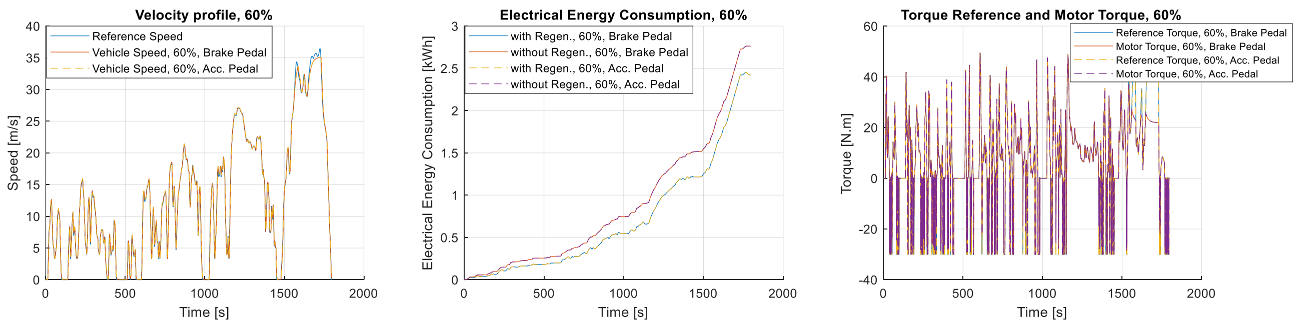


Figure 33. 60% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

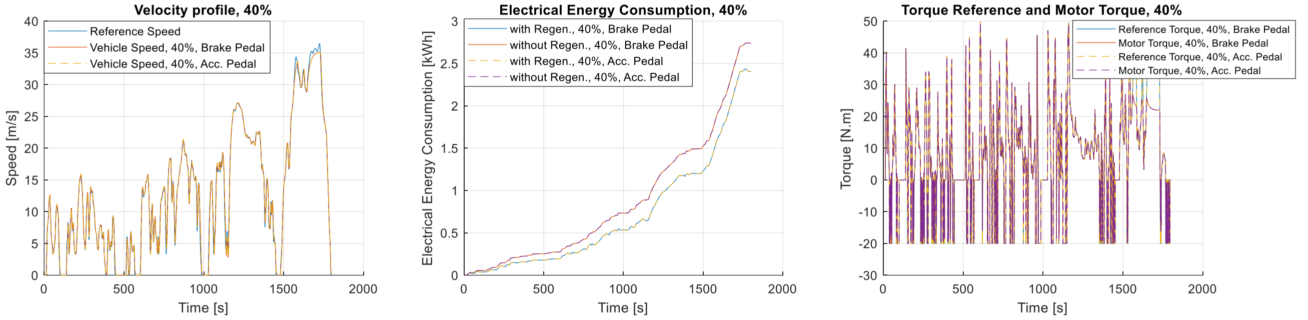


Figure 34. 40% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

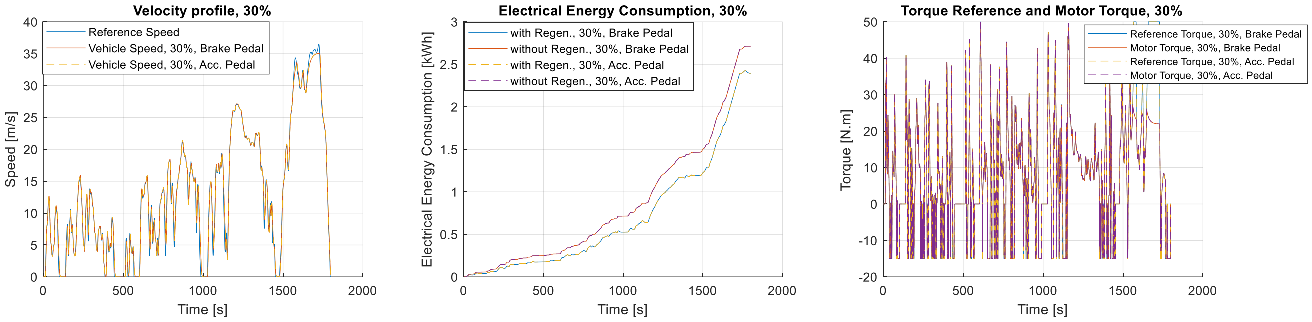


Figure 35. 30% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

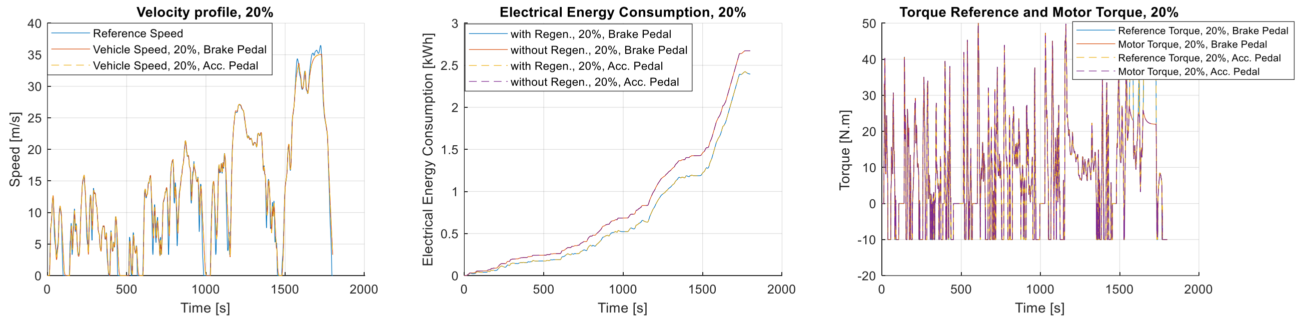


Figure 36. 20% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

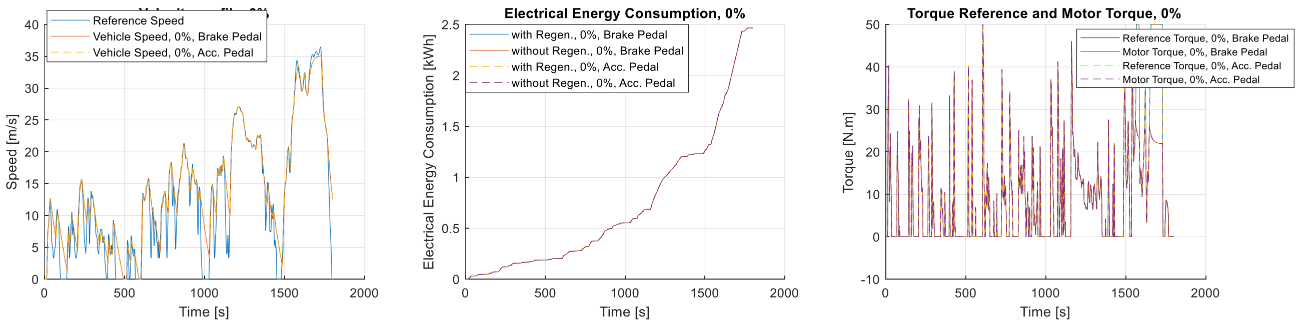


Figure 37. 0% on/off regenerative braking with both pedal strategy – WLTP Class 3 cycle

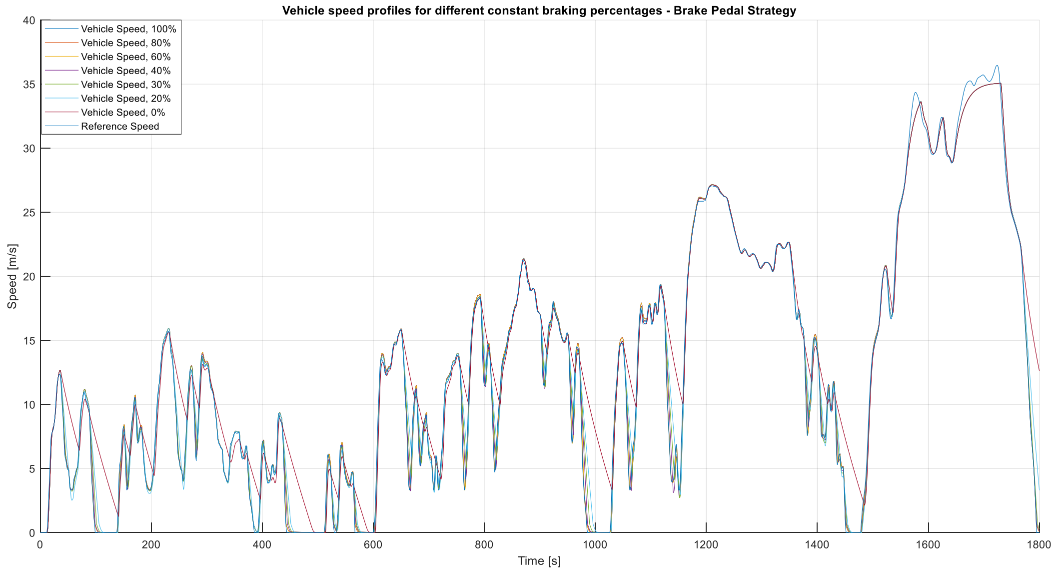


Figure 38. All the velocity profiles simulated with brake pedal strategy – WLTP Class 3 cycle

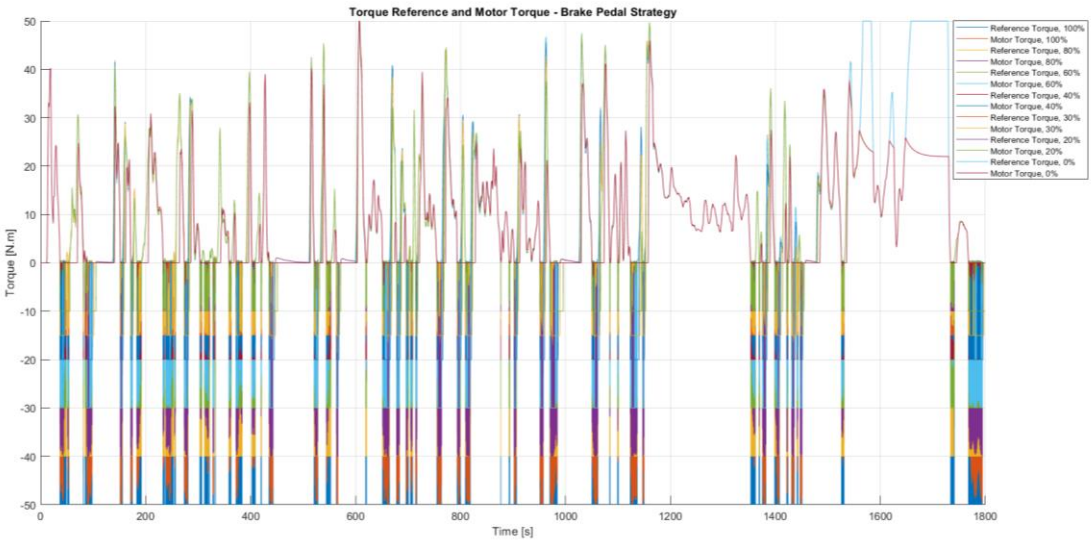


Figure 39. All the torque profiles simulated with brake pedal strategy – WLTP Class 3 cycle

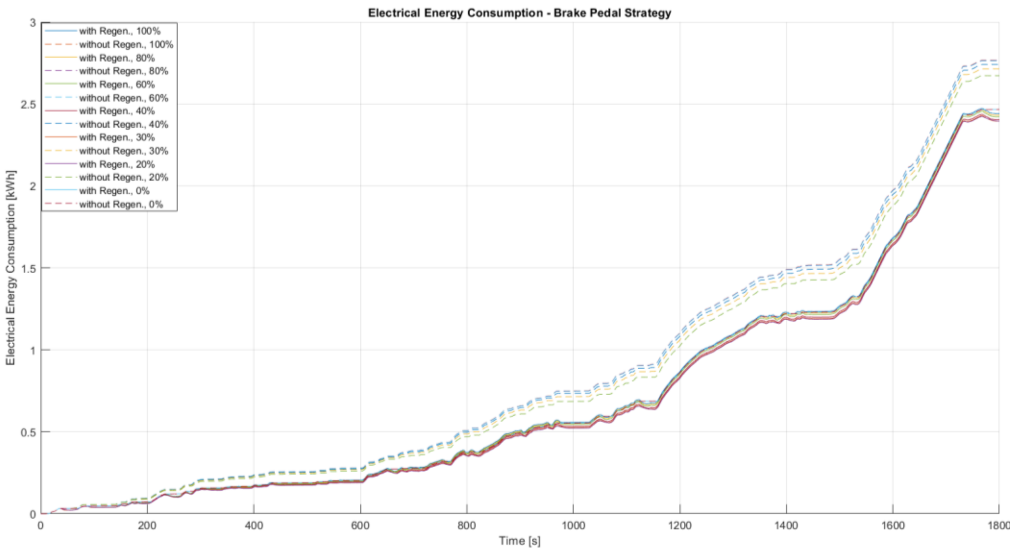


Figure 40. All the electrical energy consumption profiles simulated with brake pedal strategy – WLTP Class 3 cycle

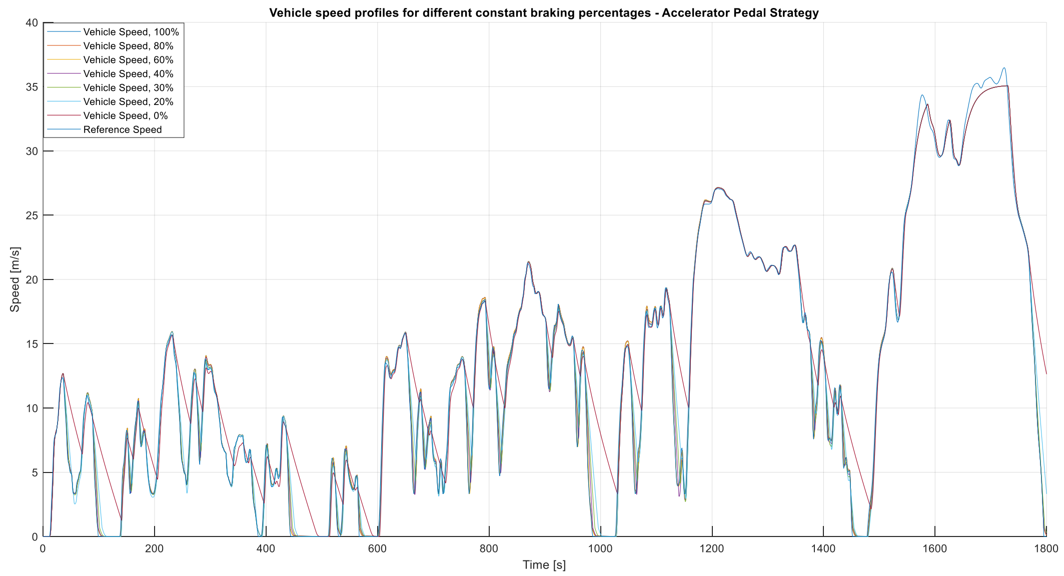


Figure 41. All the velocity profiles simulated with accelerator pedal strategy – WLTP Class 3 cycle

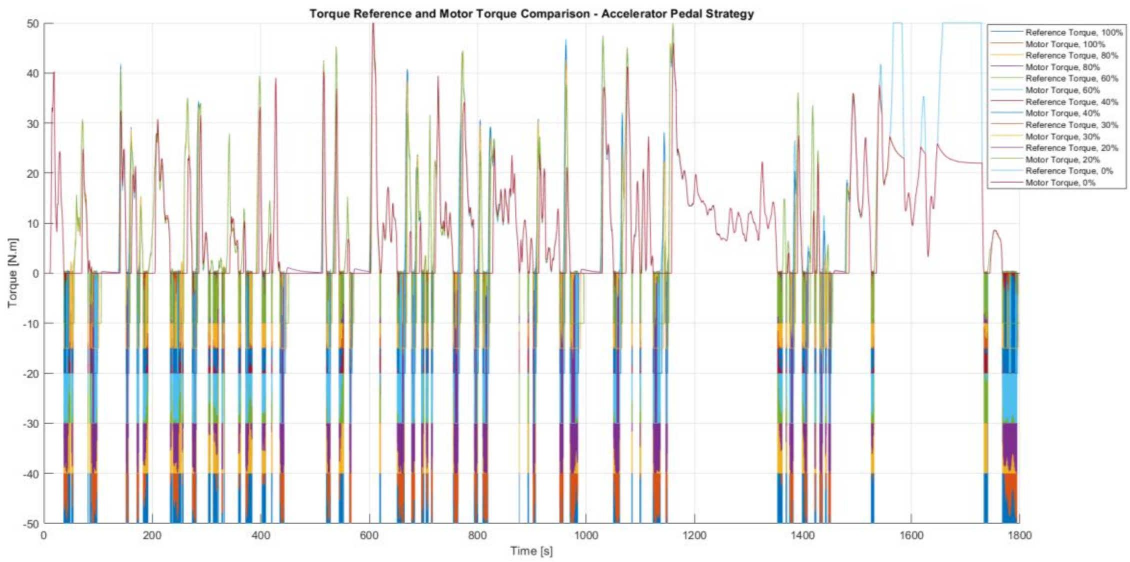


Figure 42. All the torque profiles simulated with brake pedal strategy – WLTP Class 3 cycle

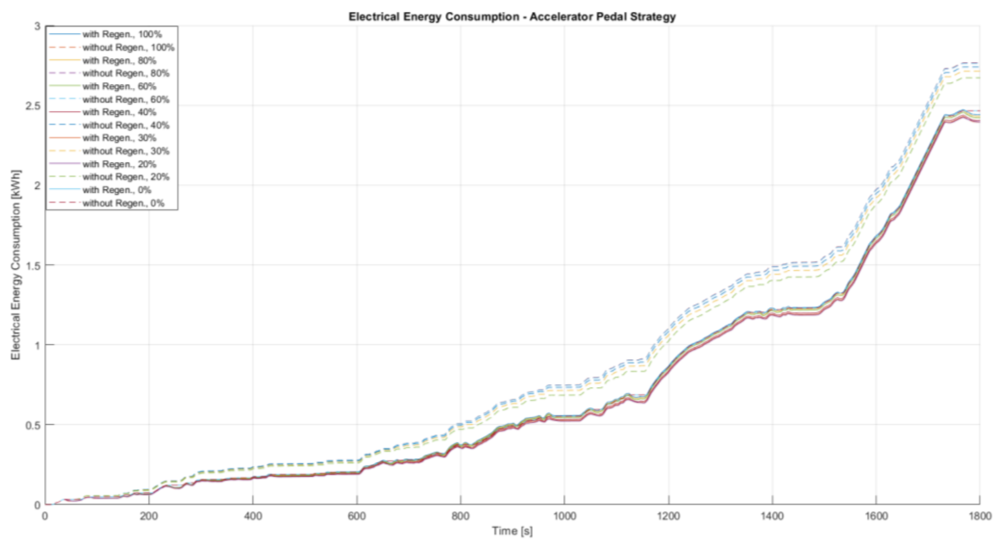


Figure 43. All the electrical energy consumption profiles simulated with brake pedal strategy – WLTP Class 3 cycle

Reg. level [%]	EE w/ regen [kWh] - Brake pedal signal	EE w/ regen [kWh] - Acc. pedal signal
100	2.440819782	2.440729421
80	2.431495652	2.431628766
60	2.421902053	2.422016542
40	2.403815758	2.404030713
30	2.394856997	2.394727538
20	2.39461765	2.394670455
0	2.466026965	2.465976624

Reg. level [%]	EE w/o regen [kWh] - Brake pedal signal	EE w/o regen [kWh] - Acc. pedal signal
100	2.766507202	2.766284326
80	2.765079754	2.765203245
60	2.762972589	2.763030008
40	2.740438725	2.740656423
30	2.713519484	2.713506061
20	2.672380537	2.67245934
0	2.466026965	2.465976624

Reg. level [%]	Saved energy [kWh] - Brake pedal signal	Saved energy [kWh] - Acc. pedal signal
100	0.32568742	0.325554905
80	0.333584102	0.33357448
60	0.341070536	0.341013466
40	0.336622966	0.33662571
30	0.318662486	0.318778524
20	0.277762887	0.277788885
0	0	0

Reg. level [%]	Velocity error [(m/s) ^2] - Brake pedal signal	Velocity error [(m/s) ^2] - Acc. pedal signal
100	0.235965572	0.236163284
80	0.236412225	0.236527111
60	0.262888444	0.26286561
40	0.509744485	0.510057963
30	0.85059836	0.850213811
20	1.710993642	1.711708532
0	8.703852838	8.704050949

Table 2. Summary table displayed as in form of heatmaps to better visualize the comparisons - WLTP Class 3 cycle

- Minimum electrical energy consumed with brake pedal signal strategy and regeneration= 2.3946 [kWh] with 20% braking
- Minimum electrical energy consumed with accelerator pedal signal strategy and regeneration= 2.3947 [kWh] with 20% braking
- Considering both acceleration and brake pedal signal cases with regeneration the minimum electrical energy consumed happens with brake pedal strategy and 20% braking
- Minimum electrical energy consumed with brake pedal signal strategy but without regeneration= 2.466 [kWh] with 0% braking
- Minimum electrical energy consumed with accelerator pedal signal strategy but without regeneration= 2.466 [kWh] with 0% braking
- Considering both acceleration and brake pedal signal cases without regeneration the minimum electrical energy consumed happens with accelerator pedal strategy and 0% braking

- Maximum electrical energy saved with brake pedal signal strategy through regeneration= 0.34107 [kWh] with 60% braking
- Maximum electrical energy saved with accelerator pedal signal strategy through regeneration= 0.34101 [kWh] with 60% braking
- Considering both acceleration and brake pedal signal cases with regeneration the maximum electrical energy saving happens with brake pedal strategy and 60% braking
- Minimum error following the reference speed cycle with brake pedal signal strategy happens with 100% braking
- Minimum error following the reference speed cycle with accelerator pedal signal strategy happens with 100% braking
- Considering both acceleration and brake pedal signal strategies the best case following the reference cycle that leads to least error happens with brake pedal strategy and 100% braking

3.5 Conclusions

By looking at the summary tables it can be said that the two strategies, brake pedal signal or acceleration pedal signal used for activation of regenerative on/off braking, as expected result in extremely close values. Thus, it can be understood that they behave in the same way.

As it can be seen, in case of NEDC cycle, the vehicle is able to follow closely the reference speed cycle by using 100% of the maximum braking torque down to 40%. But starting from 30% the error increases noticeably which is confirmable also by looking at the vehicle speed profile figures.

On the other hand, maximum energy saving through regeneration occurs with 40% of maximum regenerative torque while minimum electrical energy consumption in case of regeneration occurs at 30 % of braking.

For WLTP class 3 the same situation happens for what regards following the reference speed cycle. However maximum energy saving through regeneration occurs with 60% braking and minimum electrical energy consumption with regeneration occurs at 20% braking.

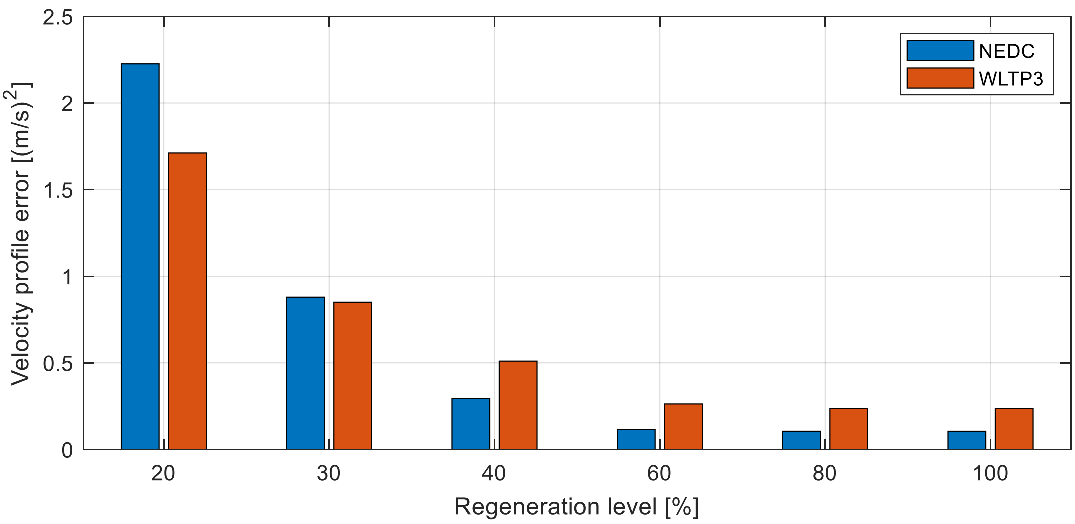


Figure 44. Velocity profile errors with different regen. Levels

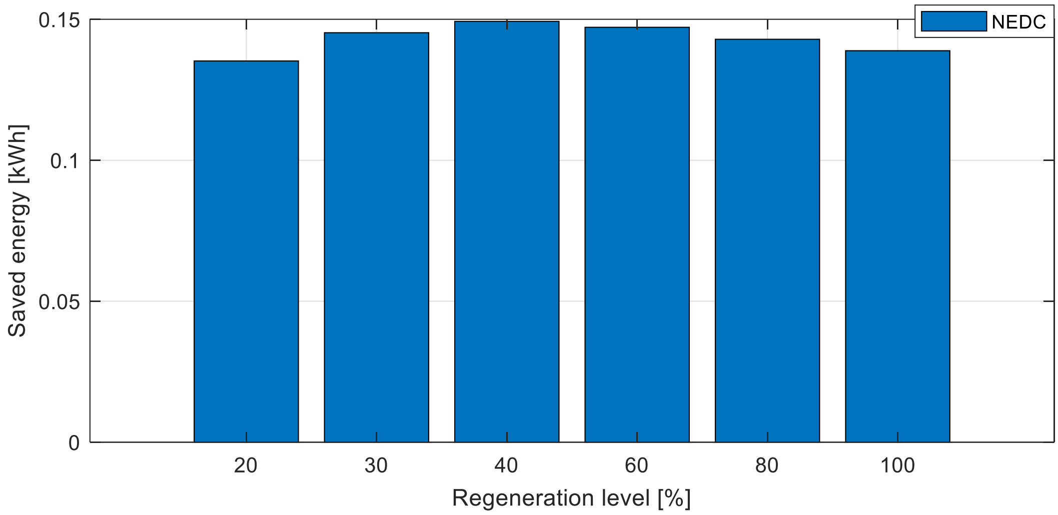


Figure 45. Saved energy with different reg. levels in NEDC

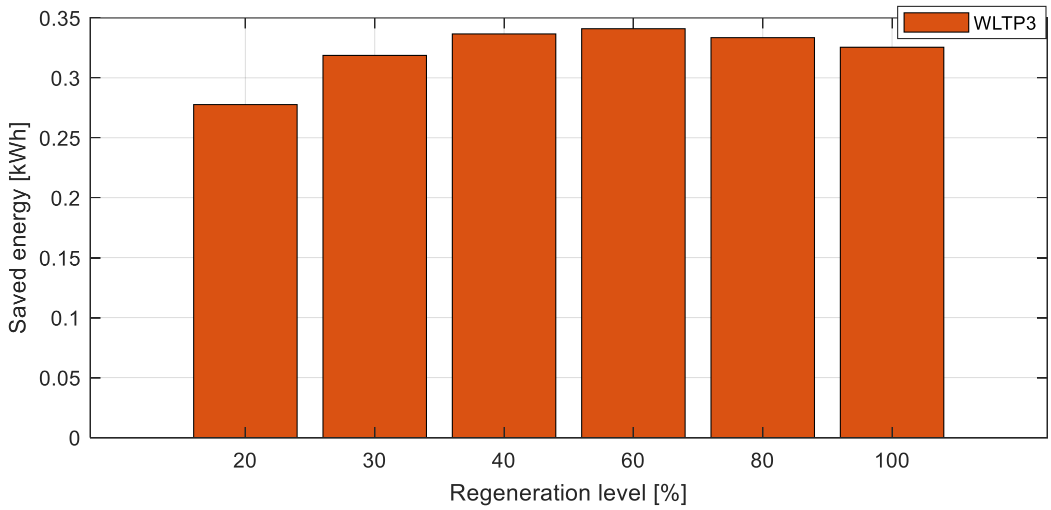


Figure 46. Saved energy with different reg. levels in WLTP Class 3

In the end, 40% regeneration could be chosen as a compromise considering both comfort issues and performance of the vehicle regarding its regeneration capabilities and the possibility to follow a desired reference cycle without exploiting additionally the hydraulic braking.

4 Chapter IV. Sensitivity Analysis on Rolling Resistance

4.1 Introduction

When implementing a model of the vehicle in Simulink many parameters of the vehicle in general or its components should be known in advance as they play a major role on defining the precision of simulation results. Obtaining some of these parameters requires standard procedures to be performed on the real vehicle which means consuming time and money. Hence, there could be a sort of compromise on choosing models that require a smaller number of parameters but indeed having less accurate simulation results. Furthermore, some parameters could be approximated through calculations however their sensitivity on possible changes that may occur in reality should be taken into account since simulation results could be hugely different from experimental ones if a parameter has a high sensitivity. As it will be shown later in the following chapters the vehicle under study whose experimental data will be used for model validation, does not have any standardly obtained coast-down coefficients but rather they are simply calculated only considering aerodynamic and rolling resistances. Coast-down coefficients should be obtained through experimental tests but since such tests were not yet performed, the Simulink model in this thesis uses the computed ones as the alternative solution.

Two different expressions could be used to estimate the rolling resistance and consequently coast-down coefficients. One expression takes into account the inflation pressure and vertical load of the tire and the other focuses on tire's energy efficiency class.

An important preliminary step before implementing the computed coast-down coefficients inside the Simulink model, is to perform a sensitivity analysis on the calculated coast-down coefficients in order to measure how sensitively they vary corresponding to the possible changes that could occur in reality due to the variation of tires' inflation pressure, the vertical load or even changing the efficiency class of tires.

The purpose is to see which of these parameters could play a more dominant role in changing the computed coast-down coefficients.

Furthermore, it is important to know whether the experimental results happen to be in the vicinity of the calculated coast-down coefficients’ sensitivity phase or not.

4.2 Expression related to tire's energy efficiency class

In order to take into account the tire's energy efficiency class the following formula could be used:

$$F_r(t) = \left(f_0 + f_2 V^2(t)\right) mg \cos\left(\alpha(t)\right)$$

Where f_2 is constant and $f_0 = f_{RCC} - f_2 V_{80}^2$ depending on the Rolling Resistance Coefficient efficiency class (EU label).

RRC [kg/t]	Energy efficiency class
RRC ≤ 6.5	A
6.6 ≤ RRC ≤ 7.7	B
7.8 ≤ RRC ≤ 9.0	C
Empty	D
9.1 ≤ RRC ≤ 10.5	E
10.6 ≤ RRC ≤ 12.0	F
RRC ≥ 12.1	G

Table 3. RRC factors for different energy efficiency classes [6]

Considering a level road and only aerodynamic and rolling resistances, this expression gives the following computed coast-down coefficients:

$$F_0 = f_0 mg$$

$$F_1 = 0$$

$$F_2 = f_2 mg + \frac{1}{2}\rho C_x A$$

This is the relation that was originally exploited in the model as well. In this report three efficiency classes A, C and G are chosen to be studied and compared. As it will be also further explained followingly, two different vertical loads are considered for calculations exploiting this expression: curb and gross masses of the vehicle being 800 kg and 1200 kg respectively.

- C_x = 0.3600
- A = 1.8160 $[m^2]$
- F_0 for class G and 800kg load = 116.0729 $[N]$
- F_2 for class G and 800kg load = 0.4380 $[N\,\frac{s^2}{m^2}]$
- F_0 for class G and 1200kg load = 174.1093 $[N]$
- F_2 for class G and 1200kg load = 0.4635 $[N\,\frac{s^2}{m^2}]$
- F_0 for class C and 800kg load = 40.7321 $[N]$
- F_2 for class C and 800kg load = 0.4380 $[N\,\frac{s^2}{m^2}]$
- F_0 for class C and 1200kg load = 61.0981 $[N]$
- F_2 for class C and 1200kg load = 0.4635 $[N\,\frac{s^2}{m^2}]$
- F_0 for class A and 800kg load = 23.4665 $[N]$
- F_2 for class A and 800kg load = 0.4380 $[N\,\frac{s^2}{m^2}]$
- F_0 for class A and 1200kg = 35.1997 $[N]$
- F_2 for class A and 1200kg = 0.4635 $[N\,\frac{s^2}{m^2}]$

As expected according to the above expressions changing the efficiency class but keeping the same vertical load does not have any effect on F_2 as its value remains the same. However, F_0 changes noticeably.

4.3 Expression related to tire inflation pressure and vertical load

According to the SAE suggestion mentioned in [7] the following empirical model can be exploited in order to take into account the effect of inflation pressure and vertical load:

$$f = \frac{K'}{1000}\left(5.1 + \frac{5.5 \times 10^5 + 90F_z}{p} + \frac{1100 + 0.0388F_z}{p}V^2\right)$$

in which K' is 1 for conventional tires and 0.8 for radial tires. It should be also noticed that normal force F_z, pressure p and vehicle speed V are all entered with their SI unit.

Using the aforementioned expression leads to the following computed coast-down coefficients:

$$F_0 = \frac{K'}{1000}\left(5.1 + \frac{5.5 \times 10^5 + 90F_z}{p}\right)mg$$

$$F_1 = 0$$

$$F_2 = \frac{K'}{1000}\left(\frac{1100 + 0.0388F_z}{p}\right)mg + \frac{1}{2}\rho C_x A$$

In the following it will be depicted how sensitively F_0 and F_2 change by varying the tire inflation pressure at fixed vertical loads and by varying the vertical load at fixed inflation pressures.

4.3.1 Vertical load

Vertical load on the tires depends mainly on the vehicle weight, road inclination angle and related aerodynamic coefficients being the lift coefficient C_z and the pitch coefficient C_{my}. Assuming that the road grade is 0 and considering that the analysis is being performed for a small city vehicle which is mainly working at low speeds and thus neglecting the aerodynamic forces and moments, the situation can be simplified. Hence, the vertical load will be changing solely due to the vehicle's weight variations.

Three main situations representing different vehicle weights could be considered:

- Curb mass: mass of the vehicle with standard equipment
- Curb mass + driver
- Gross mass: mass of the vehicle including all the passengers and the luggage

Regarding the vehicle under study the curb and gross masses are 800 kg and 1200 kg respectively. Now it will be seen how changing the vertical load while keeping the same standard tire inflation pressure (1.8 bar) will change the rolling resistance.

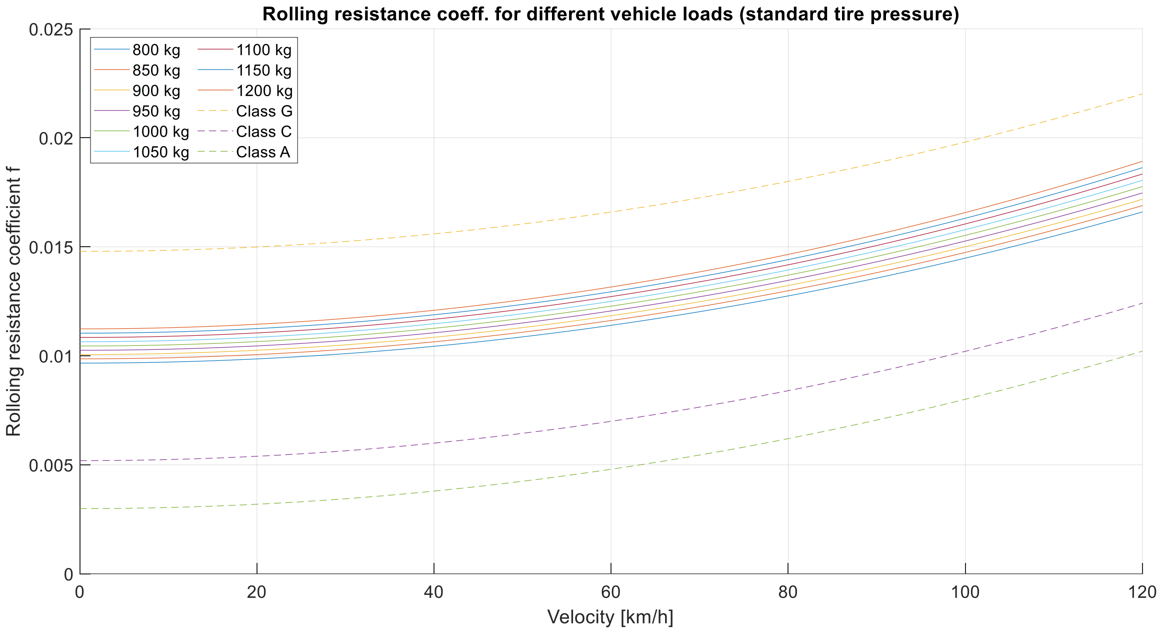


Figure 47. Rolling resistance coefficient for different vertical loads at fixed 1.8 [bar] tire inflation pressure

It is evident that by increasing the vertical load rolling resistance, F_0 and F_2 all grow.

4.3.2 Tire inflation pressure

Similar to the vertical load, tire inflation pressure impacts the rolling resistance value as well. Four different conditions could be considered. Minimum, measured, standard and maximum amount of possible inflation pressure being 1, 1.7, 1.8 and 3 bars respectively. At this step different tire inflation pressures ranging from minimum up to maximum amount (1 to 3 bars), while keeping the vertical load constant as the curb mass, are put into calculation to find the consequent changes on the rolling resistance.

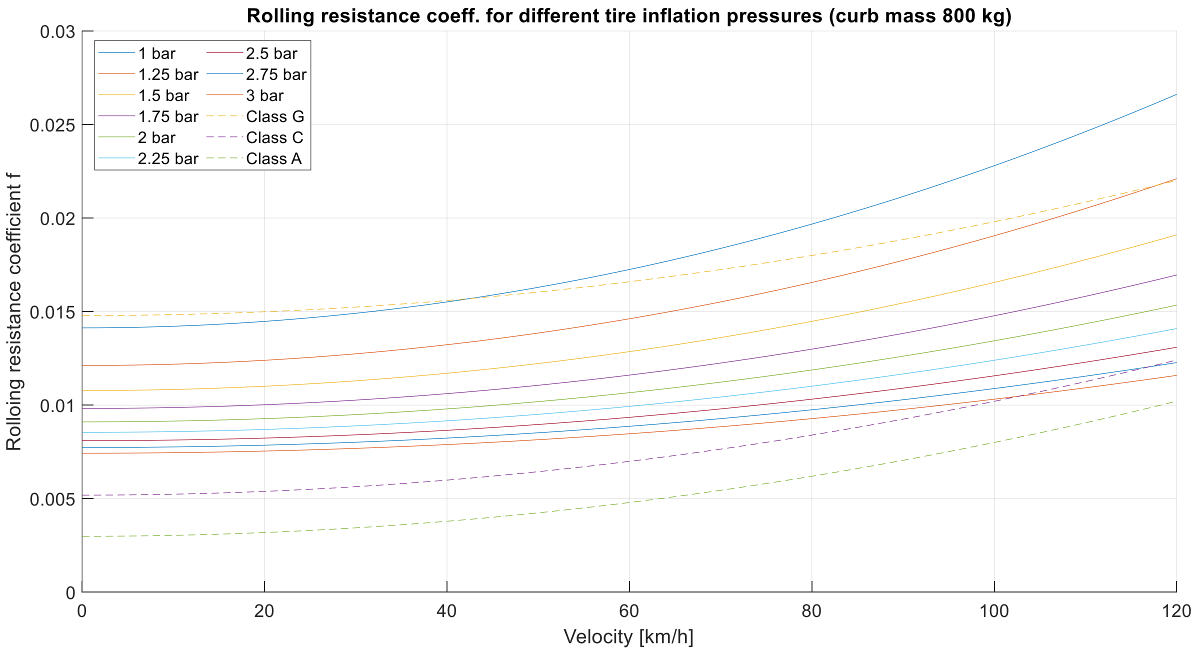


Figure 48. Rolling resistance coefficient for different tire inflation pressures at fixed vertical load (800kg)

Looking at the plot it is understandable that by increasing the tire inflation pressure rolling resistance decreases considerably.

4.4 Variation of calculated coast-down coefficients

At this step a broad analysis is carried out to see how changing each parameter related to rolling resistance will eventually affect the calculated coast-down coefficients. Three different parameters that could impact the coast-down coefficients through rolling resistance are vertical load, tire inflation pressure and energy efficiency class of the tire.

Followingly the importance of each parameter will be evaluated by calculating the relative change that they cause on the calculated coast-down coefficients so that it could be understood which aspect is more important to be invested on e.g. whether accurately measuring and setting the tires’ pressure or simply changing the tires' efficiency class.

It is important to study how much the coast-down coefficients vary when moving from the lightest vehicle to the heaviest at fixed tire inflation pressure or when moving from the lowest tire inflation pressure to the highest inflation pressure at fixed vehicle weight or when moving from a lower efficiency class of the tire to a higher efficiency class.

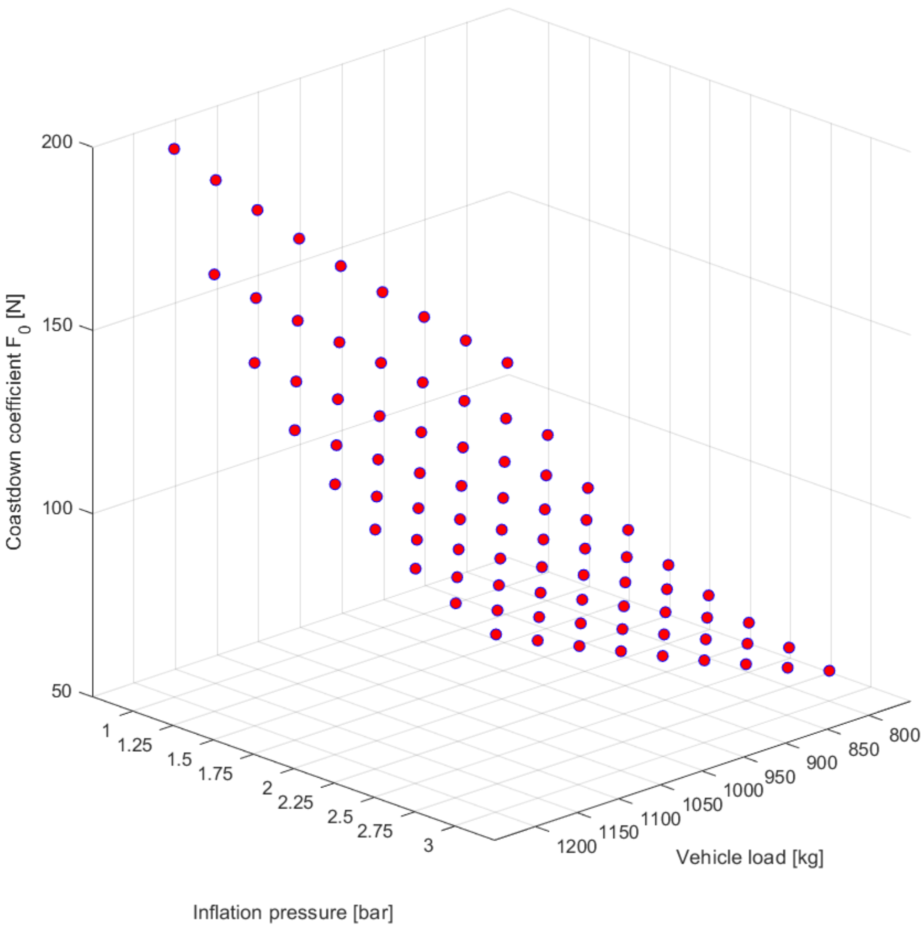


Figure 49. F_0 for different combinations of vehicle load and inflation pressure

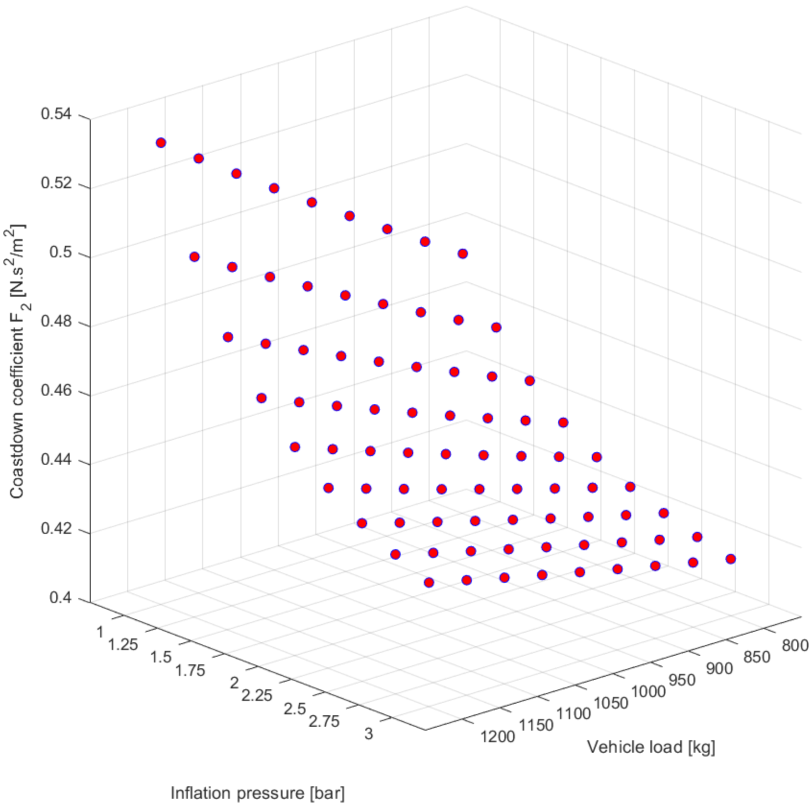


Figure 50. F_2 for different combinations of vehicle load and inflation pressure

It is observable that both F_0 and F_2 grow by increasing the vertical load or decreasing the inflation pressure.

4.4.1 F_0 changes due to variation of tire inflation pressure

Moving from the minimum inflation pressure 1 bar up to the maximum 3 bar, F_0 values could change considerably. This analysis is performed while keeping each time a fixed level of vertical load.

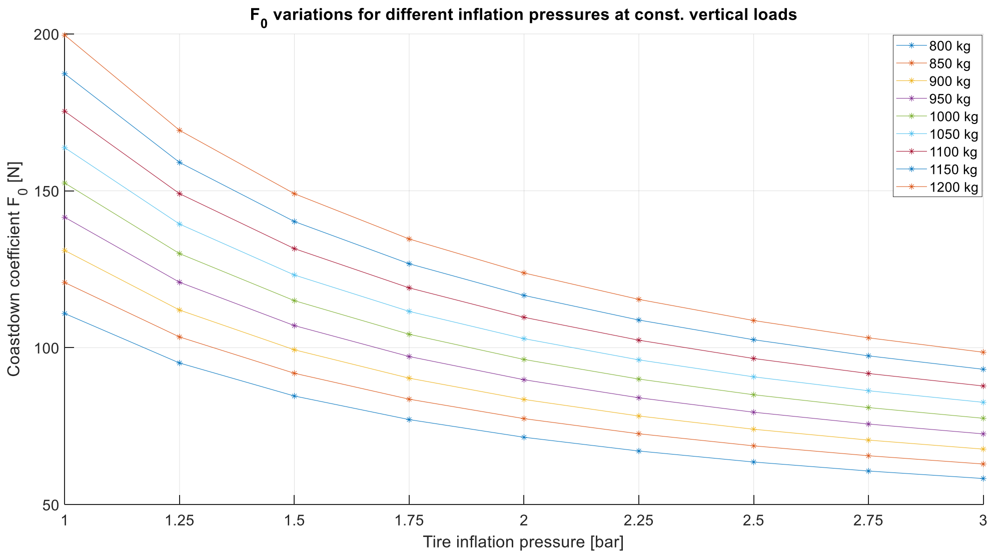


Figure 51. F_0 variations for different inflation pressures at constant vertical loads

Relative changes:

- F_0 decrease moving from minimum to maximum inflation pressure with the lightest vertical load = 47.4176 [%]
- F_0 decrease moving from minimum to maximum inflation pressure with the heaviest vertical load = 50.625 [%]
- Average F_0 decrease moving from minimum to maximum inflation pressure for all vertical loads = 49.1065 [%]

It is evident that increasing the inflation pressure F_0 decreases and the relative decrease of F_0 in percentage moving from 1 bar to 3 bars is almost the same at all fixed vertical loads being on average 49%.

4.4.1.1 What happens in reality

It has been demonstrated that by increasing the inflation pressure from 1 bar to 3 bar it is possible to reduce F_0 considerably. But the point is in reality such assumption is not applicable and the real case might be for example moving from a deflated tire with 1.75 bar to the normal inflation condition e.g. 2 bar.

- F_0 absolute decrease on average for all vertical loads moving from 1.75 bar to 2 bar inflation pressure = 8.1149 [N]
- F_0 relative decrease on average for all vertical loads moving from 1.75 bar to 2 bar inflation pressure = 7.6909 [%]

It can be seen that in reality only about 7% of decrease may be obtained in F_0 by adjusting the inflation pressure from 1.75 bar to 2 bar.

4.4.2 F_0 changes due to variation of vertical load

Next step is moving from the lightest vehicle being its curb mass (800 kg) to the heaviest being its gross mass (1200 kg) while keeping a fixed inflation pressure at each time.

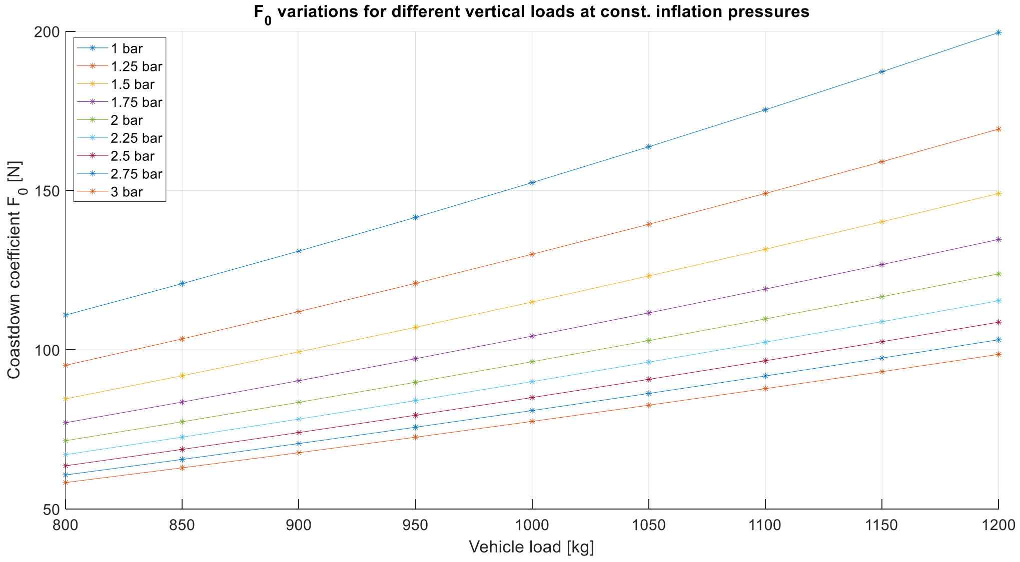


Figure 52. F_0 variations for different vertical loads at constant inflation pressures

Relative changes:

- F_0 increase moving from lightest to heaviest vehicle with minimum inflation pressure= 79.9912 [%]
- F_0 increase moving from lightest to heaviest vehicle with maximum inflation pressure= 69.0122 [%]
- Average F_0 increase moving from lightest to heaviest vehicle for all tire inflation pressures= 73.7773 [%]

It is seen that by increasing the vertical load F_0 increases and again the relative increase is almost the same at all fixed inflation pressures being about 73% on average.

4.4.3 F_2 changes due to variation of tire inflation pressure

Similar to the F_0, the same analysis is done for F_2 changing tire inflation pressure at fixed vertical loads.

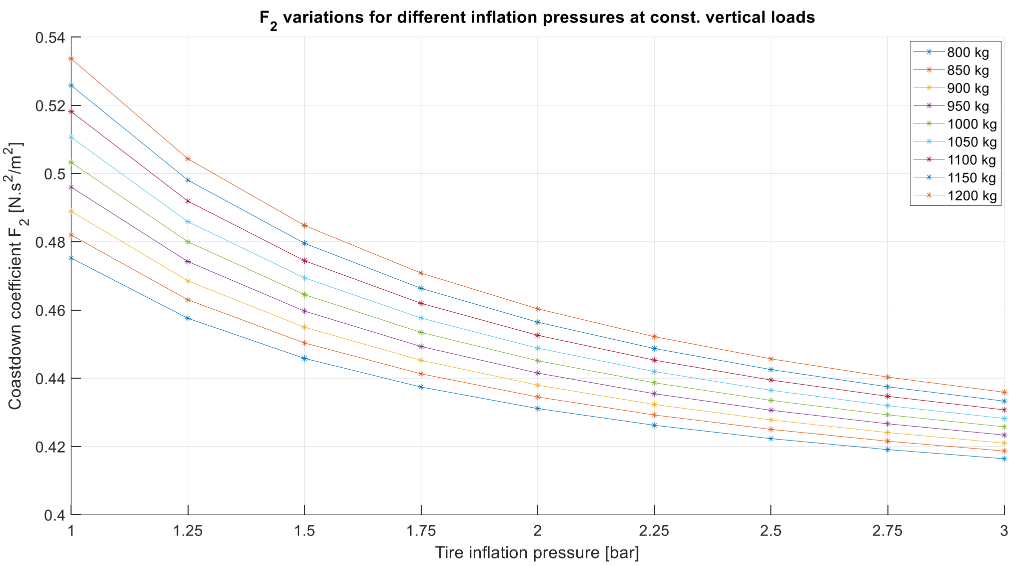


Figure 53. F_2 variations for different inflation pressures at constant vertical loads

Relative changes:

- F_2 decrease moving from minimum to maximum pressure with the lightest vertical load = 12.3708 [%]
- F_2 decrease moving from minimum to maximum pressure with the heaviest vertical load = 18.3158 [%]
- Average F_2 decrease moving from minimum to maximum pressure for all vertical loads = 15.3728 [%]

Like F_0, also F_2 decreases when inflation pressure increases however here the amount of relative decrease is much lower being only about 15% on average.

4.4.3.1 What happens in reality

Similar to F_0 it is also important to see how much F_2 might decrease in reality if inflation pressure is adjusted from 1.75 bar to 2 bars rather than from 1 bar to 3 bars.

- F_2 absolute decrease on average for all vertical loads moving from 1.75 bar to 2 bar inflation pressure = 0.0083355 [N.s^2/m^2]
- F_2 relative decrease on average for all vertical loads moving from 1.75 bar to 2 bar inflation pressure = 1.8312 [%]

It can be seen that in reality only about 1.8% of decrease may be obtained in F_2 by adjusting the inflation pressure from 1.75 bar to 2 bar which is even much less than what was previously seen for F_0.

4.4.4 F_2 changes due to variation of vertical load

Similar to F_0 the same analysis is done for F_2 changing vertical load at fixed tire inflation pressures.

