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Master Thesis

The Idle coasting opportunity as Eco-innovation and its benefit in real world

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Abstract

Recently the European Commission introduced in its regulatory framework the WLTP, a new homologation test procedure regarding pollutant and CO_2 emissions measurement from new passenger cars. Manufacturers are requested to undergo challenging efforts if they want to meet their specific CO_2 targets with new driving cycle more and more representative of real world and new testing procedures more and more stringent. Besides, new targets are being discussed for the next coming years according to EU long-term goal to reduce greenhouse gases emissions of 80-95% with respect to 1990 levels.

In the short-term it is important to develop cheap and effective strategies that allow to improve the fuel efficiency of new vehicles with modest investments, assuring at the same time an actual benefit in the real world from the consumer point of view. One possible solution is the widespread introduction of Idle coasting feature on passenger cars both with automatic and manual transmission through e-clutch.

In this work there is a brief introduction on new regulatory framework, focusing on Idle coasting Eco-innovation opportunities. Then the benefits of this technology on a sample vehicle have been assessed by means of the GT-Suite software and a possible control strategy of the Idle coasting feature has been calibrated. NEDC and WLTC driving cycles in parallel with the mNEDC have been chosen to evaluate the CO_2 saving accountable for homologation purpose. The effects on a trial proposal of a modified WLTC have been analysed as well. At the same time the benefit of Engine off coasting has been assessed. Finally, the measurements of FCA fleet of sample vehicles equipped with Idle coasting have been statistically examined trying to assess the fuel efficiency over a large number of driving missions.

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1. Introduction

The trend of GHG emissions in Europe shows a significant reduction of around 24% in 2015 with respect to the levels of 1990. This was due to a grown share of renewable energy sources and less carbon intensive fuels usage, a general improvement in energy utilization efficiency, a progressive motion towards service-oriented economy and to a smaller extent the effect of economic recession and slightly warmer winters (leading to the decrease in energy demand for heating).

One of the most relevant exception in this general trend is the transport sector, which showed an increase of about 20% in the same period. GHG emissions from the transport segment increased up until 2008 when they encountered a slight reduction due to economic recession and then began again to grow in last years.