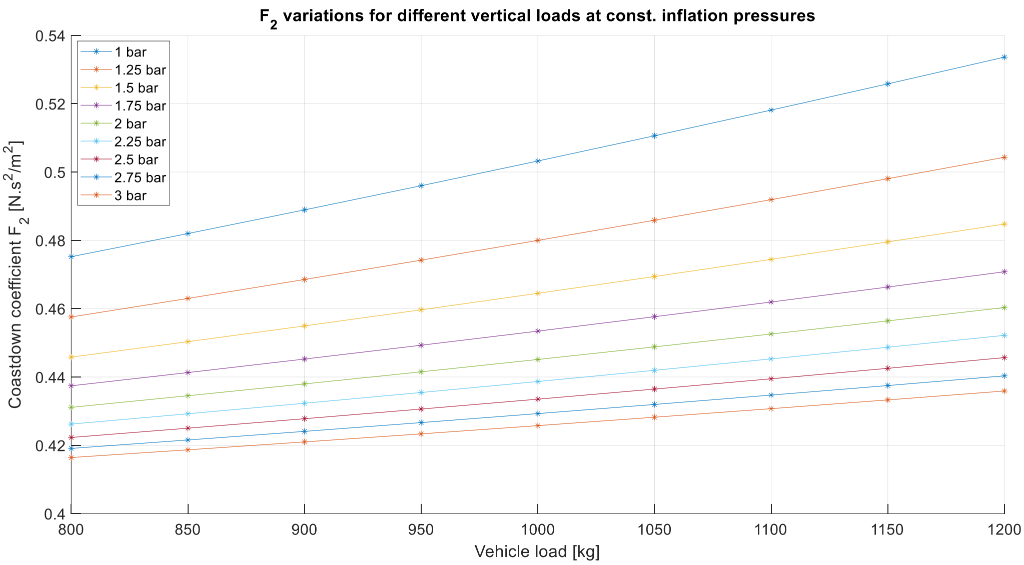


Figure 54. F_2 variations for different vertical loads at constant inflation pressures

Relative changes:

- F_2 increase moving from lightest to heaviest vehicle with minimum inflation pressure = 12.2954 [%]
- F_2 increase moving from lightest to heaviest vehicle with minimum inflation pressure = 4.6771 [%]
- Average F_2 increase moving from lightest to heaviest vehicle for all tire inflation pressures = 7.4479 [%]

Similar to F_0, also F_2 increases when moving to a heavier vehicle situation but in case of F_2 the relative increase is much smaller being only about 7% on average.

4.4.5 Changes due to variation of energy efficiency class

Next, it is of interest to see how coast-down coefficients vary when changing the energy efficiency class of the tires. But it should be remembered that as seen earlier, only F_0 depends on the efficiency class whereas F_2 according to the expressions showed, results to be equal for all the efficiency classes.

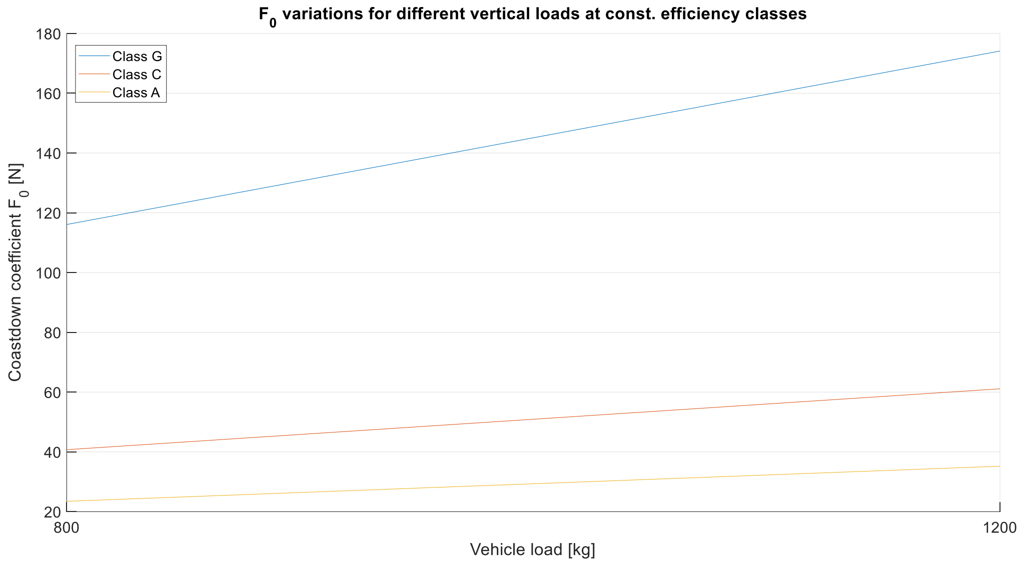


Figure 55. F_0 variations for different vertical loads at constant efficiency classes

4.4.5.1 F_0 absolute and relative changes due to variation of energy efficiency class

- F_0 absolute decrease moving from class G tire to class C with curb mass (800 kg vertical load) = 75.3408 [N]
- F_0 relative decrease moving from class G tire to class C with curb mass (800 kg vertical load) = 64.9082 [%]
- F_0 absolute decrease moving from class C tire to class A with curb mass (800 kg vertical load) = 17.2656 [N]
- F_0 relative decrease moving from class C tire to class A with curb mass (800 kg vertical load) = 42.3882 [%]
- F_0 absolute decrease moving from class G tire to class C with gross mass (1200 kg vertical load) = 113.0112 [N]
- F_0 relative decrease moving from class G tire to class C with gross mass (1200 kg vertical load) = 64.9082 [%]
- F_0 absolute decrease moving from class C tire to class A with gross mass (1200 kg vertical load) = 25.8984 [N]
- F_0 relative decrease moving from class C tire to class A with gross mass (1200 kg vertical load) = 42.3882 [%]

As seen, moving from class G to class C a large decrease in F_0 is achieved while a smaller decrease is achieved when moving from class C to class A. Furthermore, the relative changes are the same at both vertical loads, 800 kg and 1200 kg, but the absolute change is higher with gross weight.

4.4.5.2 F_0 vertical load dependency for different energy efficiency classes

It has been already depicted how varying the vertical load at constant inflation pressure affects the F_0 value. However, those figures were displaying results of the expression introduced earlier which is used for analyzing the effects of changing vertical load and inflation pressure while in the discussion of energy efficiency class a different expression is exploited. Hence it is interesting to see according to this expression how F_0 changes when varying the vertical load at each energy efficiency class.

- F_0 increase from lightest to heaviest vehicle with G class tire= 50 [%]
- F_0 increase from lightest to heaviest vehicle with C class tire= 50 [%]
- F_0 increase from lightest to heaviest vehicle with A class tire= 50 [%]

As depicted, according to the efficiency class expression all the efficiency classes seem to have the same 50% relative change in F_0 when moving from curb mass to gross mass but since the more efficient classes have smaller F_0 values, the resultant absolute change is much smaller with respect to the less efficient classes.

It should be noted that the previous expression which focused more precisely on variations of inflation pressures and vertical loads showed different but close results being on average 73%.

4.4.5.3 F_2 changes due to variation of energy efficiency class

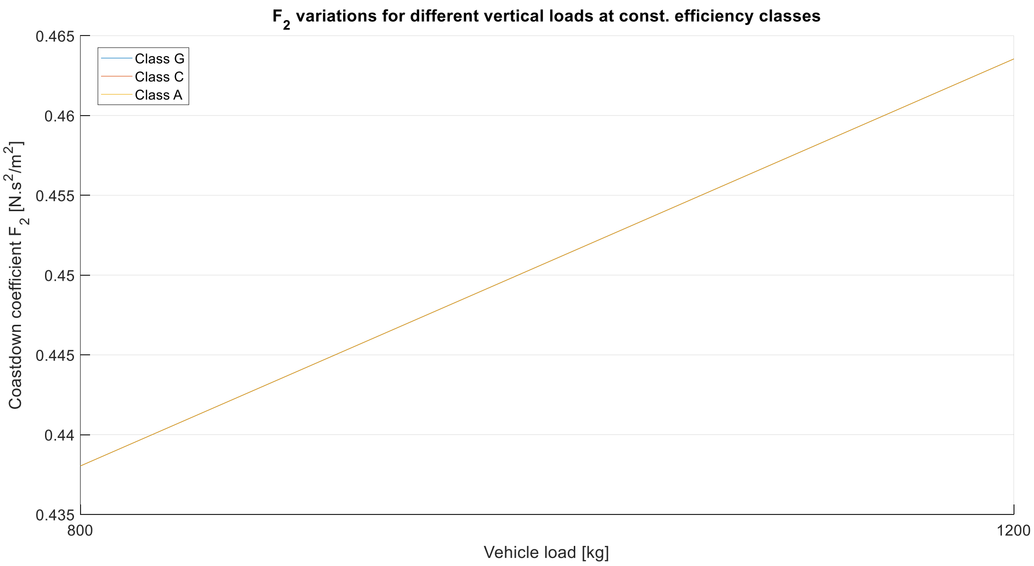


Figure 56. F_2 variations for different vertical loads at constant energy efficiency classes

It has already been mentioned that F_2 does not depend on the energy efficiency class. This is also demonstrated in the following example of moving from class G to class C with curb mass. Since the other cases will simply have the same situation they are not mentioned anymore.

- F_2 decrease moving from class G tire to class C with curb mass (800 kg vertical load) = 0 [%]

4.4.5.4 F_2 vertical load dependency for different energy efficiency classes

It is interesting to see how sensitive F_2 is when changing the vertical load at each energy efficiency class.

- F_2 increase moving from lightest to heaviest vehicle with class G tire= 5.8228 [%]

This dependency for F_2 is one order of magnitude less than what was found for F_0. Furthermore, All the classes show the same behavior.

4.5 Conclusions

- By increasing the vertical load rolling resistance and computed coast-down coefficients, F_0 and F_2, increase and vice versa.
- By increasing the tire inflation pressure rolling resistance and computed coast-down coefficients, F_0 and F_2, decrease and vice versa.
- Minimum rolling resistance and computed coast-down coefficients, F_0 and F_2, are obtained with maximum tire inflation pressure and lightest vehicle.
- Maximum rolling resistance and computed coast-down coefficients, F_0 and F_2, are obtained with minimum tire inflation pressure and heaviest vehicle.
- By increasing the tire inflation pressure for 200%, from 1 bar to 3 bar, F_0 on average decreases about 50% while F_2 on average decreases about 15% and these trends is almost the same at all fixed level vehicle weights. But considering a real-world scenario this pressure variation consists a smaller range e.g. from 1.75 bar to 2 bar in which F_0 and F_2 decrease much less, 7.6% and 1.8% respectively.
- By increasing the vehicle load about 50%, from 800 kg to 1200 kg, F_0 on average increases about 73% while F_2 on average increases about 7% and these trends is almost the same at all fixed tire inflation pressure levels.
- F_2 values tend to be much less sensitive to vertical load and tire inflation pressure variations while F_0 values vary significantly.
- Changing the energy efficiency class of tire from class G to class C, F_0 decreases about 64% while this decrease is less both absolutely and relatively when moving from class C to class A. Hence more improvement could be achieved in case of moving from worst efficiency classes to the middle ones rather than from the middle ones to the most efficient class.
- F_0 relatively increases the same 50% for all the efficiency classes when moving from curb weight to gross weight while the absolute change is much less for more efficient classes A and C compared to the worst efficient one G.
- F_2 is the same for all the energy efficiency classes and for efficiency classes it increases only about 5% when moving from curb weight to gross weight.

To sum up, it could be concluded that in case of having the worst energy efficient class tires such as class G as seen in this report, changing the efficiency class to a better one even if not the best i.e. class A but a middle one such as class C, reduces the rolling resistance and coast-down coefficient F_0 considerably compared to implementing pressure sensors in order to adjust the inflation pressure. While in case of owning tires with rather middle ranged efficiency classes such as Class C, improving the efficiency class to the best one, class A, reduces F_0 about 17 N whereas simply changing the inflation pressure from 1.75 bar to 2 bars reduces F_0 a little less, about 8 N. Hence in this case it may be more cost effective to simply adjust the pressures instead of investing for improving the efficiency class of tires. For what regards F_2, with both solutions it could be said that they almost do not make any sensible improvement.

5 Chapter V. Model validation

5.1 Introduction

The simplest one-pedal driving strategy in the vehicle under study, as shown in chapter two is the basic on/off regenerative braking activated when driver releases the accelerator pedal. In order to be able to perform simulations related to more sophisticated one-pedal strategies and compare the results with the simplest strategy already mentioned, a reliable model is needed so that its results could be trustworthy enough. In chapter two, on/off regenerative braking was introduced and its Simulink implementation was shown. However, it is yet doubtful if the results coming from simulations represent precisely experimental results conducted with the same conditions. Hence a model validation is needed. The purpose of this chapter is to perform model validation by comparing the available experimental data with the simulation results focusing mainly on two major parts: traction control model and the plant. Regarding the control there are two models: ideal control and real control for on/off electric braking. For what regards the plant as it was also mentioned in the previous chapter coast-down coefficients of the vehicle under study were not obtained through standard procedures but rather simply calculated considering rolling resistance and aerodynamic forces. Thus, an intermediate step is needed to improve the coast-down coefficients from calculated ones to those that best fit simulation results to the experimental ones. Two sets of coast-down coefficients are considered: calculated ones and best fit estimation. More explanations will be provided in the following.

The ultimate goal of this model validation is to provide a virtual prototype so that time and money consuming physical implementations and tests could be avoided.

It should be noticed that from now on code names will be used to represent control models, coefficient sets or reference cycles since numerous combinations of them will be discussed in the following parts.

5.1.1 Control models: C0 vs. C1

First, the control model itself should be validated. As already mentioned, control system implemented in the Simulink model can be either ideal or the real one representing what is already implemented in the vehicle. In the ideal case on/off regenerative braking is not considered and the regenerative torque's reference value is modulated ideally but in the real control logic the on/off regenerative braking is taken into account. First, the model with the ideal control system is simulated and next the model with the real control. Followingly their errors with respect to the experimental data are calculated and compared to see if the real control system implemented can be validated or not. It should be noticed that this comparison is done by keeping the same calculated coast-down coefficients.

From now on the control logics will be addressed as C0 being the ideal one and C1 as the on/off regenerative braking activated through brake pedal's signal and C2 as the on/off regenerative braking activated through accelerator pedal's signal. It has been already explained in chapter two that C1 and C2 have the same results. Furthermore, the experimental tests were carried out mainly with the brake pedal strategy thus only C1 will be used in simulations presented in this chapter.

5.1.2 Plant: S0 vs. S1

The plant of the Simulink model that represents the longitudinal dynamics model of the vehicle, as a first approximation uses computed coast-down coefficients however in reality they should be obtained following standard procedures. Since these standard tests were not performed for the vehicle under study, as a first choice coast-down coefficients were simply obtained from calculations considering only aerodynamic and rolling resistances using the expression discussed in the previous chapter:

$$F_0 = f_0 mg$$

$$F_1 = 0$$

$$F_2 = f_2 mg + \frac{1}{2}\rho C_x A$$

As it will be shown later although implementing the real control system improves some simulation results yet still a noticeable error will remain regarding the consumption values. This could be justified by the fact that the coast-down coefficients are not obtained through the standard procedures but rather they are simply calculated considering resistances due to aerodynamic forces and rolling resistance. However, in reality additional dissipations could occur along the driveline downstream of the gearbox that reduce the available traction force at the wheels. Furthermore, there exists possible remaining torque of the friction braking system [8]. Hence, it comes to mind how to improve the coefficients such that they would best fit the simulation results to the experimental ones. Driveline resistances as also required by the vehicle model of Simulink could be represented as a first order polynomial function of velocity while the remaining torque of hydraulic brakes could be considered as a small constant braking torque [9].

$$F_{brake} = 4\frac{T_{brake}}{R}; usually\ T_{brake} < 5\ N.m$$

where: T_{brake} is the possible remaining torque of the hydraulic braking system on each wheel and R is the tire's rolling radius. Thus, it seems that it would be best to try to tune F_0 and F_1 coefficients as they take into account the missing dissipations mentioned above. This coast-down coefficient tuning is done after implementing the real control model C1.

From now on calculated coast-down coefficients will be addressed as S0 and best fit estimation ones as S1.

5.1.3 Experiments: T1, T2, T3, T4

To validate the model some experimental data are needed to calculate the simulation errors. Four different experimental tests were carried out: no regeneration, 40% regeneration consisting both acceleration pedal and brake pedal strategies for activating on/off regenerative braking, 40% regeneration and 20% regeneration with brake pedal strategy activation. Experimental data from these tests are then converted into the proper format in which they can be compared with their corresponding simulation results. From now on the aforementioned experiments will be addressed as experiment T1, T2, T3 and T4 respectively.

Furthermore, for each experimental test its driving cycle is obtained as the input to the Simulink model. The monotonic time and speed vectors are used to define the corresponding driving cycle. Noticeably it may happen that due to curve fitting or negligible sensor measurement errors, negative elements in the speed vector may appear which in that case those elements will be replaced by zero values.

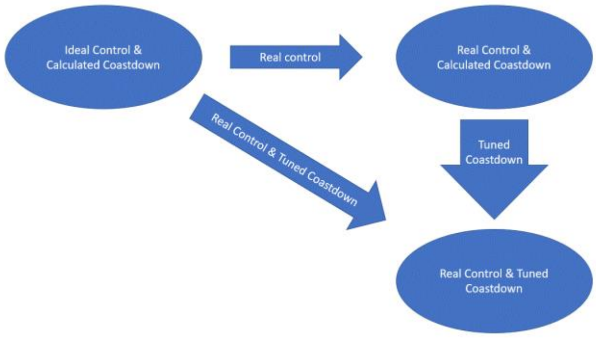


Figure 57. Overall layout of steps to be covered during this chapter

5.2 Control validation: C0, S0 vs. C1, S0

As mentioned in the introduction the first step is to see what happens when moving from ideal control C0 to the real control model C1. This comparison is done while keeping the coast-down coefficients as the calculated ones S0.

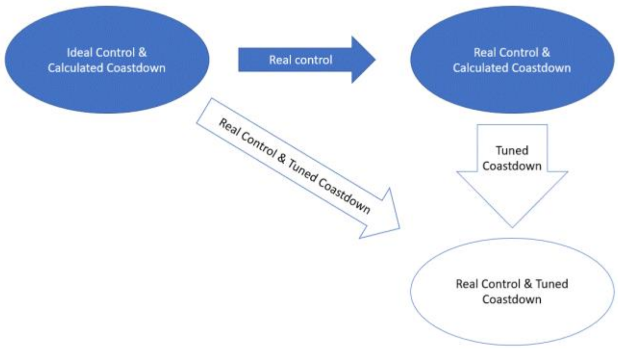


Figure 58. Control validation step

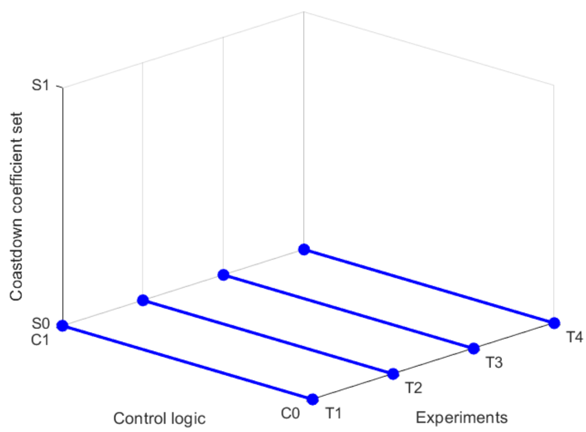


Figure 59. Comparison paths to be studied during control validation step represented by code names

5.2.1 C0, S0

In the ideal case there is no accelerator pedal mapping and no constant on/off regenerative braking. Hence the accelerator pedal and brake pedal signals are directly sent towards the electric motor block.

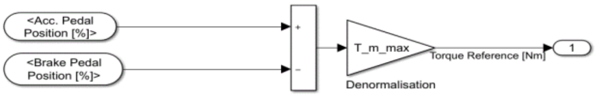


Figure 60. Simulink implementation of C0

5.2.2 C1, S0

Next the model with real control model representing on/off regenerative braking C1 will be analyzed. The aim is to see whether the model with such control model can be validated referring to the available experimental data.

Unlike the ideal control, for real control model accelerator pedal mapping, on/off regenerative braking with different constant regeneration levels and optionality for activation modes (accelerator or brake pedal signals) are considered.

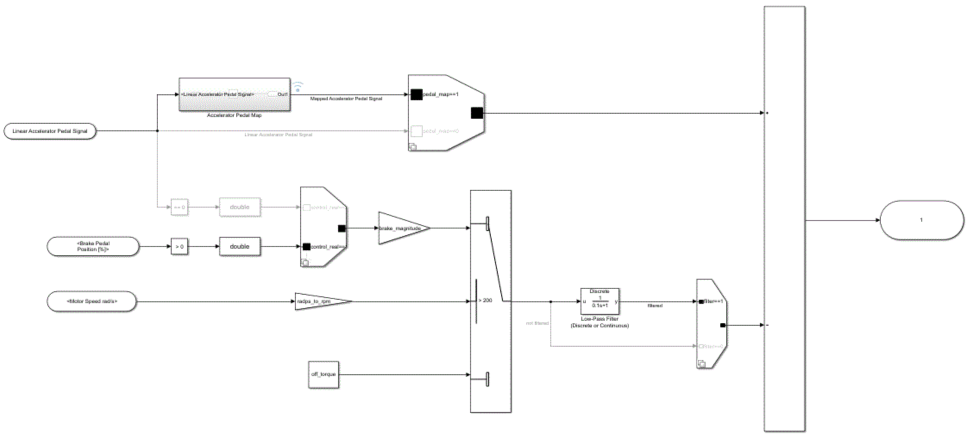


Figure 61. Simulink implementation of C1

5.2.2.1 Accelerator pedal mapping

As it has been already introduced in the second chapter, accelerator pedal mapping is done by implementing a lookup table that has 5 break points in the range of 0% to 100% pedal input being at 5%, 30%, 50%, 70% and 95%. The output of each breakpoint can be modified optionally however the experimental tests were carried out with a mapping that had only one breakpoint at 50% pedal input with output of 80%. Thus, for the simulations also the same mapping is implemented. Furthermore, in the first and the last 5% the outputs are 0% and 100% respectively.

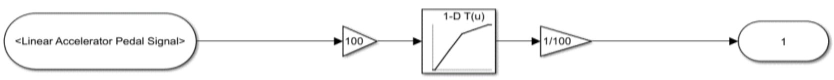


Figure 62. Simulink implementation of accelerator pedal mapping

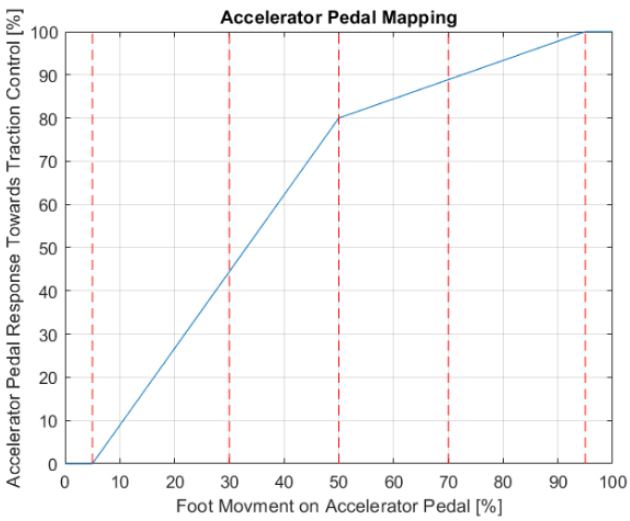


Figure 63. Accelerator pedal mapping of the vehicle during the experimental tests

5.2.2.2 On/off regenerative braking's level

Different on/off regenerative braking levels with respect to the maximum regenerative torque of the electric motor can be chosen inside the model as a parameter. As previously mentioned, 4 different experimental tests were carried out where three of them were performed with 40% and 20% regenerative braking levels and one with no regeneration. Consequently, for each case the regeneration level is set as the corresponding one used in the tests.

For what regards the first test where no regenerative braking was available and the vehicle was simply using hydraulic braking, only without regeneration values are of interest. Hence, for that case the simulations are carried out with 100% regeneration level only to be able to follow the reference driving cycle and simulation results related to regeneration are simply ignored. It would be interesting to compare the simulation results without regeneration with those coming from the ideal control model and see if the model can be still validated even if in reality another braking system was being used.

5.2.2.3 On/off regenerative braking's activation mode

Two different approaches can be used for activating the on/off regenerative braking. Either when the driver completely releases the accelerator pedal or when the driver slightly pushes the brake pedal. In chapter three is has already been demonstrated that these two approaches do not change the final result.

Additionally, the experimental tests were conducted with the brake pedal activation approach except the second one where it was also partly done with the accelerator pedal signal strategy. Thus, in the simulations the brake pedal activation approach is used.

5.2.2.4 Lower speed limit

It should be noticed that as a safety feature in order to prevent unwanted reverse motions of the vehicle when performing regenerative braking at low velocities, the whole regenerative braking system should turn off below a specified motor speed. As in the tests the limit was 200 rpm, also in the real control model this value is considered.

5.2.2.5 Filter

Excessive activations and deactivations of regenerative braking with on/off system can harm the electrical and mechanical equipment in the vehicle. This problem is avoided by the use of various filters along the electronic features of the vehicle. In the real control model, a simple low pass filter with time constant of 100 ms is applied.

$$G(s) = \frac{1}{Ts + 1};T = 0.1\ [s]$$

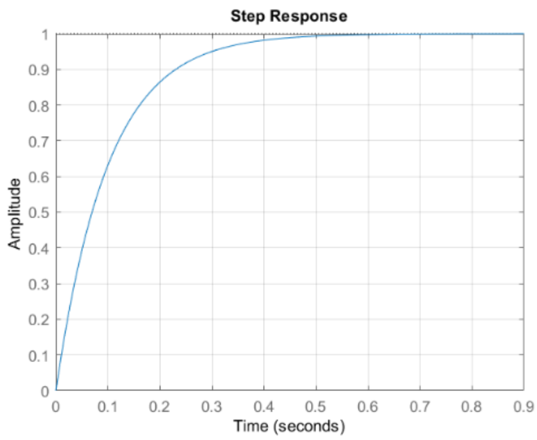


Figure 64. Step response of the low pass filter implemented in Simulink model of the real control system C1

5.3 Plant validation: C1, S0 vs. C1, S1

Next step is to validate the plant itself. As already discussed earlier the plant's coast-down coefficients are first chosen as the calculated ones (S0) instead of standardly obtaining them. These calculations give the following coast-down coefficients for S0 parameter set:

$$F_0 = 116.07\ [N]$$
$$F_1 = 0$$
$$F_2 = 0.438\ \left[N\frac{s^2}{m^2}\right]$$

Then it will be seen how implementing the tuned F_0 and F_1 coefficients (S1), improves the results specially consumption values. But before putting the tuned coefficient set inside the model and see the final results, an intermediate step is required to find the optimum choice of F_0 and F_1 values that would best fit simulation results to the experimental ones. To find them, a range of F_0 and F_1 values will be put into the model and the simulation results will be compared with the experimental ones. As the effort is to reduce as much as possible the error of consumption values, specific consumption with regeneration is chosen to be the final value compared to its corresponding experimental value since it contains both information about energy consumption, regeneration capabilities and distance covered.

After comparing the experimental data and simulation results for various combinations of F_0 and F_1 it will be possible to choose a best fit scenario such that the model gives simulation results closest possible to the corresponding experimental values.

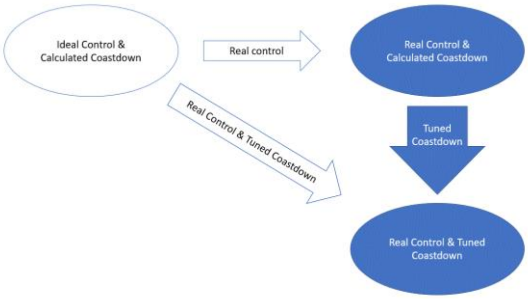


Figure 65. Plant validation step

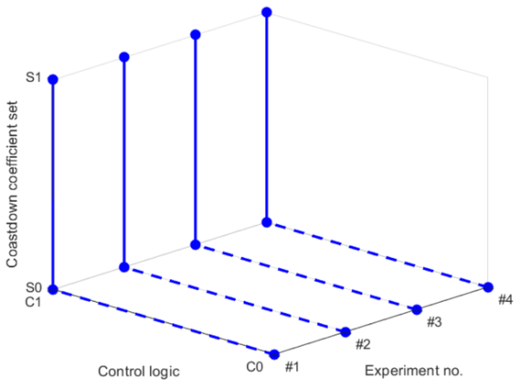


Figure 66. Comparison paths to be studied during plant validation step represented by code names

5.3.1 Parameter tuning

After defining a proper range for possible F_0 and F_1 values being 116 to 170 [N] and 0 to 10 [N.s/m] respectively and setting the target as the pair of coefficients that give the minimum error for specific consumption with regeneration value, all possible combinations are simulated and the errors are reported in a heat map as the following:

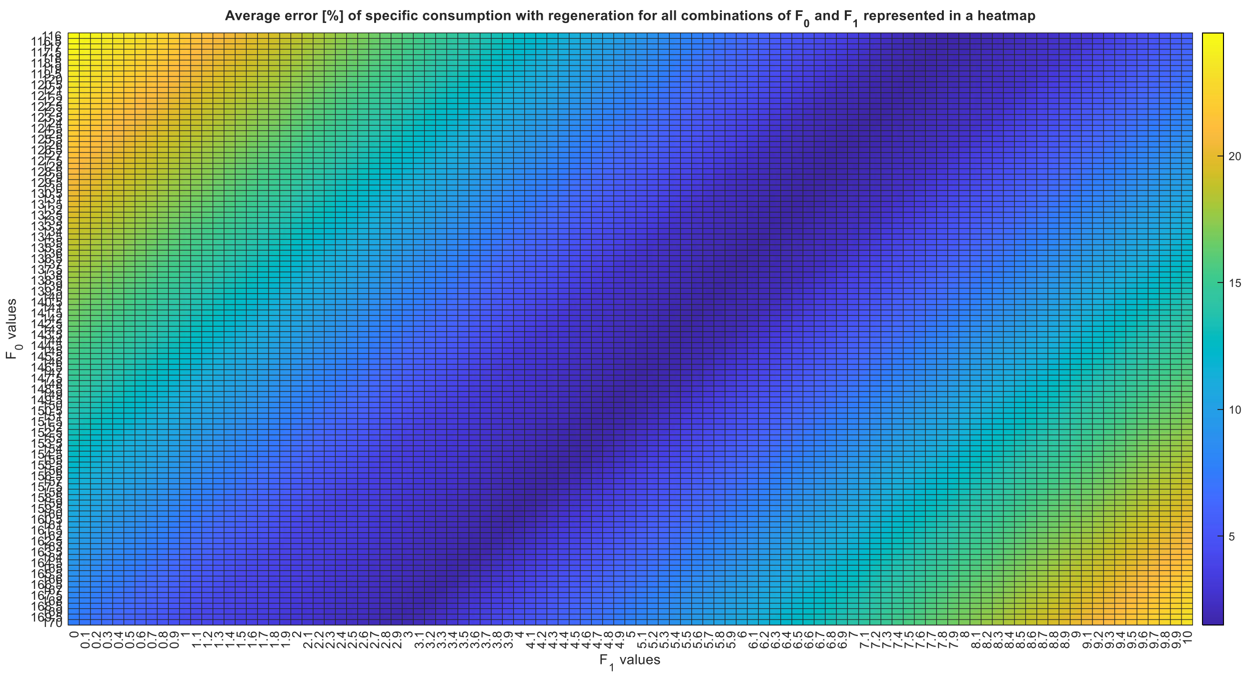


Figure 67. Avg. error [%] of specific consumption with reg. for all combinations of F_0 and F_1 represented in a heatmap

The minimum error among all combinations belongs to:

$$F_0 = 125.5 \ [N]$$
$$F_1 = 7 \ [N\frac{s}{m}]$$
$$F_2 = same\ as\ before$$

which results to be 1.4954 %. This new parameter set will be addressed as S1 and it will be put into simulation with C1 (real) control model.

5.4 Simulation results

In this section each set of control model, parameter set and reference driving cycle as explained previously is simulated and the following results are displayed:

- Velocity profiles
- Current profiles
- Electrical power profiles
- Electrical energy profiles
- Accelerator pedal positions

In the next section it will be seen how at each step i.e. control validation and plant validation simulation results relatively change.

5.4.1 C0,S0 case

5.4.1.1 T1 test

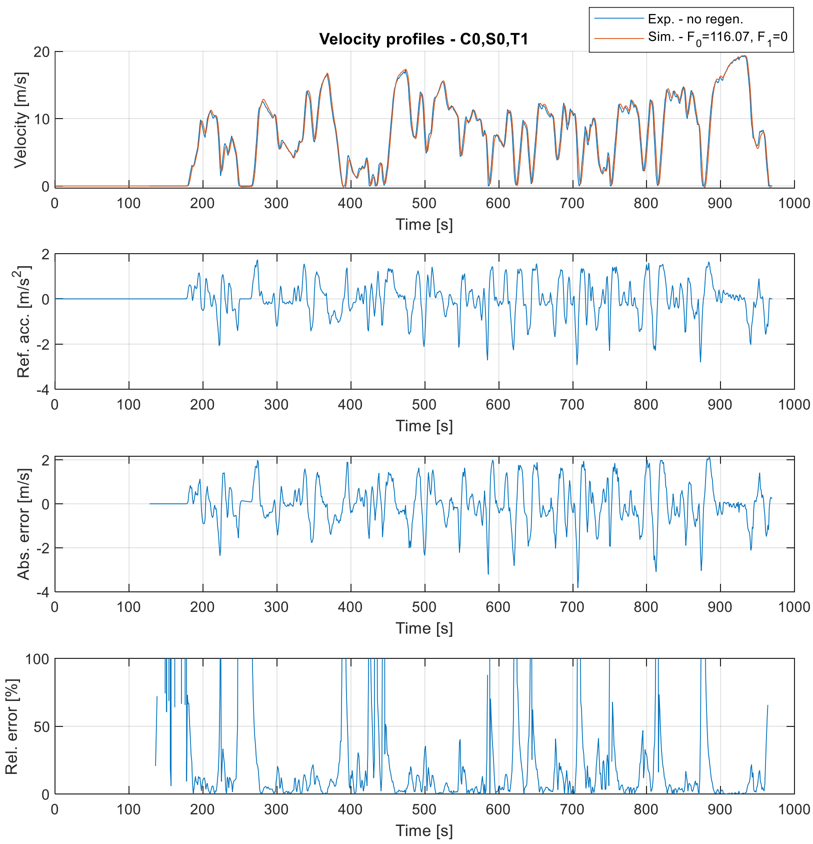


Figure 68. Velocity profile and its error simulated with C0,S0,T1

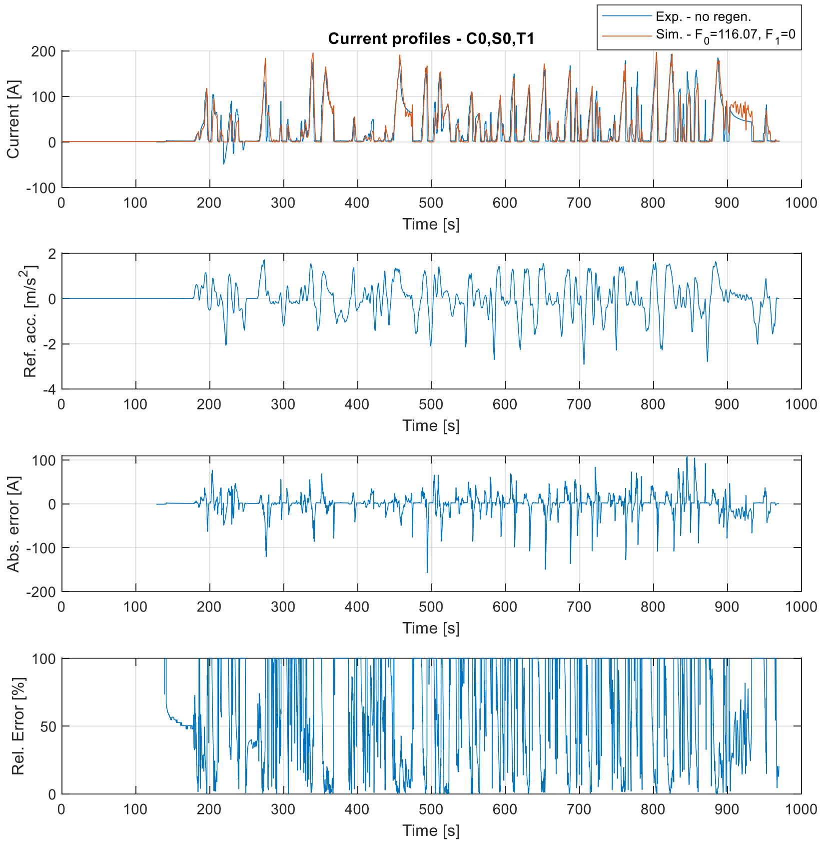


Figure 69. Current profile and its error simulated with C0,S0,T1

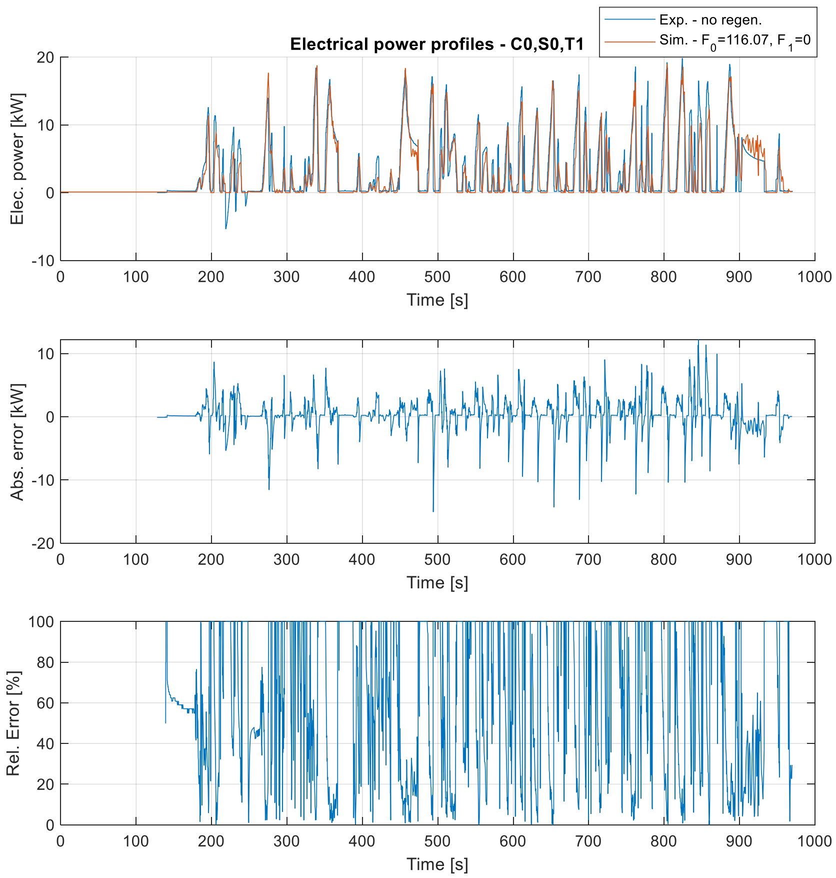


Figure 70. Electrical power profile and its error simulated with C0,S0,T1

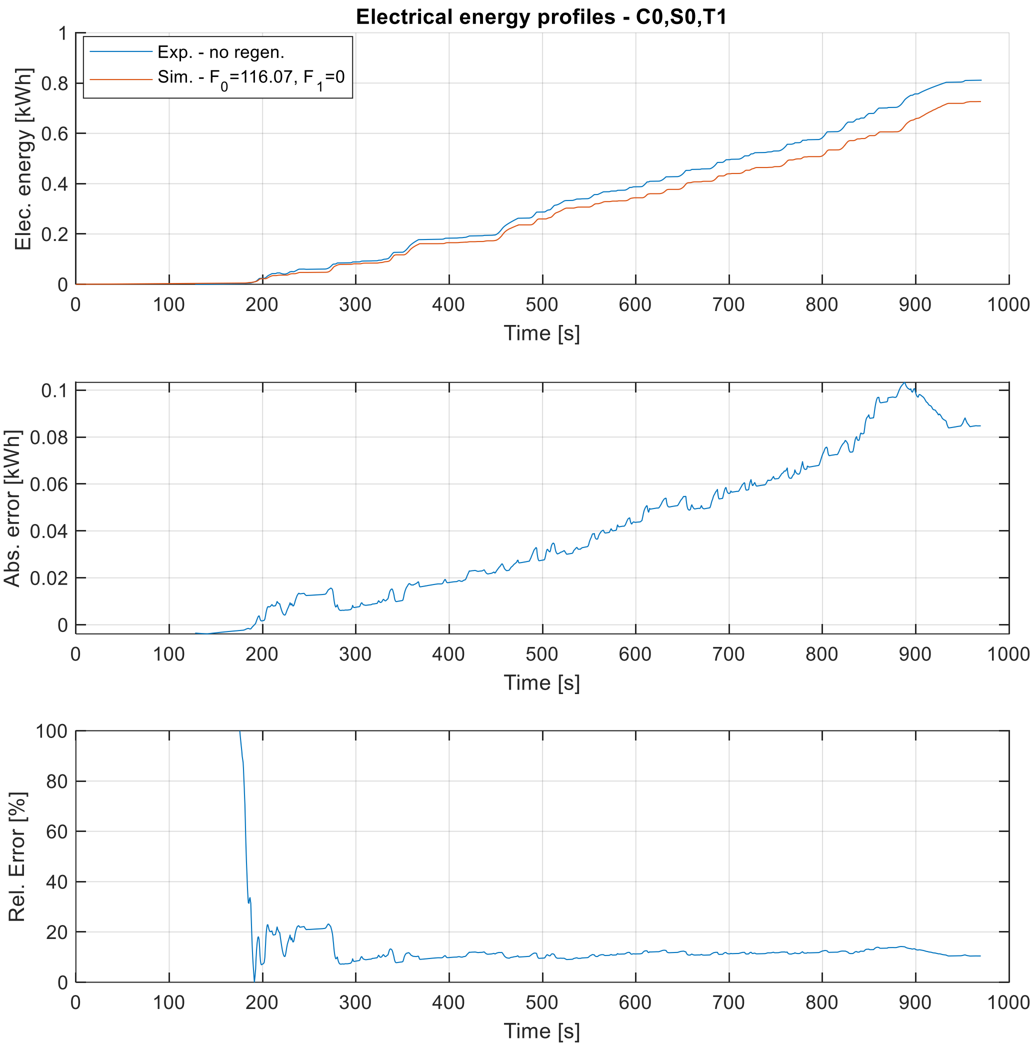


Figure 71. Electrical energy profile and its error simulated with C0,S0,T1

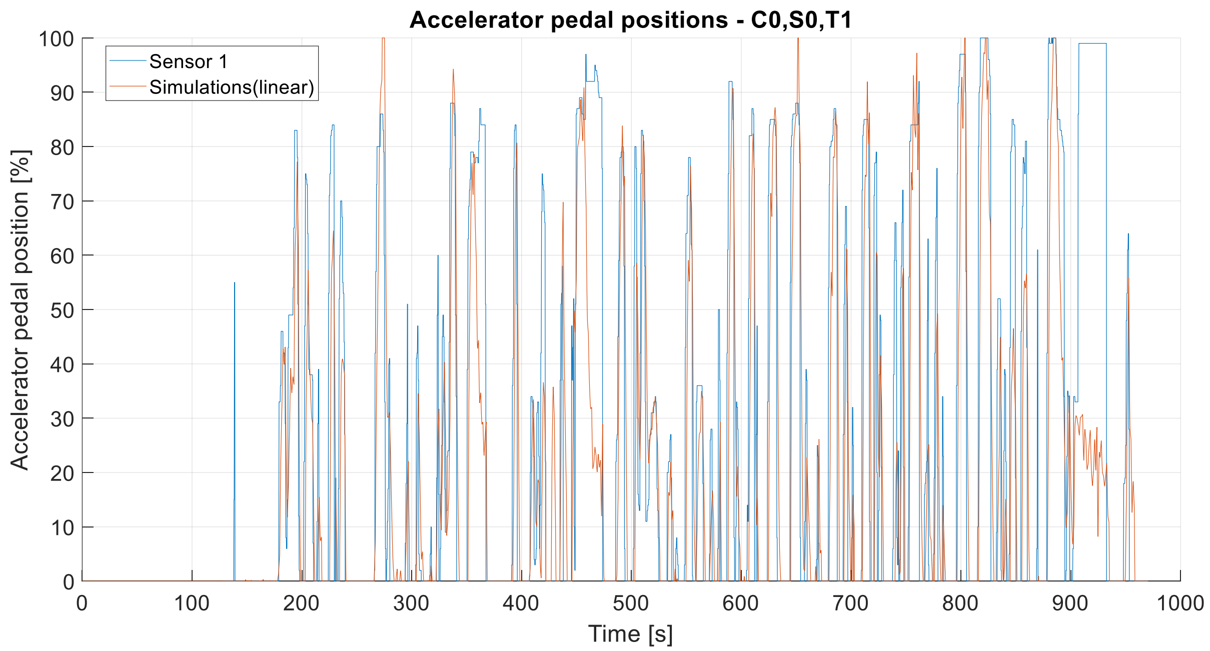


Figure 72. Accelerator pedal positions simulated with C0,S0,T1

5.4.1.2 T2 test

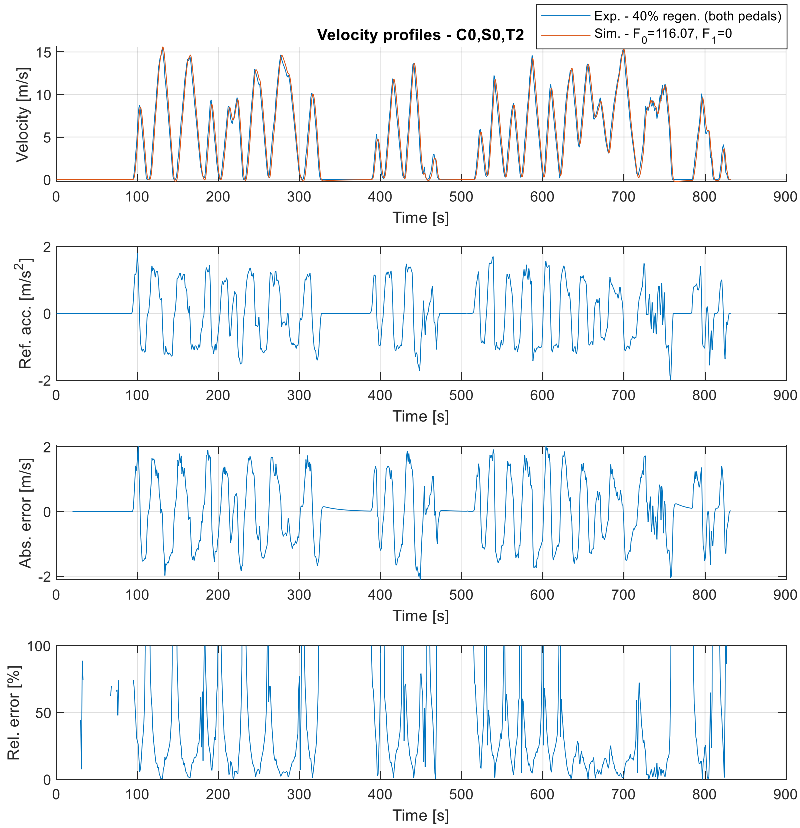


Figure 73. Velocity profile and its error simulated with C0,S0,T2

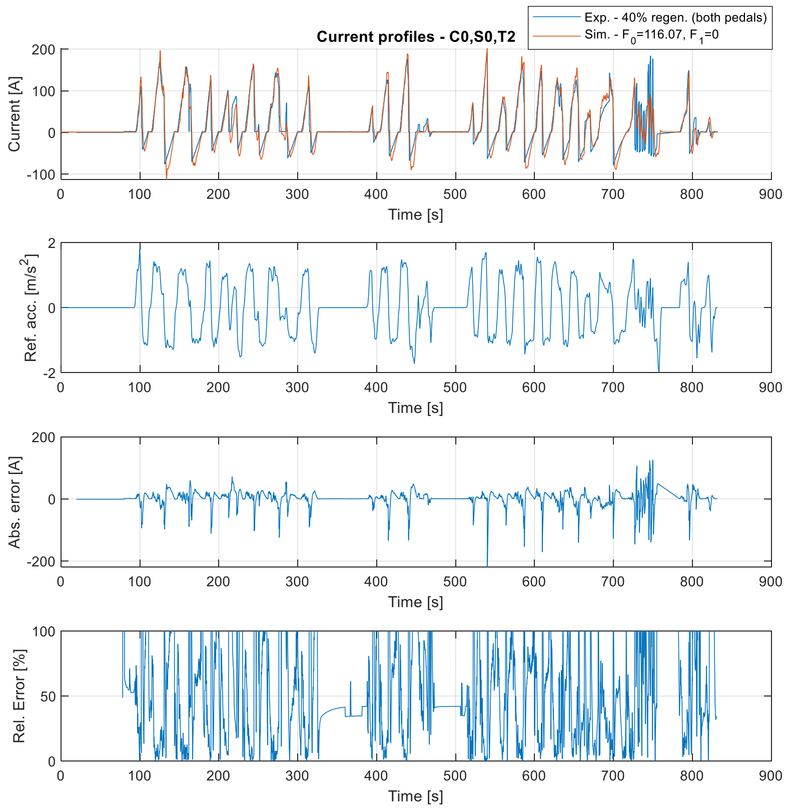


Figure 74. Current profile and its error simulated with C0,S0,T2

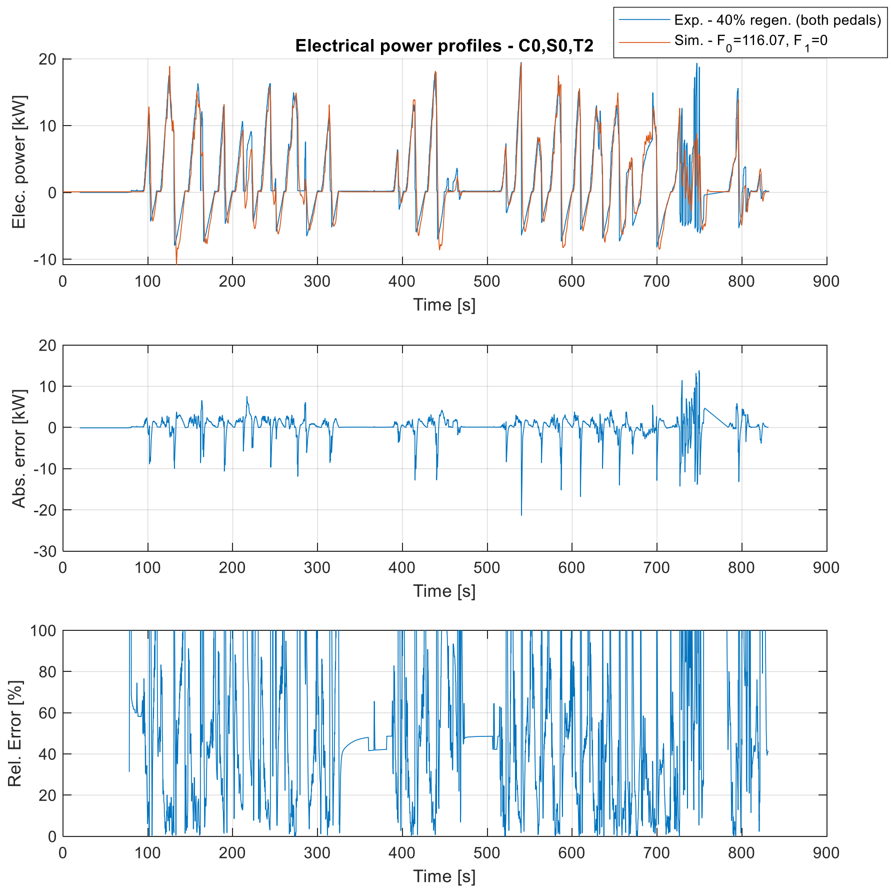


Figure 75. Electrical power profile and its error simulated with C0,S0,T2

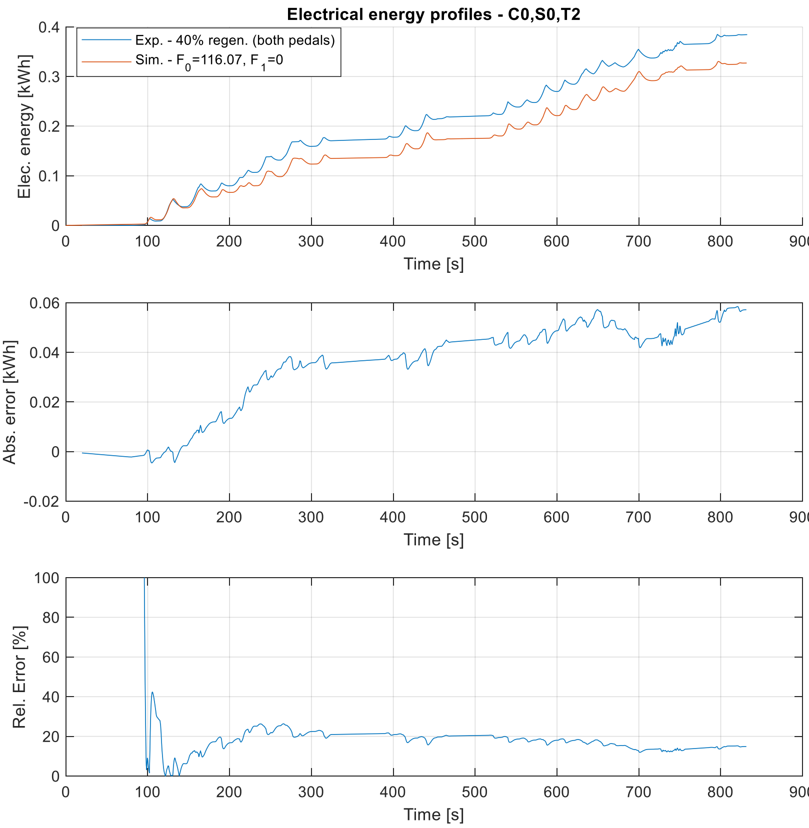


Figure 76. Electrical energy profile and its error simulated with C0,S0,T2

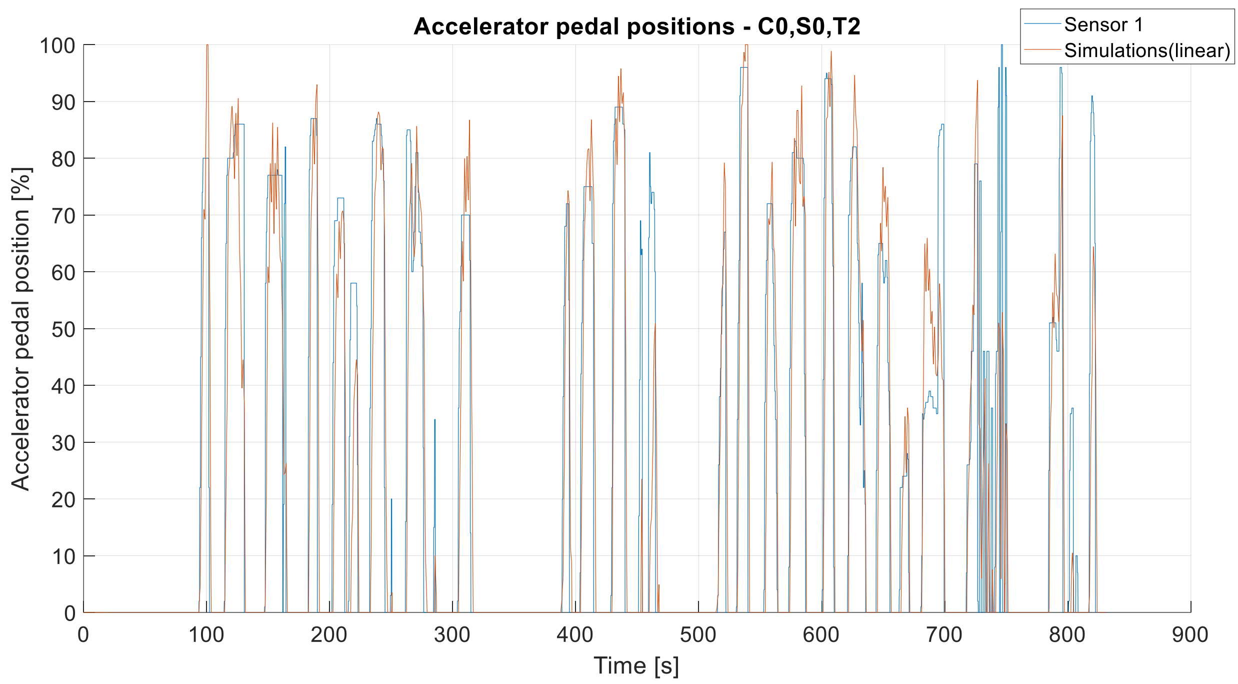


Figure 77. Accelerator pedal positions simulated with C0,S0,T2

5.4.1.3 T3 test

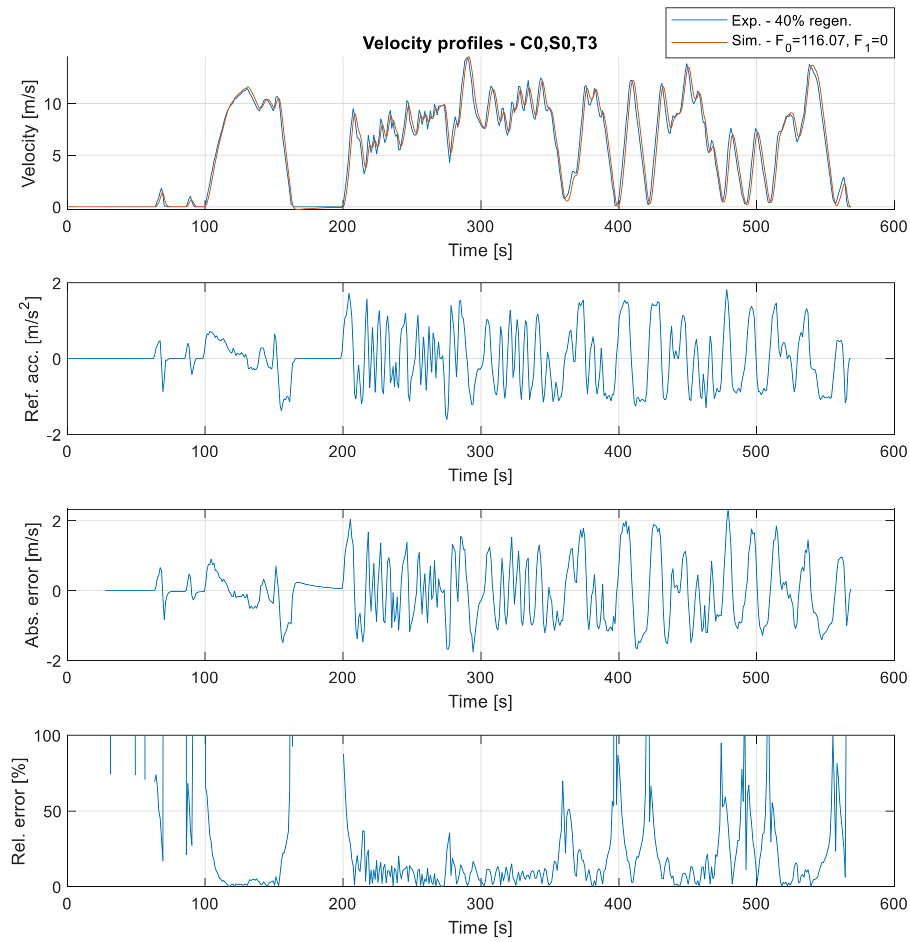


Figure 78. Velocity profile and its error simulated with C0,S0,T3

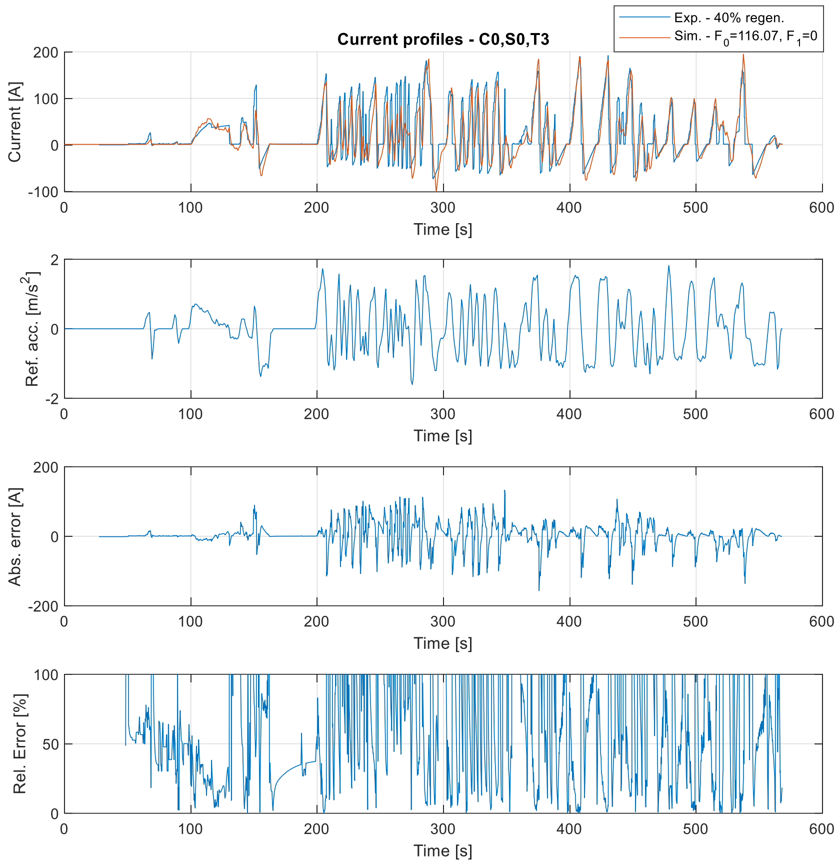


Figure 79. Current profile and its error simulated with C0,S0,T3

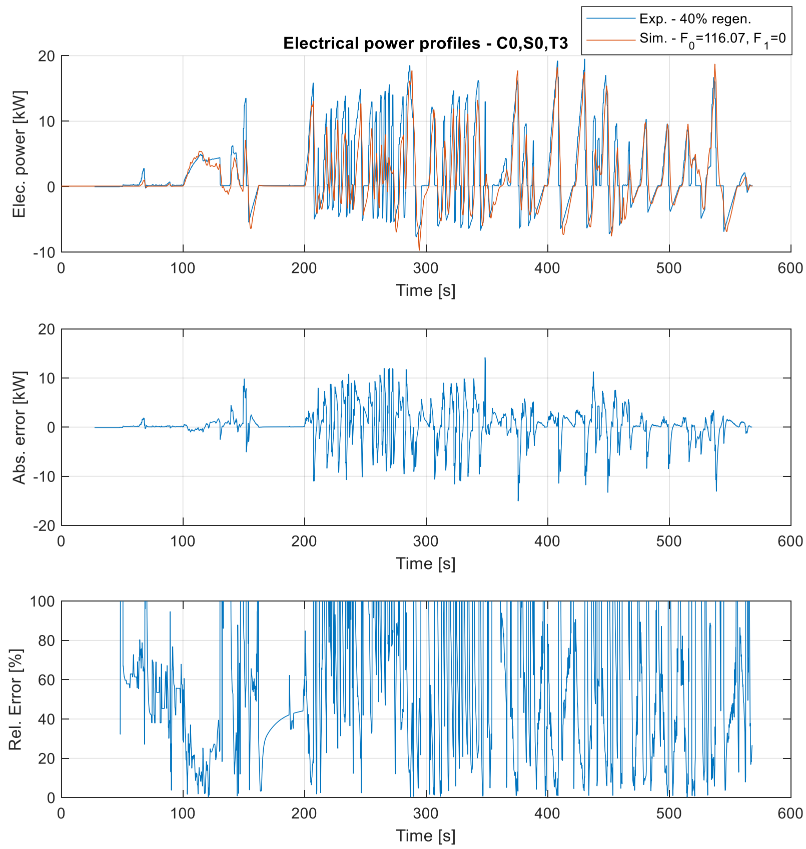


Figure 80. Electrical power profile and its error simulated with C0,S0,T3

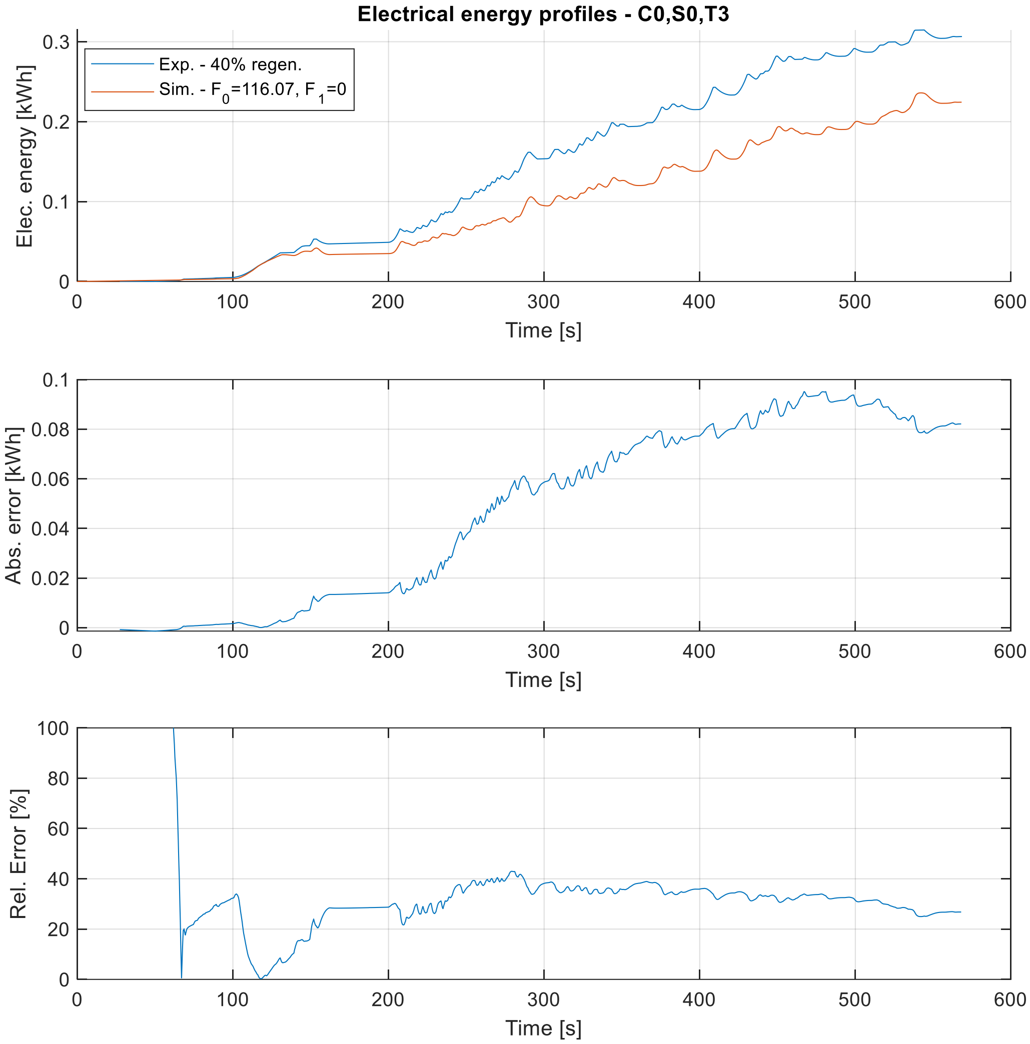


Figure 81. Electrical energy profile and its error simulated with C0,S0,T3

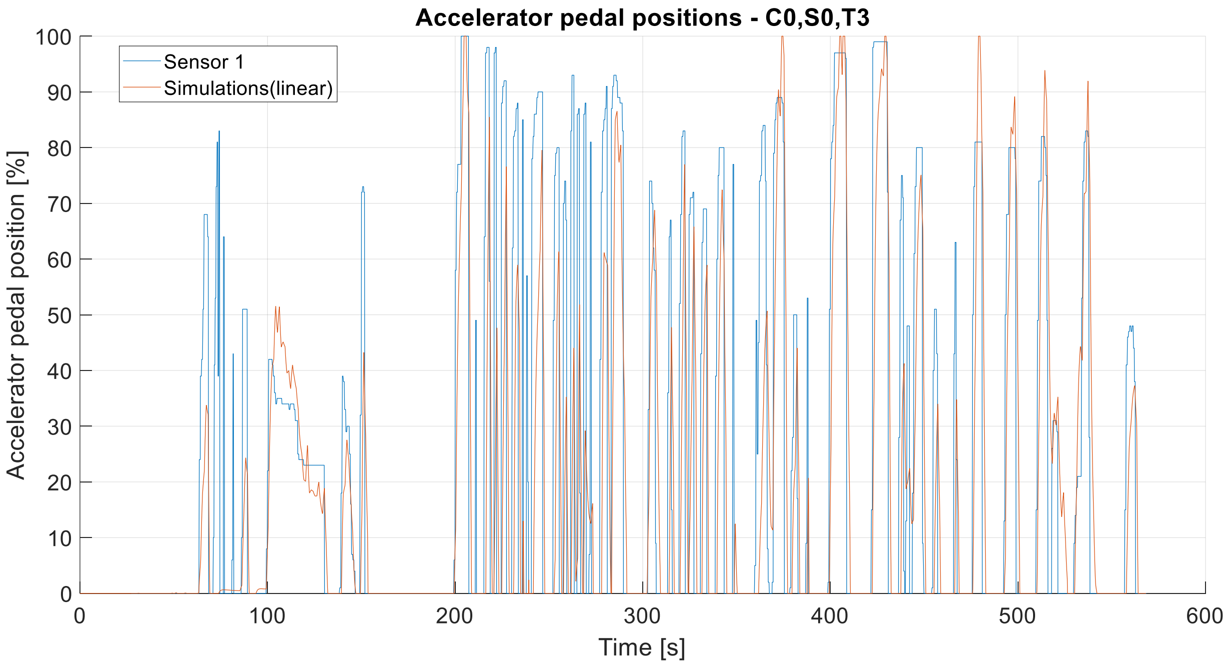


Figure 82. Accelerator pedal positions simulated with C0,S0,T3

5.4.1.4 T4 test

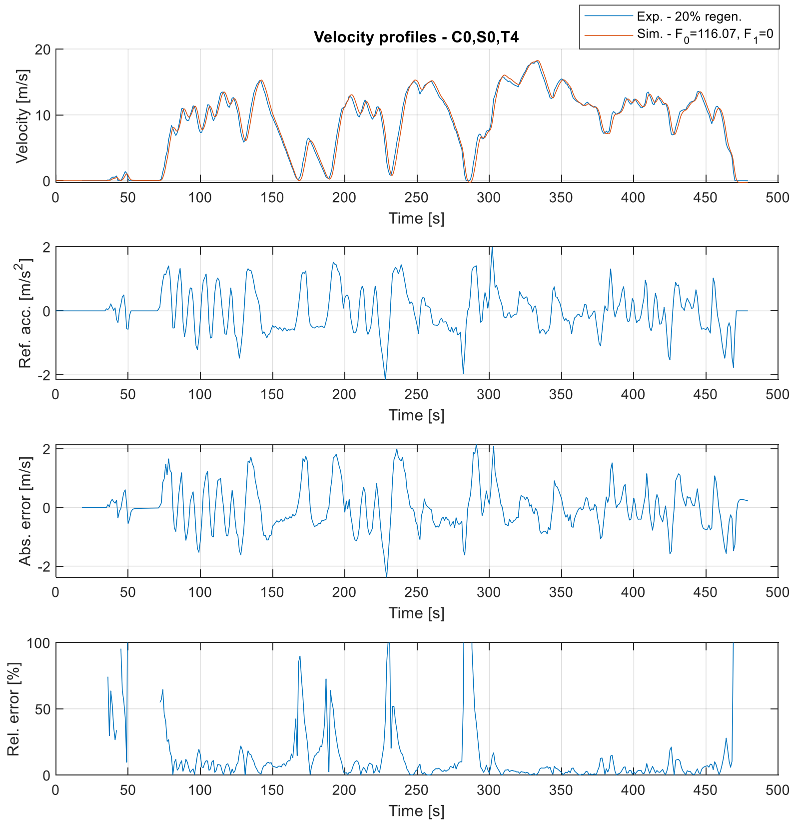


Figure 83. Velocity profile and its error simulated with C0,S0,T4

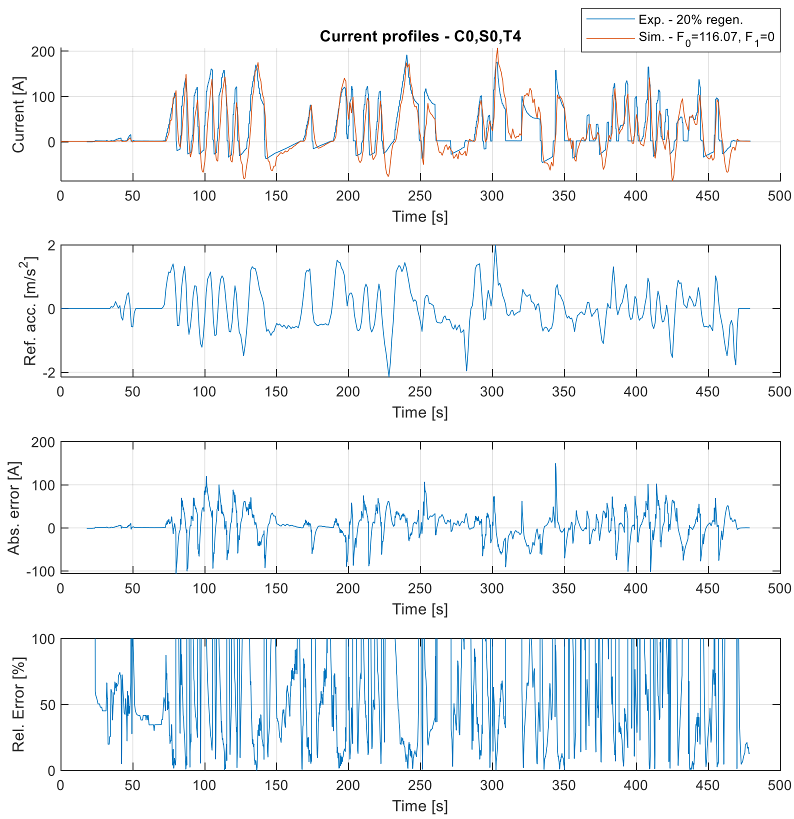


Figure 84. Current profile and its error simulated with C0,S0,T4

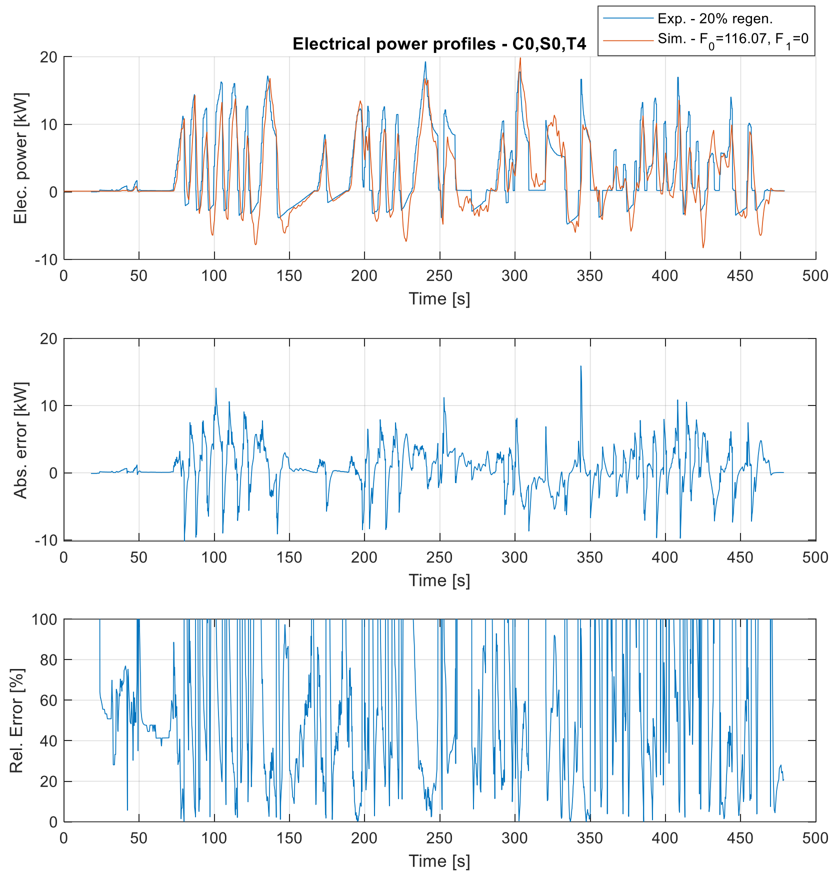


Figure 85. Electrical power profile and its error simulated with C0,S0,T4

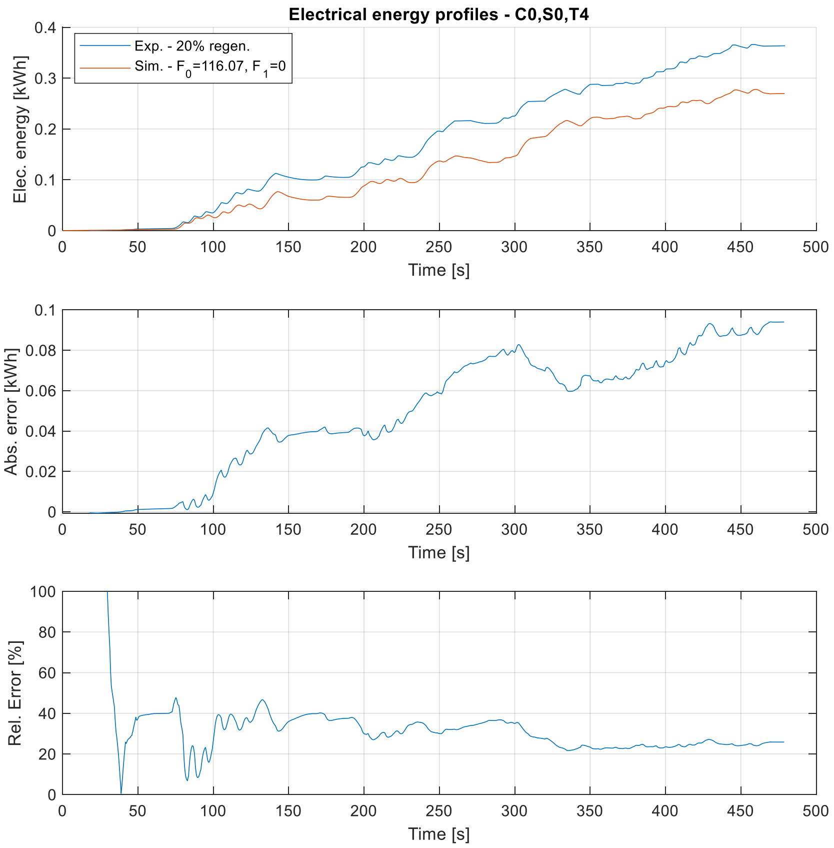


Figure 86. Electrical energy profile and its error simulated with C0,S0,T4

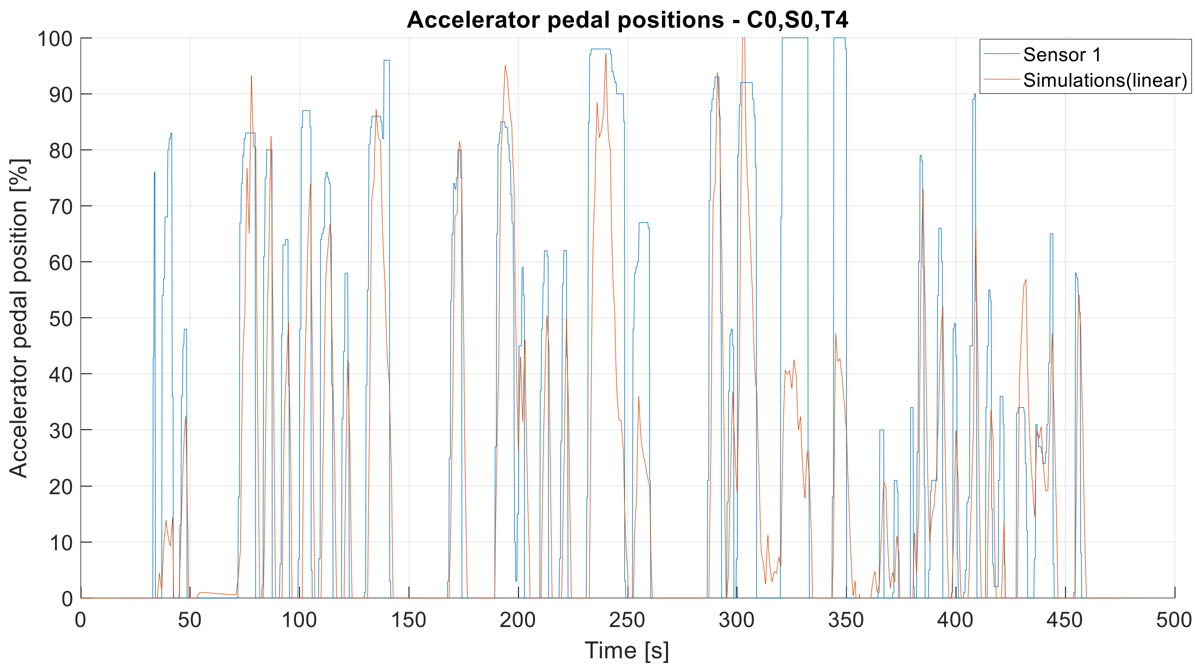


Figure 87. Accelerator pedal positions simulated with C0,S0,T4

5.4.2 C1,S0 case

5.4.2.1 T1 test

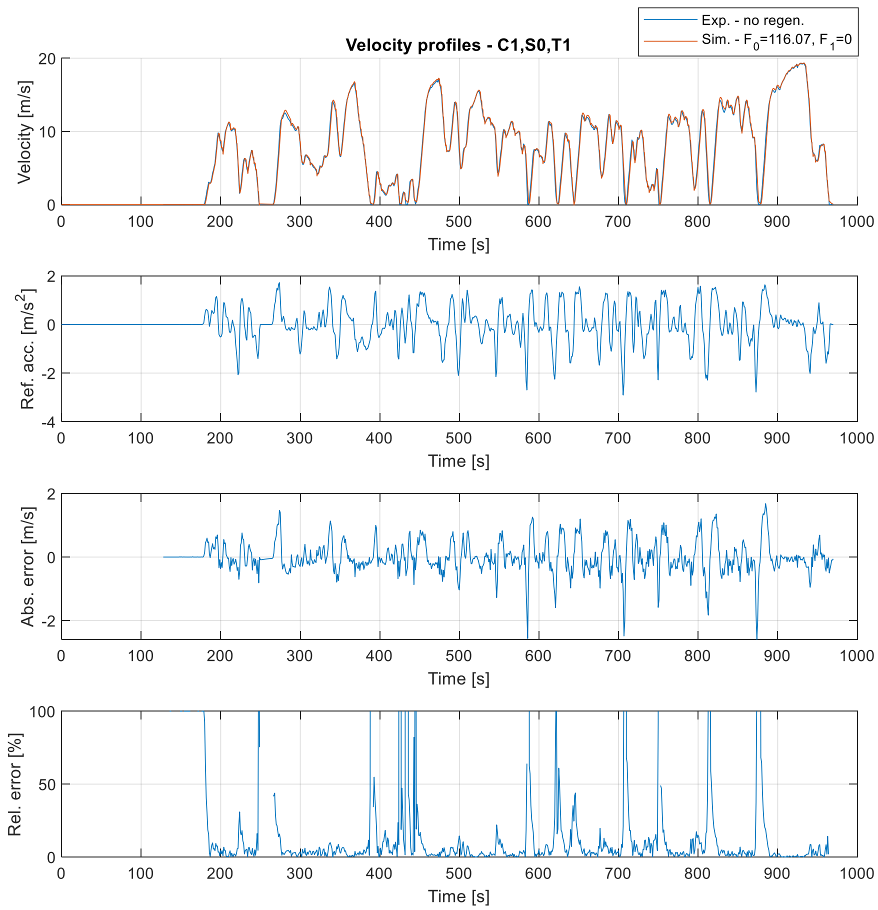


Figure 88. Velocity profile and its error simulated with C1,S0,T1

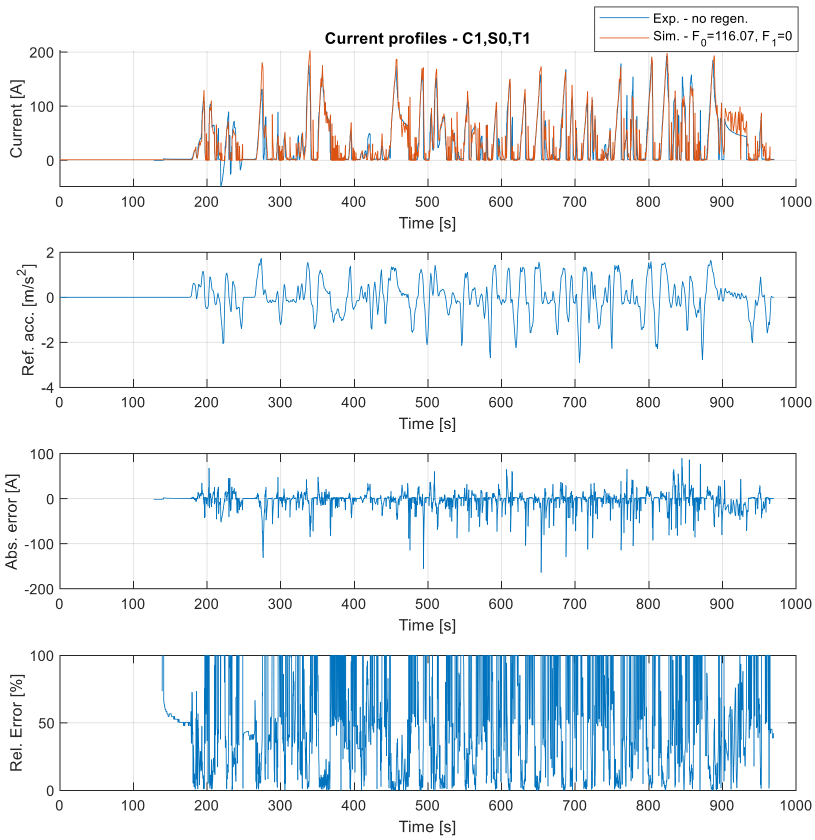


Figure 89. Current profile and its error simulated with C1,S0,T1

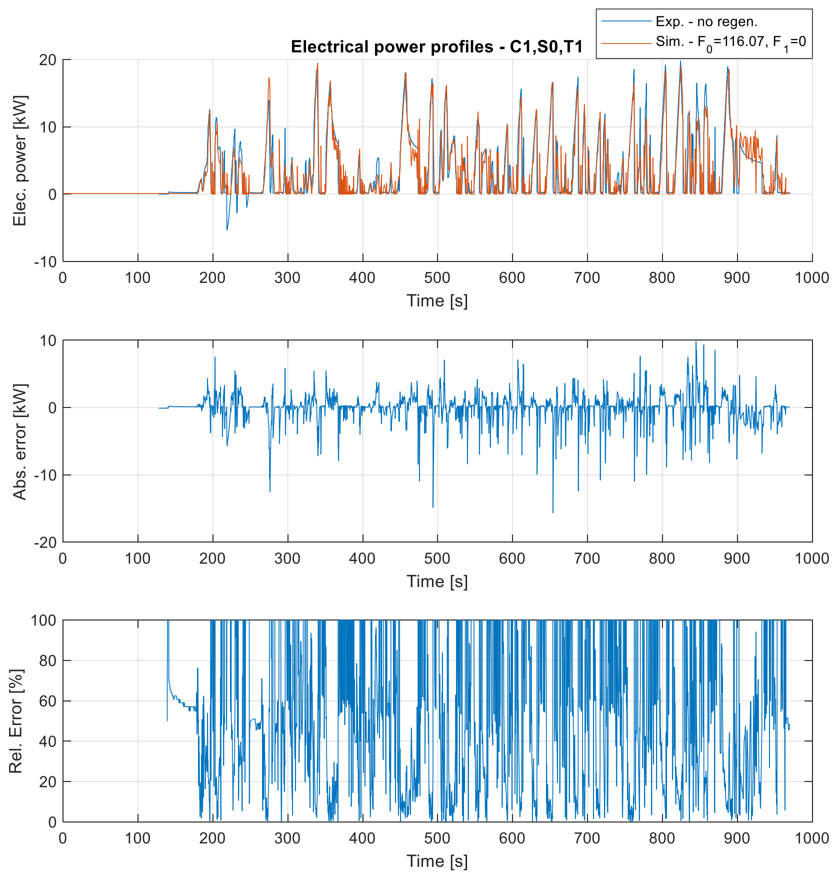


Figure 90. Electrical power profile and its error simulated with C1,S0,T1

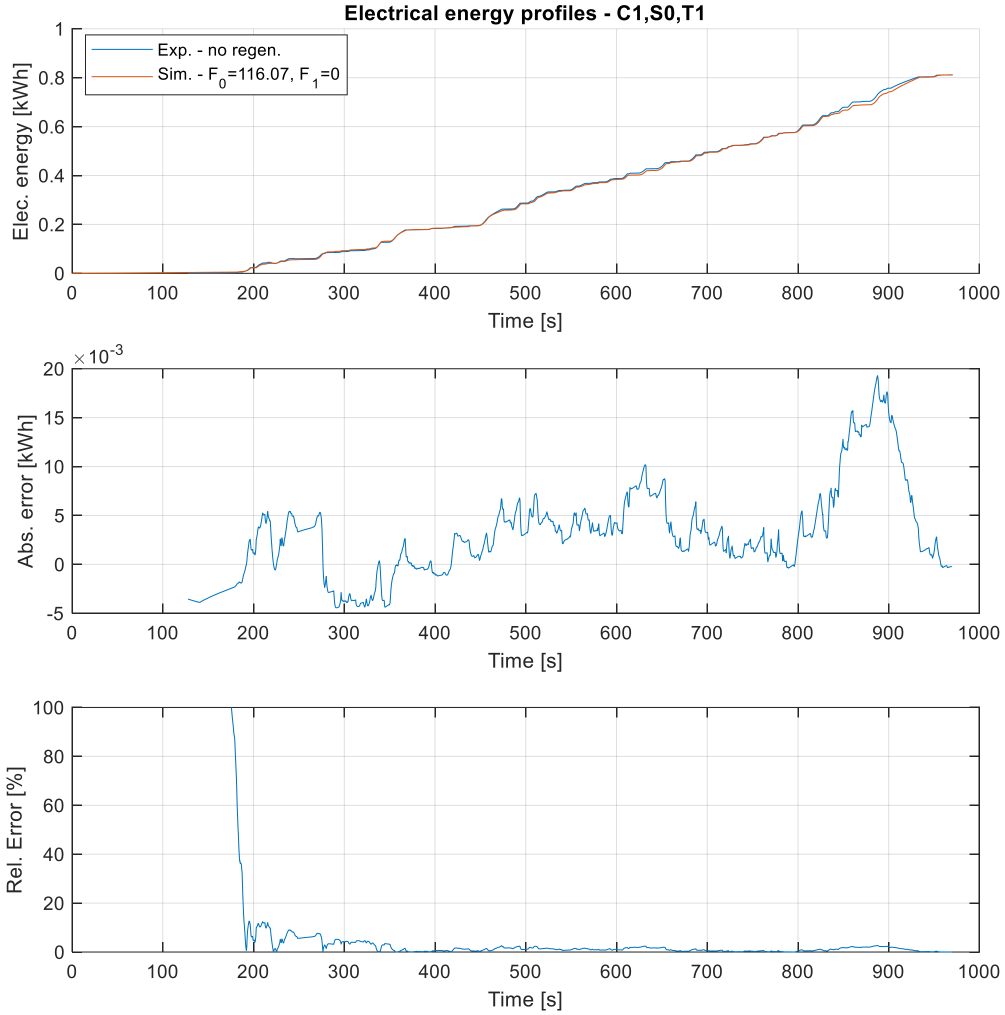


Figure 91. Electrical energy profile and its error simulated with C1,S0,T1

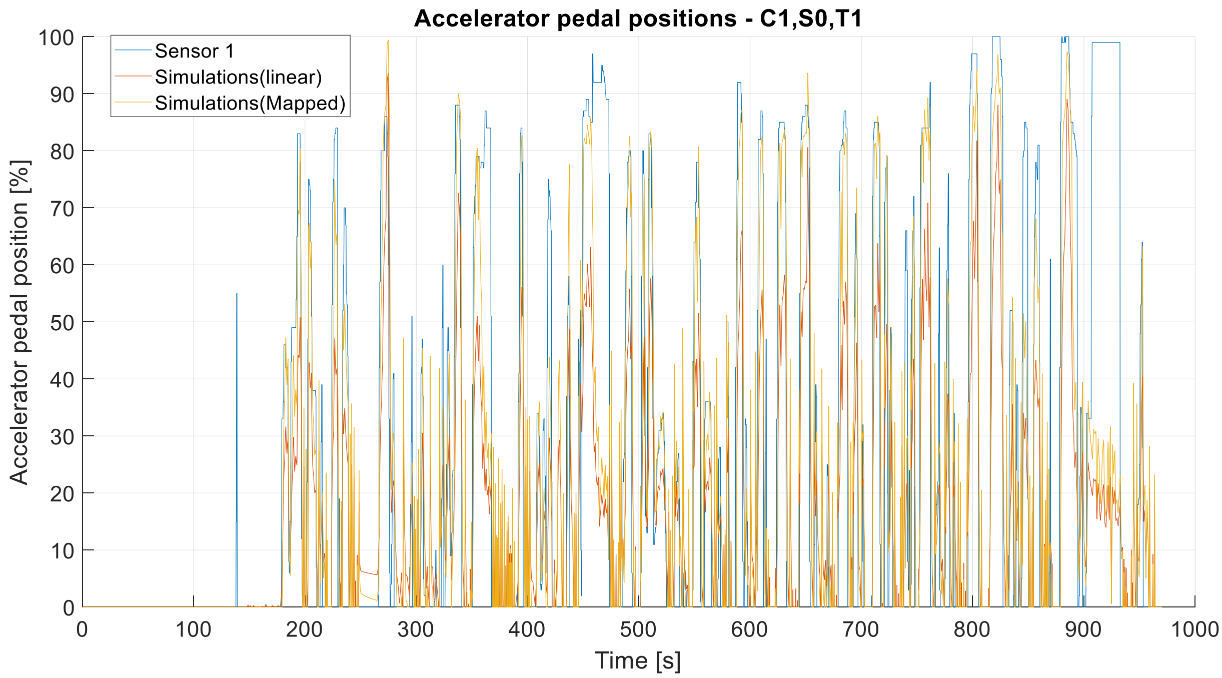


Figure 92. Accelerator pedal positions simulated with C1,S0,T1

5.4.2.2 T2 test

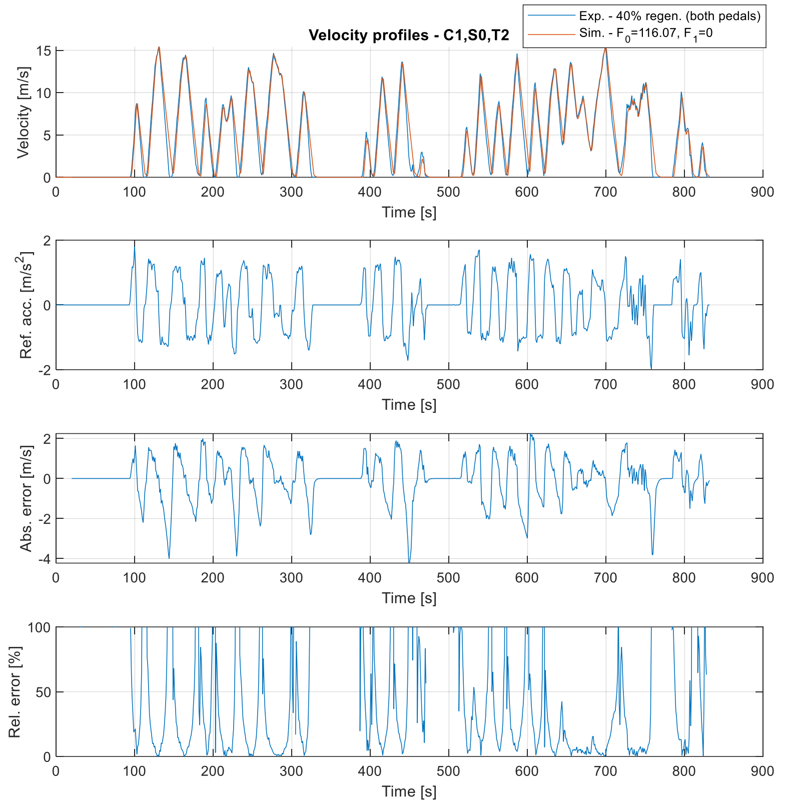


Figure 93. Velocity profile and its error simulated with C1,S0,T2

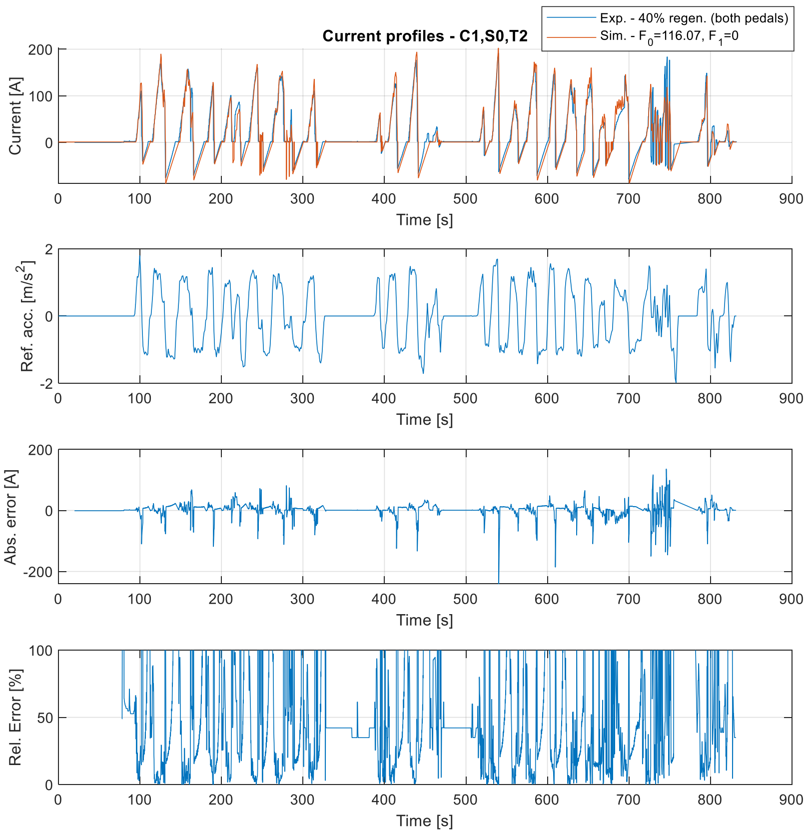


Figure 94. Current profile and its error simulated with C1,S0,T2

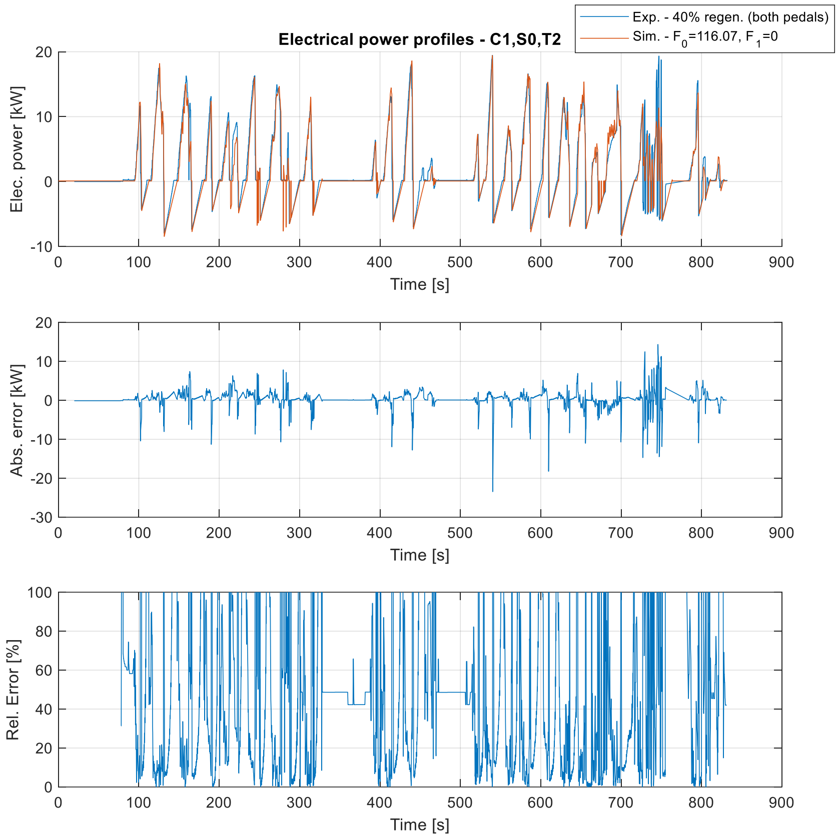


Figure 95. Electrical power profile and its error simulated with C1,S0,T2

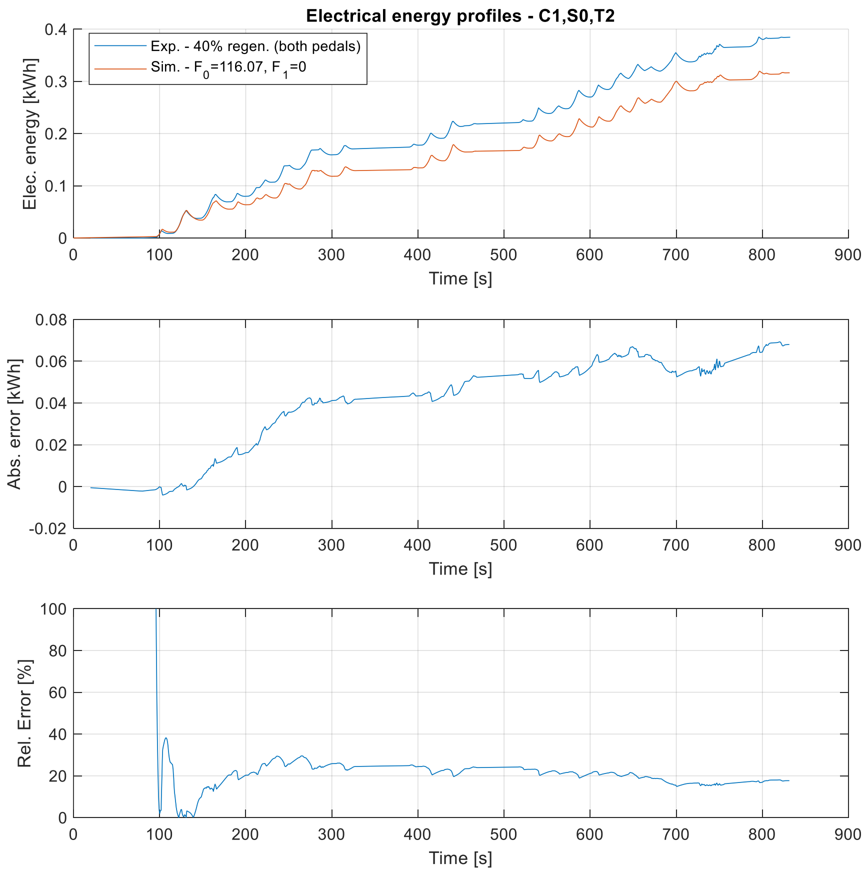


Figure 96. Electrical energy profile and its error simulated with C1,S0,T2

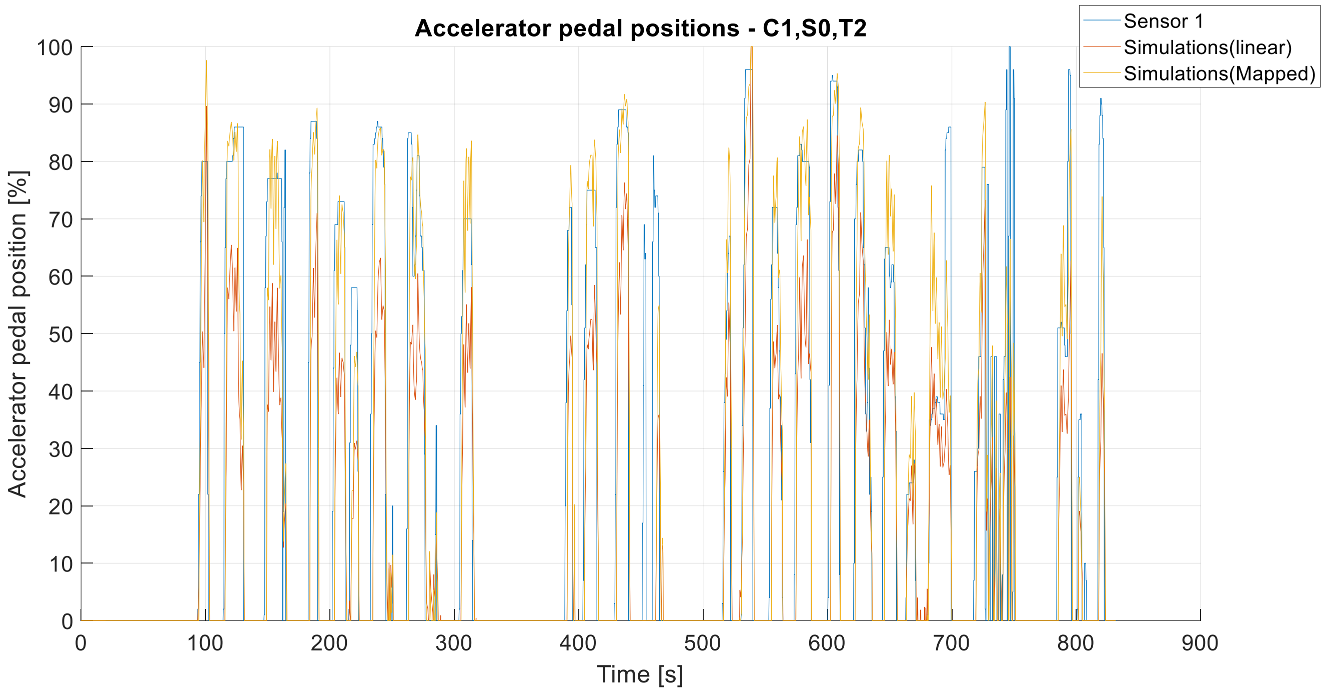


Figure 97. Accelerator pedal positions simulated with C1,S0,T2

5.4.2.3 T3 test

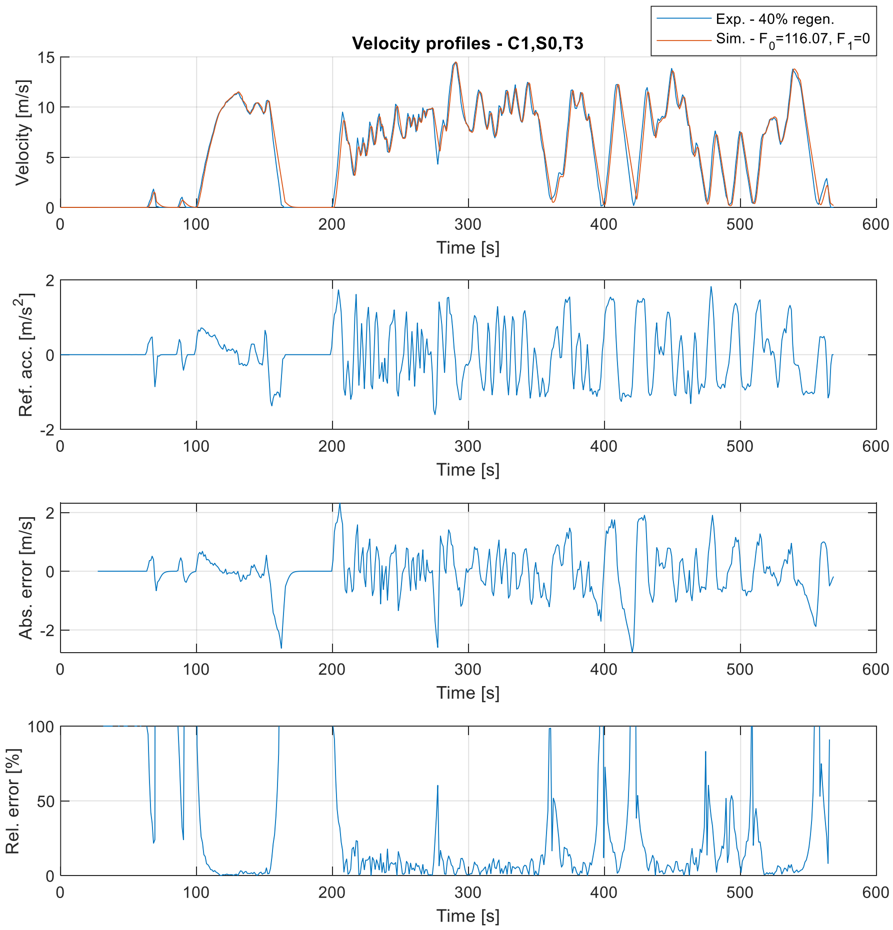


Figure 98. Velocity profile and its error simulated with C1,S0,T3

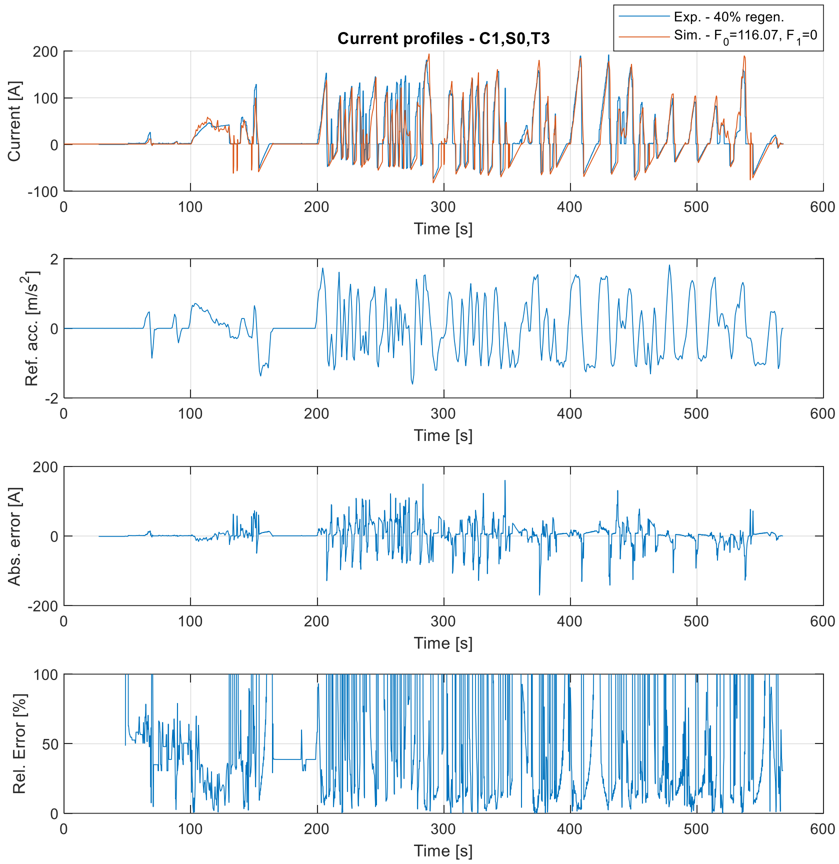


Figure 99. Current profile and its error simulated with C1,S0,T3

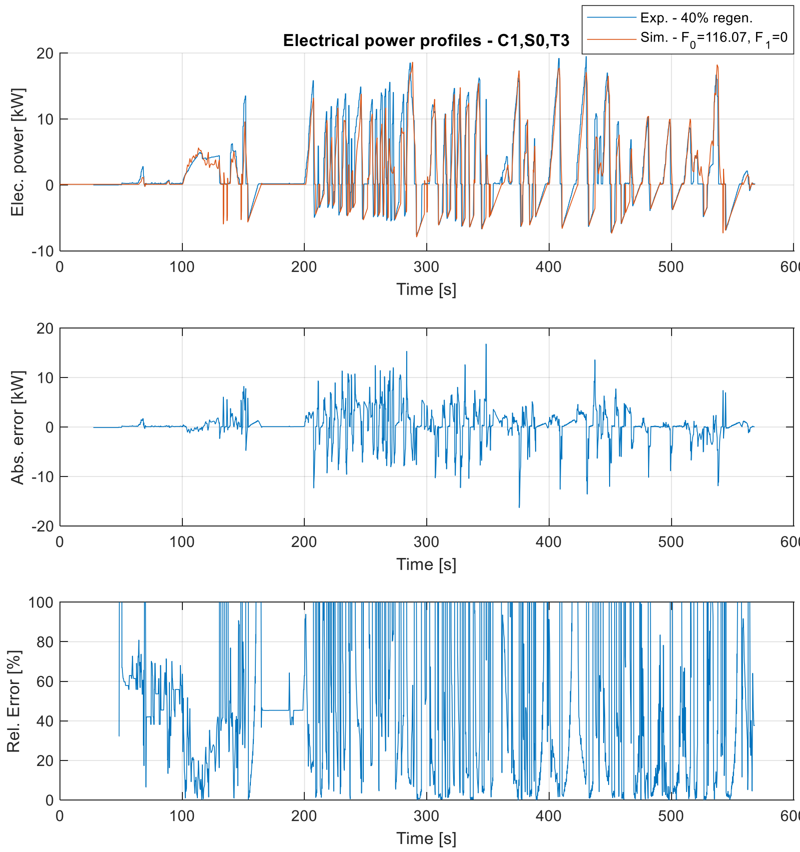


Figure 100. Electrical power profile and its error simulated with C1,S0,T3

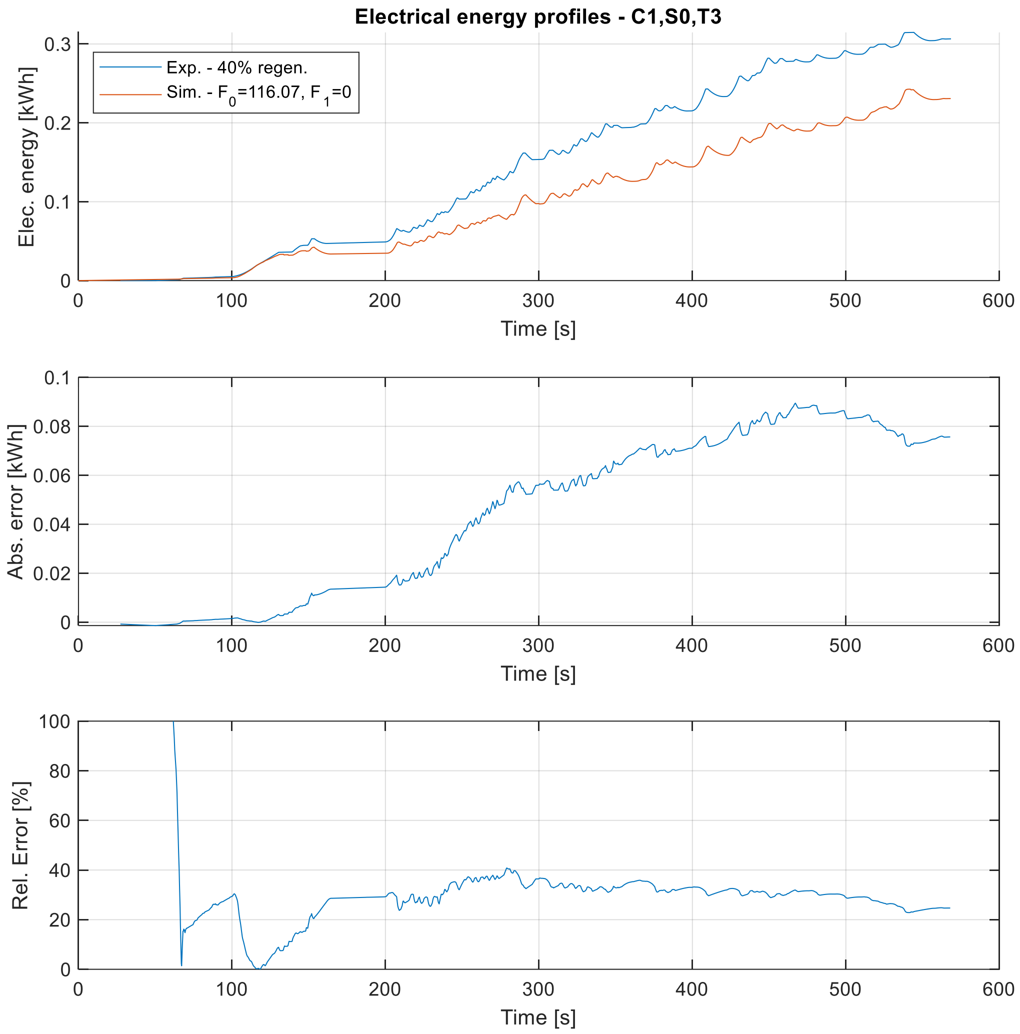


Figure 101. Electrical energy profile and its error simulated with C1,S0,T3

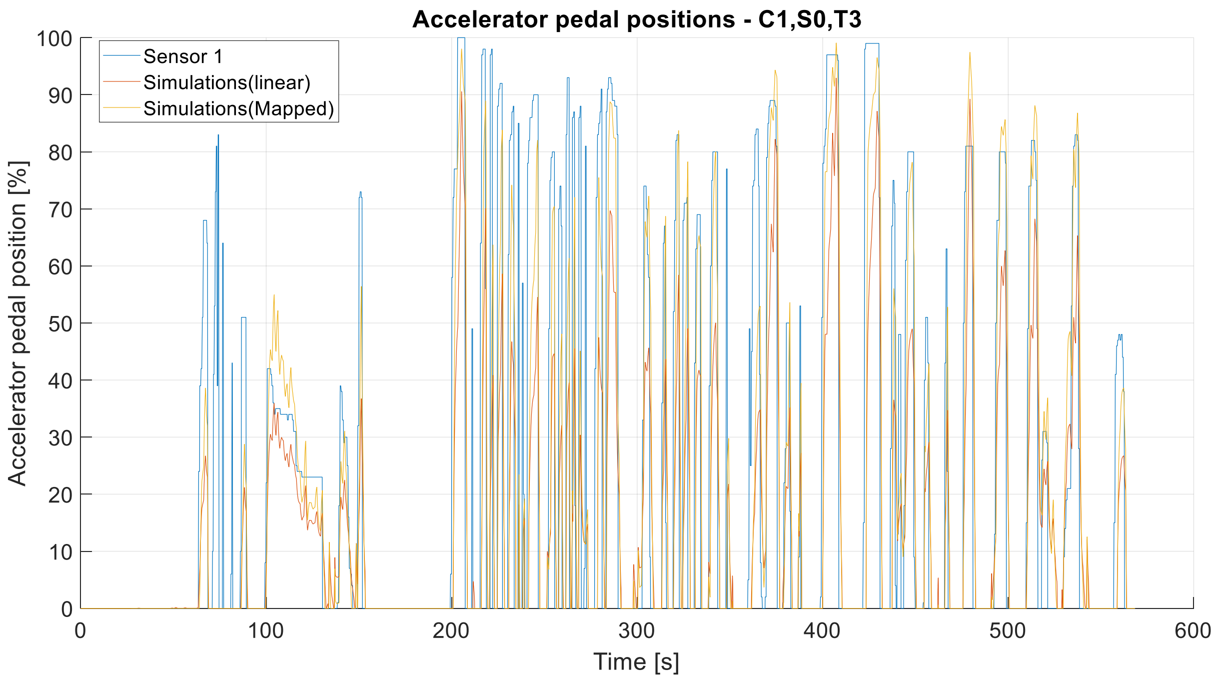


Figure 102. Accelerator pedal positions simulated with C1,S0,T3

5.4.2.4 T4 test

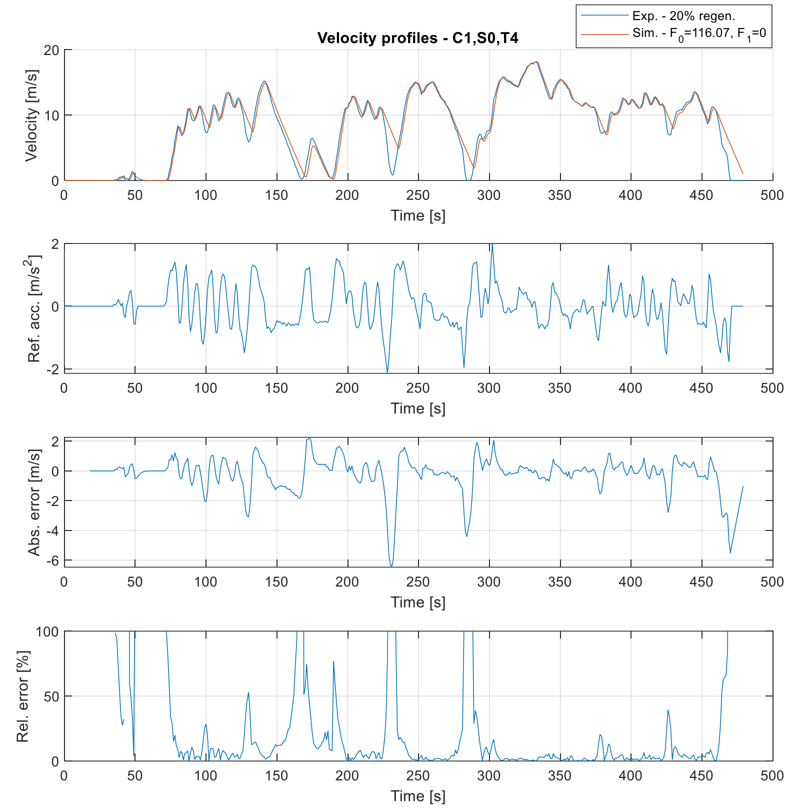


Figure 103. Velocity profile and its error simulated with C1,S0,T4

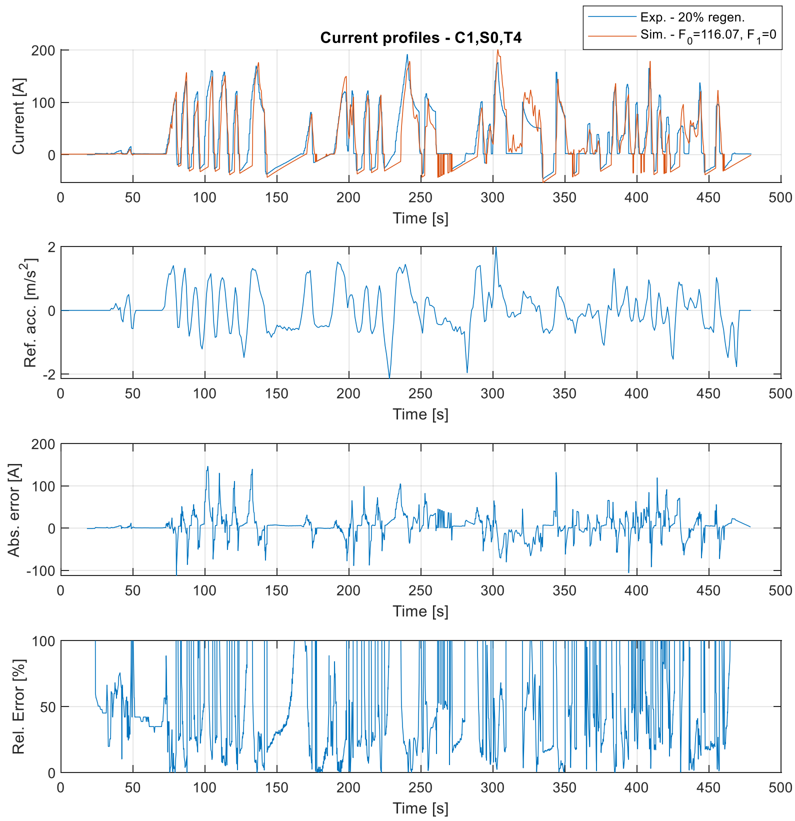


Figure 104. Current profile and its error simulated with C1,S0,T4

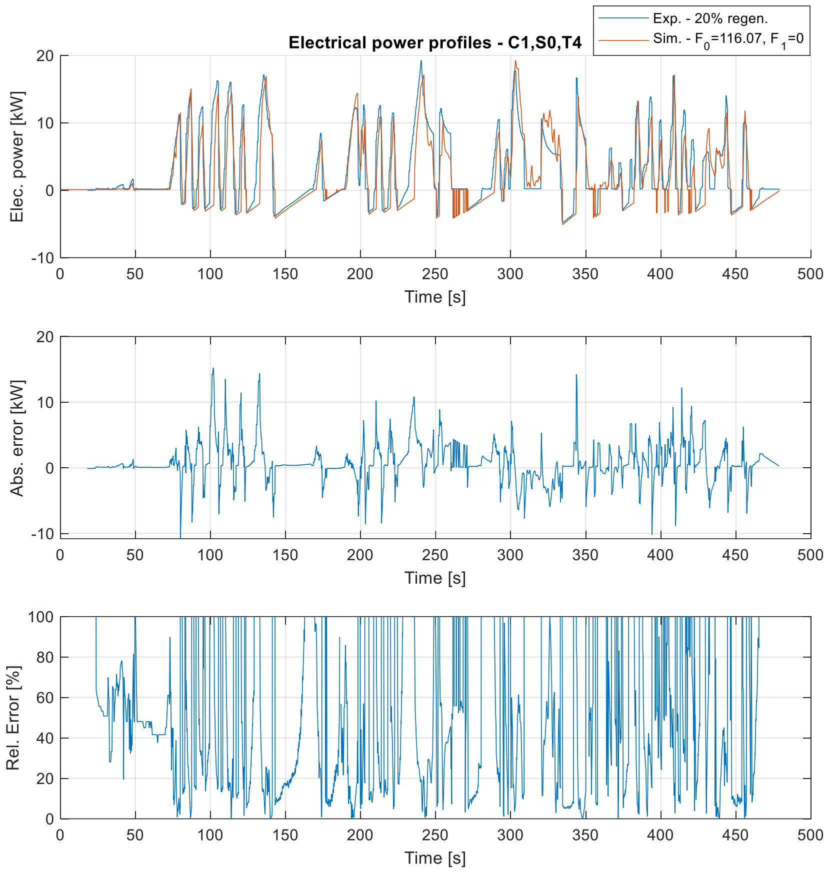


Figure 105. Electrical power profile and its error simulated with C1,S0,T4

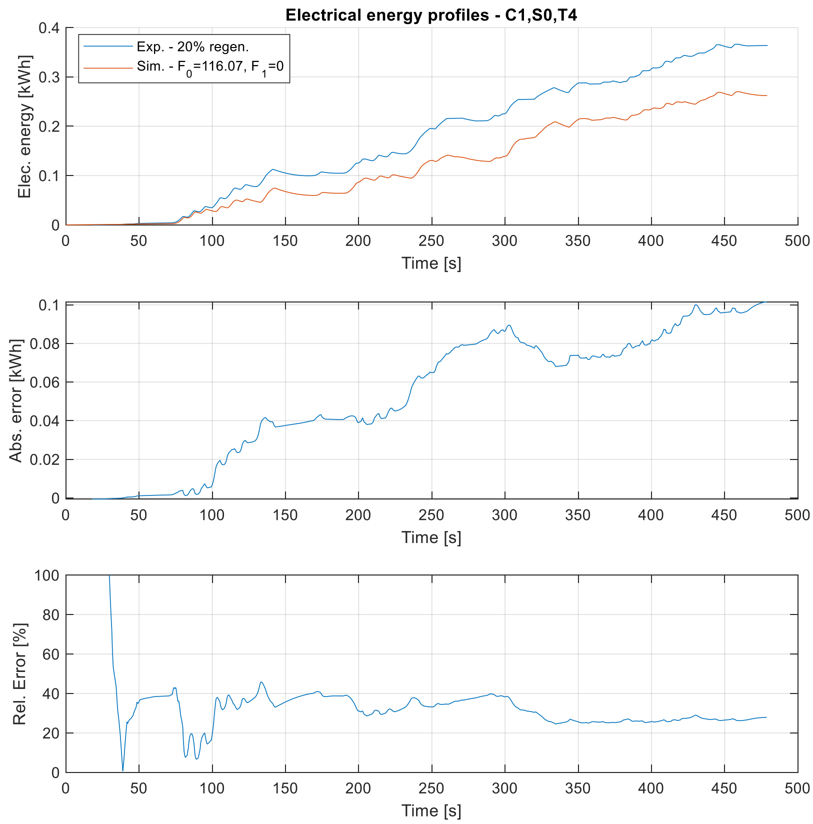


Figure 106. Electrical energy profile and its error simulated with C1,S0,T4

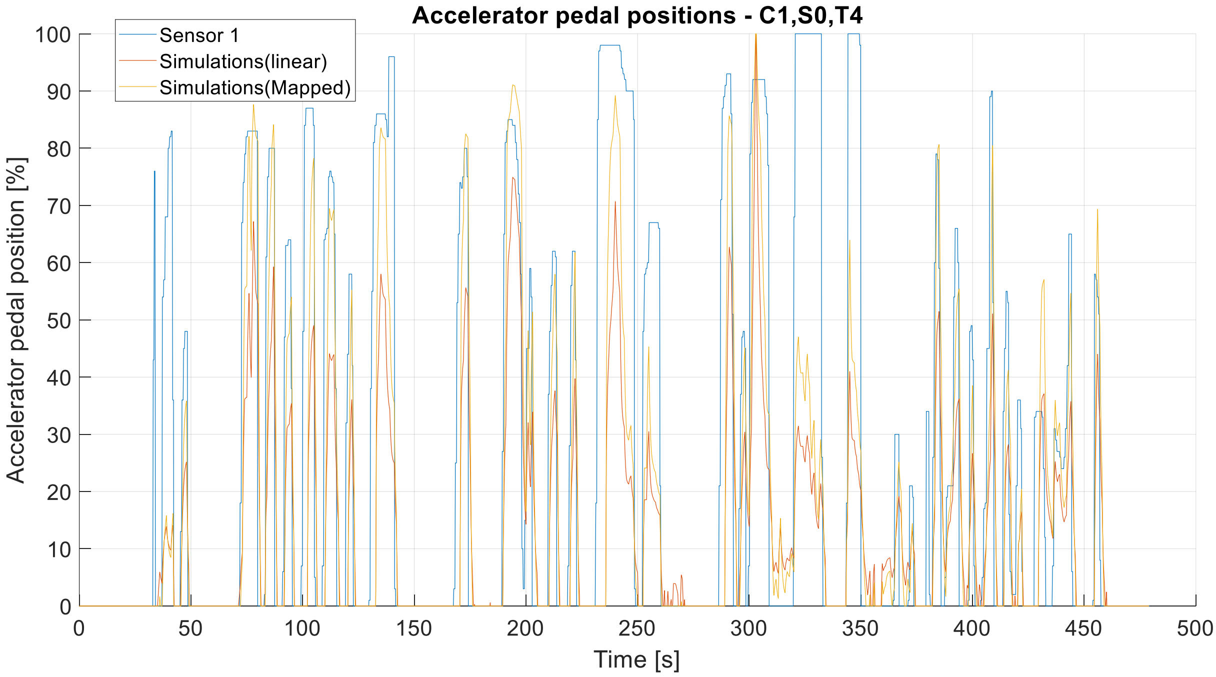


Figure 107. Accelerator pedal positions simulated with C1,S0,T4

5.4.3 C1,S1 case

5.4.3.1 T1 test

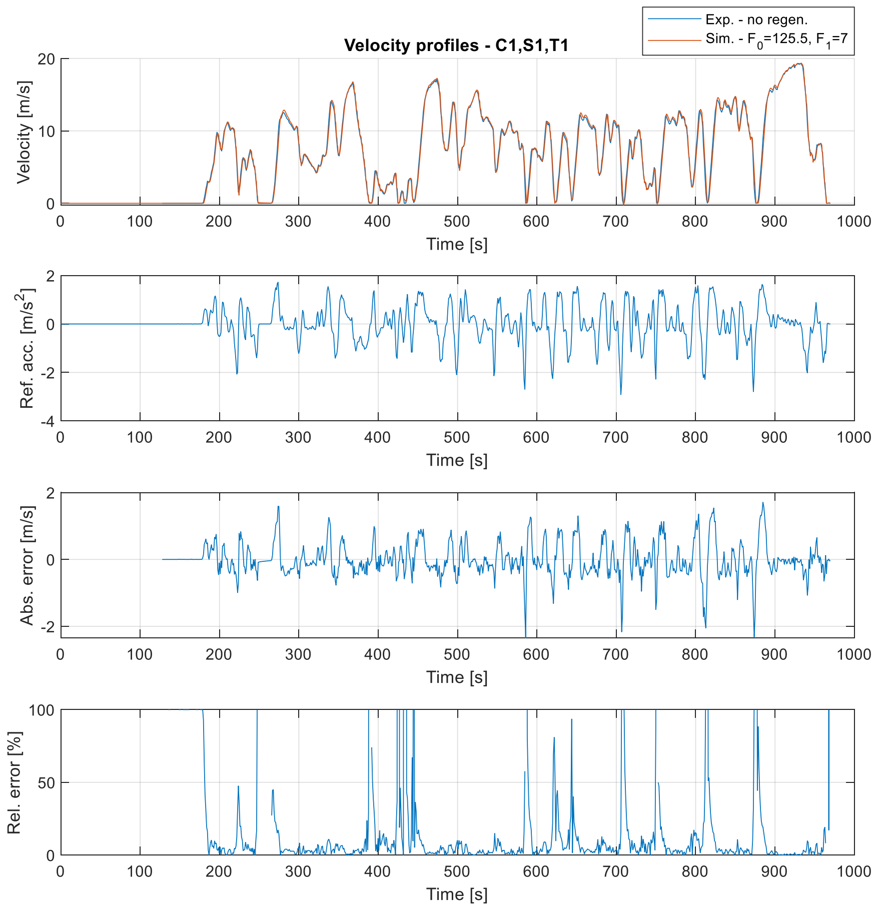


Figure 108. Velocity profile and its error simulated with C1,S1,T1

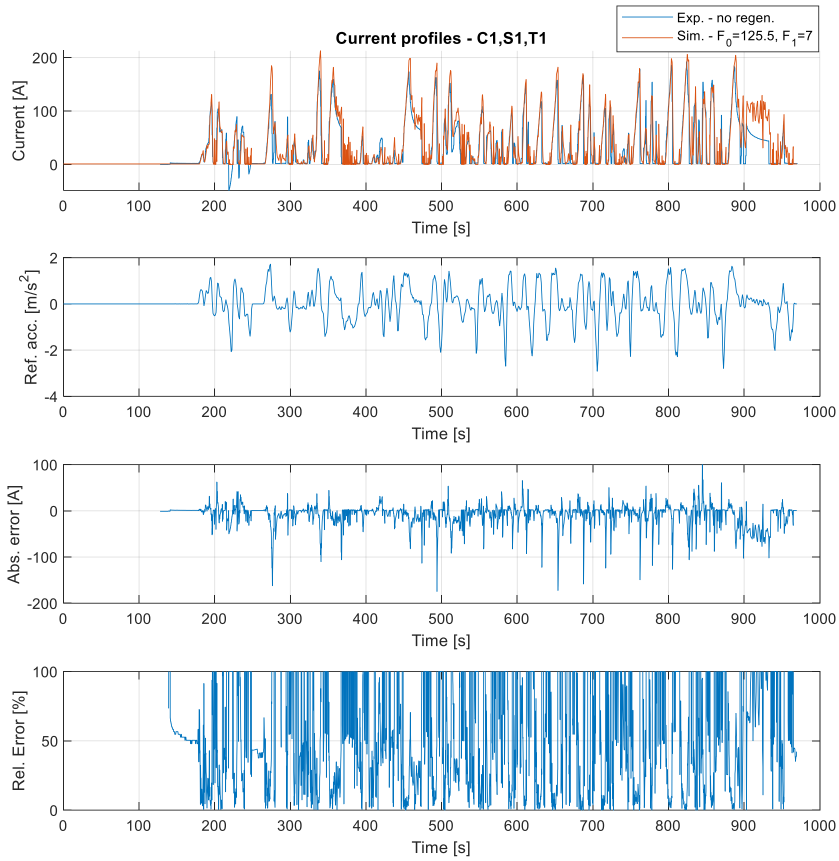


Figure 109. Current profile and its error simulated with C1,S1,T1

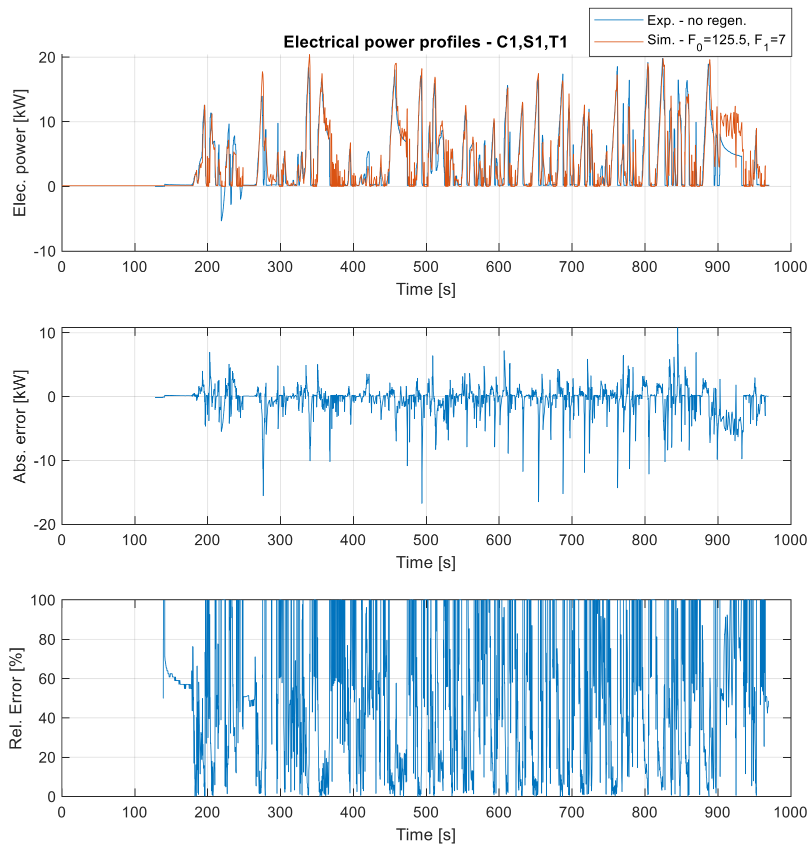


Figure 110. Electrical power profile and its error simulated with C1,S1,T1

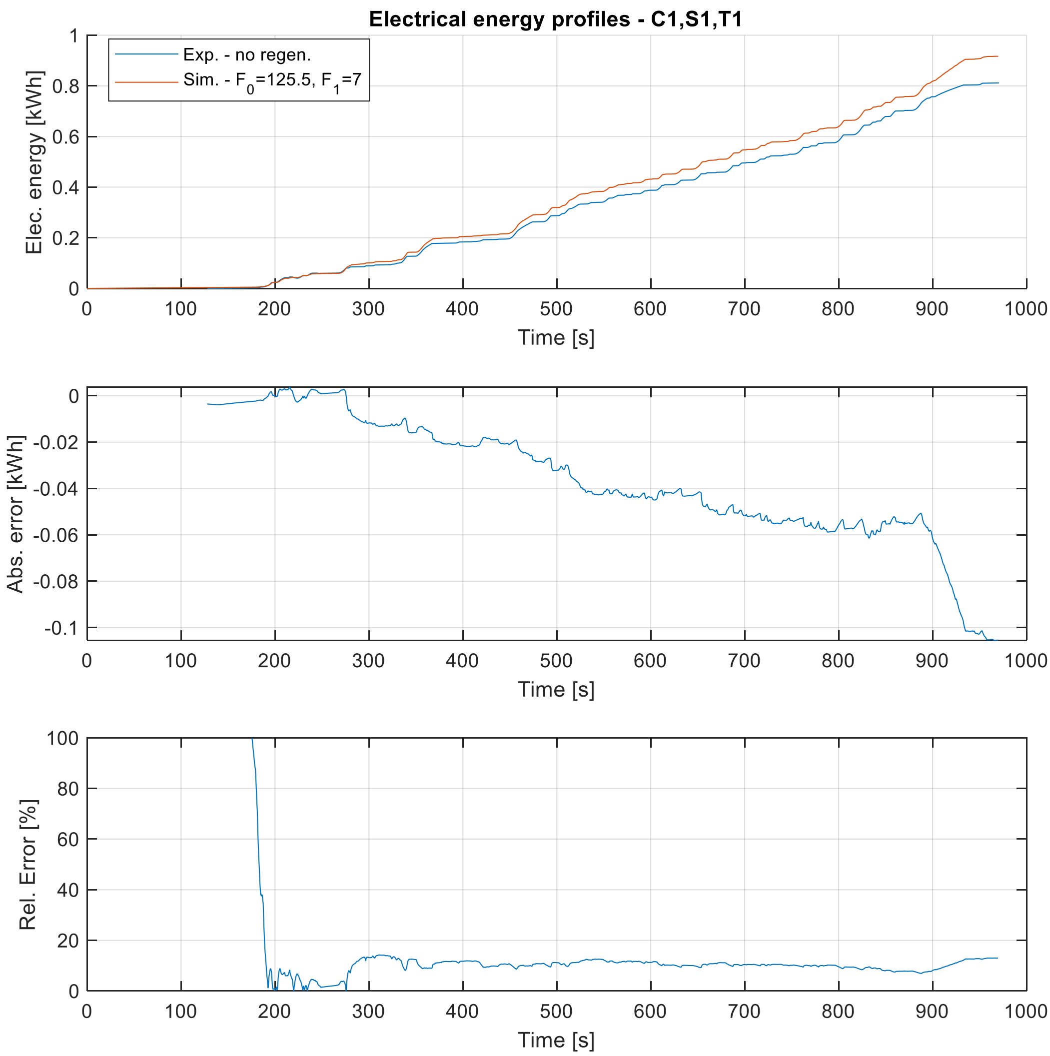


Figure 111. Electrical energy profile and its error simulated with C1,S1,T1

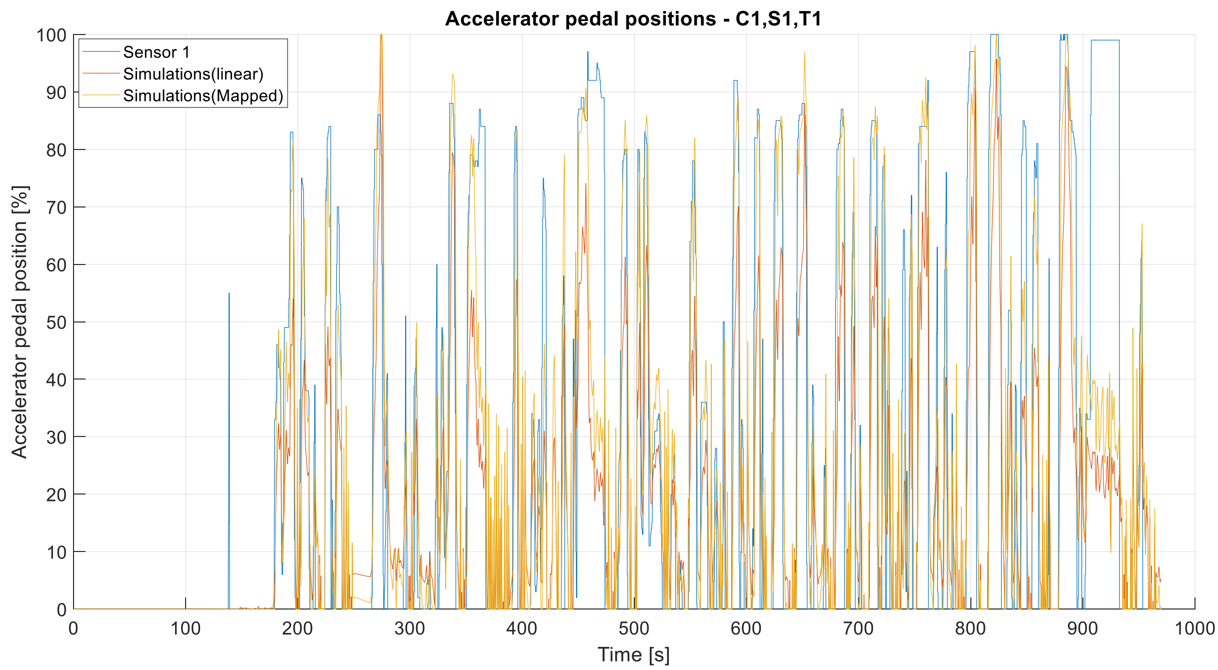


Figure 112. Accelerator pedal positions simulated with C1,S1,T1

5.4.3.2 T2 test

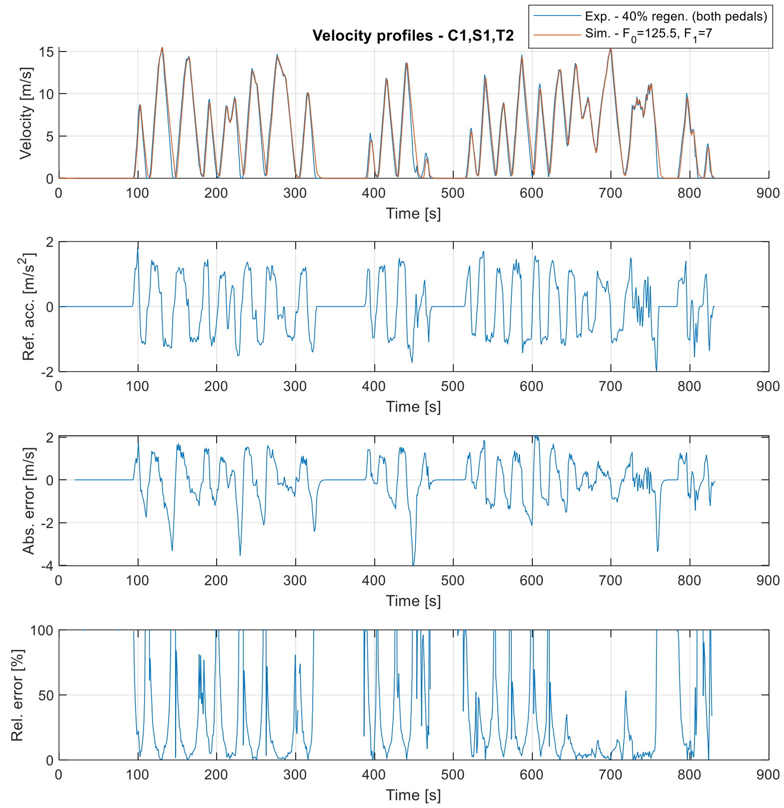


Figure 113. Velocity profile and its error simulated with C1,S1,T2

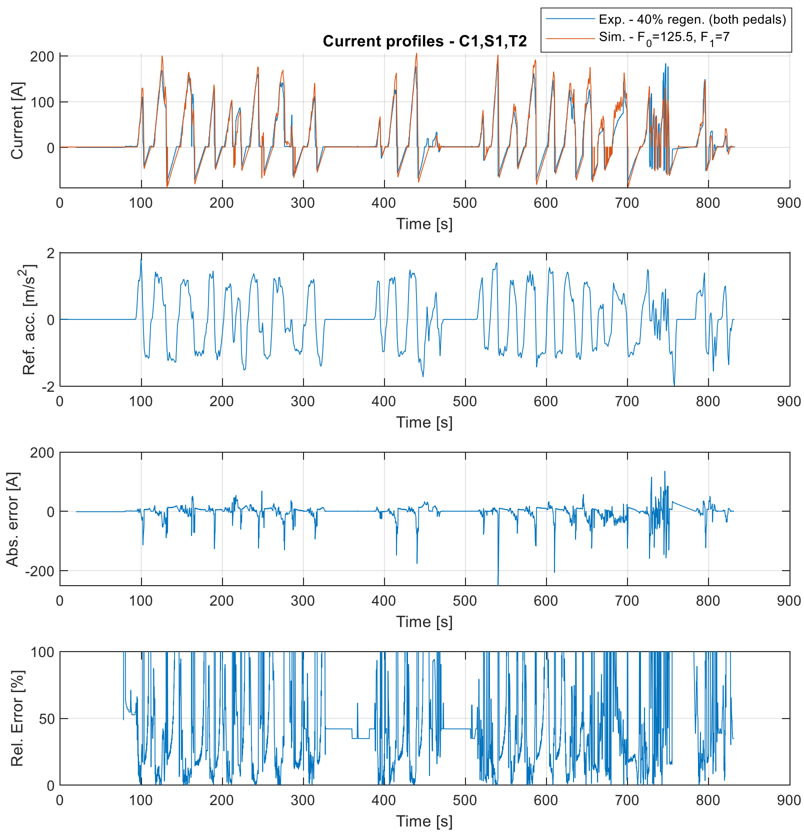


Figure 114. Current profile and its error simulated with C1,S1,T2

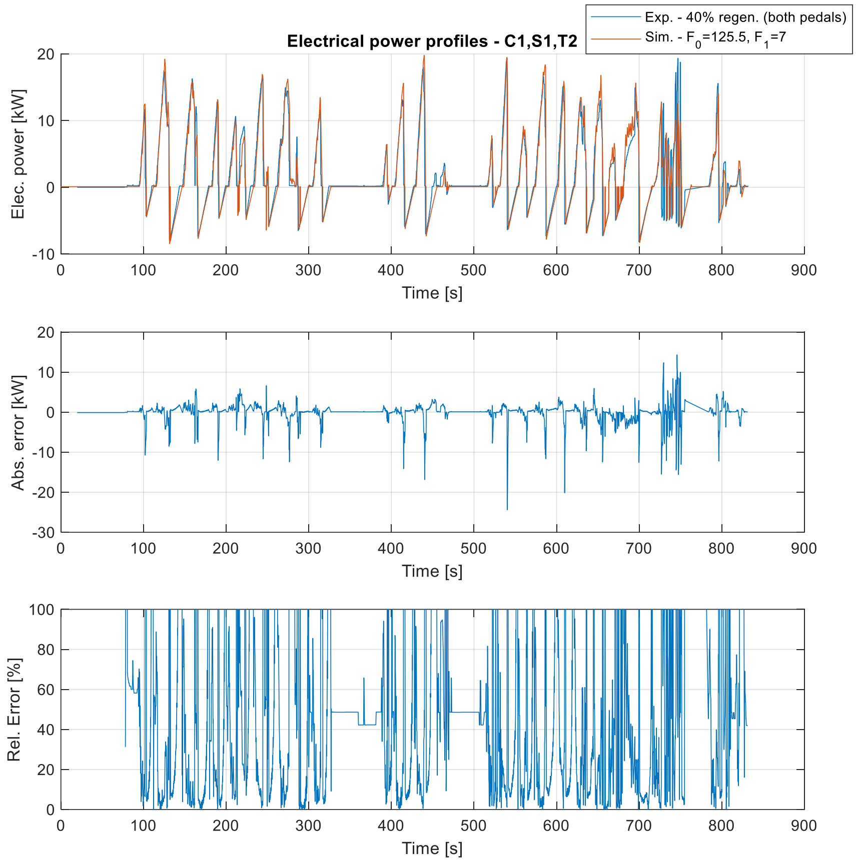


Figure 115. Electrical power profile and its error simulated with C1,S1,T2

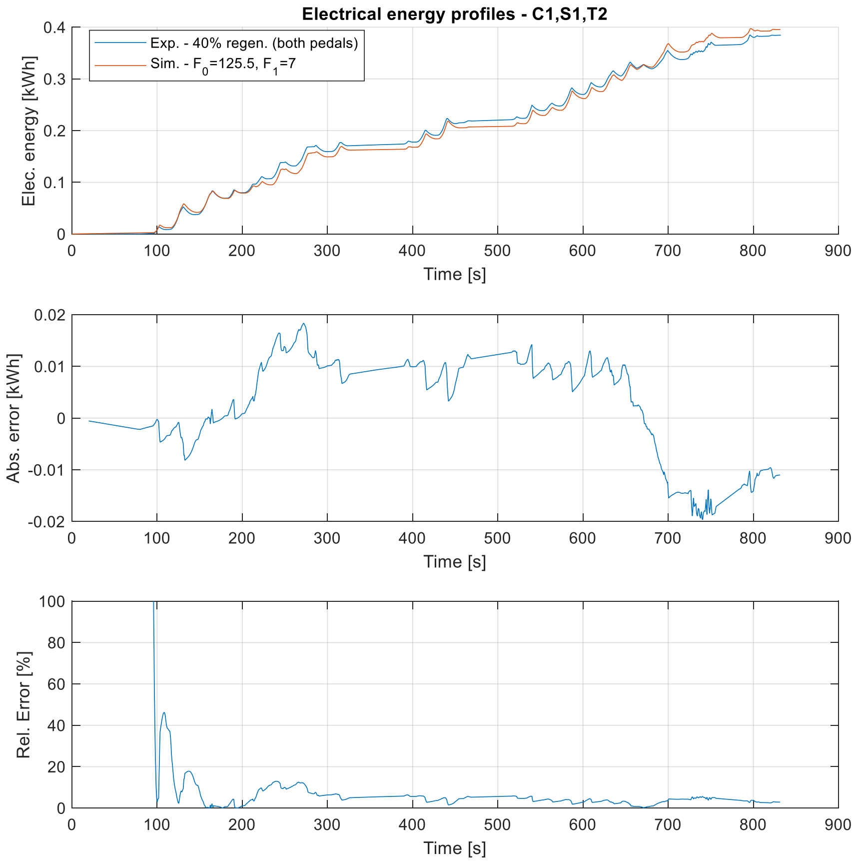


Figure 116. Electrical energy profile and its error simulated with C1,S1,T2

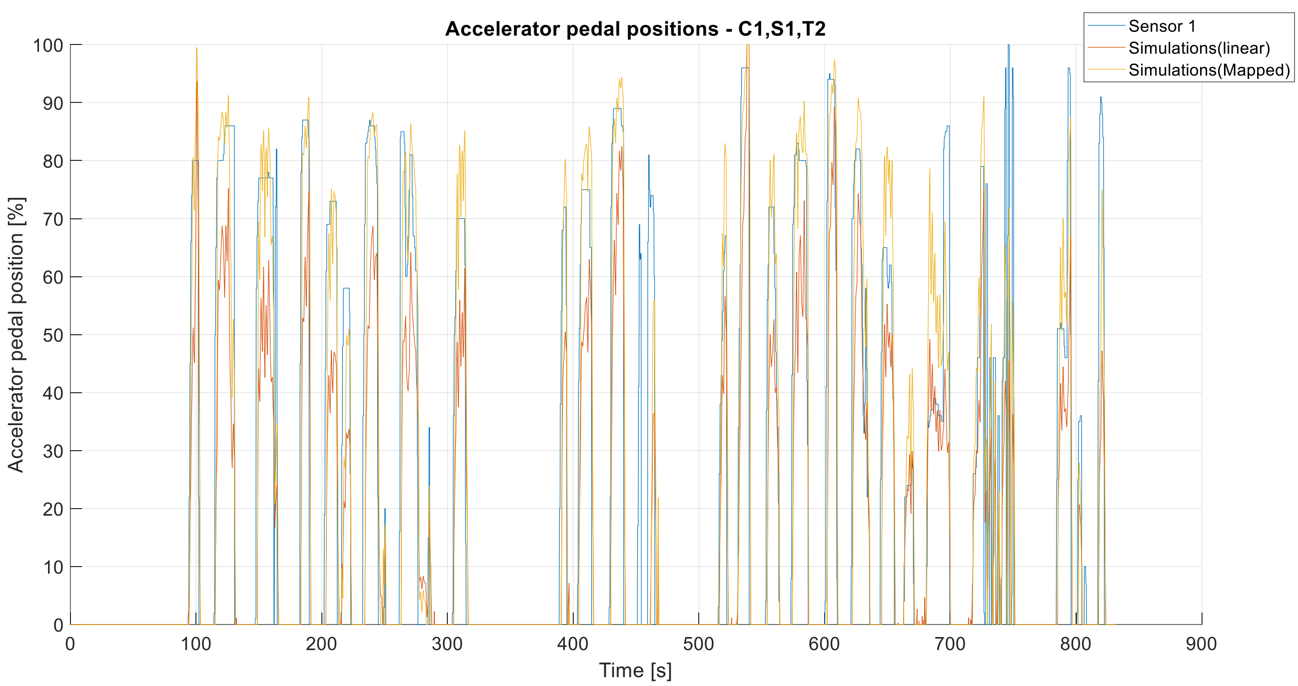


Figure 117. Accelerator pedal positions simulated with C1,S1,T2

5.4.3.3 T3 test

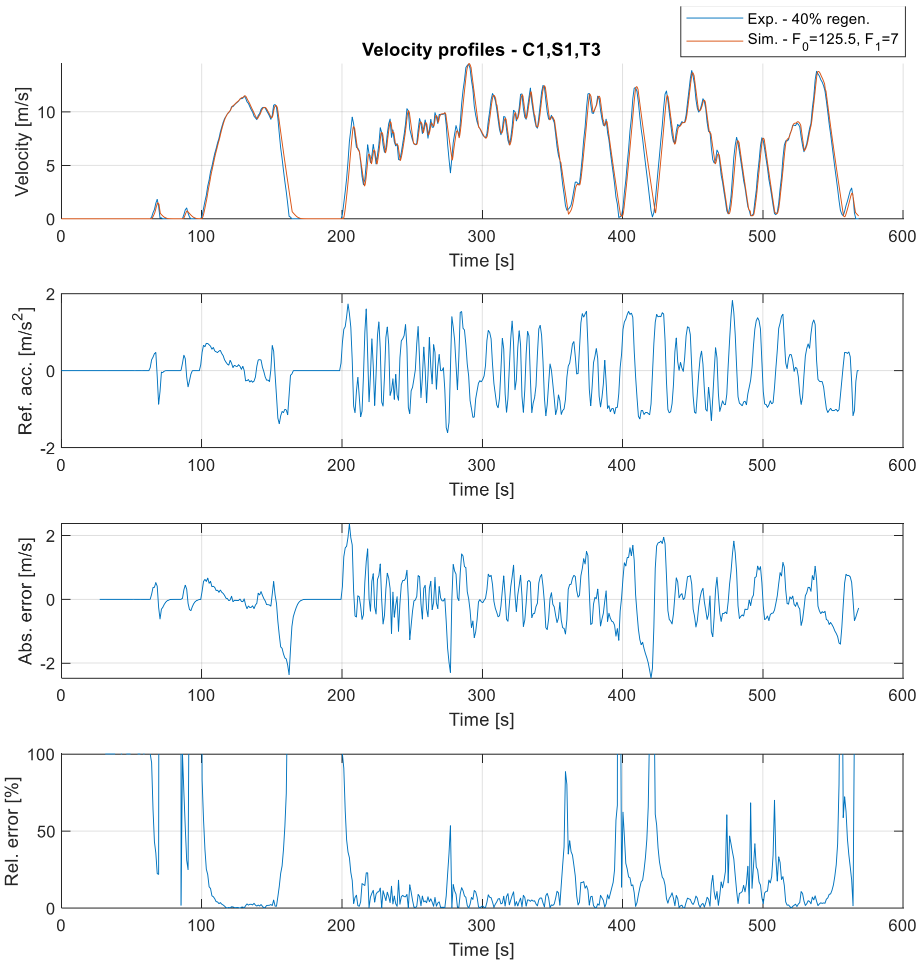


Figure 118. Velocity profile and its error simulated with C1,S1,T3

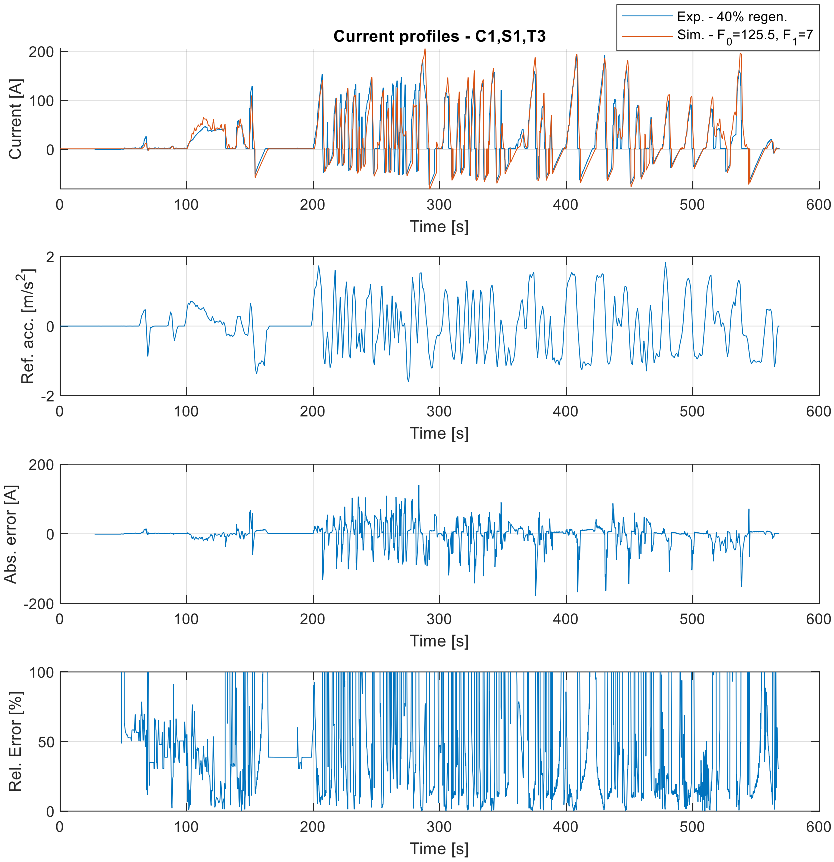


Figure 119. Current profile and its error simulated with C1,S1,T3

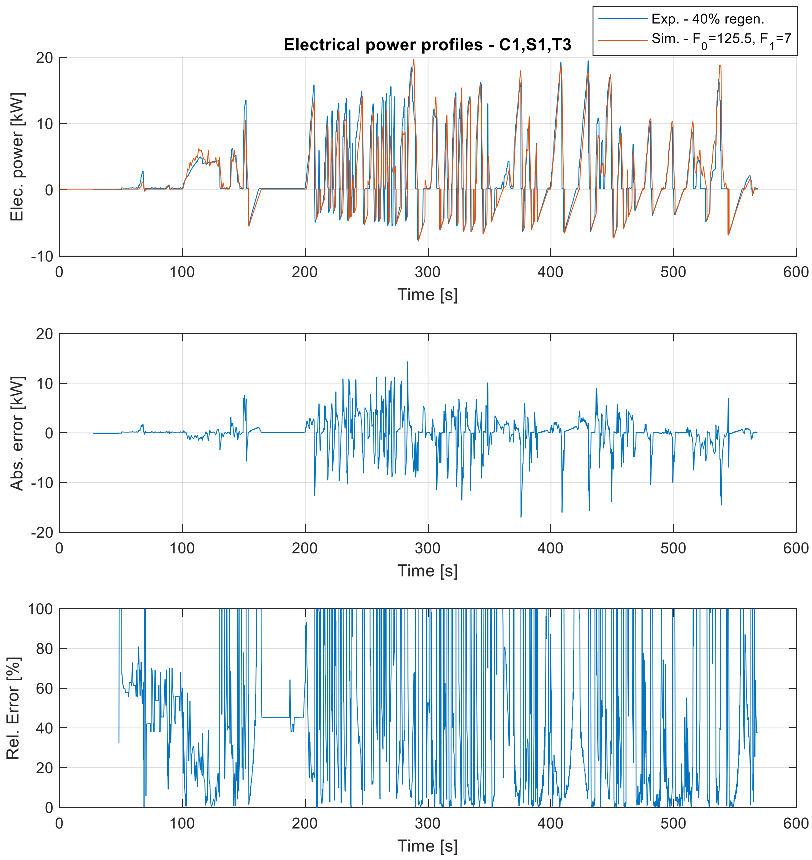


Figure 120. Electrical power profile and its error simulated with C1,S1,T3

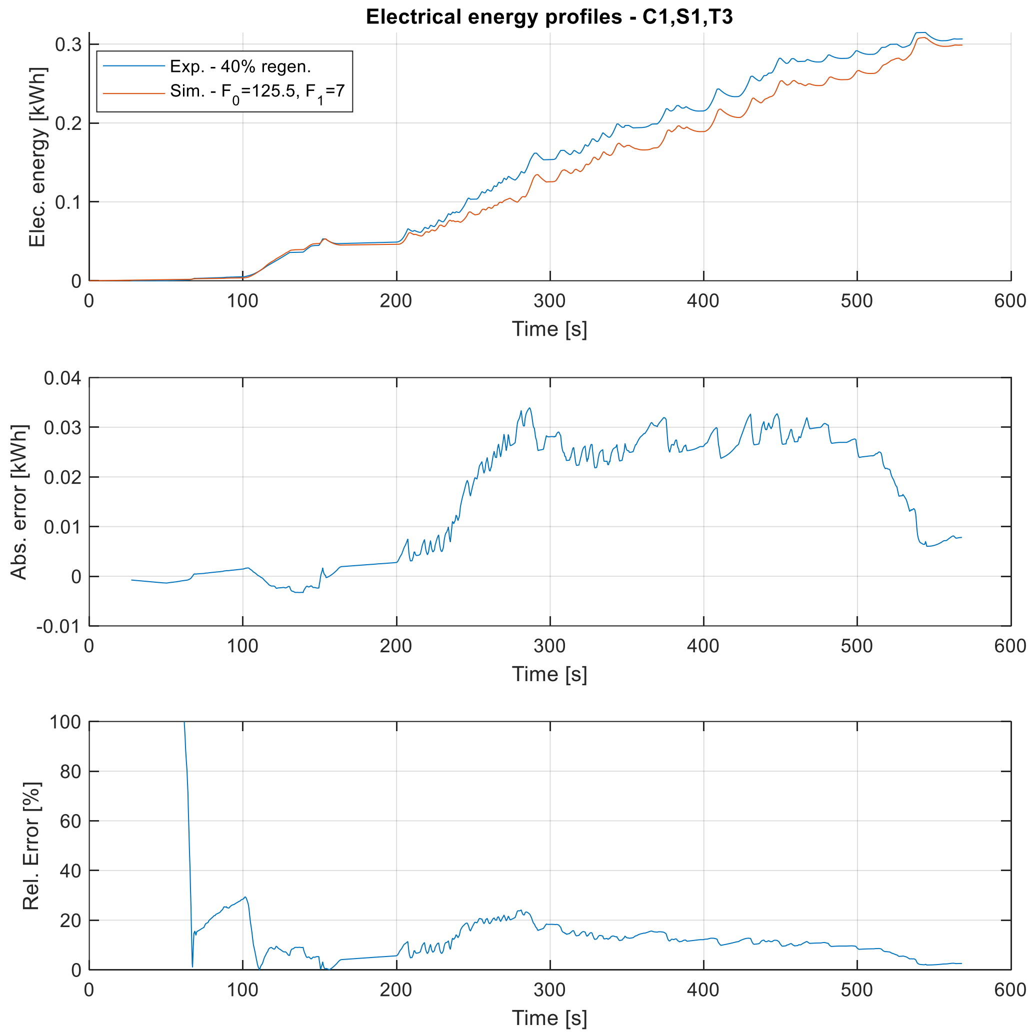


Figure 121. Electrical energy profile and its error simulated with C1,S1,T3

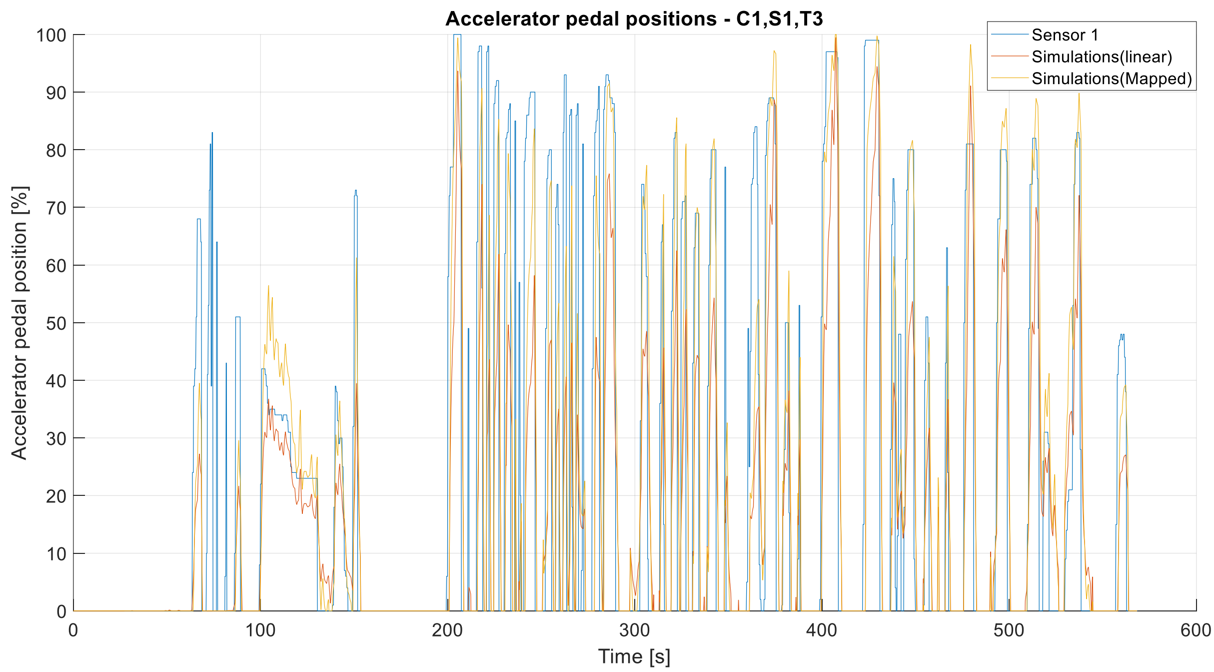


Figure 122. Accelerator pedal positions simulated with C1,S1,T3

5.4.3.4 T4 test

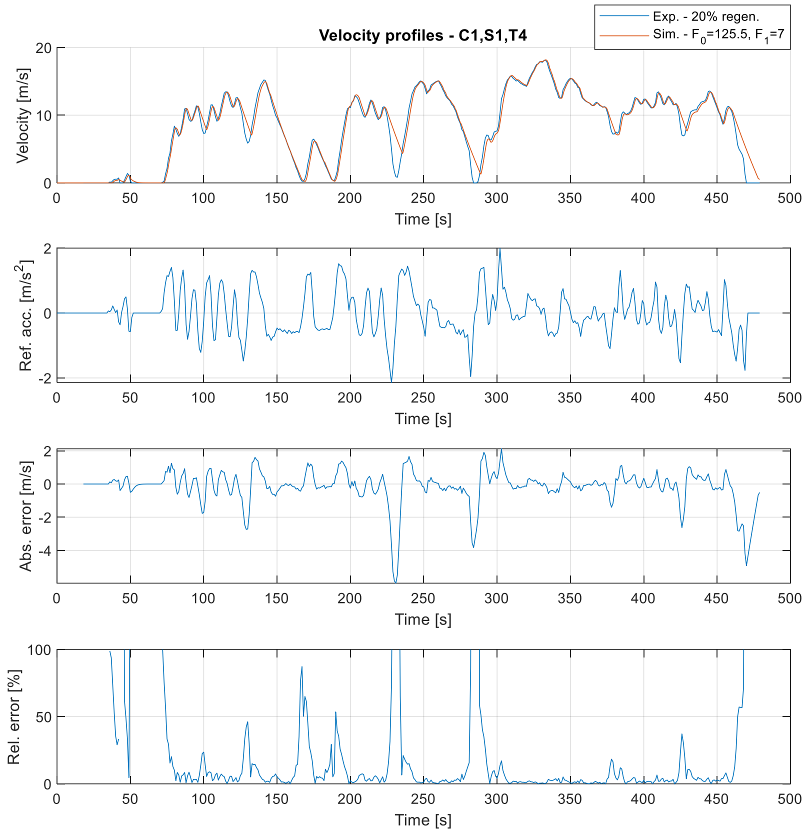


Figure 123. Velocity profile and its error simulated with C1,S1,T4

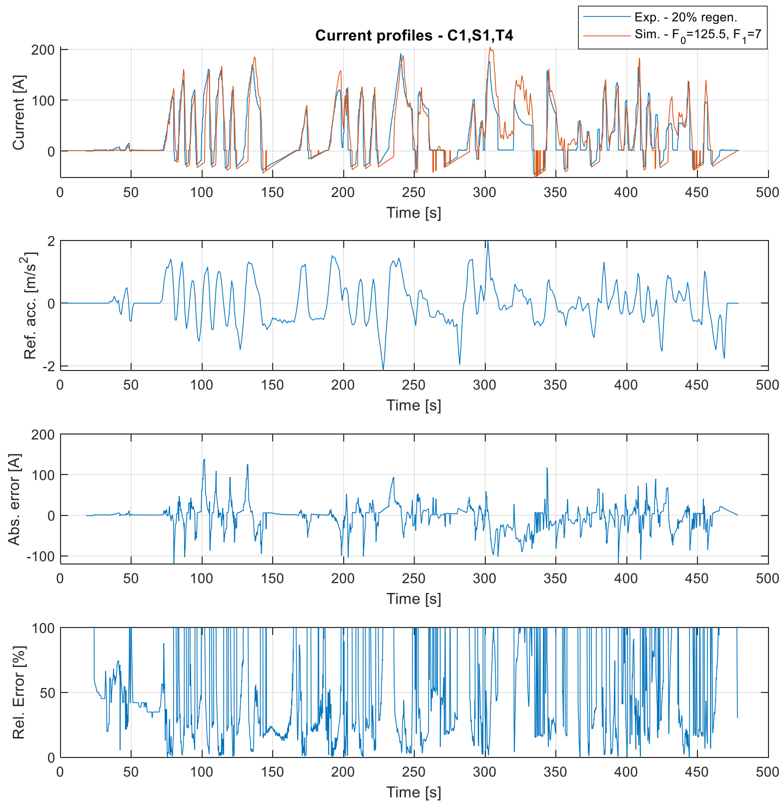


Figure 124. Current profile and its error simulated with C1,S1,T4

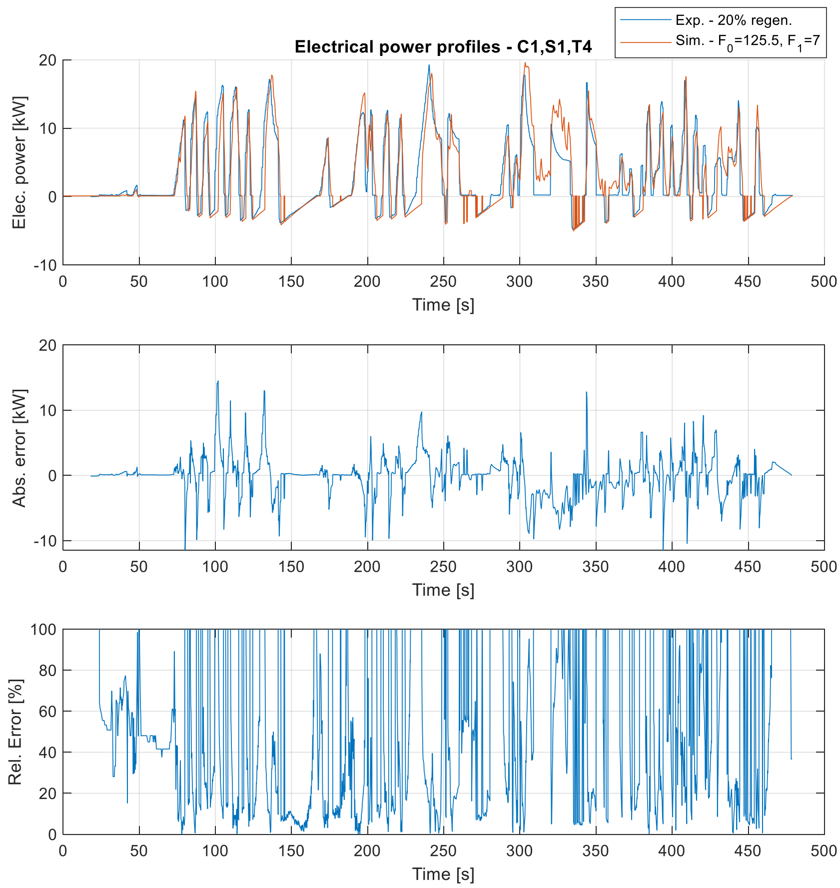


Figure 125. Electrical power profile and its error simulated with C1,S1,T4

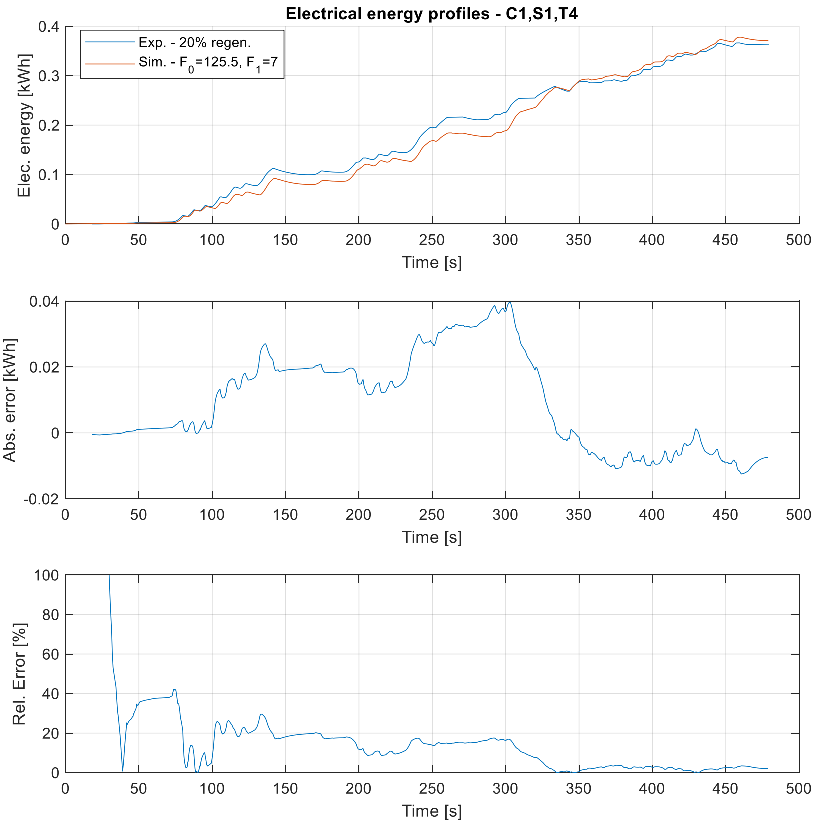


Figure 126. Electrical energy profile and its error simulated with C1,S1,T4

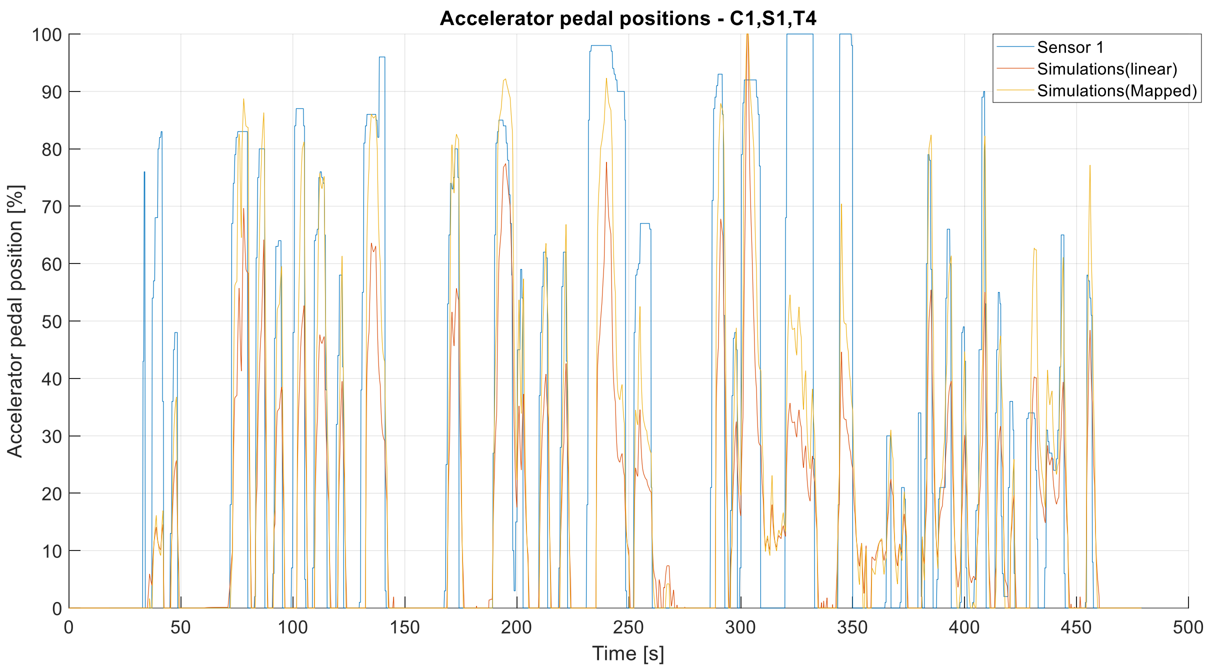


Figure 127. Accelerator pedal positions simulated with C1,S1,T4

5.5 Comparison: C0S0 vs. C1S0

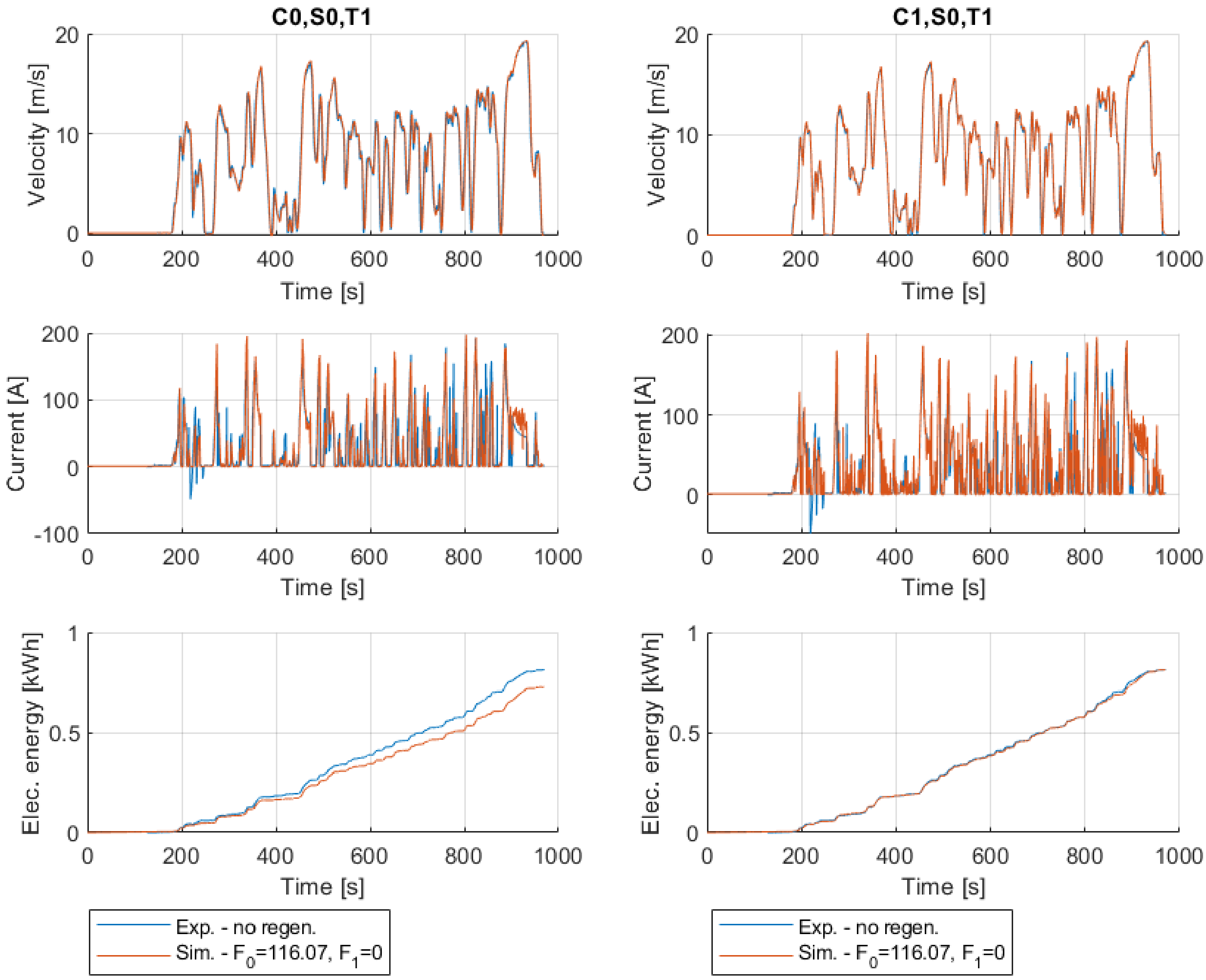
After performing all the simulations regarding control system validation, now the errors of the two cases of ideal control C0 and real control C1 (both with calculated coast-down coefficients S0) are analyzed here. First each single experiment will be studied for the two cases and then the overall error distributions will be shown.

5.5.1 Single experiment comparison

As said, first it will be seen how for each experiment the results differ. Results related to each driving cycle are depicted in a single figure summarizing the key outcomes of the simulations. As it will be seen velocity, current and energy profiles are chosen to be displayed while electrical power is not reported which is due to the fact that in the Simulink model a constant voltage is considered for the battery hence electrical power profile gives almost the same information as current profile. Additionally, errors regarding accuracy of velocity profile, current profile and specific consumption are mentioned.

It should be also mentioned that specific consumption values are reported considering regeneration for experiments that were carried out with regeneration while for the first experiment where no regeneration occurred and simply hydraulic brakes were being exploited, value of specific consumption without regeneration is taken and reported from the corresponding simulation.

5.5.1.1 T1



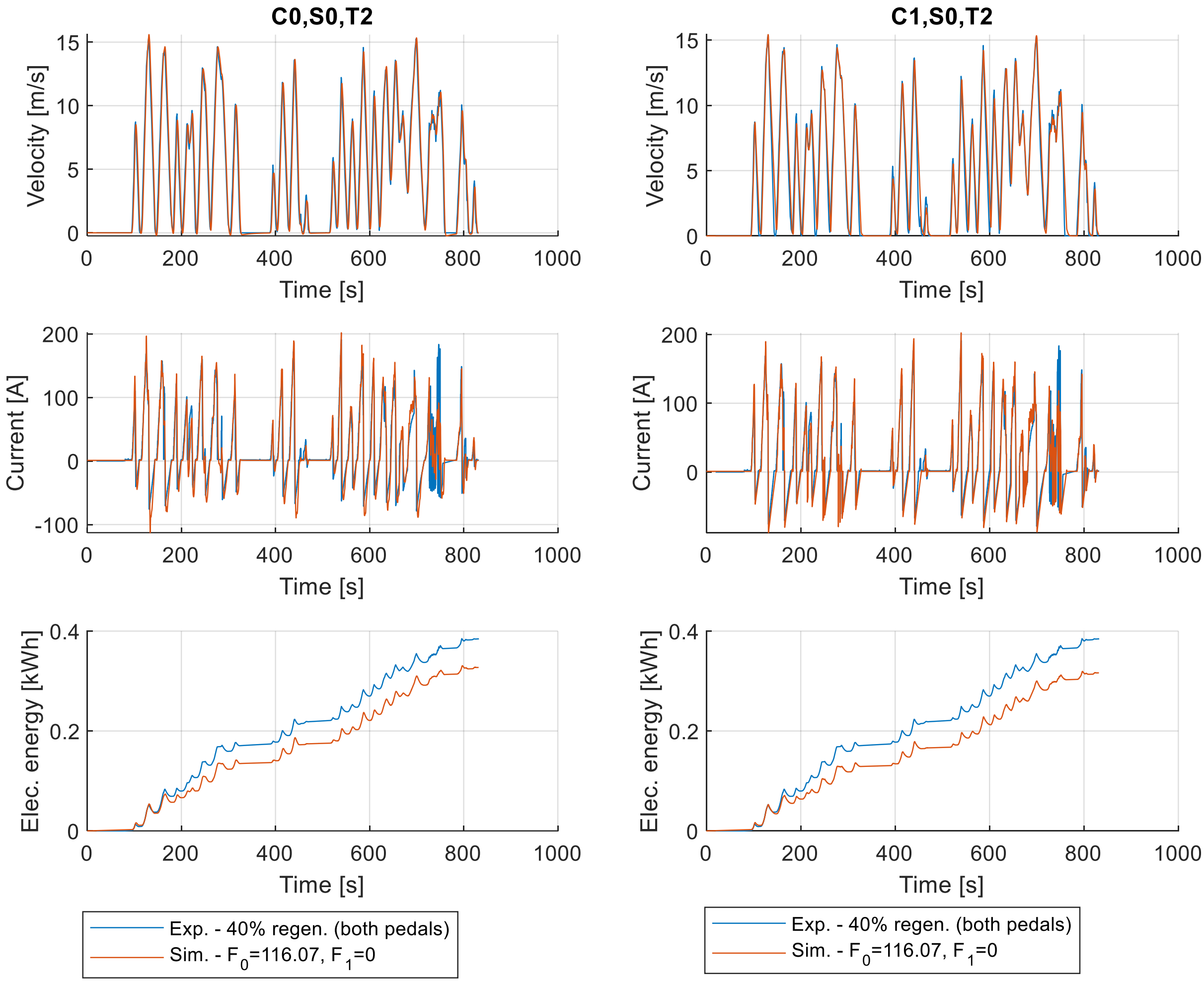
Velocity profile error = 0.76204 [$(m/s)^2$]
Current profile error = 481.4621 [A^2]
Experimental specific consumption = 123.9614 [Wh/km]
Simulated specific consumption = 109.7539 [Wh/km]
Specific consumption error = 11.4613 [%]

Velocity profile error = 0.22816 [$(m/s)^2$]
Current profile error = 354.5415 [A^2]
Experimental specific consumption= 123.9614 [Wh/km]
Simulated specific consumption= 122.9357 [Wh/km]
Specific consumption error= 0.82743 [%]

Figure 128. C0,S0,T1 vs. C1,S0,T1

As it could be seen for the experiment T1 (without regeneration) with C1 velocity profile's error is smaller. The current profile's error decreases too. Regarding specific consumption the error is decreased one order of magnitude with C1. Hence in T1 where no regeneration was applied C1S0 model gives improved results with respect to C0S0.

5.5.1.2 T2



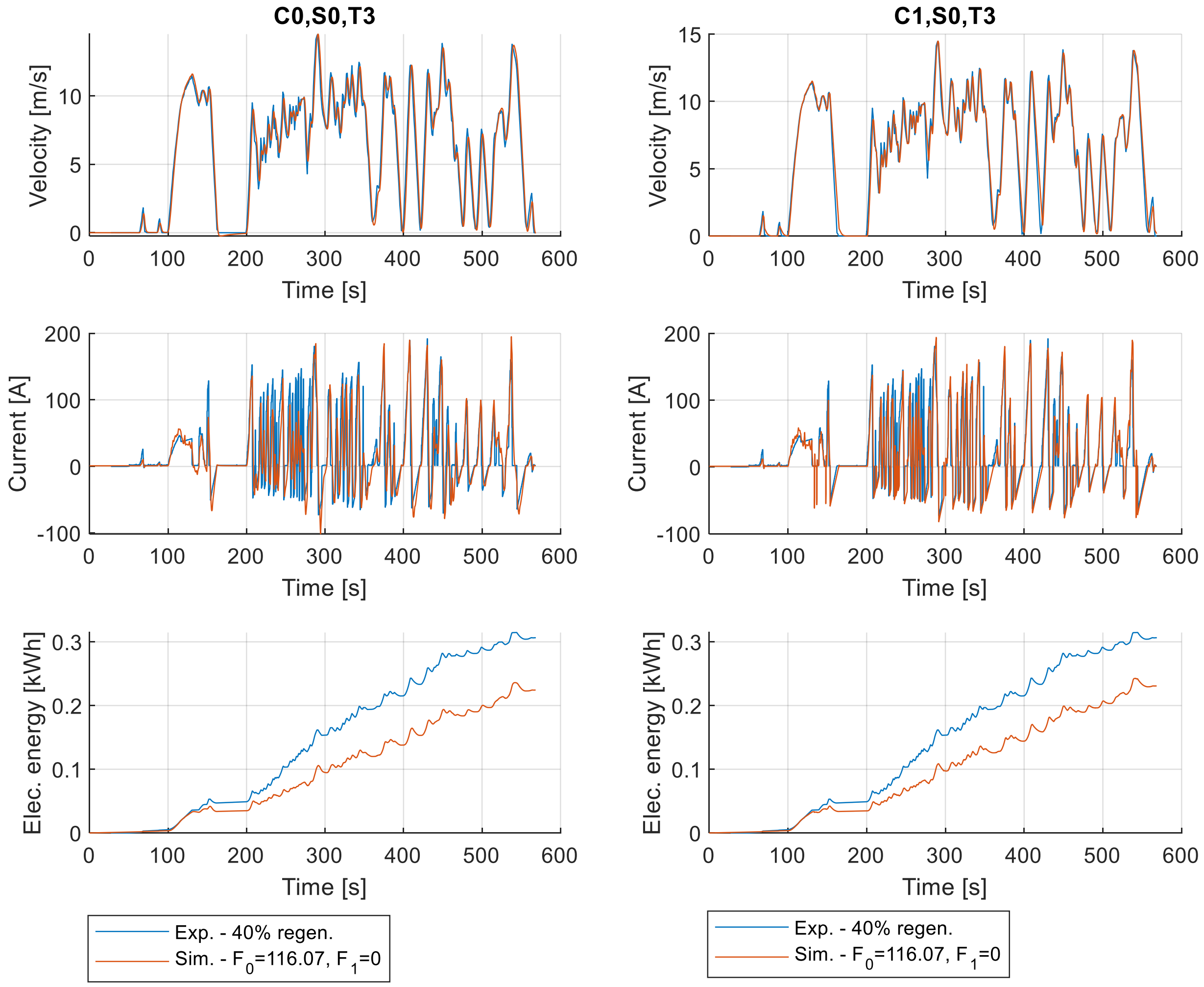
Velocity profile error = 0.86195 [$(m/s)^2$]
Current profile error = 643.9095 [A^2]
Experimental specific consumption = 105.9055 [Wh/km]
Simulated specific consumption = 90.0344 [Wh/km]
Specific consumption error = 14.9861 [%]

Velocity profile error = 1.1552 [$(m/s)^2$]
Current profile error = 488.5319 [A^2]
Experimental specific consumption= 105.9055 [Wh/km]
Simulated specific consumption= 85.3036 [Wh/km]
Specific consumption error= 19.4531 [%]

Figure 129. C0,S0,T2 vs. C1,S0,T2

In T2 experiment where 40% regeneration was applied including both pedal strategies, with C1 velocity profile shows a bigger error while current profile's error is reduced. Specific consumption shows a slightly increased amount of error as well. But the increase of error in velocity profile or specific consumption is not noticeable. Hence in T2 with C1S0 current profile improves while velocity and specific consumption lose some precision.

5.5.1.3 T3



Velocity profile error = 0.64334 [(m/s)^2]
Current profile error = 1098.9072 [A^2]
Experimental specific consumption = 96.9044 [Wh/km]
Simulated specific consumption = 70.8477 [Wh/km]
Specific consumption error = 26.8891 [%]

Velocity profile error = 0.55961 [(m/s)^2]
Current profile error = 890.6653 [A^2]
Experimental specific consumption= 96.9044 [Wh/km]
Simulated specific consumption= 72.6397 [Wh/km]
Specific consumption error= 25.0398 [%]

Figure 130. C0,S0,T3 vs. C1,S0,T3

In case of T3, with C1 a slight improvement in both velocity and current profile errors is achieved. Also, specific consumption reduces around 2%. Hence S0C1 proves to be better than S0C0 in all aspects for simulating the T3 experiment.

5.5.1.4 T4

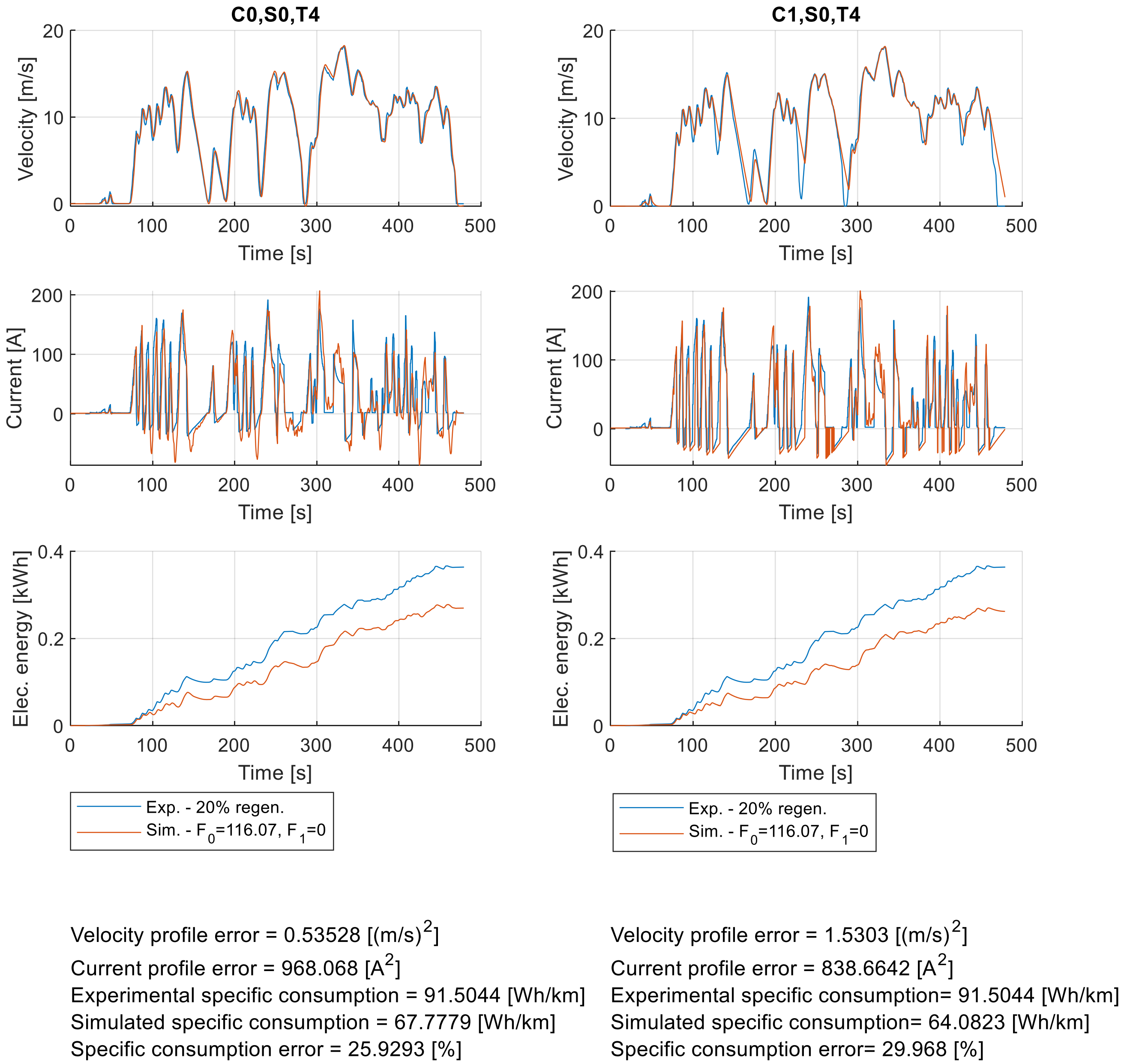


Figure 131. C0,S0,T4 vs. C1,S0,T4

Finally, in the last experiment T4, a sharp increase in the velocity profile's error is observed. It is understandable that with the given level of constant regenerative brake level in T4 which is 20% of the maximum torque, the simulated model simply cannot follow the deceleration phases as performed in the real test. One explanation could be the fact that in the real test brake pedal activation method was used in order to active the regenerative braking. Although the driver pushed the brake pedal slightly to active the regenerative braking without applying a sensible hydraulic brake, in any case the role of hydraulic brakes could not be neglected. Thus, in reality such deceleration levels might have been partly achieved by the hydraulic brakes whereas in the simulation this phenomenon is not taken into account. To overcome this problem, it is suggested to use the acceleration pedal activation method in the future experiments.

Meanwhile it could be seen that current profile has less error with C1. But Specific consumption shows about 4 percent increased error in C1 compared to C0.

5.5.2 Overall error comparison

An important factor to consider is how these errors are distributed for each experimental data set. Hence average, median, standard deviation and other distribution characteristics are calculated and displayed on the following figures.

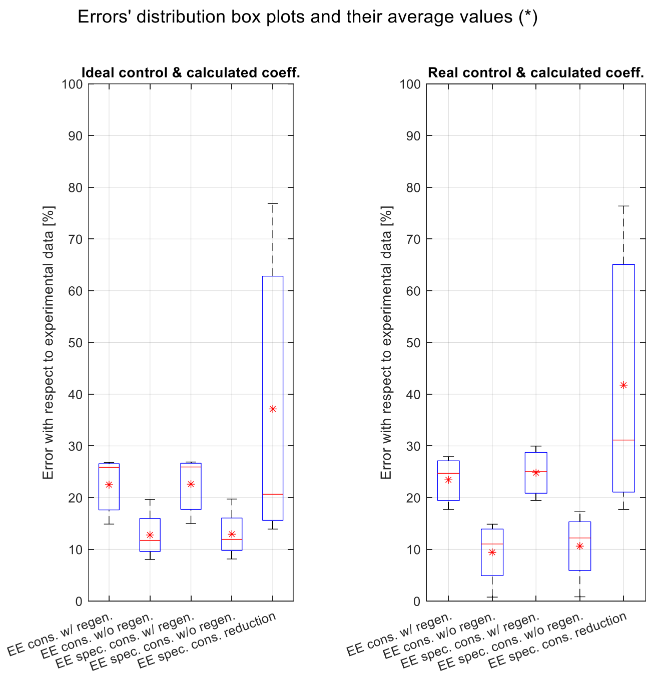


Figure 132. Distribution of consumption errors reported in box plots – C0,S0 vs. C1,S0

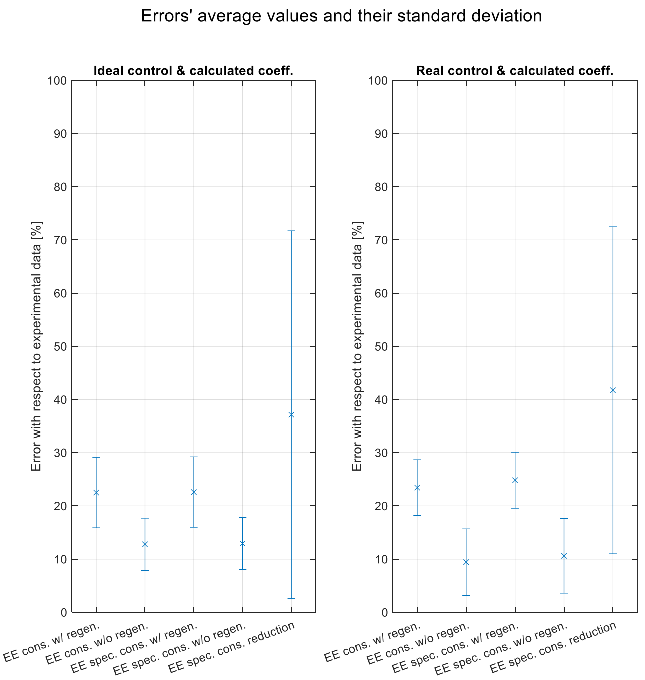


Figure 133. Average and corresponding standard deviation of consumption errors – C0,S0 vs. C1,S0

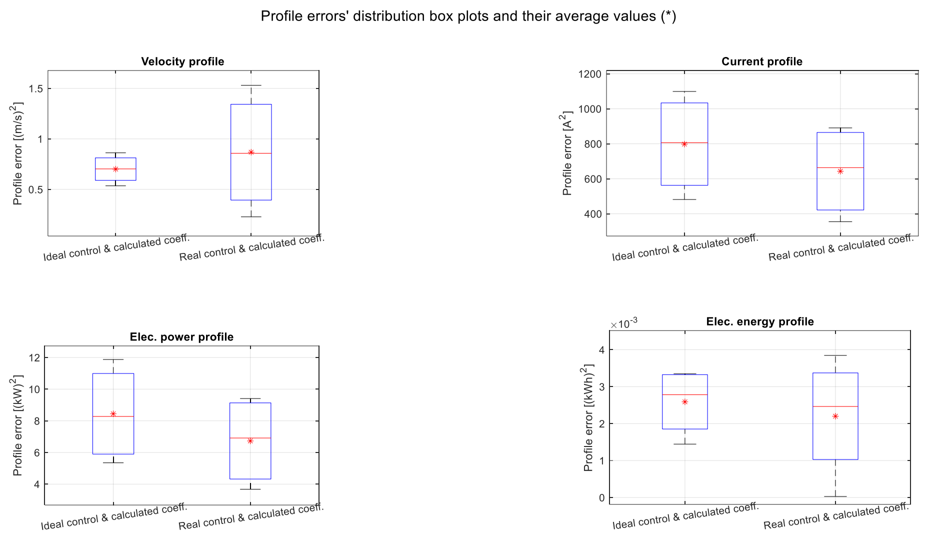


Figure 134. Distribution of profile errors reported in box plots – C0,S0 vs. C1,S0

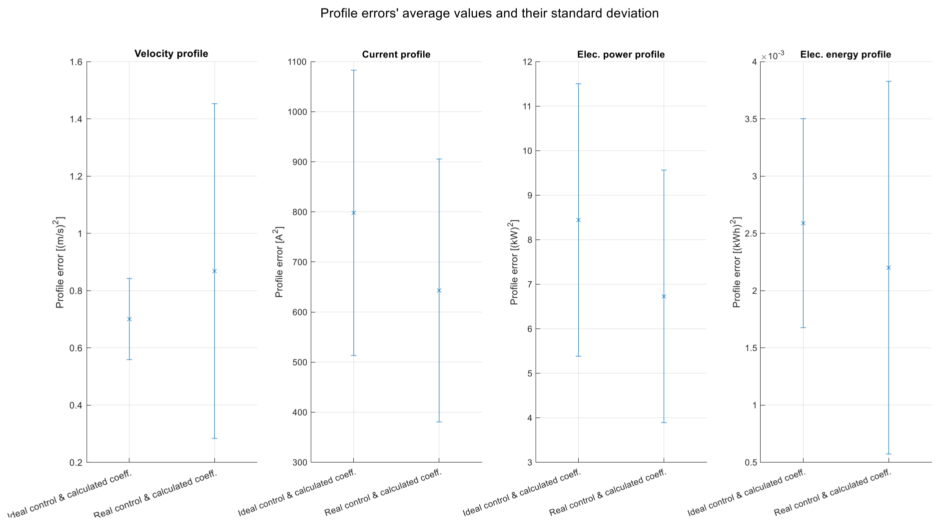


Figure 135. Average and corresponding standard deviation of profile errors – C0,S0 vs. C1,S0

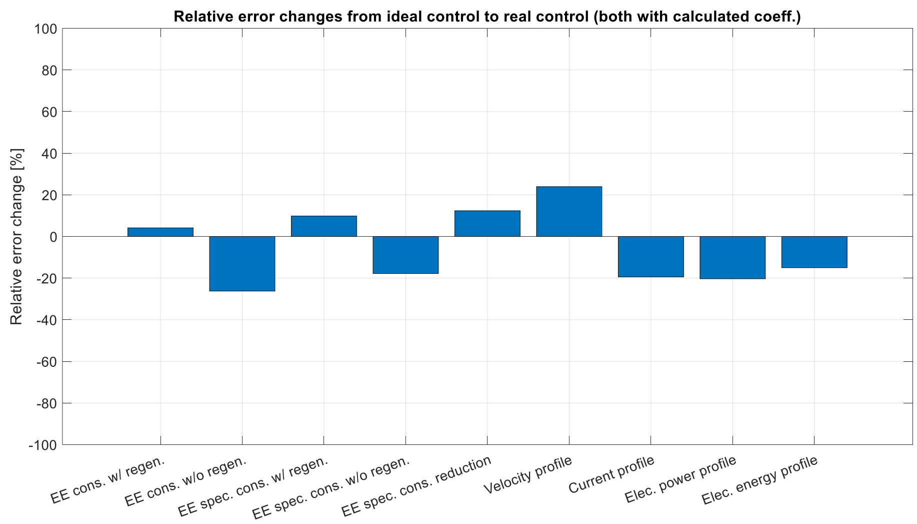


Figure 136. Relative error changes moving from ideal control to real control with calculated coast-down coefficients

5.5.3 Observations

As it can be seen by maintaining the same calculated coast-down coefficients S0 and changing the control model from ideal C0 to the real one C1 where on/off regenerative braking, pedal mapping, activation strategy, etc. are considered the following changes occur:

- Errors of consumption values with regeneration increase slightly.
- Errors of consumption values without regeneration decrease noticeably.
- Velocity profile error increases about almost 24% which is partly explainable as the ideal control can output a more smooth braking signal that enables the simulation to follow more precisely the reference speed cycle whereas with real control model repetitive activation/deactivation of regenerative braking hinders the possibility to follow the reference speed cycle as precise as the ideal control model. Furthermore, a huge amount of error comes from T4 experiment. As explained earlier in T4 experiment comparison section, hydraulic braking could be playing a major role in creating this error whereas in simulations such phenomenon is not considered. Thus, more investigation should be performed to be able to understand if the increment in velocity error comes solely from control strategy or it may have other reasons.
- Although the final consumption values with regeneration were shown to have relatively a slight increase of error but it can be noticed that the current profile, electrical power profile and instantaneous energy profile have noticeable decrease in their profiles' error. Thus, the dynamic behavior of the electrical systems improves and becomes closer to the experimental one.

It should be kept in mind that these conclusions are not yet strong enough for a general statement as the absolute errors are close and more experimental data could be used for a better understanding of relative changes in the errors.

5.6 Comparison: C1S0 vs. C1S1

So far it has been seen how implementing the real control model C1 mainly improved the simulation results of current, electrical power and electrical energy profiles as well as consumption values without regeneration. However as already explained before, a proper parameter tuning is needed to reduce errors regarding consumption values specially those related to regeneration and to able to validate the plant. After performing all the simulations regarding this step, now the corresponding errors for the two cases of calculated coast-down coefficients S0 and fitted ones S1 (both with C1) are analyzed here. First each single experiment will be compared as before for the two cases and then again the overall error distributions will be studied.

5.6.1 Single experiment comparison

First it will be seen how for each experiment the results differ.

5.6.1.1 T1

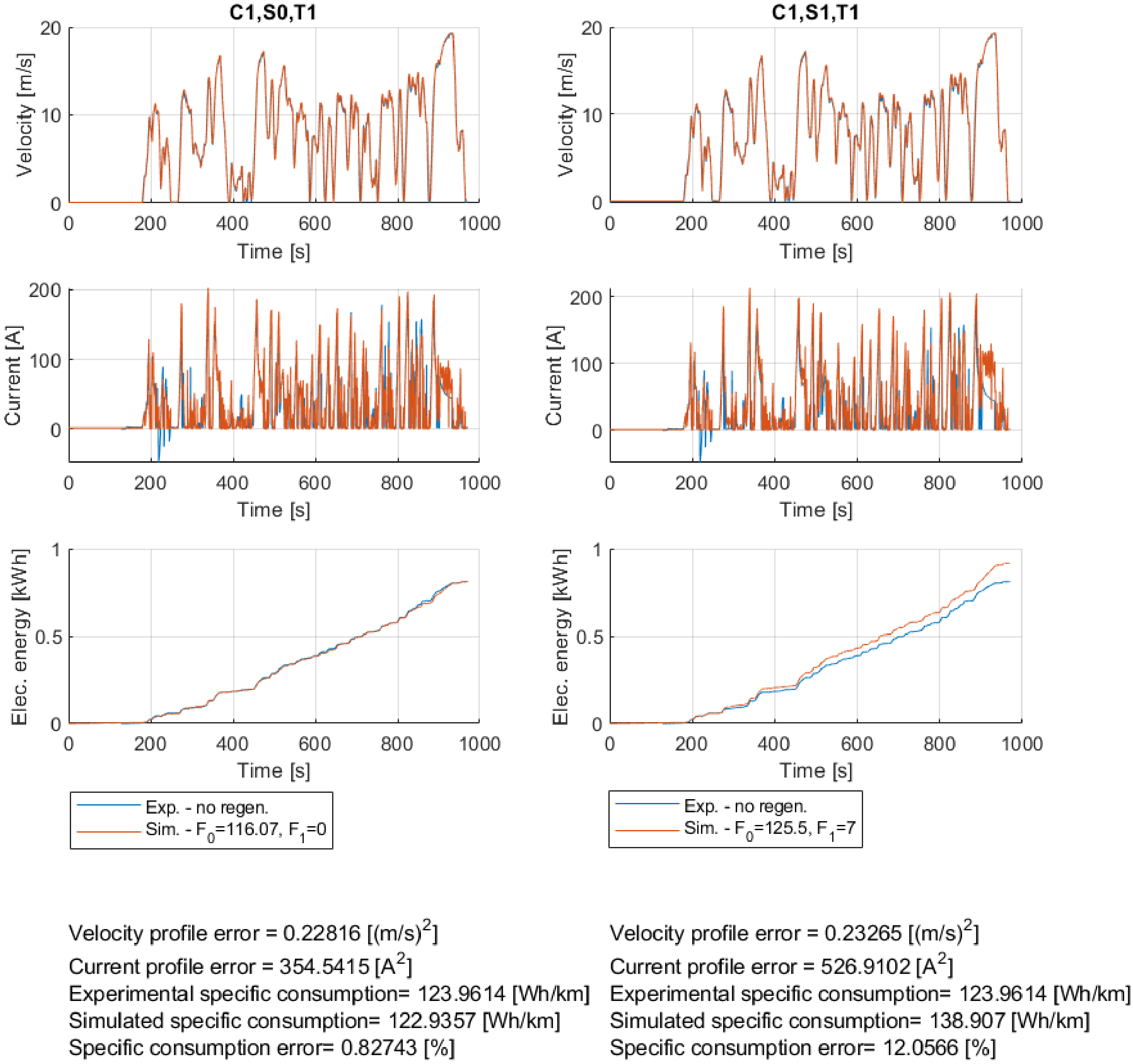
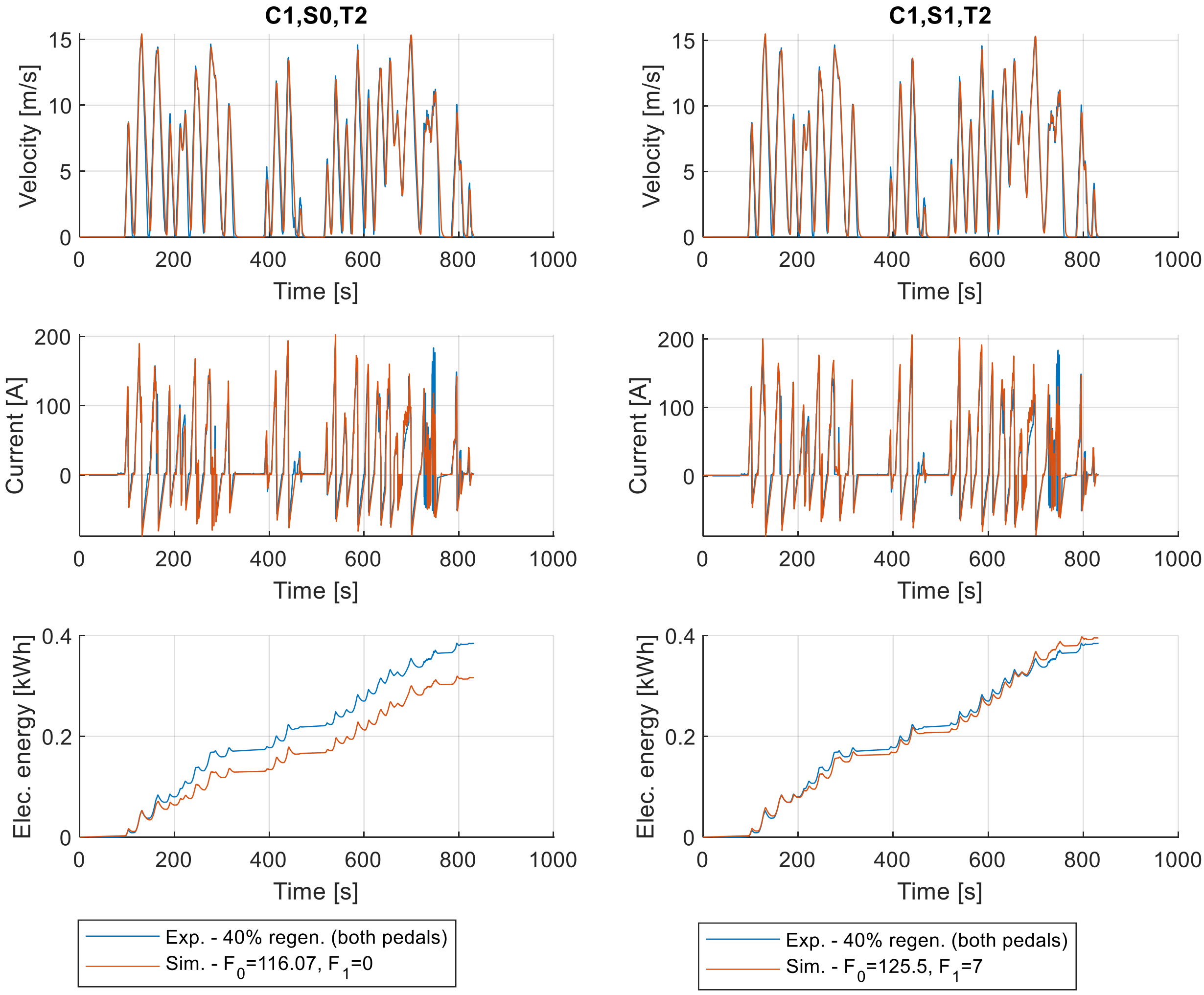


Figure 137. C1,S0,T1 vs. C1,S1,T1

As observable in T1 experiment where no regeneration was applied, using C1,S1 instead of C1,S0 causes a negligible increase of error in velocity profile. A modest error increase in the current profile could be seen too. What is yet more important to notice is the fact that specific consumption error increases from 0.8% to about 12%. Hence in case of no regeneration a sharp increase of error for specific consumption happens.

5.6.1.2 T2

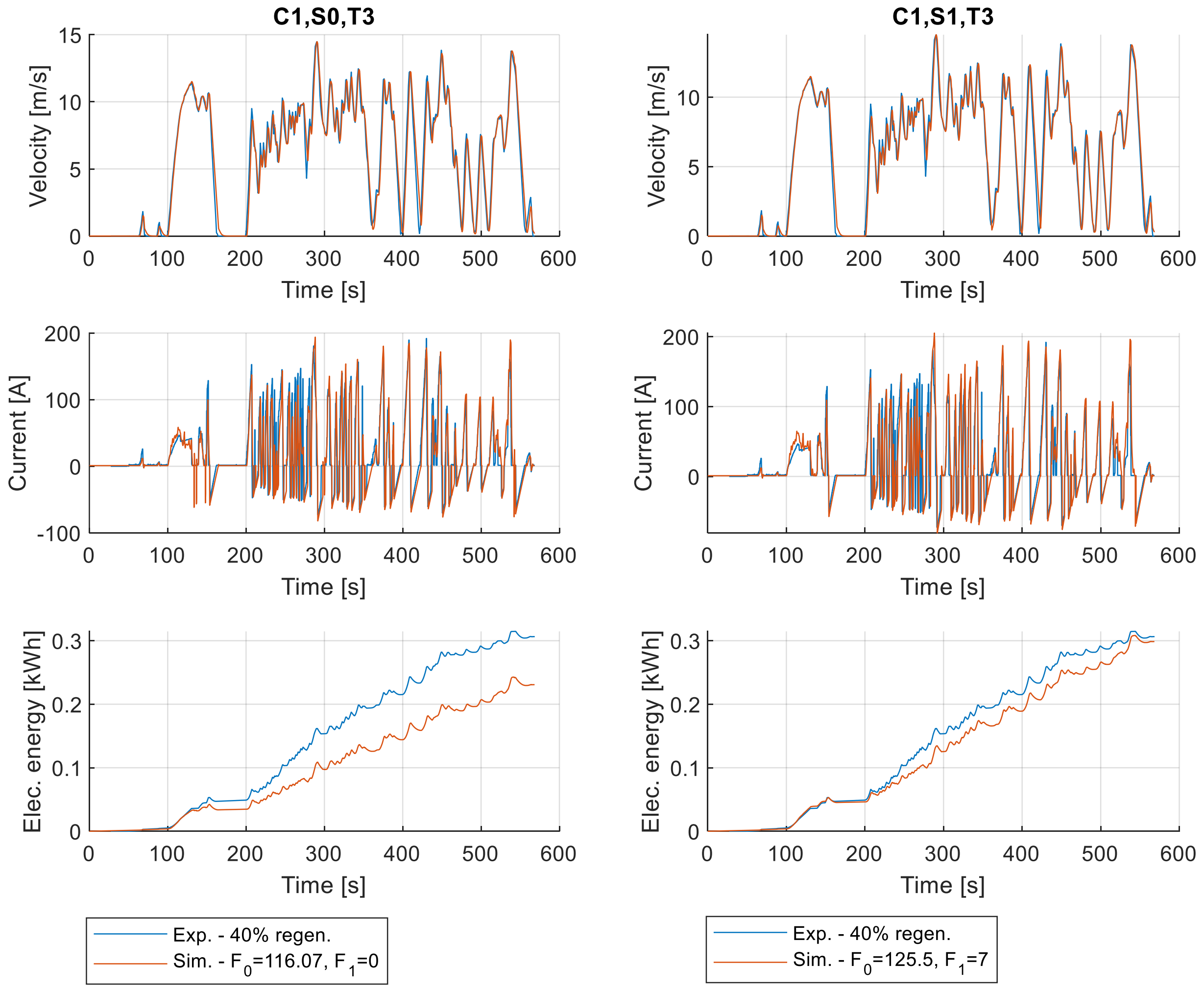


C1,S0,T2	C1,S1,T2
Velocity profile error = 1.1552 [(m/s)^2]	Velocity profile error = 0.82631 [(m/s)^2]
Current profile error = 488.5319 [A^2]	Current profile error = 569.6647 [A^2]
Experimental specific consumption= 105.9055 [Wh/km]	Experimental specific consumption= 105.9055 [Wh/km]
Simulated specific consumption= 85.3036 [Wh/km]	Simulated specific consumption= 107.6971 [Wh/km]
Specific consumption error= 19.4531 [%]	Specific consumption error= 1.6917 [%]

Figure 138. C1,S0,T2 vs. C1,S1,T2

Regarding experiment T2 using S1 improves the velocity profile moderately whereas current profile deteriorates a little. But most importantly, specific consumption error reduces from 19.4% in case of S0 to only about 1.7% with S1 which is a huge achievement.

5.6.1.3 T3



C1,S0,T3	C1,S1,T3
Velocity profile error = 0.55961 [$(m/s)^2$]	Velocity profile error = 0.48149 [$(m/s)^2$]
Current profile error = 890.6653 [A^2]	Current profile error = 903.8895 [A^2]
Experimental specific consumption= 96.9044 [Wh/km]	Experimental specific consumption= 96.9044 [Wh/km]
Simulated specific consumption= 72.6397 [Wh/km]	Simulated specific consumption= 94.198 [Wh/km]
Specific consumption error= 25.0398 [%]	Specific consumption error= 2.7929 [%]

Figure 139. C1,S0,T3 vs. C1,S1,T3

A similar trend to T2 is also achieved for T3. By using C1,S1 instead of C1,S0, velocity profile error decreases whereas current profile error increases negligibly. However, specific consumption error reduces to a great extent from 25% down to about 2.8%.

5.6.1.4 T4

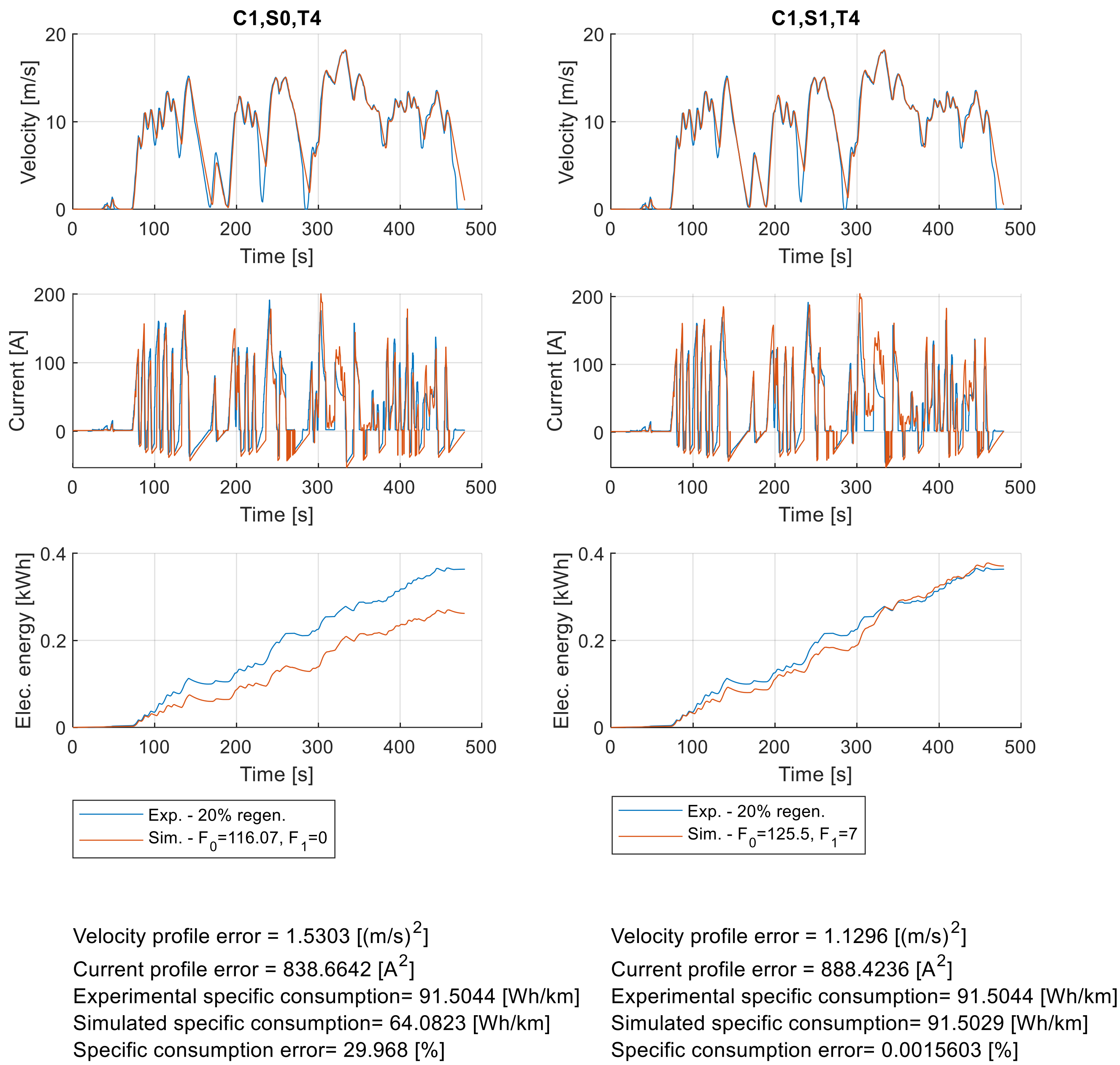


Figure 140. C1,S0,T4 vs. C1,S1,T4

Again, the same pattern as T3 and T2 happens for T4. By implementing C1S1 velocity profile error decreases whereas current profile error grows moderately. What is most evident is the huge amount of reduction in specific consumption error which reduces from around 30% for C1S0 to extremely small value of 0.00156% for C1S1.

5.6.2 Overall error comparison

Like what was done in control validation section, also here errors' distribution for different experimental tests are presented to have a clear vision on how errors change when moving from C1,S0 to C1,S1. Average, median, standard deviation and other distribution characteristics are calculated and displayed in the following statistical figures. As it will be seen the differences moving from C1,S0 to C1,S1 are much more highlighted than those observed previously for

C0,S0 vs. C1,S0 since huge improvements occur specifically for what regards consumption values whether with regeneration or without.

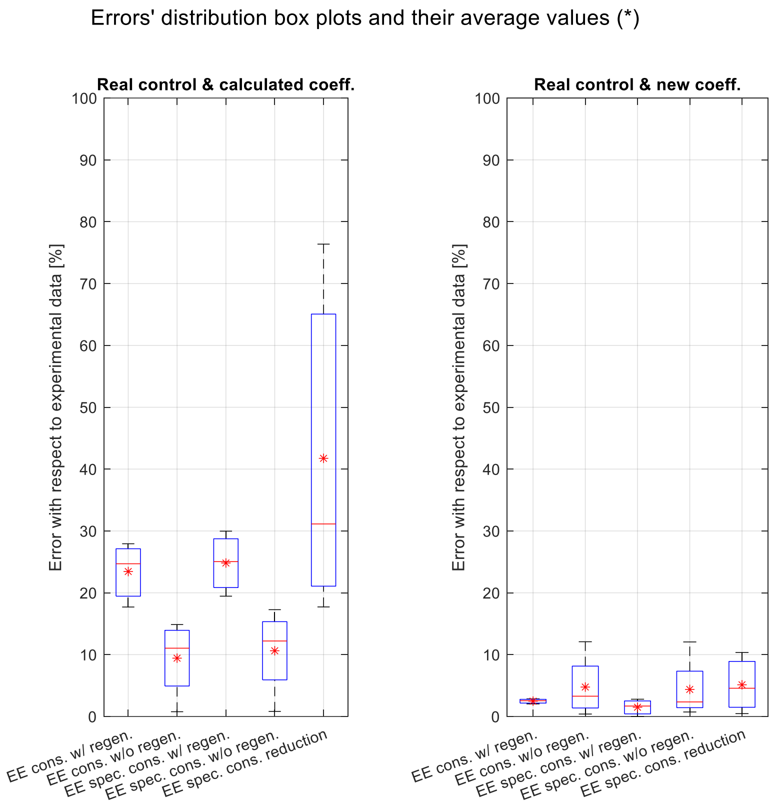


Figure 141. Distribution of consumption errors reported in box plots – C1,S0 vs. C1,S1

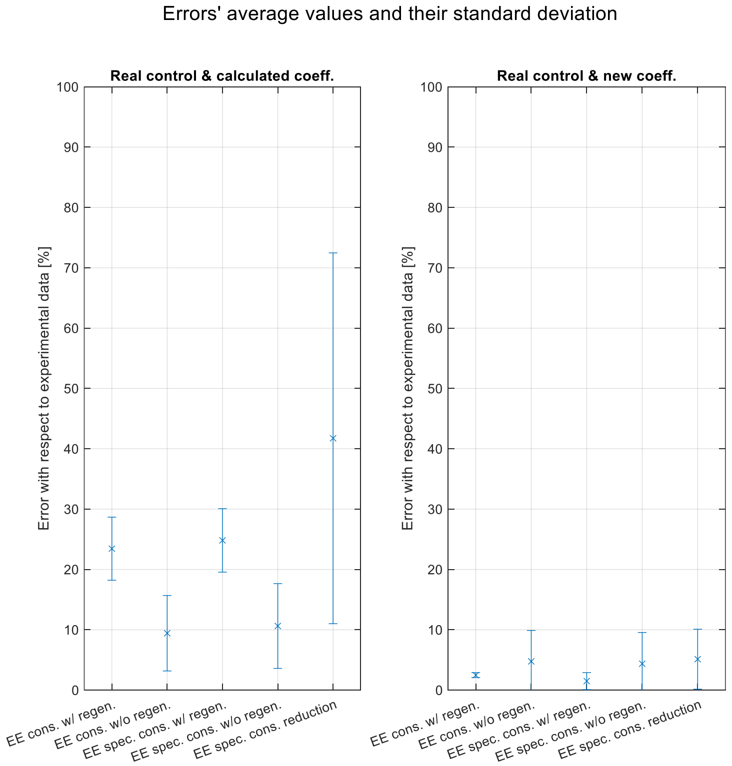


Figure 142. Average and corresponding standard deviation of consumption errors – C1,S0 vs. C1,S1

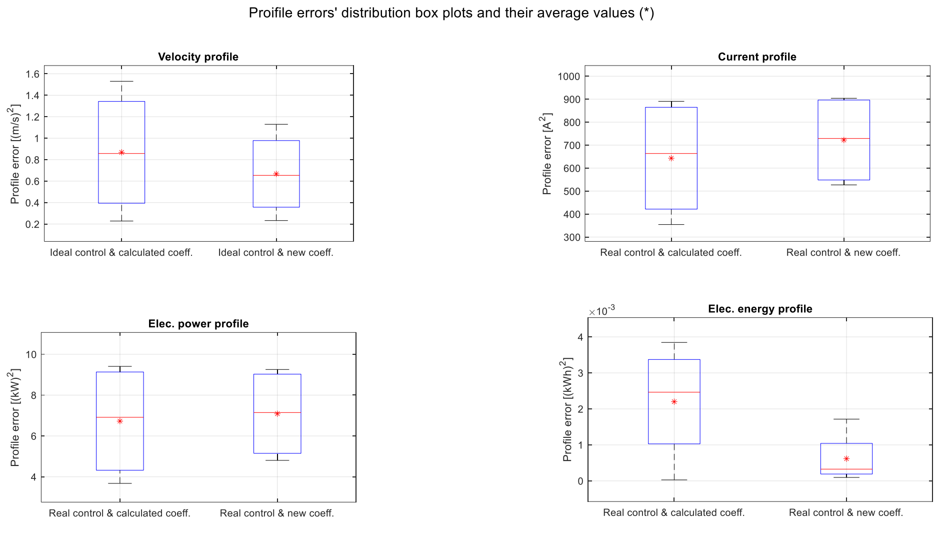


Figure 143. Distribution of profile errors reported in box plots – C1,S0 vs. C1,S1

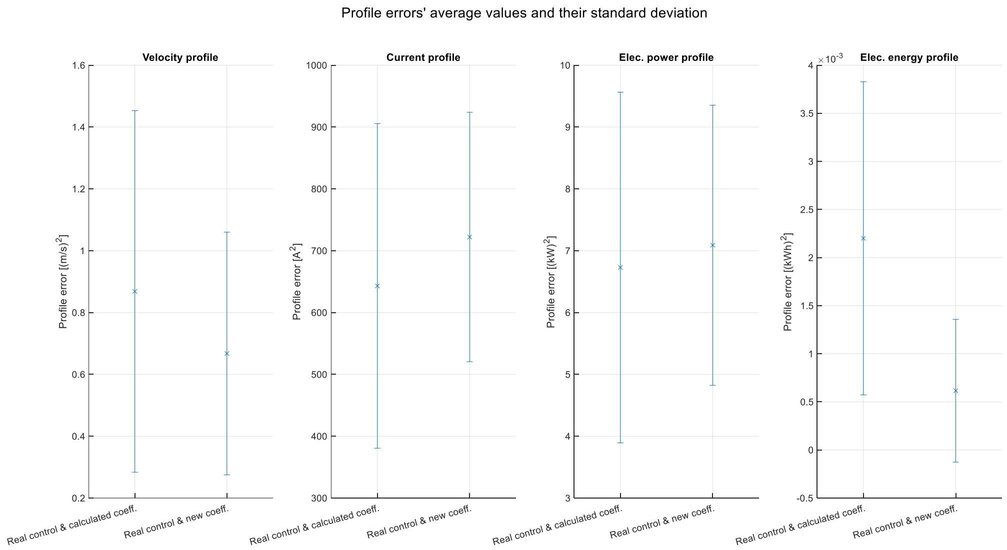


Figure 144. Average and corresponding standard deviation of profile errors – C1,S0 vs. C1,S1

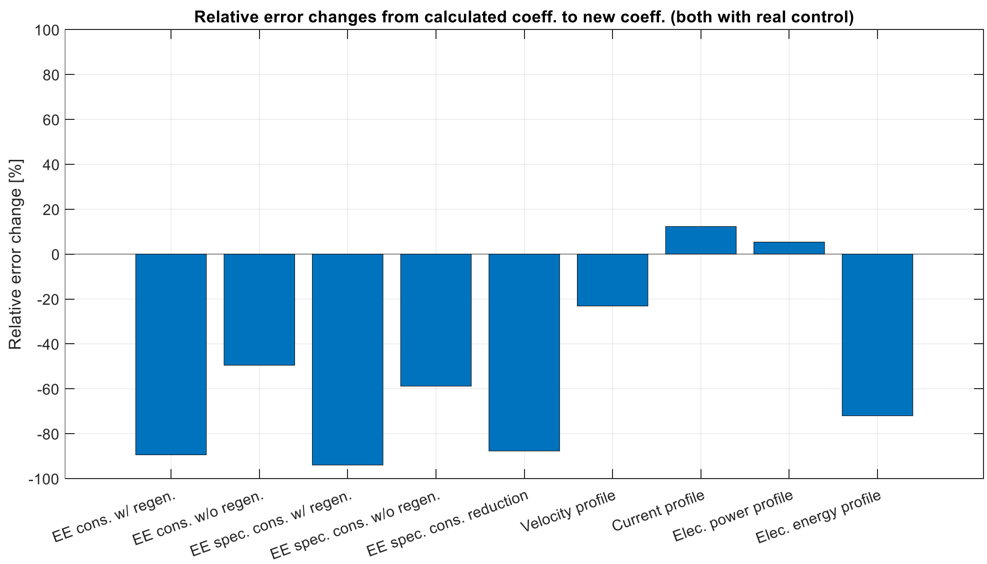


Figure 145. Relative error changes moving from calculated coast-down coeff. to the tuned ones with real control model

5.6.3 Observations

It can be seen that by using C1,S1 instead of C1,S0 generally:

- The errors regarding consumption values either with regeneration or without, decrease relatively to a great extent. However, it was observed that in T1 experiment where no regeneration was applied specific consumption error rather increased. On the other hand, in all other cases where there was regeneration this error decreased considerably. It should be also noted that although simulation results of T1 could be further improved by modeling the hydraulic brakes, the main purpose of this model validation is to provide a virtual prototype capable of simulating one-pedal strategies were regeneration is a fundamental aspect of the vehicle thus the error regarding the T1 (no regeneration) experiment is somehow irrelevant to the final purpose.
- Current profiles and electrical power profiles have slightly increased error which is observable in their profile error values but they were already improved with the real control model.
- Electrical energy profiles' error decreases considerably.
- Velocity profile's error decreases noticeably.

It can be understood that tuning the coast-down coefficients will greatly reduce the errors of consumption values and electrical energy profile however the dynamic behavior of current and electrical power profiles get modestly worsened while velocity profile improves.

5.7 Final comparison: C0S0 vs. C1S1

In the previous sections it has been seen that how improving the control model gives beneficial results regarding current profile, electrical power profile, electrical energy profiles and consumption without regeneration values while also deteriorating some results such as consumption values with regeneration or velocity profile. On the other hand, in the plant validation it was seen that consumption values were improved whereas current and electrical power profiles had increased error. Finally, it would be interesting to see how these improvements and deteriorations offset each other in the end when comparing the original model with ideal control C0 and calculated coast-down coefficients S0 and the new model with both real control C1 and tuned coast-down coefficients S1.

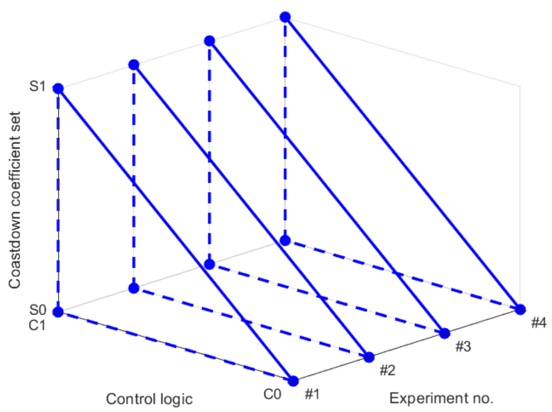


Figure 146. Comparison paths to be studied for the overall comparison represented by code names

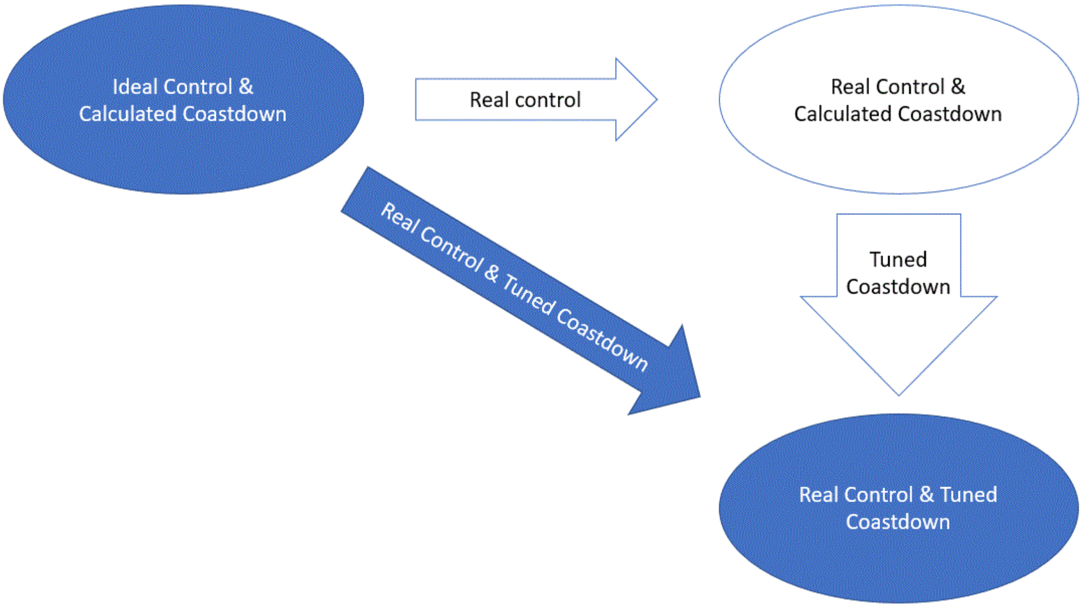


Figure 147. Final step

5.7.1 Error comparison

All the simulations have been already performed and their corresponding errors, average values and standard deviations have been also obtained. Here the errors of the two mentioned cases are compared.

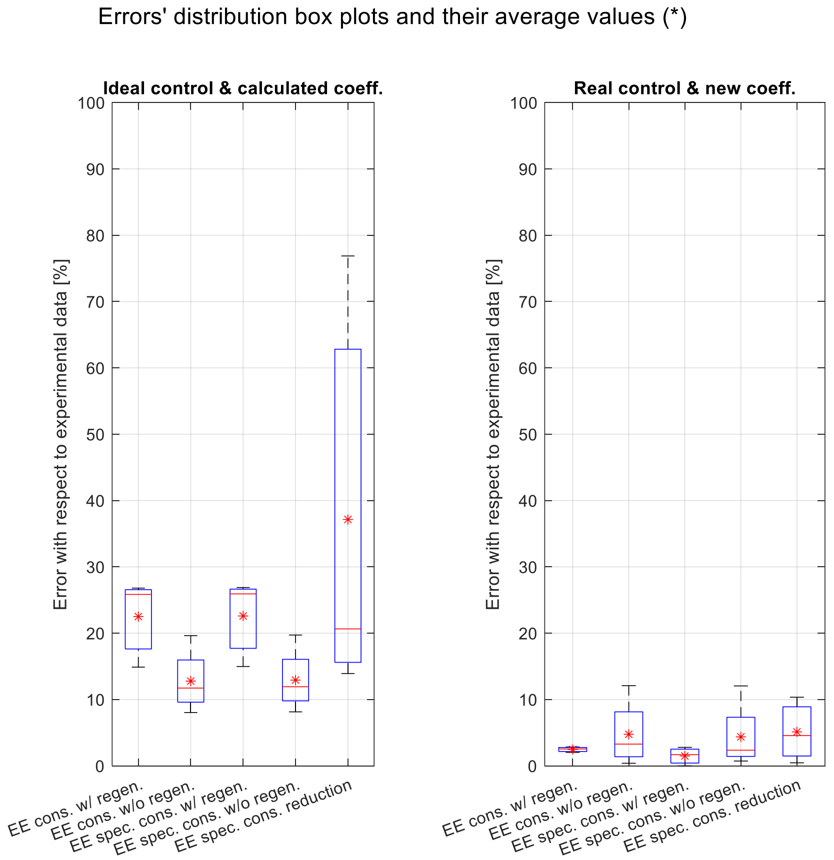


Figure 148. Distribution of consumption errors reported in box plots – C0,S0 vs. C1,S1

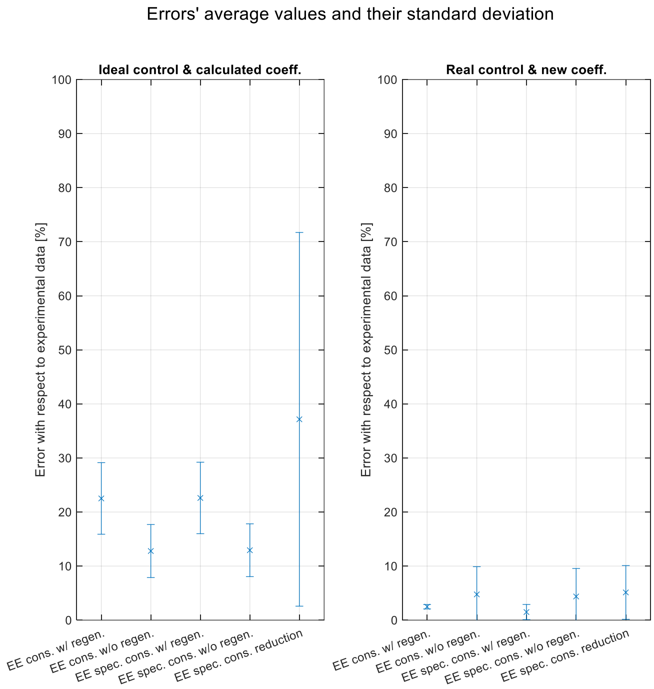


Figure 149. Average and corresponding standard deviation of consumption errors – C0,S0 vs. C1,S1

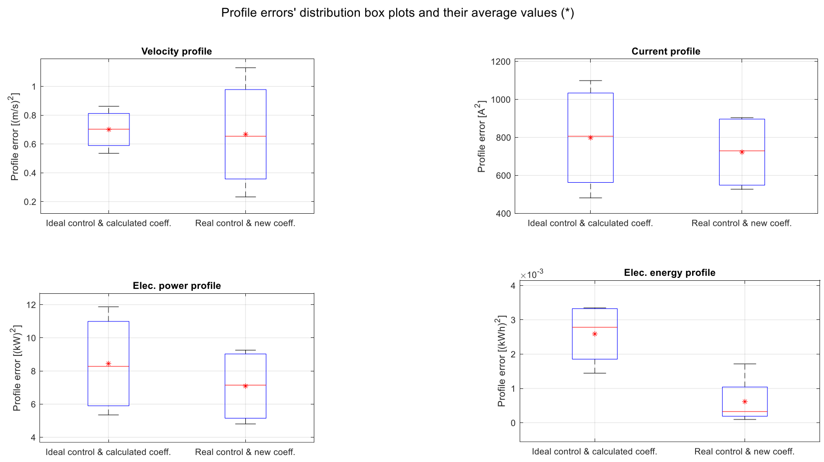


Figure 150. Distribution of profile errors reported in box plots – C0,S0 vs. C1,S1

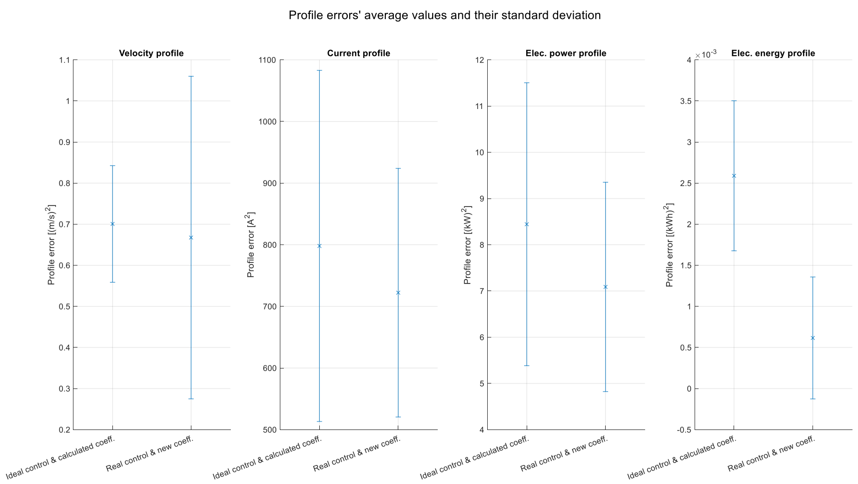


Figure 151. Average and corresponding standard deviation of profile errors – C0,S0 vs. C1,S1

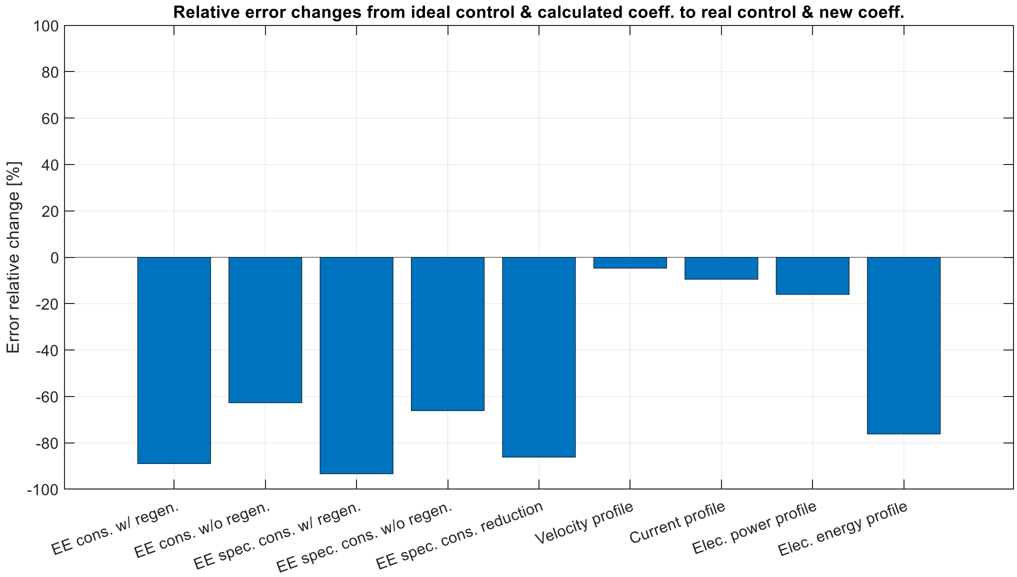


Figure 152. Overall relative error changes moving from original model to the new one with tuned coeff. and real control

5.7.2 Observations

It can be seen that overall implementing the real control model C1 and using tuned coast-down coefficients S1 will decrease the error in all the targets that were subject to study in this report. It should be highlighted that reduction in error for what regards the consumption with regeneration value which is the most important aspect of this developed model reaches even higher than 90% which is a great achievement.

5.8 Conclusions

In this chapter a complete analysis on the model validation has been performed. Specifically, two parts, the control logic and the plant (coast-down coefficients), were analyzed by considering ideal C0 vs. real C1 control and calculated S0 vs. tuned S1 coast-down coefficients.

It has been demonstrated that using the real control logic C1 mainly improves the behavior of the electrical aspects of the model: current profile, electrical power profile and electrical energy consumption profile. Whereas tuning the coast-down coefficients mainly decreases the consumption values.

At first it was seen that keeping the calculated coast-down coefficients S0 and only changing the control logic from ideal C0 to real C1, increased the error for some targets such as consumption with regeneration values or velocity profile. But on the other hand, the problem of hydraulic braking interference should be addressed as well. Hence it could be understood that implementing the real control gives yet better and improved results if unwanted interference from neglected sources do not occur in the experiments.

With real control C1 and tuned coast-down coefficients S1 average errors regarding consumption values resulted to be all lower than 6% whereas with ideal control C0 and calculated coefficients S0 average errors were in the range of 12 to 37%.

Overall, by implementing both the real control C1 and the tuned coast-down coefficients S1 in all the targets:

- Electrical energy consumption with regeneration final value
- Electrical energy consumption without regeneration final value
- Specific electrical energy consumption with regeneration final value
- Specific electrical energy consumption with regeneration final value
- Specific electrical energy consumption reduction final value
- Velocity profile
- Current profile
- Electrical power profile
- Electrical energy consumption profile

the error with respect to experimental data T1, T2, T3 and T4 decrease compared to the original model where ideal control C0 and calculated coast down coefficients S0 were used.

6 Chapter VI. Consumption evaluation of standard cycles

6.1 Introduction

In the previous chapter a thorough analysis on model validation was performed and it was shown that consumption values, specifically with regeneration ones, were simulated with high accuracy. In this chapter this virtual prototype that has been already validated is employed to perform simulations and evaluate the electrical energy consumption in some of the standard driving cycles. The model contains C1 control (real on/off regenerative braking with brake pedal activation strategy) and S1 parameters (tuned coast-down coefficients). It should be added that as it was studied in chapter three 40% regenerative braking is chosen here.

6.2 Driving cycles and simulation targets

The following six driving cycles will be evaluated:

- NEDC urban (up to 780 seconds)
- NEDC extra urban (from 780 to 1180 seconds)
- NEDC Full
- WLTP class 3 low - medium (up to 1000 seconds)
- WLTP class 3 high - extra high (from 1000 to 1800 seconds)
- WLTP Class 3 Full

For each cycle four values are retrieved from simulations:

- Electrical energy consumption with regeneration [kWh]
- Electrical energy consumption without regeneration [kWh]
- Electrical energy specific consumption with regeneration [Wh/km]
- Electrical energy specific consumption without regeneration [Wh/km]
- Electrical energy specific consumption reduction with regeneration [%]

6.3 Results

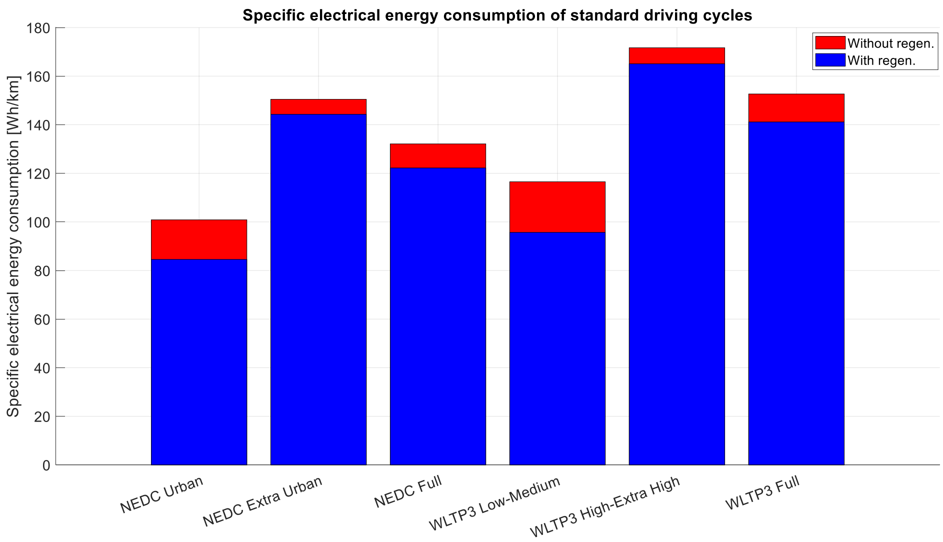


Figure 153. Specific electrical energy consumption of standard driving cycle

6.4 Conclusions

Driving Cycles	EE cons. w/ regen. [kWh]	EE cons. w/o regen. [kWh]	EE spec. cons. w/ regen. [Wh/km]	EE spec. cons. w/o regen. [Wh/km]	EE spec. cons. Reduction [%]
NEDC Urban	0.344193967	0.410469454	84.56884774	100.8528102	-16.14626543
NEDC Extra Urban	0.999784513	1.042310738	144.313923	150.4523721	-4.0799949
NEDC Full	1.343658216	1.452459601	122.2117214	132.1076937	-7.490837237
WLTP3 Low Medium	0.753231945	0.917221015	95.69496718	116.5290924	-17.87890458
WLTP3 High Extra High	2.46495624	2.563657216	165.0700048	171.6796843	-3.850006761
WLTP3 Full	3.216573495	3.478858653	141.1445883	152.6537705	-7.539402532

Table 4. Consumption evaluation of standard cycles with C1,S1 model with 40% regenerative braking

Regarding the NEDC cycle, it could be seen that specific consumption of the urban cycle is lower than the extra urban part. In addition to that, specific consumption reduction due to the regeneration in urban cycle is 4 times more than that of the extra urban. The same observations are also valid WLTP class 3.

7 Chapter VII. One-pedal driving strategies

7.1 Introduction

In the previous chapters detailed analyses were performed on the basic on/off regenerative braking and consequently the simplest one-pedal driving strategy C2. Additionally, a validated model was developed that allows performing further simulations on the vehicle under study. Finally, it is now time to perform a general analysis on different possible one-pedal driving strategies and compare them for what regards their ability to follow a specific driving cycle, electrical energy consumption and regeneration capabilities. Additionally, the issue of comfort from driver's point of view regarding the acceleration/deceleration phases and foot activity on the pedals e.g. number of pedal shifts will be addressed too.

The more sophisticated one-pedal strategies will be compared with the simplest one i.e. the basic on/off regenerative braking with acceleration pedal strategy to see whether they result in any beneficial change or not.

The simulations are performed for different standard driving cycles.

7.1.1 Standard driving cycles

The following six standard driving cycles are to be evaluated:

- NEDC urban (up to 780 seconds)
- NEDC extra urban (from 780 to 1180 seconds)
- NEDC Full
- WLTP class 3 low - medium (up to 1000 seconds)
- WLTP class 3 high - extra high (from 1000 to 1800 seconds)
- WLTP Class 3 Full

7.2 Strategies

Different strategies are first introduced and after a preliminary analysis four of them are chosen for deeper investigation. These strategies are chosen such that they could follow the desired reference cycles without the need to use hydraulic braking.

7.2.1 Basic on/off regenerative braking with brake pedal: C1,S1

C1,S1 model was previously introduced and validated with the corresponding experimental data. It was seen that the consumption errors of this model for different targets were less than 6% with respect to the available real-world test results. Thus, its simulation results could be considered trustworthy enough to be used as a comparison reference for the other strategies.

As studied before, the regeneration level for C1,S1 in these simulations is chosen as 40% with respect to the maximum regenerative torque of the motor. Furthermore the same parameters introduced earlier such as accelerator pedal mapping, filter's time constant and minimum motor rpm for regenerative functioning are maintained.

In C1 accelerator pedal mapping does not contain any negative output since regenerative braking is activated only when brake pedal is slightly pushed.

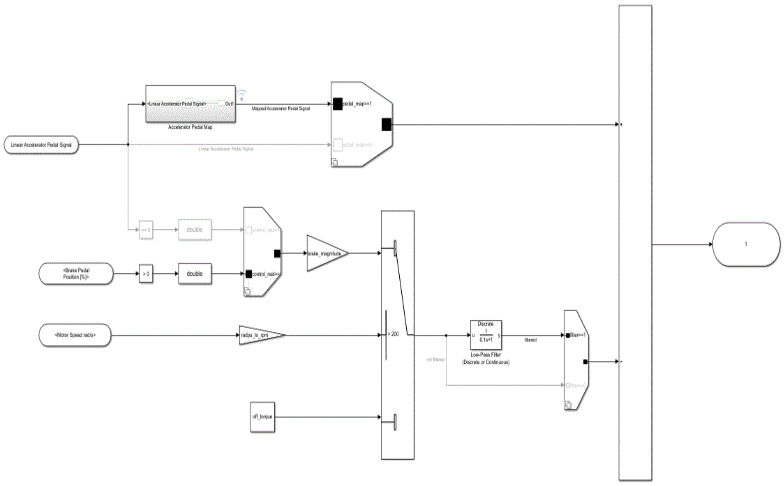


Figure 154. Simulink implementation of C1

C1 consists a simple accelerator pedal mapping with 5 break points which could be chosen manually and the connection between these points is linear. In accordance to the previously performed experimental tests and studies carried out in the previous chapter, here the points are chosen as the following:

- First 5% gives zero output
- Last 5% gives 100% output
- 80% output at 50% input

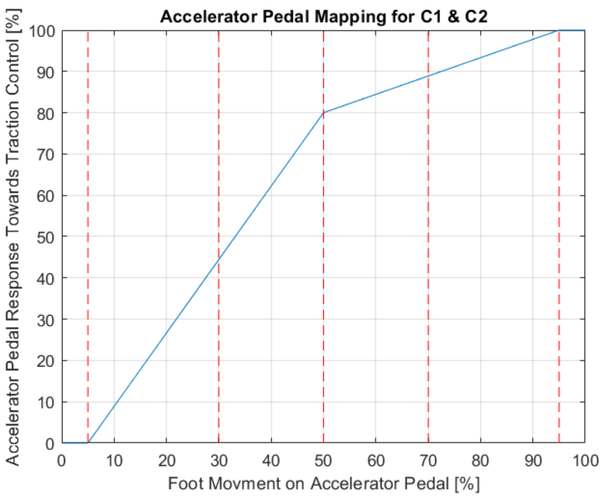


Figure 155. Accelerator pedal mapping for C1 and C2

7.2.2 Simplest one pedal strategy: C2, S1

The simplest one pedal strategy could be considered as a slight modification to C1 such that braking is performed not when the driver pushes the brake pedal but simply when he takes his foot off the pedal. In previous chapters it was shown that for what regards energy consumption C1 and C2 give the same results.

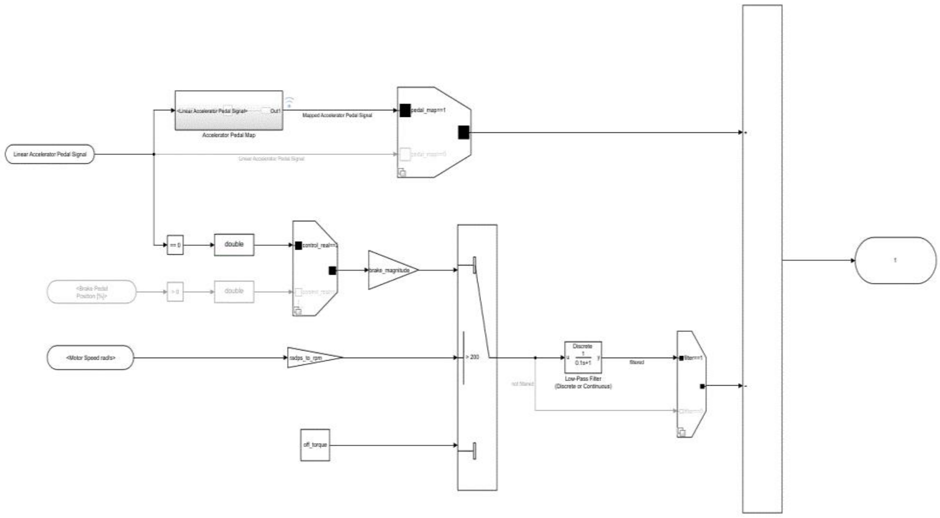


Figure 156. Simulink implementation of C2

The parameters in C2 are the same as C1. Also, the accelerator pedal mapping is considered the same. The only difference as mentioned is how on/off regenerative braking gets activated.

7.2.3 REDS strategy: C3.3, S1

This strategy is a solution previously studied by the academic tutor of this thesis, Professor Stefano Carabelli. However, in order to adapt it to the vehicle under study some modifications were applied with respect to the original design. In REDS strategy accelerator pedal mapping consists the following phases:

- Regenerative braking
- Coasting
- Proportional acceleration

Hence unlike C1 or C2, the driver is able to perform regenerative braking while still keeping his foot on the accelerator pedal. The magnitude of regenerative braking changes depending on the velocity of the vehicle according to a deterioration profile.

Accelerator pedal mapping contains different phases as the following:

- First 5% zero output
- 5% to 15% regenerative braking
- 15% to 25% zero output to enable coasting
- 25% to 90% linearly increasing output from 0% to 100%
- last 10% gives 100% output

In order to regulate the magnitude of regenerative braking at high vehicle speeds a derating relation is implemented. This deterioration reduces the magnitude of the maximum regenerative torque, being the second break point in the accelerator pedal map, linearly from 100% at 5 kmph down to zero at 80 kmph. Thus, in velocities higher than 80 kmph to avoid dangerous braking maneuvers there is no more regenerative region in the accelerator pedal map.

However the abovementioned regeneration functioning is true only for when working solely with REDS one-pedal strategy and relying to the regenerative braking that is available in the regeneration range (5% to 15% of the accelerator pedal input); but it should be noted that the application of basic on/off regenerative braking (C1 or C2) to perform supplementary regenerative braking could be still available as it will be shown later in more complicated strategies C3.1 and C3.2 where both REDS strategy and on/off regenerative braking are used. This is the reason that code name C3.3 is used for this strategy since C3.1 refers to the mixture of REDS and C1 while C3.2 refers to mixture of REDS and C2.

An important aspect of this kind pedal mapping is how moving between different phases is handled. For example, if the pedal mapping described remains constant and the vehicle is about to move forward from a stopped position, the driver should first pass through the regeneration and coasting phase to reach the traction region. This means that the vehicle could first move backwards while passing through the regeneration phase which is completely unacceptable. To overcome this phase handling problem when the vehicle starts moving it needs to reach at least 5 kmph in order to activate the regenerative braking. So, a sort of hysteresis functioning is put inside the controller for defining switching on and switching off points.

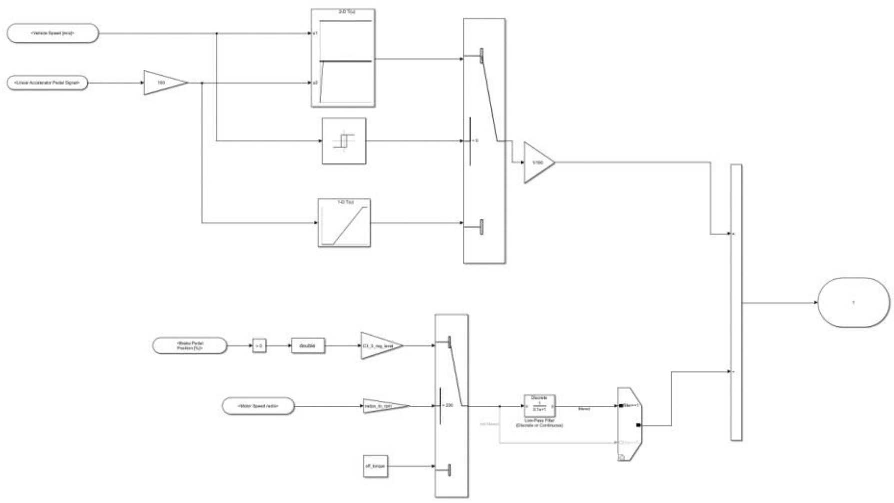


Figure 157. Simulink implementation of C3.3

7.2.4 Hydraulic brakes for C3.3

An important point about this strategy is that after some trial and error it was understood that without further regenerative braking outside the accelerator pedal map it cannot follow correctly the desired driving cycles as it will lack providing enough braking torque where high deceleration values are needed and this problem caused inconsistent results with those of other strategies as the velocity profile differed considerably. Hence in order to have comparable results it was needed to consider also the application of additional brakes such as hydraulic braking or optionally some constant regenerative braking upon touching the brake pedal (similar to C1) so that it is able to follow the reference cycles completely. Otherwise the distance covered would vary with other strategies and useless results could be achieved.

For what regards hydraulic braking a simple linear relation between brake pedal position and the maximum available hydraulic braking force is implemented in Simulink. This maximum hydraulic braking force depends on the maximum deceleration that it can provide to stop the vehicle. Considering the vehicle under study which is a retrofitted old Fiat Panda, as mentioned in [10] 0.8g is considered for this vehicle.

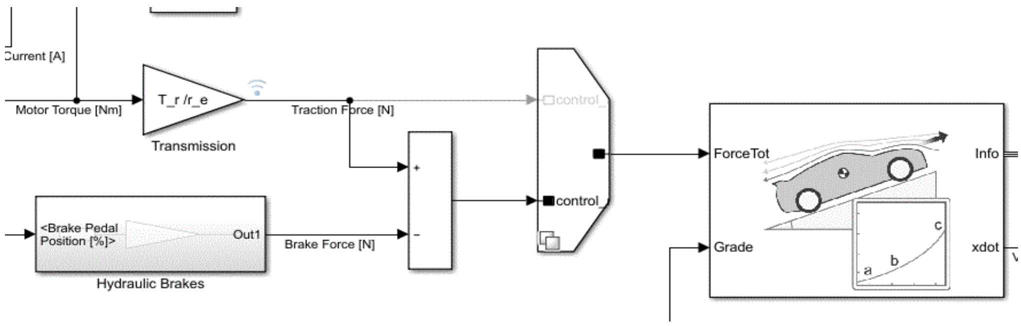


Figure 158. Implementation of hydraulic braking in the Simulink model

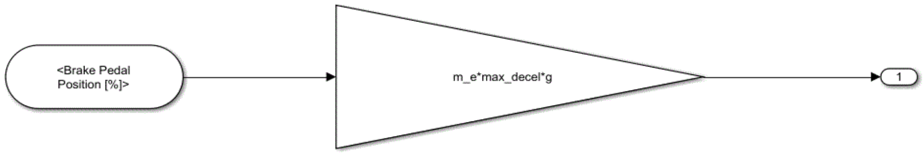


Figure 159. Linear relation between brake pedal position and maximum hydraulic braking force for the considered maximum deceleration value

Also, the possibility to have simultaneously some modest levels of regenerative braking is provided in the model. However, in this case it is null because the purpose is to observe mainly how REDS works besides hydraulic braking not constant regenerations. The latter will be mainly focused in the following strategies C3.1 and C3.2.

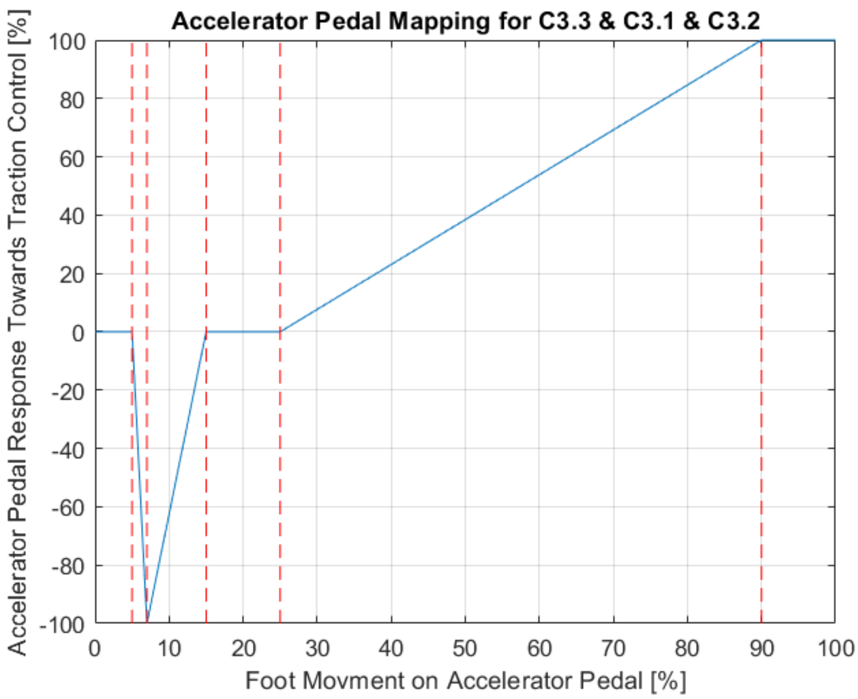


Figure 160. REDS accelerator pedal mapping used in C3.3, C3.1 and C3.2

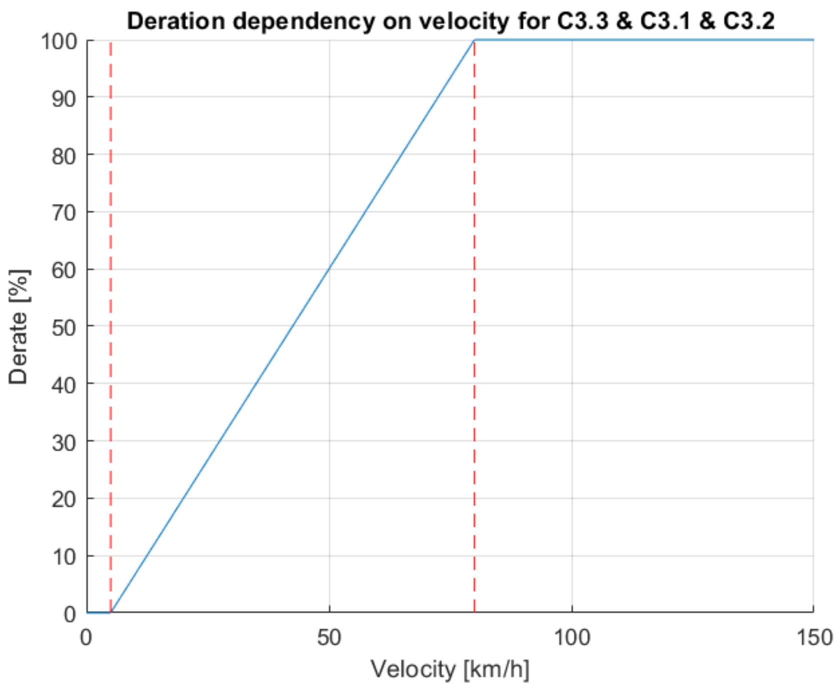


Figure 161. Degradation of maximum regenerative braking in REDS strategy

7.2.5 REDS and C1 together: C3.1, S1

It might happen that at certain points of the driving cycle REDS strategy could not be able to follow the desired driving cycle as the amount of regenerative braking provided through the accelerator pedal mapping may not be enough for the required deceleration. Hence at these points the driver could use supplementary regenerative braking provided by the basic on/off regenerative braking which gets activated through the brake pedal. However, this strategy should be analyzed if it is beneficial for what regards the energy consumption or comfort issues.

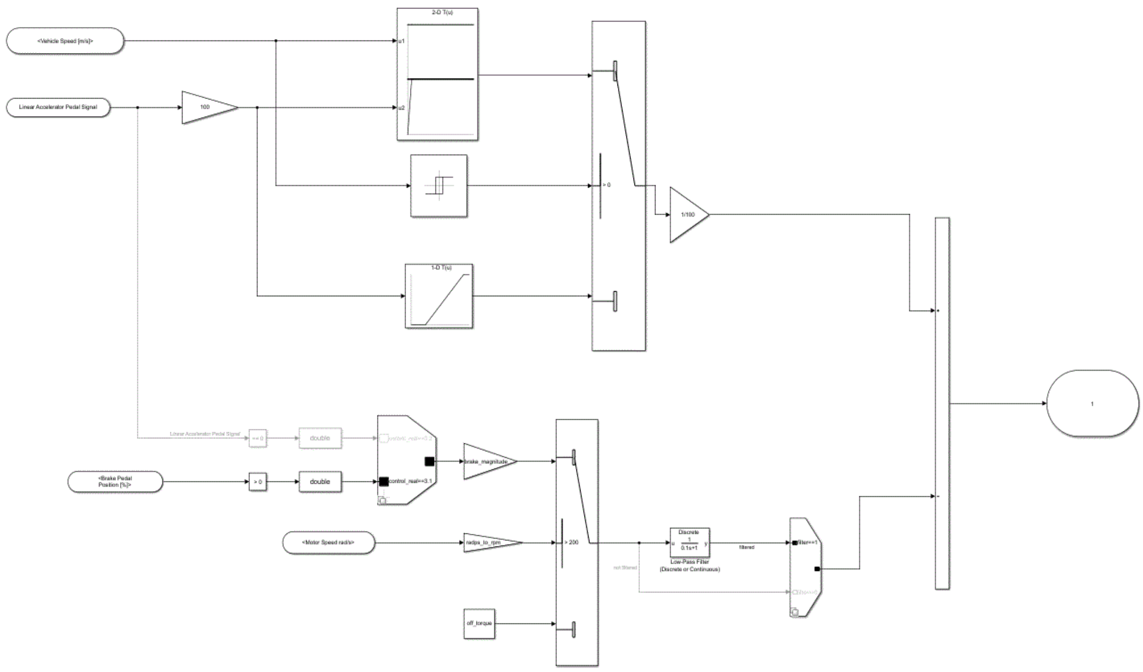


Figure 162. Simulink implementation of C3.1

7.2.6 REDS and C2 together: C3.2, S1

Similar to the previous one (C3.1), in order to improve the large deceleration requirements C2 strategy could be exploited as well besides REDS. An interesting point about this condition is the fact that even the supplementary on/off braking is provided only through one pedal's signal being the accelerator pedal. Hence this solution may be considered as the most complete one-pedal strategy compared to the previous ones.

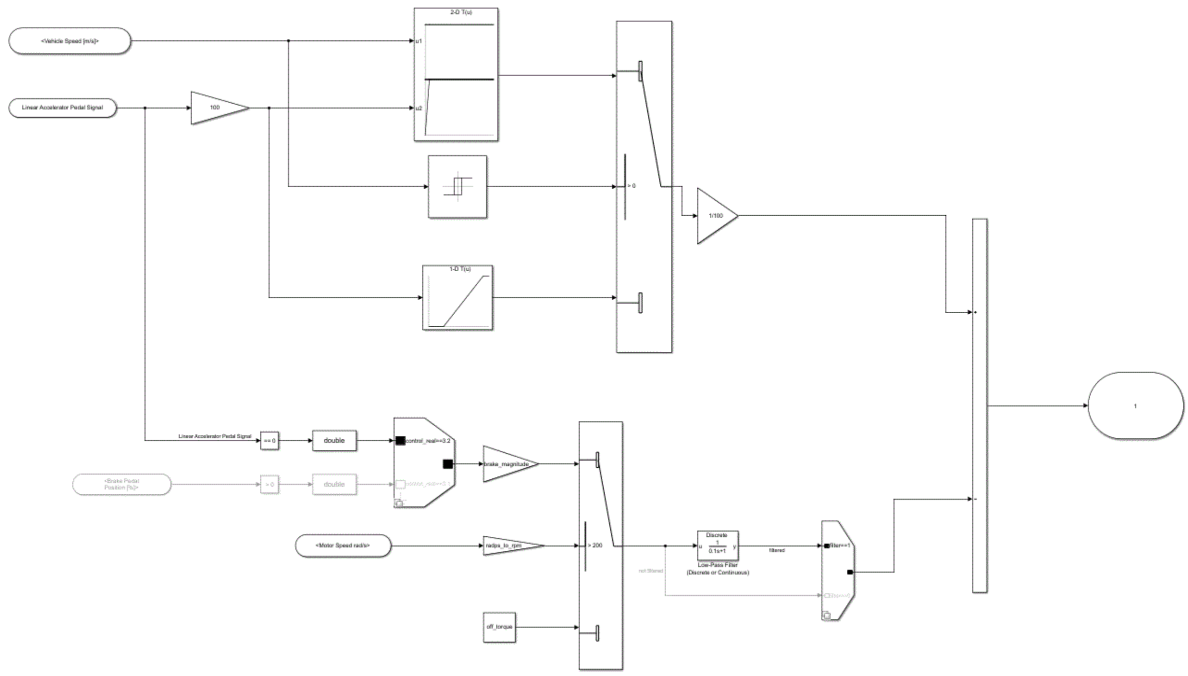


Figure 163. Simulink implementation of C3.2

7.2.7 OPD: C4

This is an interesting strategy that has been developed and studied in [11] and it was also previously employed in a project carried out in another master thesis in Politecnico di Torino [12]. In this strategy unlike the previous ones the regions of regenerative braking, coasting and traction inside the accelerator pedal map change continuously depending on the velocity of the vehicle. Furthermore, the magnitude of the regenerative braking is maximum in middle range while it decreases for low and high speeds.

In this strategy as the velocity increases regeneration and coasting regions expand. In this way at higher velocities coasting becomes more highlighted in order to minimize energy consumption. The three regeneration, coasting and traction regions are defined by the following relations:

$$P_{cu} = \emptyset \left(\frac{V}{V_{max}}\right)^{\frac{1}{m}}$$

$$P_{cl} = \emptyset \left(\frac{V}{V_{max}}\right)^{\frac{1}{m}} - C_h \left(\frac{V}{V_{max}}\right)$$

Where P_{cu} and P_{cl} define the upper and lower accelerator pedal positions respectively for the coasting range; V_{max} is the maximum velocity of the vehicle and Φ defines the pedal position at top velocity where coasting region finishes, and traction becomes available; C_h is the widest coasting range that occurs at top speed. In this way for the complete velocity range of the vehicle P_{cu} and P_{cl} positions define two border lines that specify the three phases of regeneration, coasting and traction. These border lines could be shaped by the parameter m.

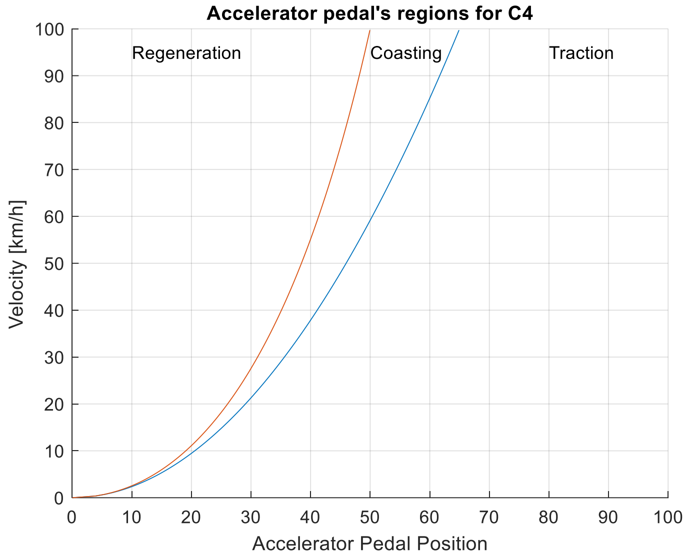


Figure 164. Variation of regeneration, coasting and traction regions over the velocity range of the vehicle with C4 strategy

Originally in [11] different expressions for specifying the magnitude of traction or regenerative torque is specified but here for the sake of simplicity linear interpolation of pedal position between the extremes of each region is performed as the following:

- If pedal position is smaller than P_{cl} i.e. being in the regeneration zone then the magnitude of regenerative braking with respect to the maximum regenerative braking available at the corresponding velocity of the vehicle equals to $\frac{P_{cl}-P}{P_{cl}}$
- If pedal position is higher than P_{cu} i.e. being in the traction zone then magnitude of the tractive torque with respect to the maximum torque of the electric motor equals to $\frac{P-P_{cu}}{P_{\max trq}-P_{cu}}$ where $P_{\max trq}$ is the pedal position where maximum traction torque is asked from the motor which as it was seen in various sections it is chosen as 95%.

Although an additional step of sensitivity analysis and optimization of the parameters for the vehicle under study is required but for now based on some trial and errors and also reviewing the situation in [12], a preliminary estimation of the parameters is performed as the following:

Φ	65[%]
m	2
C_h	15[%]
V_{max}	100 kmph
$P_{max\ trq}$	95[%]

Table 5. Parameter values for C4 strategy

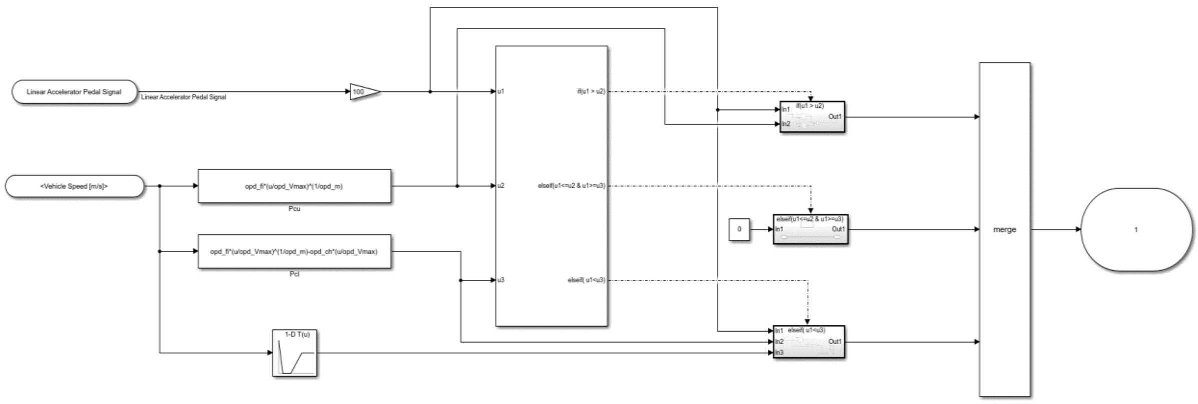


Figure 165. Simulink implementation of C4

The maximum regenerative braking could be modified depending on the velocity in order to reduce regenerative torque applied at low or high velocities. This issue is important for a smooth driving at low velocities, transitions between different pedal map regions specially at low velocities and also avoiding dangerous highly decelerating braking at high velocities. As it can be seen in the following figure, regenerative braking is fully available in the mid velocity range. It reduces when velocity drops below 20 kmph until it becomes zero when coming to full stop. On the other hand, at velocities higher than 60 kmph it reduces until it reaches half of the maximum regenerative braking of the motor at 100 kmph where afterwards it remains fixed there.

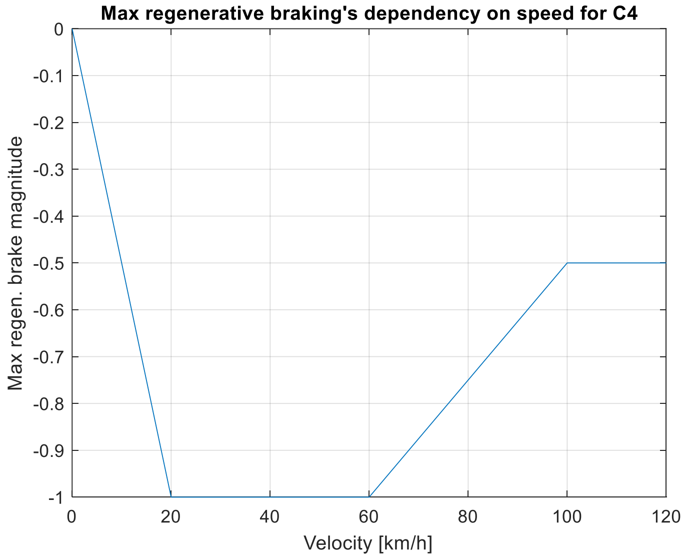


Figure 166. Maximum regenerative braking's dependency on vehicle velocity for C4 strategy

7.2.8 New strategy development: C5

After studying the positive and negative points of other strategies, a new solution has been developed in order to adopt the advantages of other models into a new one that matches the characteristics of the vehicle under study. In this new strategy inspired by OPD (C4) design, a progressive increment of regeneration and coasting ranges occurs by increasing the speed. Magnitude of maximum regenerative braking changes as well depending on the velocity of the vehicle. However, more attention is put to the imperfection of accelerator pedal's functionality.

One problem that accelerator pedal has is the fact that it might not be working precisely around its limits being 0 and 100%. Hence in this strategy the first few percentages of acceleration pedal position have constant output to eliminate the need of precise functioning. Similarly, the last 5% are chosen to have the same maximum output.

As mentioned previously for C4, also here an intermediate step is needed to find the optimum parameter values and to perform analyses on sensitivity of such parameters however for the sake of comparison widest coasting range happening at the highest velocity of the vehicle and velocity dependency of maximum regenerative braking are chosen the same as those set for C4 which will be more explained in the following.

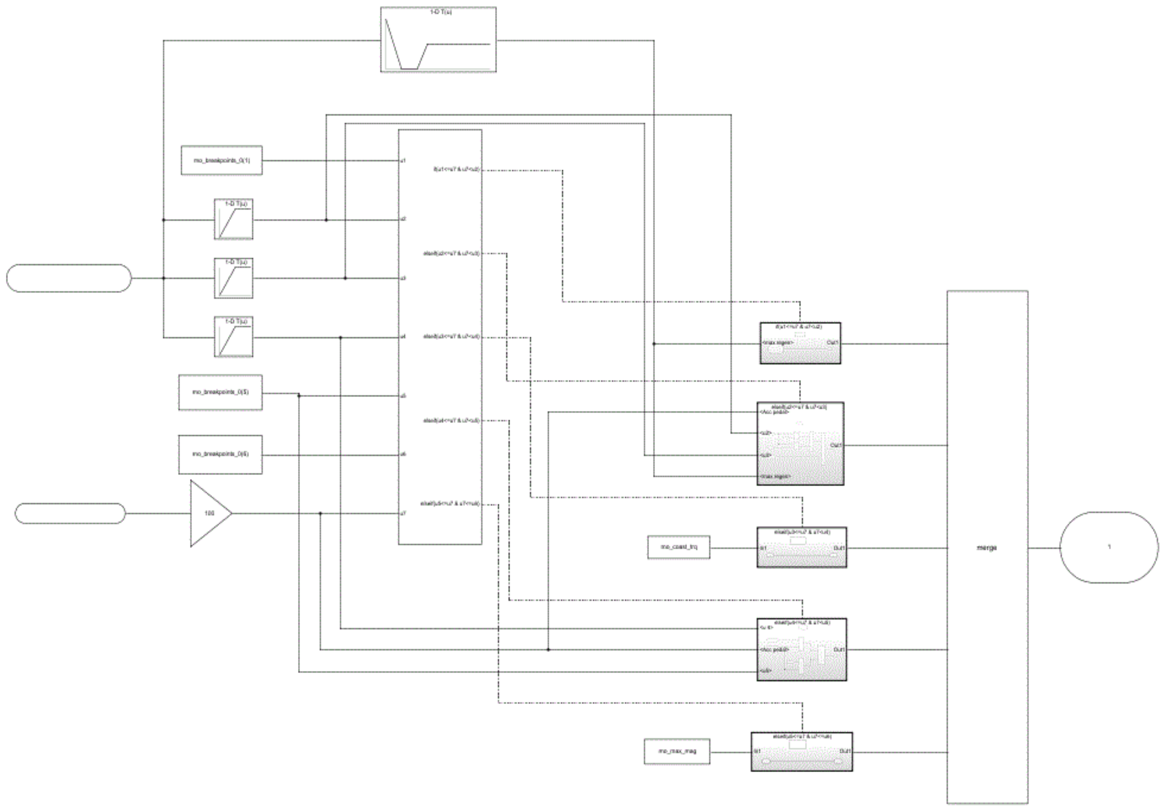


Figure 167. Simulink implementation of C5

7.2.8.1 Horizontal changes of input breakpoints

Looking at the accelerator pedal map's figure which depicts how the map changes depending on the velocity of the vehicle it can be seen that pedal positions' breakpoints start to fall apart as the velocity increases from 0 up to 100 kmph (or any other value depending on the choice) and they keep the same position for higher velocities. At 0 kmph point 1 and point 2 collapse on each other; similarly point 3 and point 4 collapse on each other too. This results a pedal mapping that provides only traction when moving off the vehicle. As the speed increases point 2 gets further from point 1 and they provide a region where constant maximum regenerative torque available depending on the velocity is given. At the same time also point 3 and point 4 move to the right. Although at the beginning point 3 and point 4 are collapsed on each other, as the speed increases point 4 moves faster than point 3 towards right. Thus, a progressive coasting region is created between them where the output torque is null. The distance between point 2 and point 3 specifies a linear regenerative braking region. Similarly, the distance between point 4 and point 5 gives a linear traction phase. Finally, from point 5 and point 6 constant maximum traction is provided.

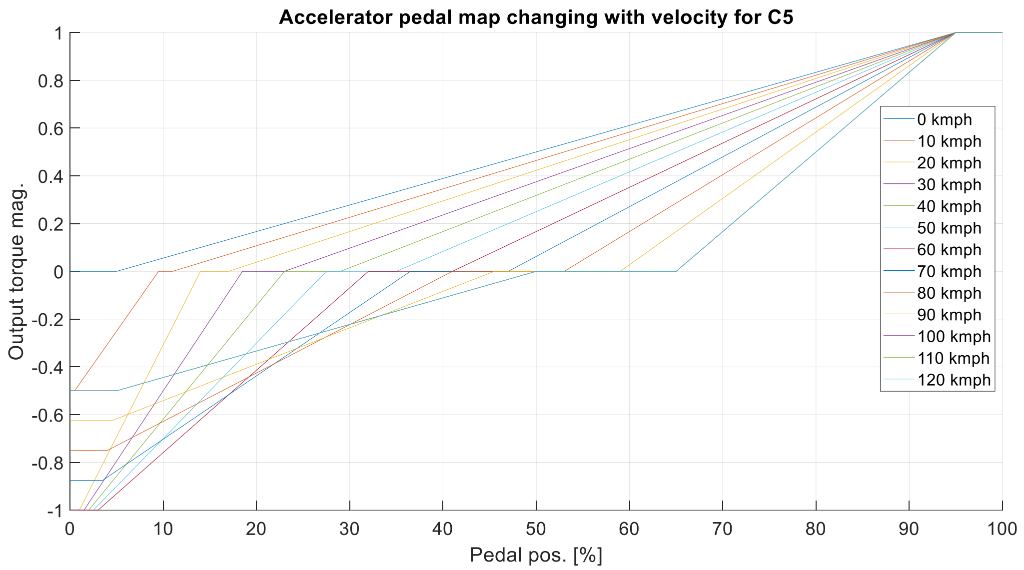


Figure 168. Accelerator pedal map changing with velocity in C5

7.2.8.2 Vertical changes of breakpoints' output

Similar to the relation used in OPD (C4), the maximum regenerative braking's magnitude is reduced at low and high velocities for the already mentioned reasons. What mainly changes vertically in the accelerator pedal map is the maximum regenerative braking's magnitude. Hence the output of the first and the second points change according to the speed dependency profile shown below. It can be seen that the maximum regenerative braking grows linearly from zero at 0kmph to maximum (-1) at 20 kmph and then it remains constant until 60kmph where it starts reducing linearly down to half (-0.5) at 100kmph and remains constant thereafter.

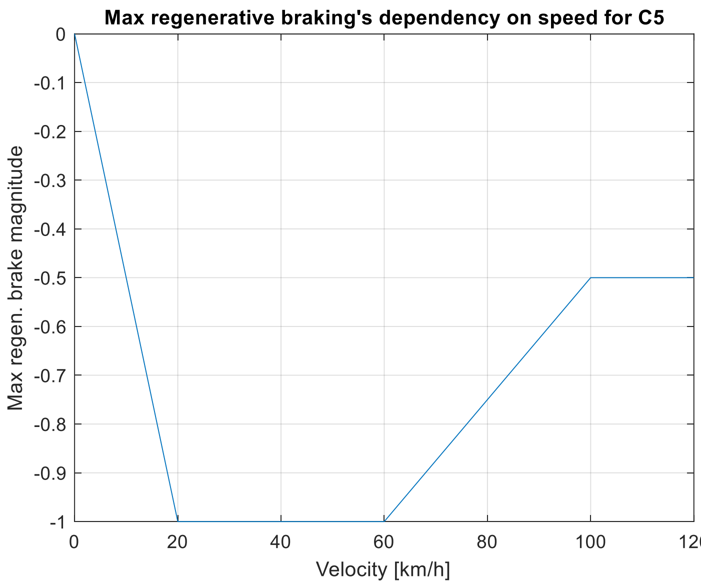


Figure 169. Maximum regenerative braking's dependency on vehicle velocity for C4 strategy

7.3 Preliminary analyses

In order to avoid elongation of the study and pass through unnecessary analyses, in this section a short summary of what was already seen during trial and errors is provided to point out why some strategies will not be reported anymore in the final comparisons.

7.3.1 C3.3: Weak energy recuperation

The main problem with C3.3 is that it relies only on the regeneration provided inside the accelerator pedal map and it needs to use in addition hydraulic braking to follow the reference cycle. As observable in the following figure it lacks in electrical energy recuperation compared to the other strategies such as C1, C2, C3.1 or C3.2. Thus, it is neglected in the future comparisons.

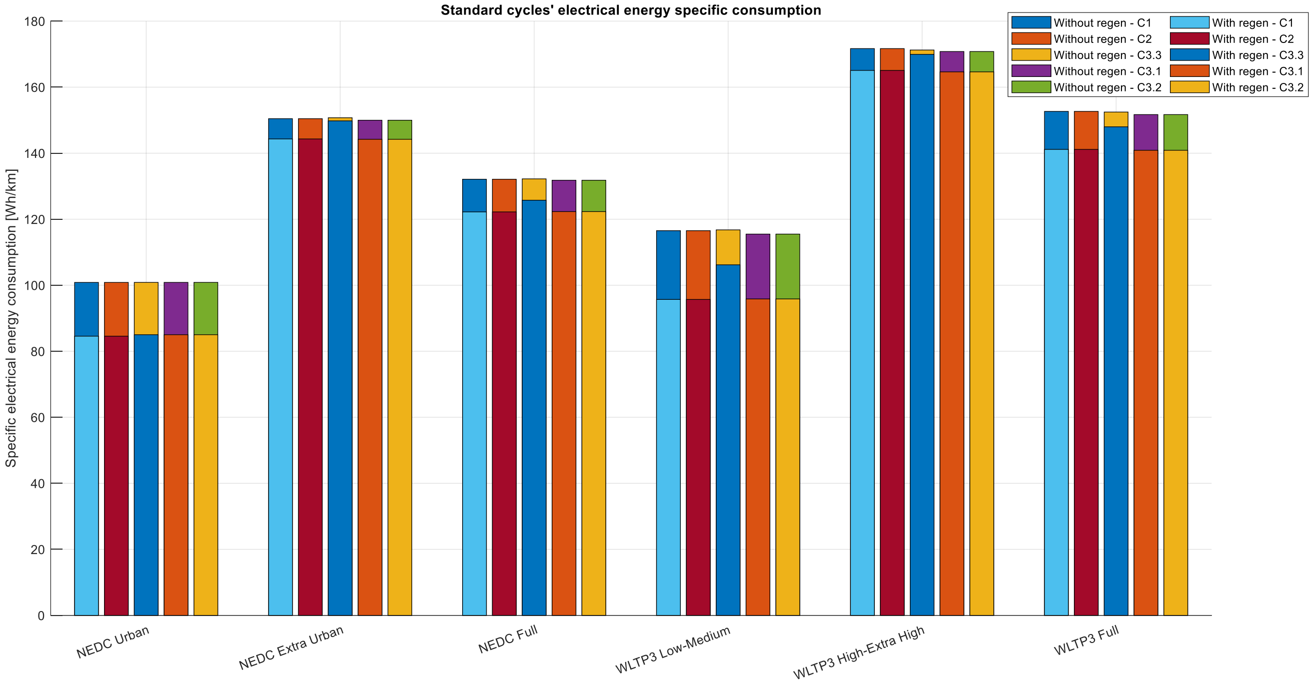


Figure 170. Specific energy consumption of C1, C2, C3.3, C3.1 and C3.2

7.3.2 Similar control logics

Some of the mentioned strategies have basically the same logic and may differ in only minor details. Hence, in order to avoid redundant simulations where basically the same results could be obtained a preliminary analysis is done to check if the outcomes of the aforementioned strategies are the same or not.

7.3.2.1 C1,S1 vs C2,S1

In chapter three it was shown that these two strategies resulted the same consumption values and velocity profile errors. This is justifiable as they employ basically the same control logic and differ only in how they get activated. This conclusion is again addressed here by pointing out key outcomes of their corresponding simulations carried out for NEDC and WLTP Class 3 cycle. An important information to notice is the pedal activity for each strategy. It can be seen that both have the same occurrence histograms for accelerator pedal positions and more importantly the same number of pedal shifts.

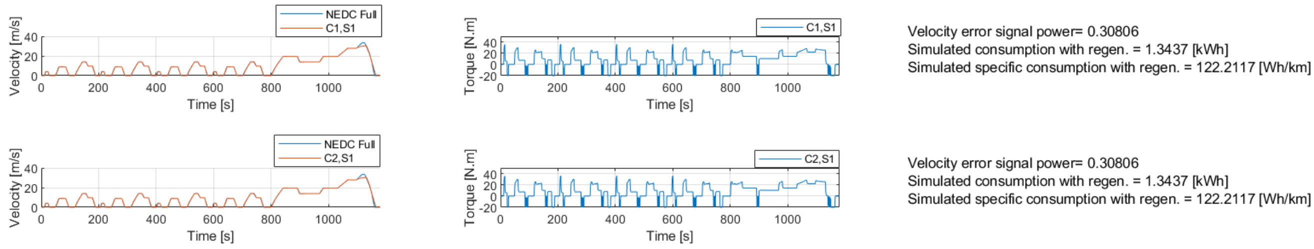


Figure 171. NEDC cycle - performance results

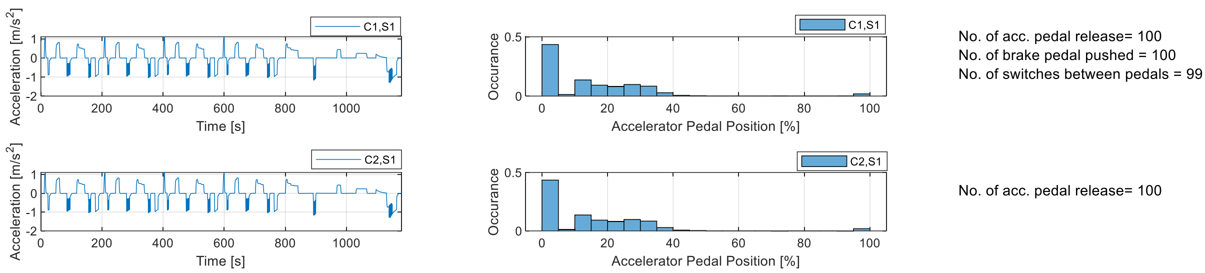


Figure 172. NEDC cycle - Comfort results

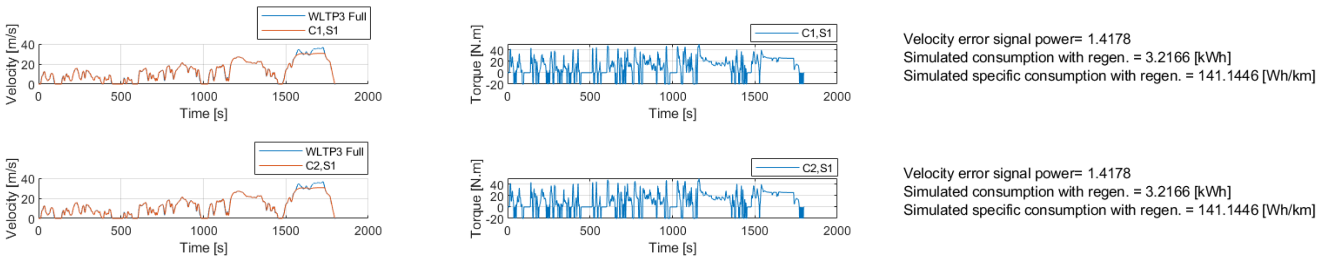


Figure 173. WLTP Class 3 cycle - performance results

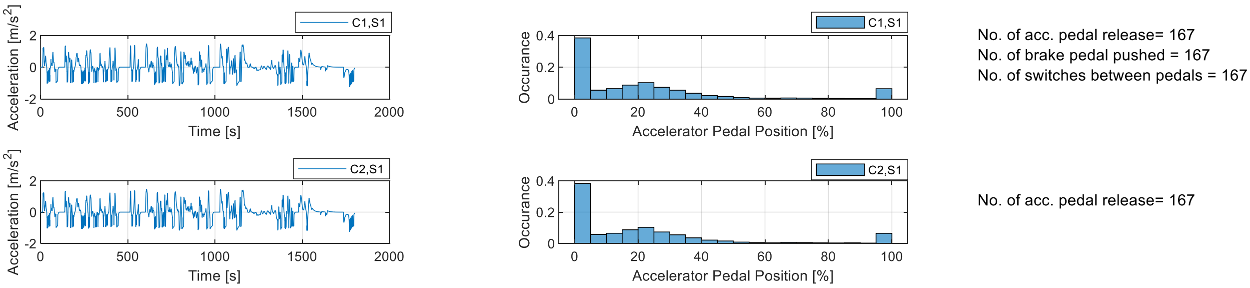


Figure 174. WLTP Class 3 cycle - Comfort results

As depicted all the results happen to be the same. Hence from now on only C2 will be used for comparison alongside other strategies as it is the true one-pedal strategy compared to C1 and in this way less redundant results will be shown in the future.

7.3.2.2 C3.1,S1 vs C3.2,S1

Similar to what has been just said about C1 and C2 also in this case C3.1 and C3.2 employ the same logic but only differing in how constant regenerative braking activates. Again, it is expected to have similar results.

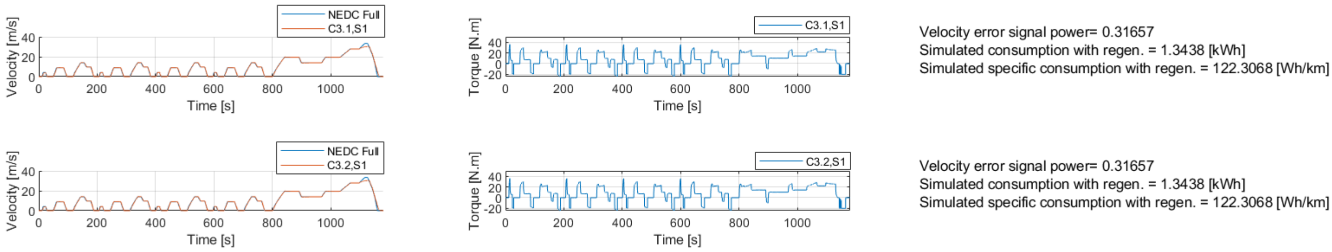


Figure 175. NEDC cycle - performance results

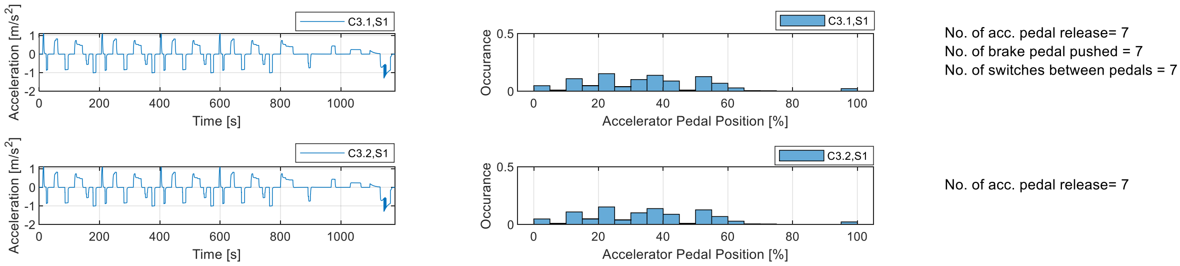


Figure 176. NEDC cycle - comfort results

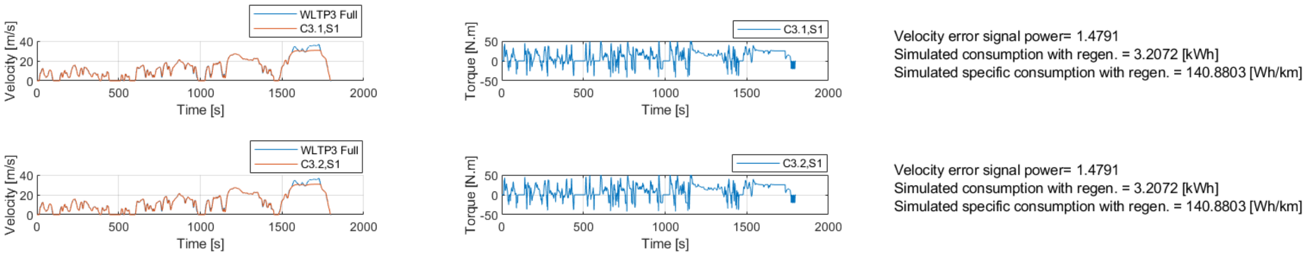


Figure 177. WLTP Class 3 cycle - performance results

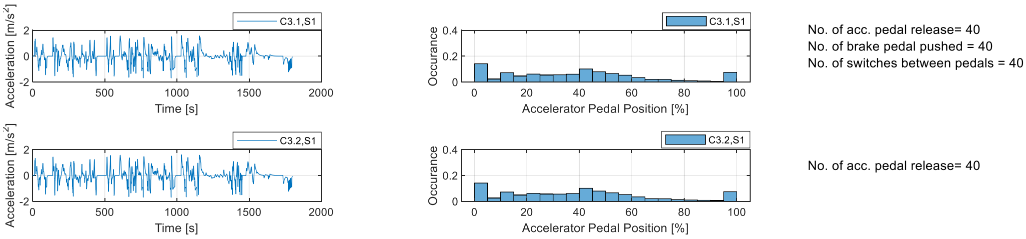


Figure 178. WLTP Class 3 cycle - comfort results

As expected, all the results are the same for C3.1 and C3.2. Thus, from now on in order to reduce redundancy only C3.2 will be used in further comparisons as it is the true one pedal strategy compared to C3.1.

7.4 Simulations results: C2,S1 - C3.2,S1 - C4,S1 - C5,S1

After eliminating redundant or insufficient solutions, the four one-pedal driving strategies: C2, C3.2, C4 and C5 are chosen to be further investigated for what regards consumption and comfort issues. Simulations are repeated for all the reference cycles with aforementioned control strategies implemented.

7.4.1 Consumptions

Looking at the consumption values in different cycles and with different control strategies it can be seen that for all the cases consumptions are almost the same with only negligible differences.

It could be seen that one-pedal strategies that exploit progressive regeneration and coasting regions with velocity, being C4 and C5, have very small improvements with respect to C2 and C3.2 which use fixed regions. However, these are extremely small differences that from engineering point of view could be neglected considering also possible simulation errors.

It should be remembered that as said before C1 and C2 have the same consumption values in all the cases. Similarly, C3.1 and C3.2 have the same consumption values too. Hence only C2 and C3.2 are represented here.

Driving Cycles	Control Strategy	EE cons. w/ regen. [kWh]	EE cons. w/o regen. [kWh]	EE spec. cons. w/ regen. [Wh/km]	EE spec. cons. w/o regen. [Wh/km]	EE spec. cons. Reduction [%]
NEDC Urban	C2	0.344194006	0.410469454	84.56885739	100.8528102	-16.14625586
	C3.2	0.345138679	0.40946414	85.01477356	100.859461	-15.70966895
	C4	0.335918752	0.398945211	82.73310064	98.25582549	-15.79827433
	C5	0.338319175	0.402252625	83.28446472	99.02304401	-15.89385526
NEDC Extra Urban	C2	0.999784513	1.042310738	144.313923	150.4523721	-4.0799949
	C3.2	0.997976509	1.037923804	144.2106291	149.9831342	-3.848769504
	C4	0.992014931	1.030521056	144.2031637	149.8005643	-3.73656845
	C5	0.991687979	1.030128706	144.1507365	149.7384407	-3.731643136
NEDC Full	C2	1.343658289	1.452459601	122.211728	132.1076937	-7.490832229
	C3.2	1.343777134	1.448051048	122.3068047	131.7975223	-7.200983285
	C4	1.328342808	1.429876074	121.3546909	130.6305631	-7.1008438
	C5	1.33030287	1.432677585	121.5311618	130.8837072	-7.145691109
WLTP3 Low Medium	C2	0.753231945	0.917221015	95.69496718	116.5290924	-17.87890458
	C3.2	0.754390287	0.909003812	95.84861864	115.4929501	-17.0091174
	C4	0.748123716	0.903677407	95.36288651	115.1912233	-17.21340935
	C5	0.749493581	0.906891174	95.52626014	115.587277	-17.35573099
WLTP3 High Extra High	C2	2.46495624	2.563657216	165.0700048	171.6796843	-3.85000676
	C3.2	2.454337145	2.546236487	164.6330289	170.7974905	-3.609222579
	C4	2.439762311	2.533308443	163.960288	170.2469048	-3.69264673
	C5	2.440282203	2.534218415	163.9656283	170.2773205	-3.706713349
WLTP3 Full	C2	3.216573495	3.478858653	141.1445883	152.6537705	-7.539402533
	C3.2	3.207184718	3.45332848	140.8803088	151.6925357	-7.127725129
	C4	3.188222081	3.437391057	140.2611181	151.222939	-7.24878176
	C5	3.190071787	3.441472814	140.3259108	151.3846206	-7.305041784

Table 6. Consumptions values of one-pedal driving strategies

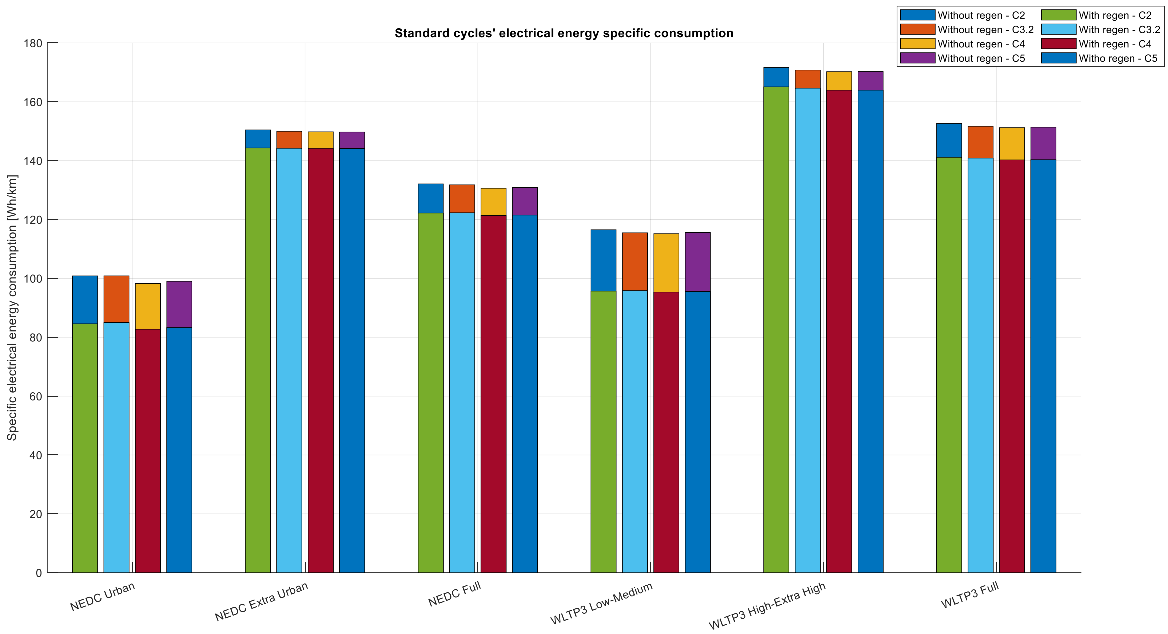


Figure 179. Specific electrical energy consumption of standard driving cycles with different one-pedal driving strategies

7.4.2 Velocity profile errors

Looking at the velocity profile errors it can be understood that apart from NEDC Urban cycle, in all other cycles C4 and C5 show improved performance in following the reference profiles as they depict less error. Comparing C4 and C5 it can be seen that they have close error values.

Driving Cycles	Control Strategy	Velocity profile error [(m/s)^2]
NEDC Urban	C2	0.084282001
	C3.2	0.088210001
	C4	0.164983669
	C5	0.140028404
NEDC Extra Urban	C2	0.738383808
	C3.2	0.777353737
	C4	0.512158457
	C5	0.510502594
NEDC Full	C2	0.308058905
	C3.2	0.316566255
	C4	0.279656891
	C5	0.263204351
WLTP3 Low Medium	C2	0.286650655
	C3.2	0.326246685
	C4	0.171947906
	C5	0.172066396
WLTP3 High Extra High	C2	2.811248804
	C3.2	2.896843726
	C4	2.781177218
	C5	2.786839678
WLTP3 Full	C2	1.417785693
	C3.2	1.47910191
	C4	1.329907913
	C5	1.332523143

Table 7. Velocity profile errors of different one-pedal driving strategies following standard driving cycles

7.4.3 Cycle by cycle analysis

7.4.3.1 NEDC Urban

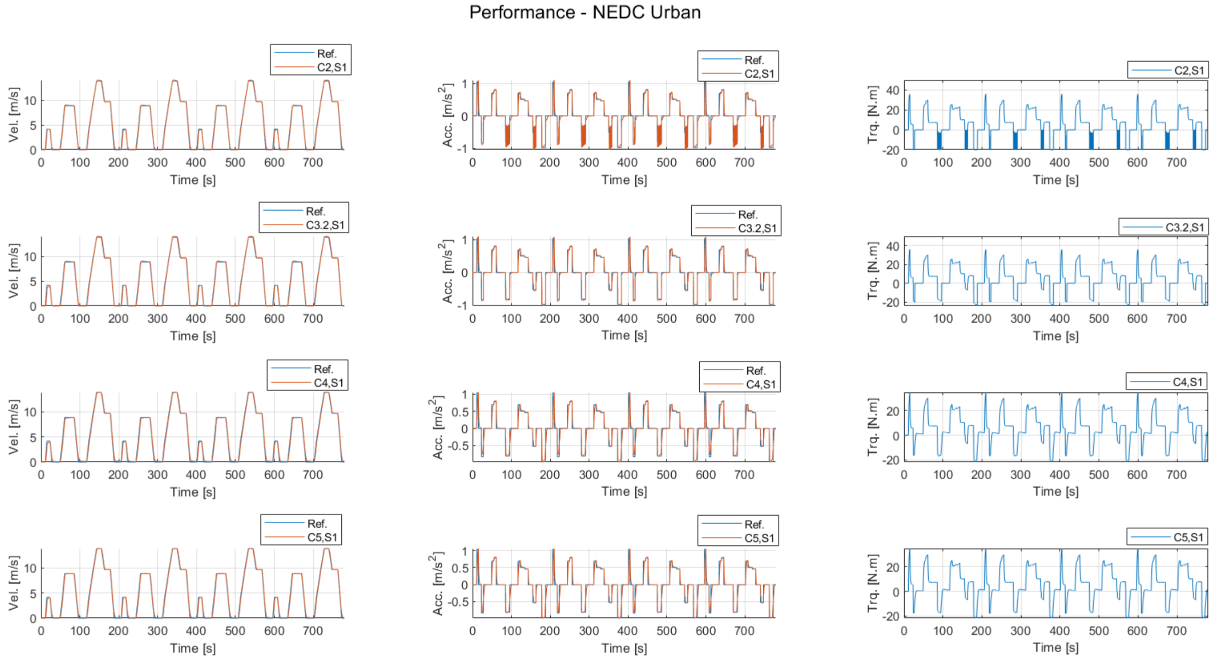


Figure 180. Performance results - NEDC Urban

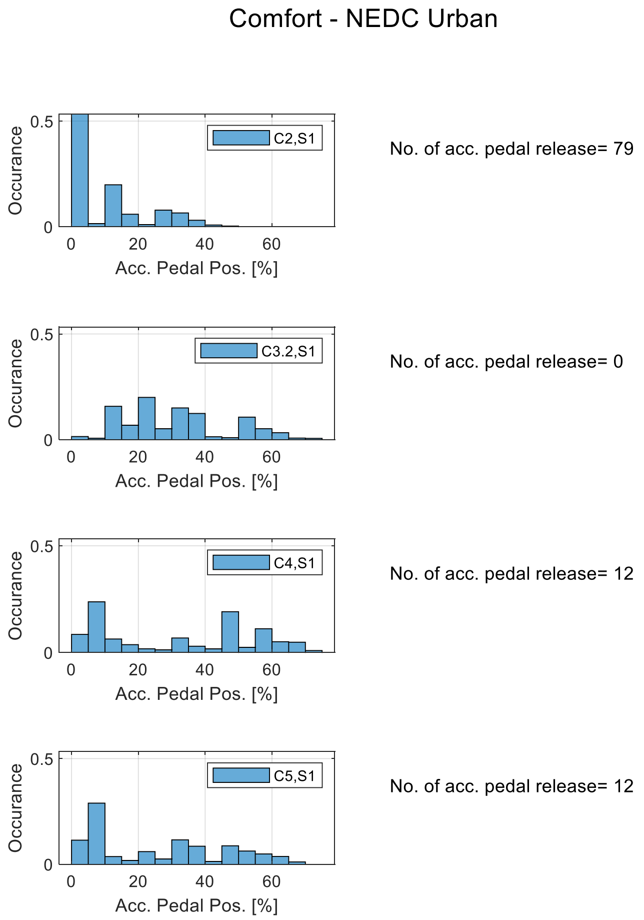


Figure 181. Comfort results regarding foot activity - NEDC Urban

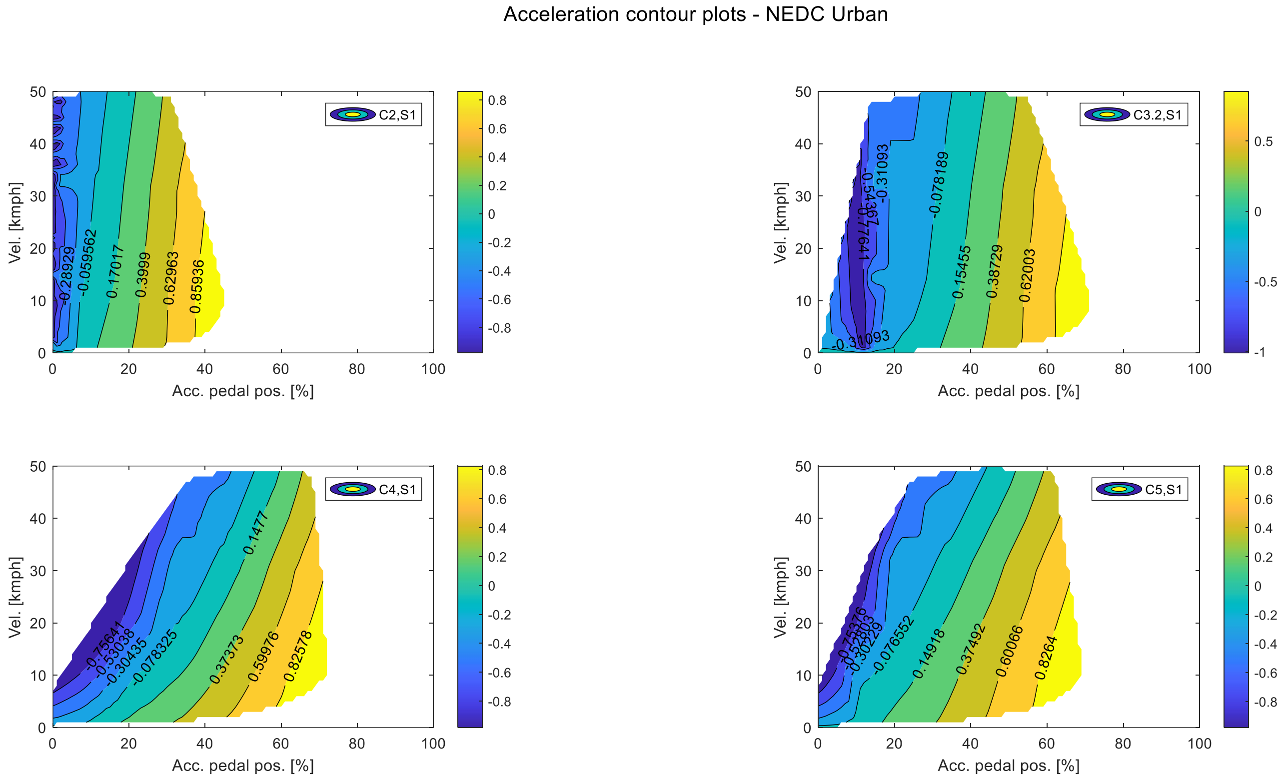


Figure 182. Acceleration contour plots - NEDC Urban cycle

In NEDC Urban cycle all the control strategies are able to follow the cycle precisely but C2 and C3.2 have lower profile errors. Specific consumptions are also close however C4 and C5 result in negligibly lower values compared to C2 and C3.2.

Looking at the comfort related results, the importance of one-pedal strategies becomes highlighted. Interestingly it is seen that driver is able to follow the cycle without releasing the accelerator pedal even once with C3.2 while for C2 driver releases the accelerator pedal 79 times. Regarding C4 and C5, they as well result in interestingly low number of accelerator pedal releases being only 12 times.

Furthermore looking at the acceleration and motor torque plots it can be noticed that in C2 due to the repetitive on/off braking at fixed levels, oscillating decelerations are experienced while for the others thanks to the continuous operation of regenerative braking, stable and continuous decelerations are experienced which give a more comfortable ride.

Analyzing the acceleration contour plots gives useful information on how different regions of regeneration, coasting and traction evolve at different velocities. Looking closely at the C2 plot it can be understood that the decelerations are concentrated in one side of the graph where accelerator pedal position goes towards 0. Furthermore, it can be seen that highest deceleration values occur similarly for all the velocity range. Even at highest velocities the same large amount of deceleration being about -0.75 m/s^2 occurs. C3.2 shows an improvement compared to C2 as it includes a wider space in the graph that gives the possibility to have less concentration of regeneration in only a small region of the graph. It can be seen that deceleration values increase in the middle speed range and then they reduce for higher velocities. Although the regeneration range is more widespread compared to C2, but it still occupies only the first few percentages of acceleration pedal positions. C4 and C5 depict similar behaviors. They spread more widely and contain a large area dedicated to deceleration and regeneration which gives the possibility of a more flexible way of driving. Additionally, maximum deceleration values are reduced noticeably compared to the previous strategies.

7.4.3.2 NEDC Extra Urban

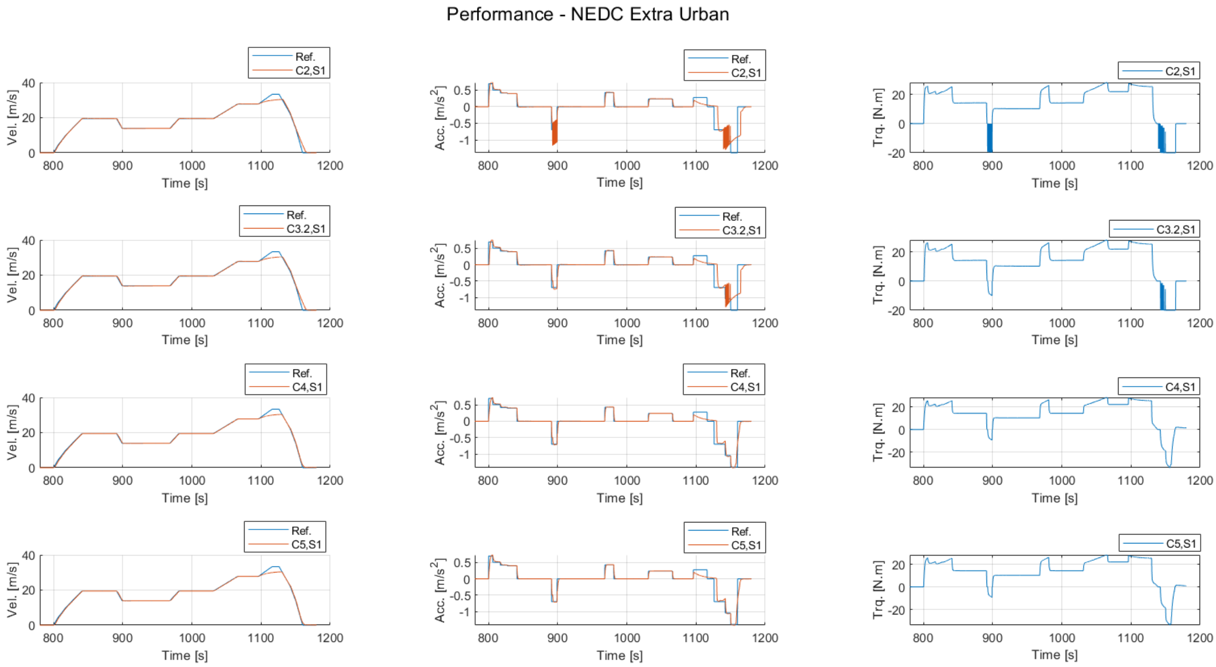


Figure 183. Performance results – NEDC Extra Urban

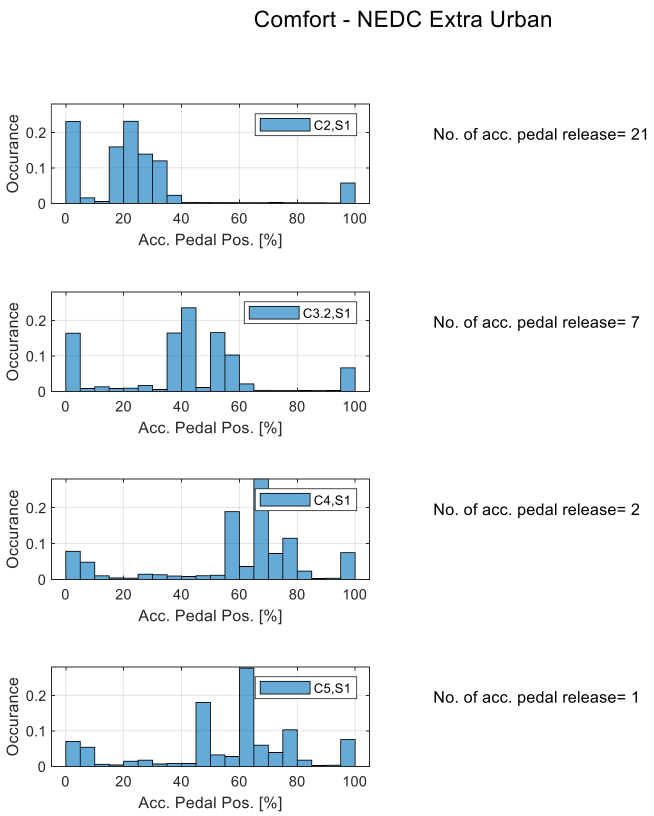


Figure 184. Comfort results regarding foot activity – NEDC Extra Urban

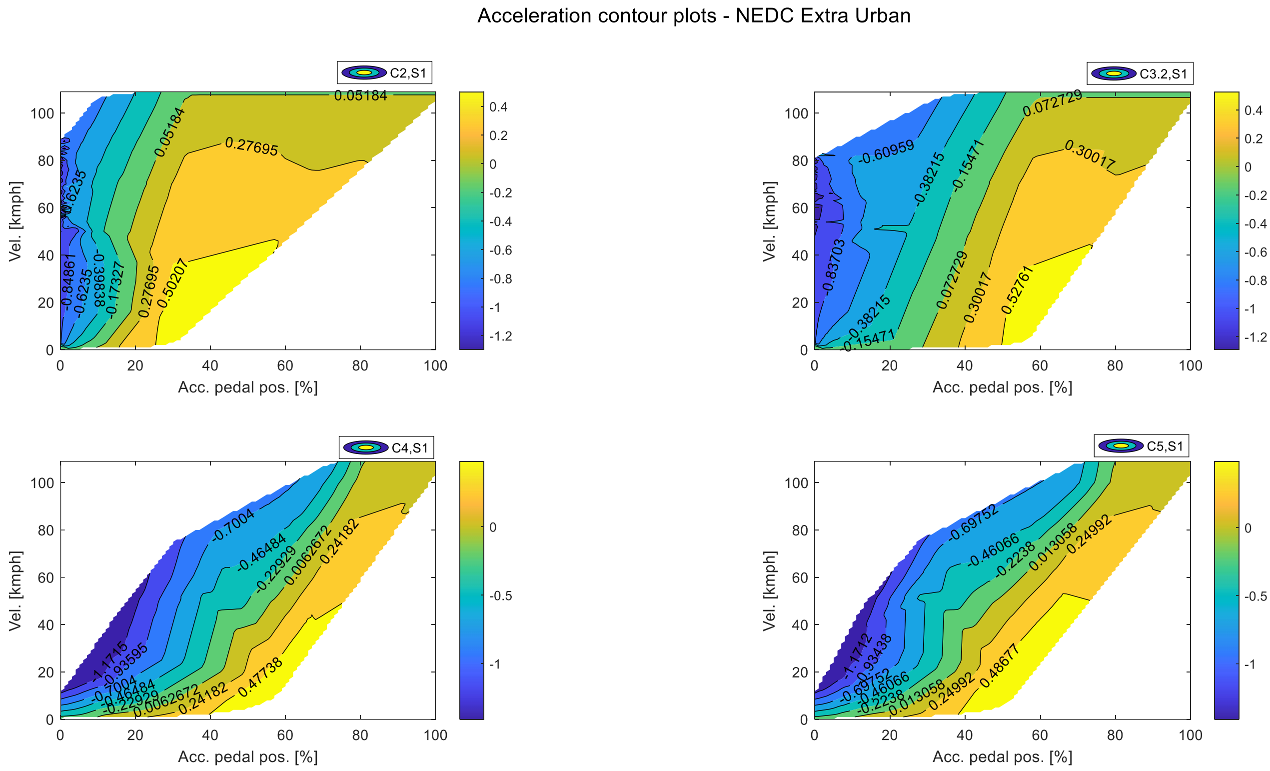


Figure 185. Acceleration contour plots – NEDC Extra Urban cycle

IN NEDC Extra Urban cycle all the strategies are able to follow closely the cycle but C4 and C5 produce lower velocity profile errors.

Consumption values are quite close while C4 and C5 are again negligibly lower than C2 and C3.2.

Moving to the comfort plots it is seen that C4 and C5 produce hugely lower number of accelerator pedal releases compared to C2 and C3.2.

Same explanations regarding deceleration and motor torque profiles are also valid here. It could be seen that in C2 and C3.2 oscillating behavior occurs which causes discomfort while C4 and C5 produce stable continuous deceleration profiles. However it should be noted that C3.2 has improved results with respect to C2 but the problem is that at certain points it relies to its regenerative on/off braking by releasing completely the accelerator pedal thus it performs commonly as C2 in those regions.

Coming to acceleration contour plots interesting results could be discussed. Here C2 and C3.2 contain a larger area inside the graph compared to C4 and C5 but the deceleration regions are more widespread in C4 and C5. Again, large decelerations happen at high speeds for C2 and C3.2 while in C4 and C5 deceleration values are highest in the mid speed range.

7.4.3.3 NEDC Full

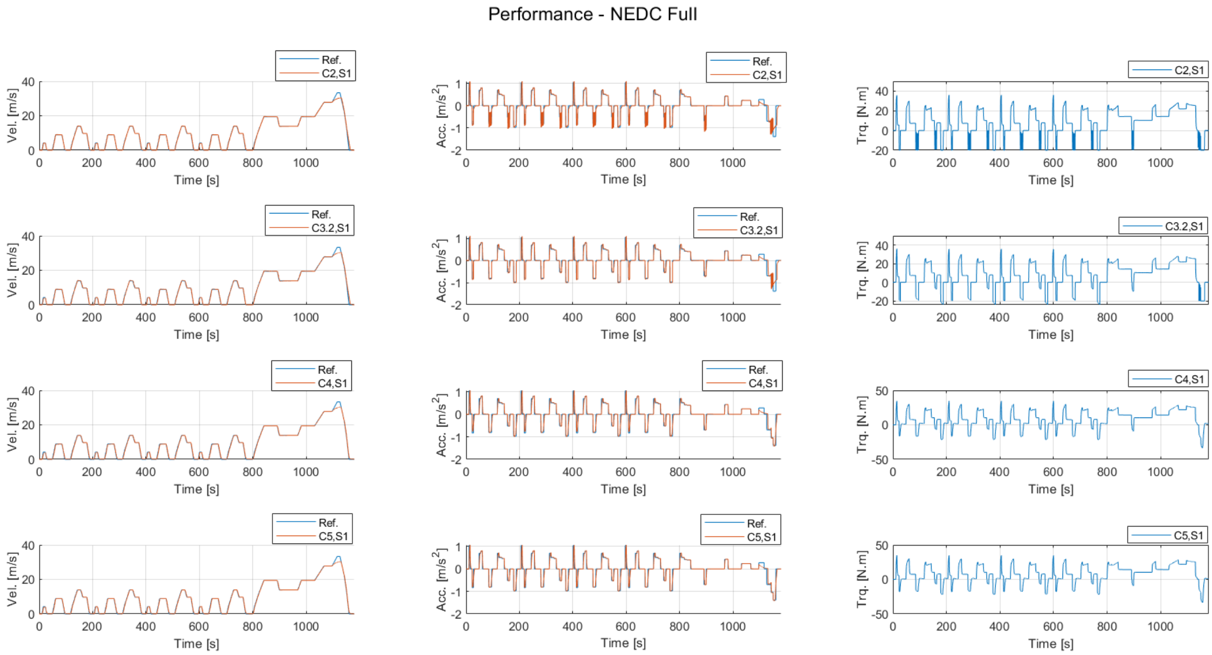


Figure 186. Performance results – NEDC Full

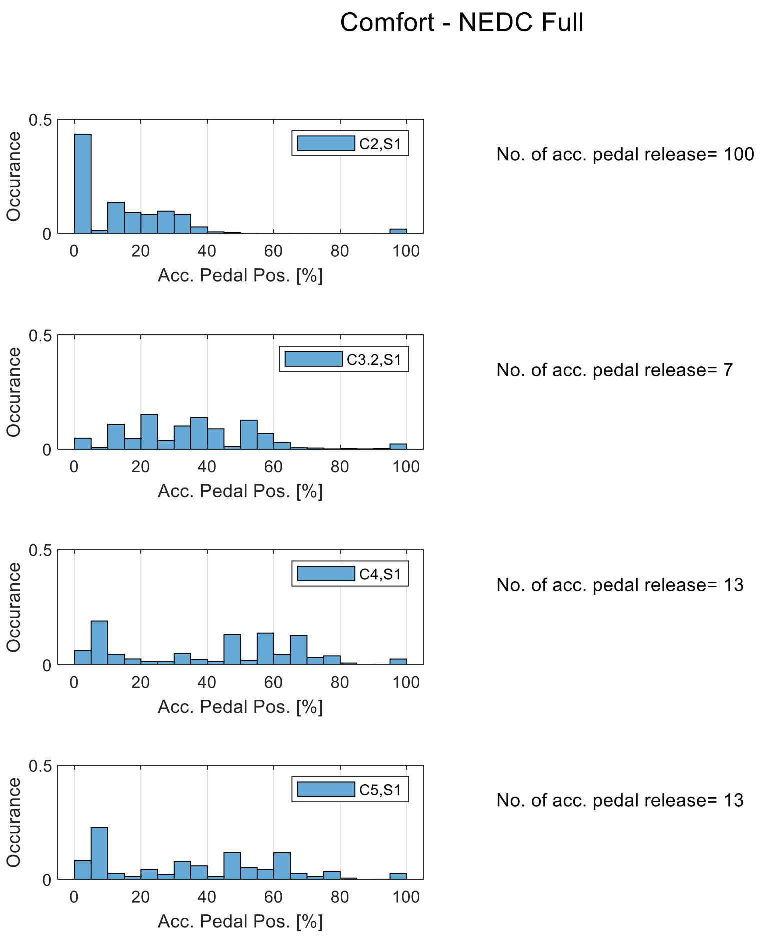


Figure 187. Comfort results regarding foot activity – NEDC Full

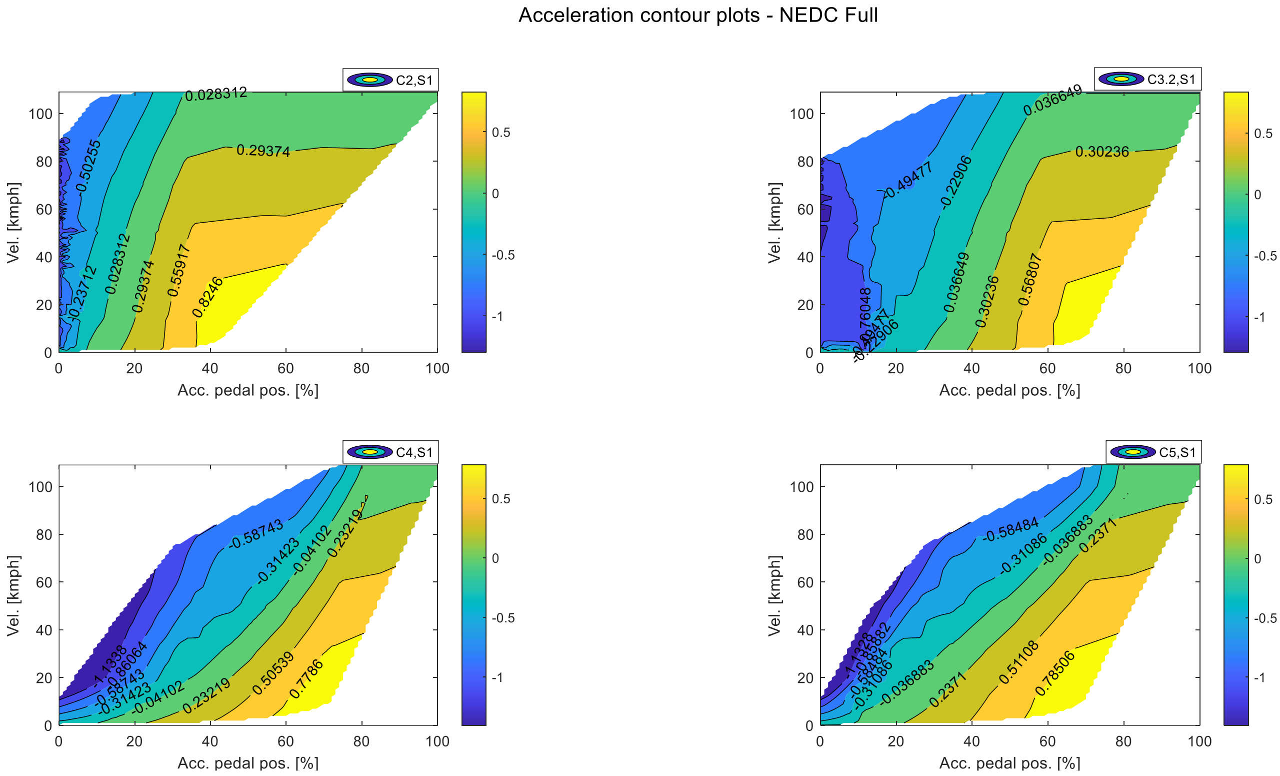


Figure 188. Acceleration contour plots – NEDC Full

Overall looking at the full NEDC cycle it can be said that C4 and C5 produce slightly lower errors in following the reference cycle compared to C2 and C3.2. Number of accelerator pedal releases are greatly lower for C3.2, C4 and C5 compared to C2while C3.2 has the minimum number.

Additionally, pedal position histograms show that in C2 the highest share of pedal positions belongs to the first few percentages that could cause discomfort due to the posture of the foot while in the other strategies pedal positions are more widespread.

Regarding the acceleration or torque profiles it is obvious that C4 and C5 produce continuous profiles while C2 and C3.2 due to their on/off regenerative control logic result in uncomfortable oscillations.

Furthermore, acceleration contour plots show that in C4 and C5 deceleration region is more widely stretched across the velocity and pedal position ranges whereas in C2 and C3.2 regeneration regions are concentrated in rather small areas. Also, at higher velocities it is seen that deceleration values are smaller for C4 and C5 while for C2 and C3.2 large deceleration values occur quite similarly across the whole velocity range which could cause attention for what regards safety issues when braking at high velocities.

7.4.3.4 WLTP Class 3 Low-Medium

The following reference cycles are subsets of WLTP Class 3 cycles. Compared to NEDC cycle, WLTP Class 3 highlights more clearly the advantages of one-pedal driving strategies since it represents a more aggressive driving style which includes increased number of braking actions.

As it will be shown in the following reduction in the number of accelerator pedal releases escalates compared to those seen previously.

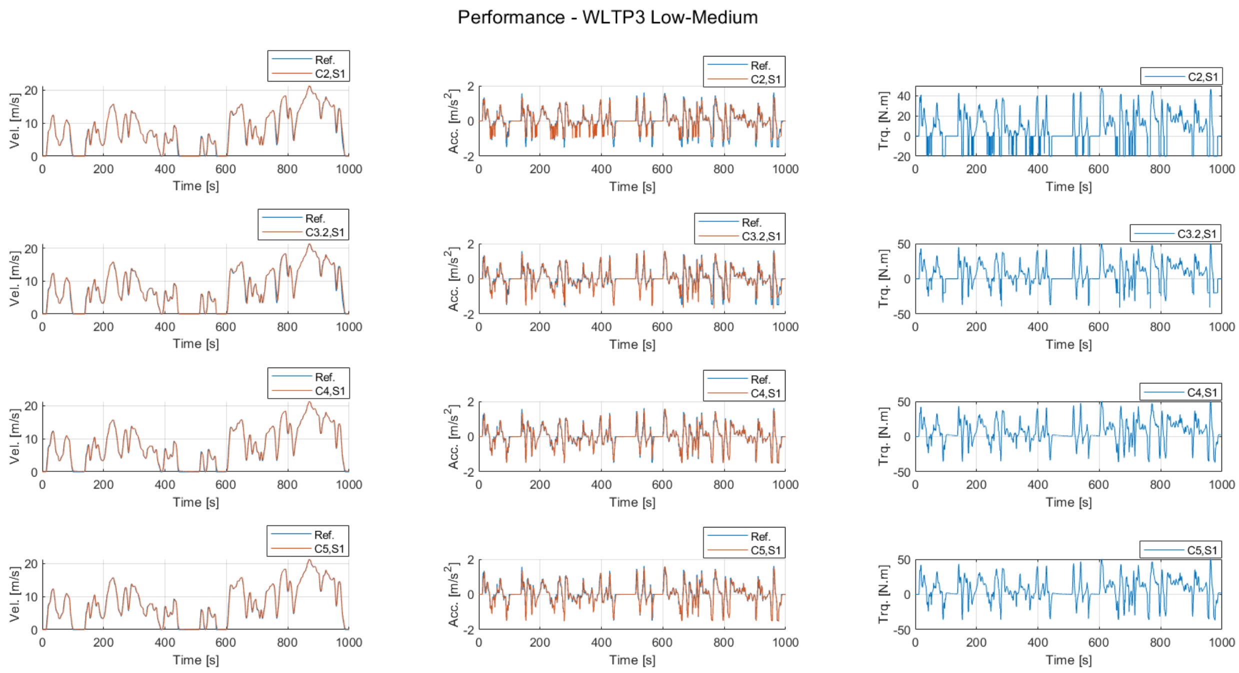


Figure 189. Performance results – WLTP Class 3 Low-Medium

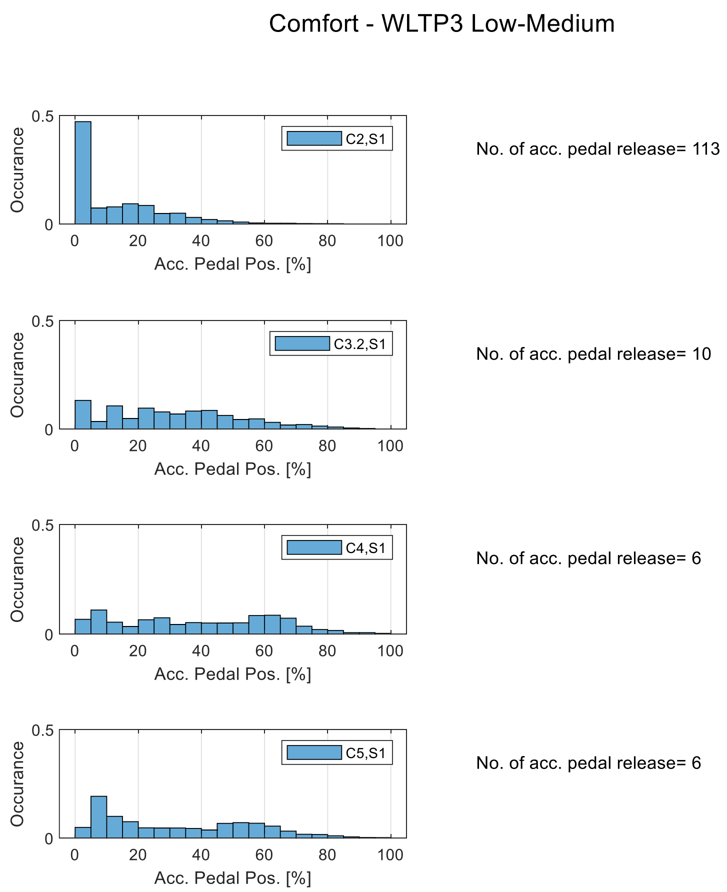


Figure 190. Comfort results regarding foot activity – WLTP Class 3 Low-Medium

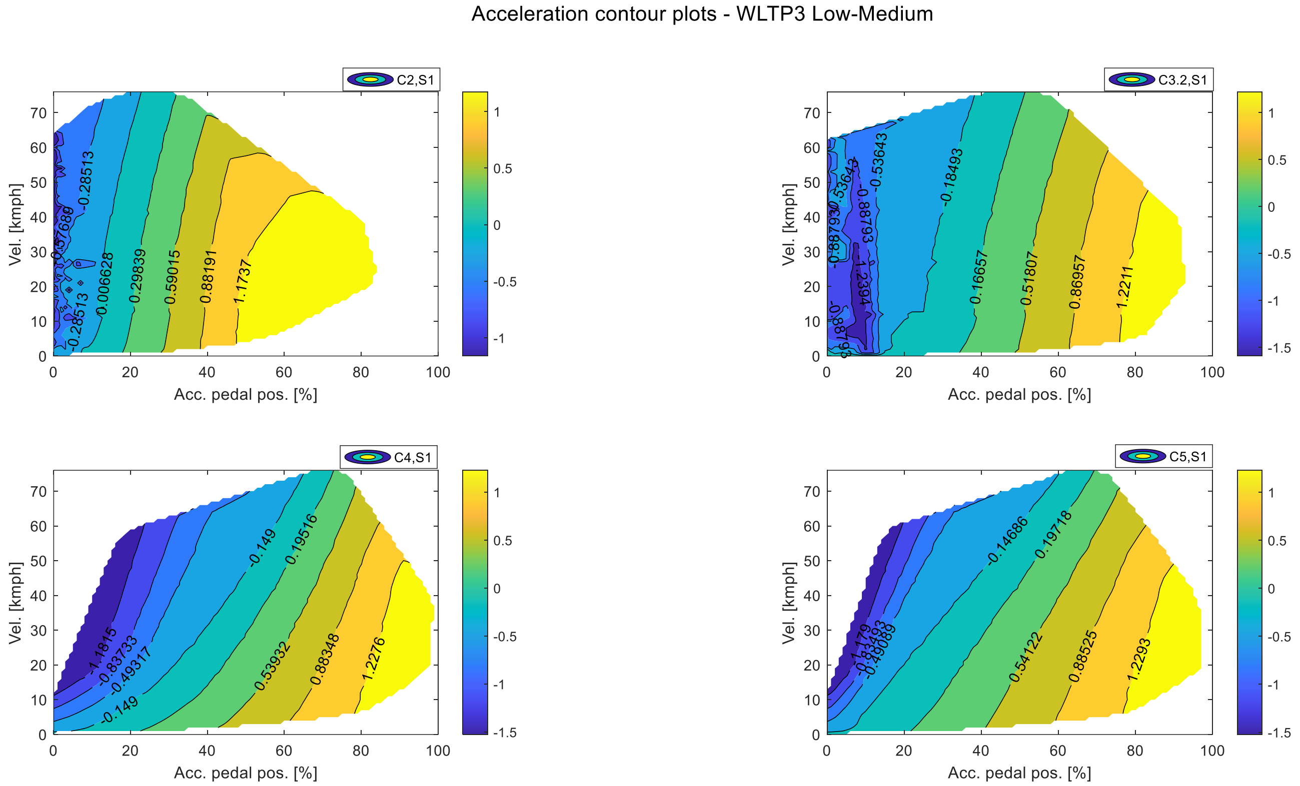


Figure 191. Acceleration contour plots – WLTP Class 3 Low-Medium

In WLTP Low-Medium the same trends seen previously are observed. Regarding the performance it is seen that C4 and C5 have lower errors following the reference cycle compared to C2 and C3.2 while the values for each pair are quite close.

Consumption values are almost the same but C4 is negligibly lower than all.

Looking at the comfort plots the impressive amount of improvement regarding the comfort is observed. The number of pedal releases reduces one order of magnitude moving from C2 to other ones. As depicted the number reduces from 113 for C2 down to 6 for C4 or C5.

Furthermore, deceleration or torque profiles are much smoother with C4 and C5 compared to repetitive on/off braking that occurs with C2 or C3.2.

Similar to the previous cycles, also here it can be seen from acceleration contour plots that in C2 and C3.2 deceleration region is concentrated in the far left side of the graph where the acceleration pedal positions are small whereas in C4 and C5 they are more stretched. Furthermore, at higher velocities large deceleration values occur for C2 and C3.2 while in C4 and C5 highest decelerations occur in the mid-range and it reduces for highest velocities.

7.4.3.5 WLTP Class 3 High-Extra High

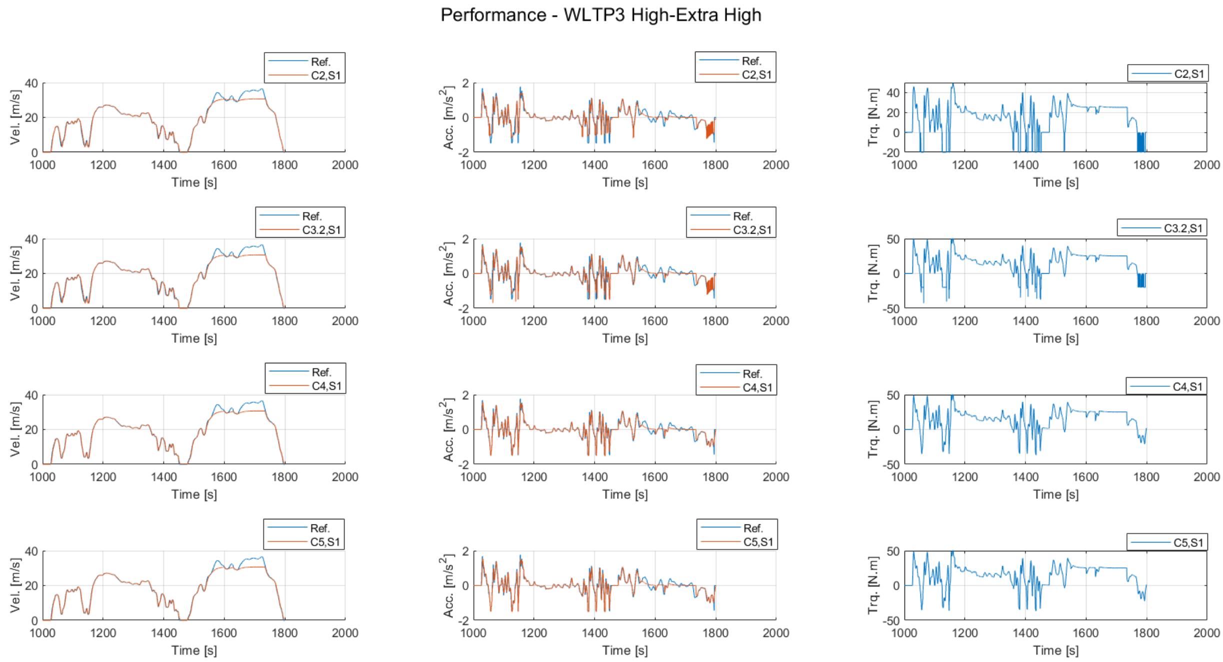


Figure 192. Performance results – WLTP Class 3 High-Extra High

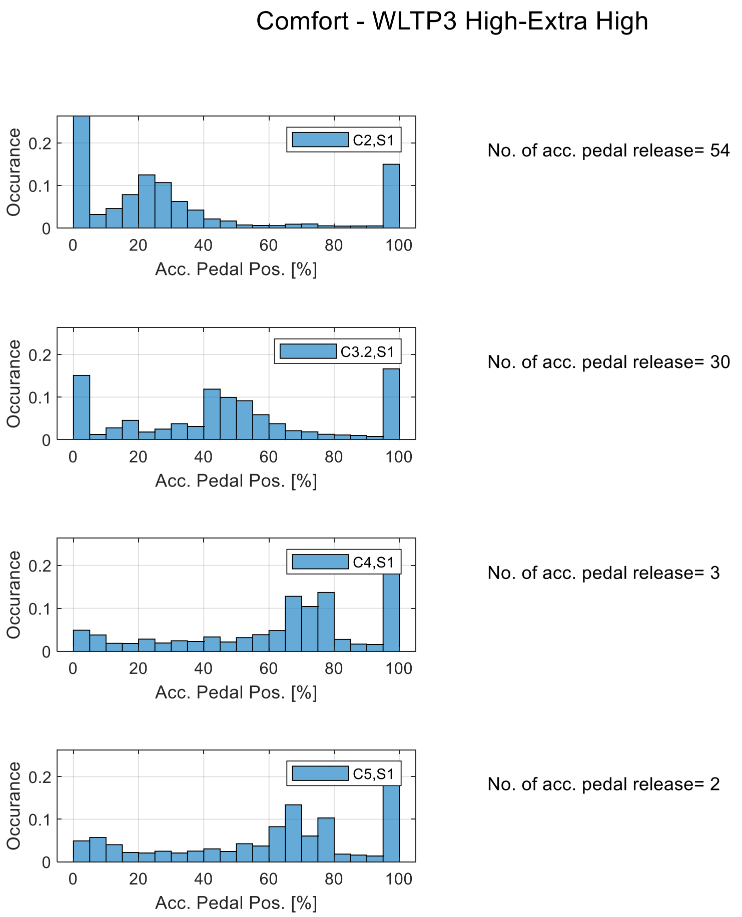


Figure 193. Comfort results regarding foot activity – WLTP Class 3 High-Extra High

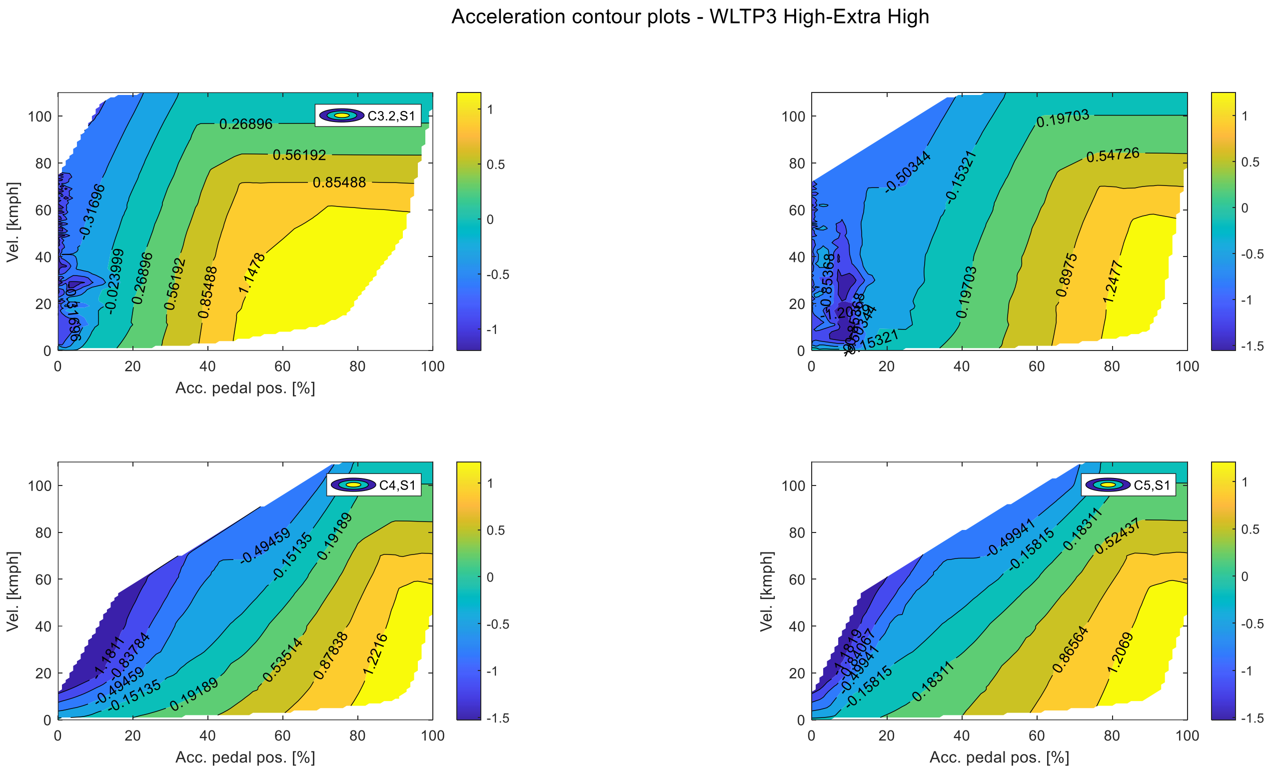


Figure 194. Acceleration contour plots – WLTP Class 3 High-Extra High

Same performance trends as WLTP Low-Medium happen also for WLTP High-Extra High cycle. Again, C4 and C5 have less velocity profile errors following the reference cycle compared to C2 and C3.2 however the difference is not noticeable.

It can be also seen that acceleration and torque profiles are smoother in C4 and C5 compared to C2 and C3.2 where oscillations occur due to the on/off regenerative braking happening when fully releasing the accelerator pedal.

Consumption values are as always close but C4 and C5 values are again negligibly lower than C2 and C3.2.

Looking at comfort plots it is observable that unlike previous cycles C3.2 does not create much difference in the number of accelerator pedal releases compared to C2 while huge success is achieved with C4 or C5.

Looking at the acceleration contour figures it is seen that C2 and C3.2 have concentrated deceleration regions in left side of the figure whereas in C4 and C5 this area is more widespread. Furthermore, maximum deceleration values are in the mid speed range for C4 and C5 and it reduces for higher velocities.

7.4.3.6 WLTP Full

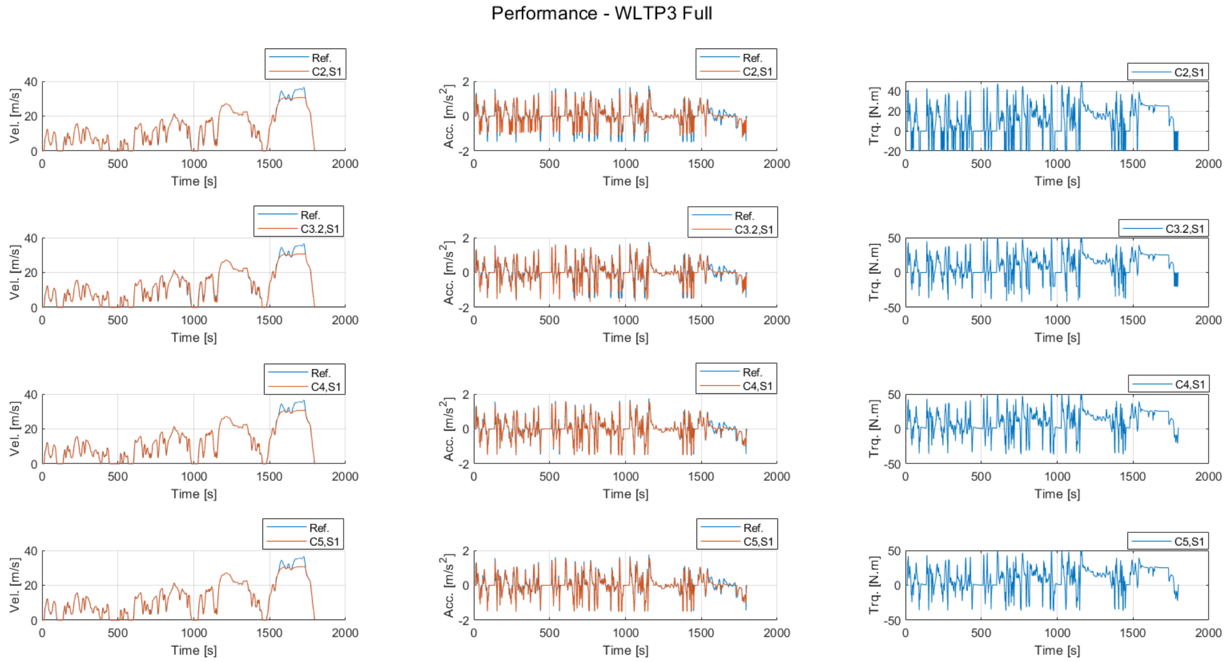


Figure 195. Performance results – WLTP Class 3 Full

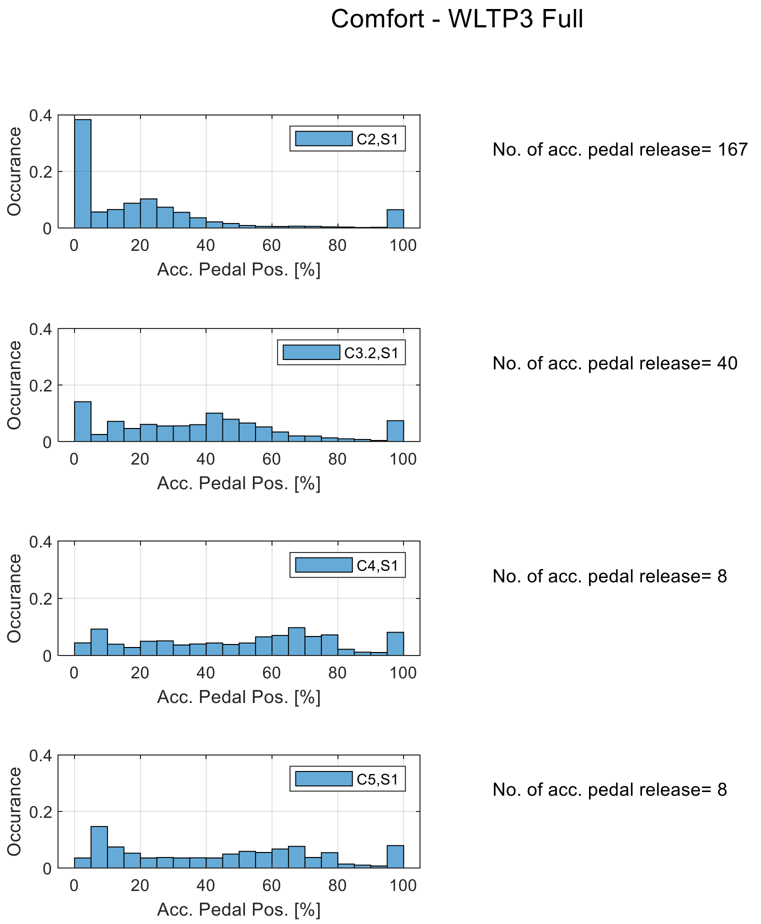


Figure 196. Comfort results regarding foot activity – WLTP Class 3 Full

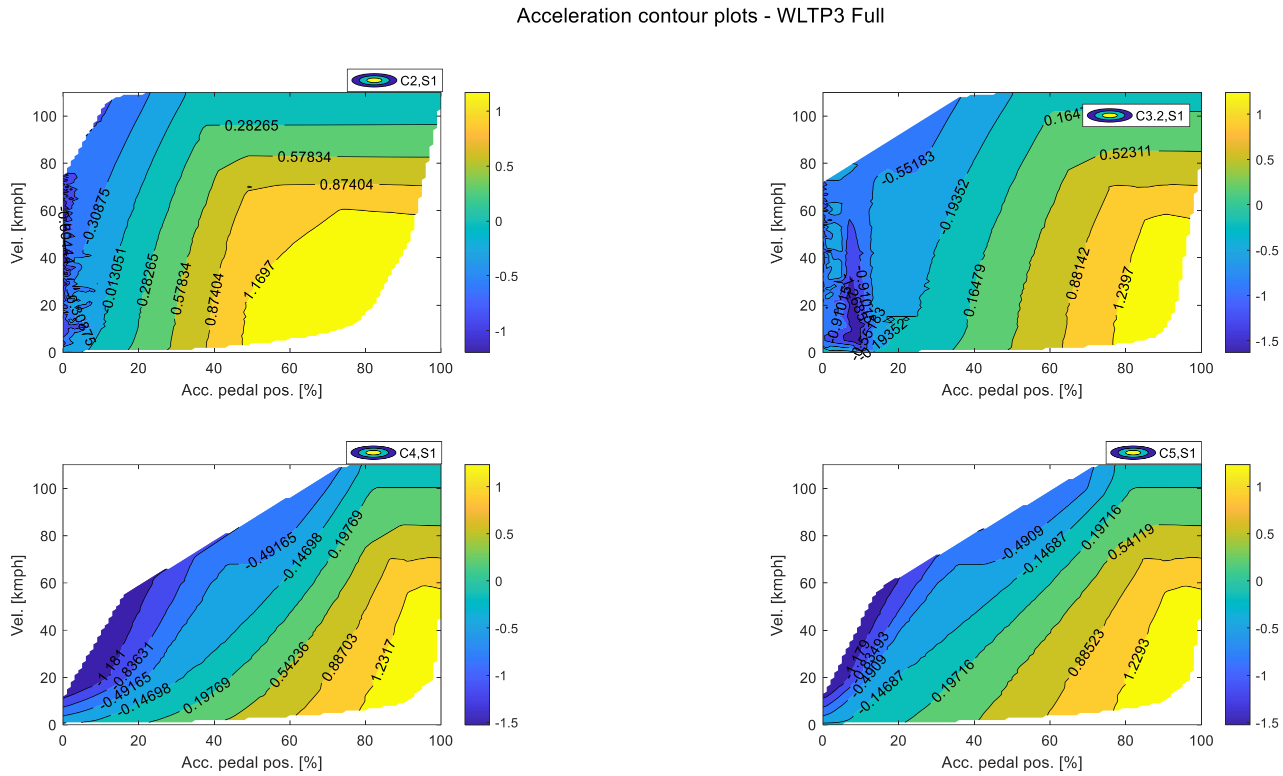


Figure 197. Acceleration contour plots – WLTP Class 3 Full

Finally looking at the WLTP Full cycle results the same patterns seen previously are obtained again. Velocity profile errors are quite close but C4 and C5 have lower values and they can follow the reference cycle more precisely compared to C2 and C3.2.

Acceleration and torque profiles are smoother with C4 and C5 while they become oscillating with C2 or C3.2 due to the nature of on/off regenerative braking.

Consumption values are almost the same but again C4 is negligibly lower than the rest.

Looking at comfort results it could be understood that although C3.2 reduces the number of acceleration pedal releases considerably with respect to C2, but the outcome of C4 or C5 is far better. It can be seen that the number reduces from 167 with C2 down to 8 with C4 or C5.

Furthermore, similar to what has been said in NEDC cycle also here it is observable from occurrence histograms that in C2 accelerator pedal is mostly positioned in the first few percentages which could cause discomfort due to the foot posture. This problem is improved in the other strategies as it can be seen that occurrence histograms are more widespread across the complete range of accelerator pedal positions.

For what regards the acceleration contour plots the same previous conclusions could be said. It can be seen that deceleration values are concentrated in a small area for C2 or C3.2 while it is more widespread for C4 or C5. Maximum deceleration values occur in the mid speed range with C4 and C5 as well.

7.4.4 Strategy by strategy results

In this section all the important simulated profiles of each control strategy are reported for the complete NEDC and WLTP Class 3 cycles.

7.4.4.1 C2

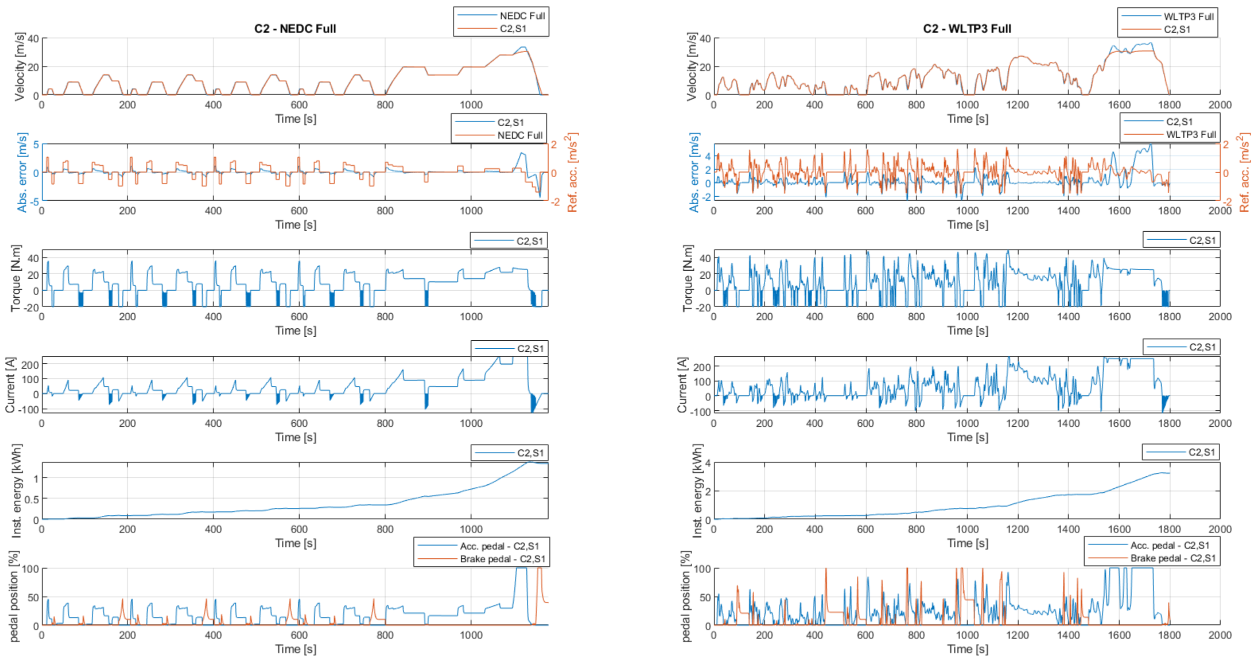


Figure 198. C2 simulation results for NEDC and WLTP Class 3 cycles

7.4.4.2 C3.2

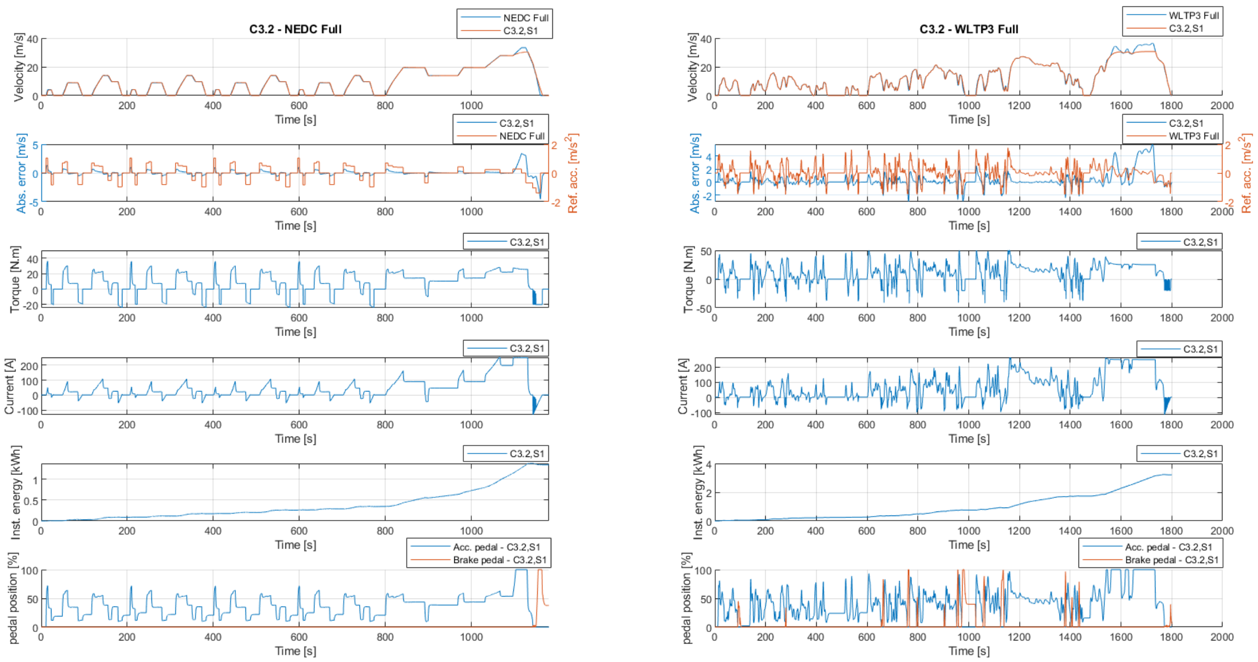


Figure 199. C3.2 simulation results for NEDC and WLTP Class 3 cycles

7.4.4.3 C4

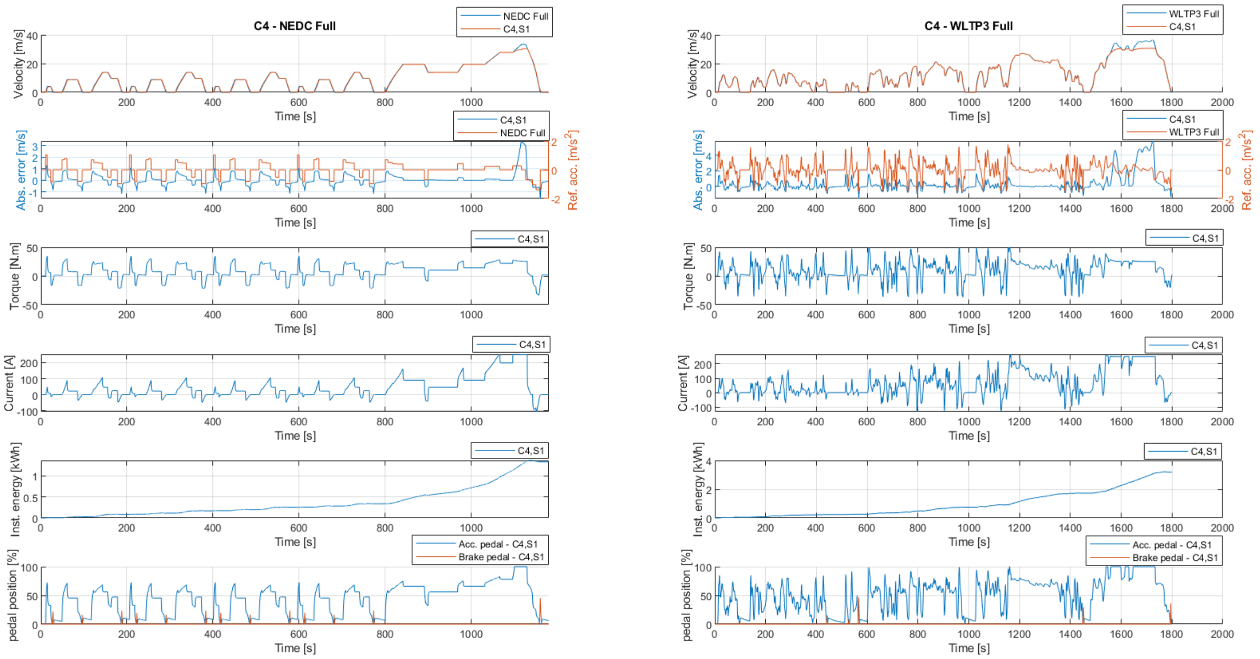


Figure 200. C4 simulation results for NEDC and WLTP Class 3 cycles

7.4.4.4 C5

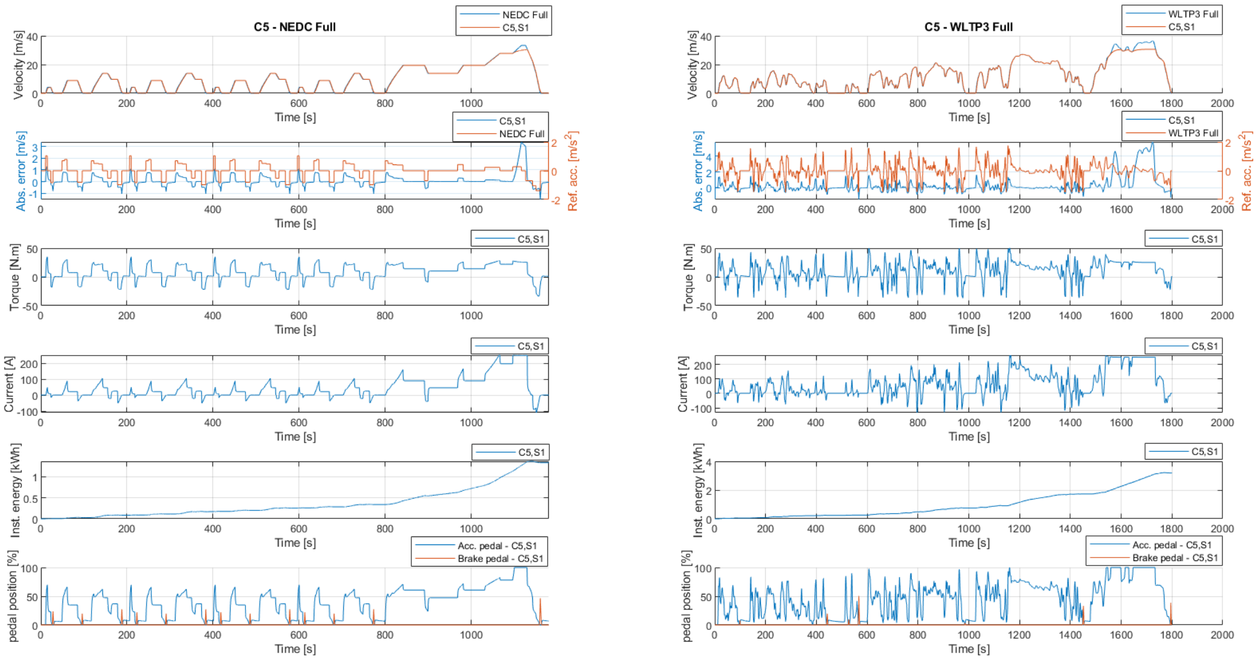


Figure 201. C5 simulation results for NEDC and WLTP Class 3 cycles

7.5 Conclusions

Looking at the results and analyzing all the driving cycles with different control systems it could be understood that:

- A great advantage achieved with C4 or C5 with respect to C2 and C3.2 is that in C4 and C5 accelerator pedal mapping is more flexible and dynamic depending on the velocity of the vehicle. For example, breakpoints move also horizontally on the input axis. This gives the possibility to have a complete map dedicated for traction when moving off which makes one-pedal driving more adaptable to normal drivers. As the velocity increases regeneration and coasting regions spread progressively. However, in C2 or C3.2 input breakpoints of the accelerator pedal map have constant positions which for instance could cause discomfort for the drivers as they have to press down the accelerator pedal to large extents before having any traction when moving off.
- Apart from NEDC Urban cycle, in all other reference cycles C4 and C5 have lower velocity profile errors following the reference cycles compared to C2 or C3.2.
- For all the cycles consumption values of all strategies are almost the same. However, C4 and C5 always show negligibly lower values with respect to C2 or C3.2. Both C4 and C5 have many tunable parameters that could change their final results. Hence it could be said that both these strategies perform slightly better than C2 or C3.2 for what regards the energy consumption values both with and without regeneration but judging which will be always better needs more investigation in their parameter analysis.
- Generally talking as it was also seen in chapter five model validation, in any case even with the best fit parameters, simulation errors are inevitable. Thus considering also the negligible differences between simulated consumption results it could be concluded that from engineering point of view electrical energy consumption is the same for the studied one-pedal driving strategies as all of them were able to follow precisely the reference cycles solely with regenerative braking.
- Although C3.2 shows smoother deceleration or motor torque profiles compared to C2 but it still relies heavily on its supplementary on/off regenerative braking upon releasing the accelerator pedal which in the end causes some oscillations. On the other hand, in C4 and C5 accelerator pedal mapping is such that they no longer need excessive full release of accelerator pedal to satisfy large decelerations requested. Hence their deceleration or torque profiles are much smoother.
- In C4 or C5 number of accelerator pedal releases or the need to shift between pedals is surprisingly lower than C2 or even C3.2. For instance, in WLTP3 Full cycle this number is 167 with C2 and it reduces to 40 with C3.2 but it even becomes as low as 8 for C4 or C5. This is a huge achievement towards the ultimate goal of one-pedal driving for what regards comfort issues.
- In histograms of acceleration pedal positions, it is depicted that with C2 the largest occurrence probability belongs to the first few percentages of the pedal position. This issue could cause discomfort to the driver due to the corresponding foot posture. Meanwhile in the other strategies it could be seen that occurrence is more widespread across the range of the pedal positions.
- Acceleration contour plots show that in C2 and C3.2 deceleration areas are mostly concentrated in small regions towards left side of the graph where pedal position moves towards zero. It has been observed that in C2 maximum deceleration values happen to be generally the same for all the velocity range which is important regarding safety issues when braking at high velocities or comfort when braking at low velocities. This aspect is modestly improved with C3.2. However, for C4 and C5 it could be seen that deceleration regions are spread across a wide range of velocity and pedal positions.

Furthermore, maximum deceleration values are positioned in the mid speed range and at higher velocities maximum deceleration is reduced which is considered as an improvement regarding longitudinal driving comfort and safety.

In the end, it can be concluded that C4 and C5 improve the simulation results hugely with respect to C2 or C3.2 regarding comfort issues considering deceleration profiles or foot activity on the pedals. But regarding electrical energy consumption, it can be said that they all have more or less the same values.

Both C4 and C5 strategies proved to be useful in realizing one-pedal driving even though they contain many tunable parameters that could change their outcome and so further steps are needed for parameter optimization and sensitivity analyses. It is understandable that the most important feature is to have a one-pedal driving strategy that includes progressive regeneration and coasting regions that increase with vehicle velocity.

Conclusion

Throughout this thesis it has been shown how a virtual prototype was developed in MATLAB/Simulink in order to be used as a tool to develop, analyze and compare different one-pedal strategies from consumption and comfort point of view. The study was mainly carried out for an old Fiat Panda retrofitted with an electrified powertrain, although the process could be repeated for any electric vehicle.

In the first chapters the basic on/off regenerative braking that the vehicle featured by default, was investigated. Different regeneration levels were analyzed to find a tradeoff considering comfort, deceleration capabilities, energy recuperation etc. It was understood that 40% regeneration with respect to the maximum regenerative torque of the electric motor of the vehicle was the right choice.

In the next step the developed model in Simulink was subject to validation by the help of acquired real world experimental data. For this reason, first real on/off regenerative braking control model of the vehicle was implemented in Simulink and it was observed that compared to the ideal control model mainly current, electrical power and electrical energy profiles improved and became closer to those acquired in the real tests. Additionally, consumption without regeneration values improved as well. Second, parameters of the plant i.e. longitudinal vehicle dynamics model should have been tuned since coast-down tests were not performed originally and they were preliminary obtained through calculations. To address this issue F_0 and F_1 values were tuned to obtain minimum error in specific consumption with regeneration value. This parameter tuning reduced the errors of consumption values considerably. Overall, the average errors of consumption values reduced to lower than 6%.

After validating the model and having reliable simulation results, more sophisticated one-pedal driving strategies were developed and compared with C2 which was the simplest strategy already employed inside the real vehicle. It was depicted that strategies featuring regeneration and coasting regions which expand progressively with velocity i.e. C4 or C5 increased enormously comfort of the driver regarding his foot activity e.g. reducing number of accelerator pedal releases from 167 with C2 down to only 8 with both C4 and C5 in WLTP Class 3 cycle. Furthermore, acceleration contour plots showed how with expandable regeneration and coasting regions, deceleration regions become more widespread across a wider range of velocities and accelerator pedal positions while also reducing deceleration values for very high or very low velocities.

However, from consumption point of view it was shown that comparing the four eligible one-pedal driving strategies (C2, C3.2, C4 and C5) that were able to follow the reference cycles precisely enough solely with regenerative braking, consumption values were almost the same and did not differ for the vehicle under study.

For sure studying different electric vehicles could also give different simulation results but the importance of this work was developing the tool to perform such comparison and analysis.

References

[1] "e-Pedal," Nissan Motor Corporation, [Online]. Available: https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/e_Pedal.html.

[2] "Nissan Serena e-POWER," Nissan, [Online]. Available: https://www.nissan.com.sg/vehicles/new/serena/performance.html.

[3] Nate Michaluk, General Motors, "One-Pedal Driving: Rapid Feature Development with Simulink," in *MathWorks Automotive Conference*, MAY 9, 2017.

[4] C. Zhao, G. Gong, C. Yu, Y. Liu, S. Zhong, Y. Song, C. Deng, A. Zhou and H. Ye, "Research on Key Factors for Range and Energy Consumption of Electric Vehicles," SAE Technical Paper 2019-01-0723, 2019, doi:10.4271/2019-01-0723.

[5] S. Jang and G. Kim, "Development of Regenerative Brake Control Strategy to Remove Brake Rust," SAE Technical Paper 2019-01-2125, 2019, doi:10.4271/2019-01-2125..

[6] European Parliament, "Regulation (EC) No 1222/2009 of the European Parliament and of the Council of 25 November 2009 on the labelling of tyres with respect to fuel efficiency and other essential parameters," *Official Journal of the European Union, L 342/46,* 22 December 2009.

[7] G. Genta and L. Morello, The Automotive Chassis, vol. 1, Springer, 2009.

[8] S. d’Ambrosio and R. Vitolo, "Potential impact of active tire pressure management on fuel consumption reduction in passenger vehicles," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 233, no. 4, p. 961–975, March 2019.

[9] S. D'Ambrosio, "Combustion Engines and their Application to Vehicles lecture notes, Unit C Engine-Vehicle Matching, Part 3 Coastdown method (preliminary considerations)," Master of Science in Automotive Engineering course ,Politecnico di Torino.

[10] N. Kudarauskas, "Analysis of emergency braking of a vehicle," *Transport,* vol. 22, no. 3, p. 154–159, 2007.

[11] J. Van Boekel, I. Besselink and H. Nijmeijer, "Design and realization of a One-Pedal-Driving algorithm for the TU/e Lupo EL," *World Electric Vehicle Journal,* vol. 7, no. 2, pp. 226-237, 2015.

[12] A. C. Ortega and B. H. Herranz, "ELECTRIC VEHICLE MODELLING WITH ONE PEDAL DRIVING AND TESTING WITH REAL SIGNALS INTERFACING AND AUTOMATIC CODE GENERATION," Master of Science in Mechatronic Engineering Thesis, Politecnico di Torino, March 2017.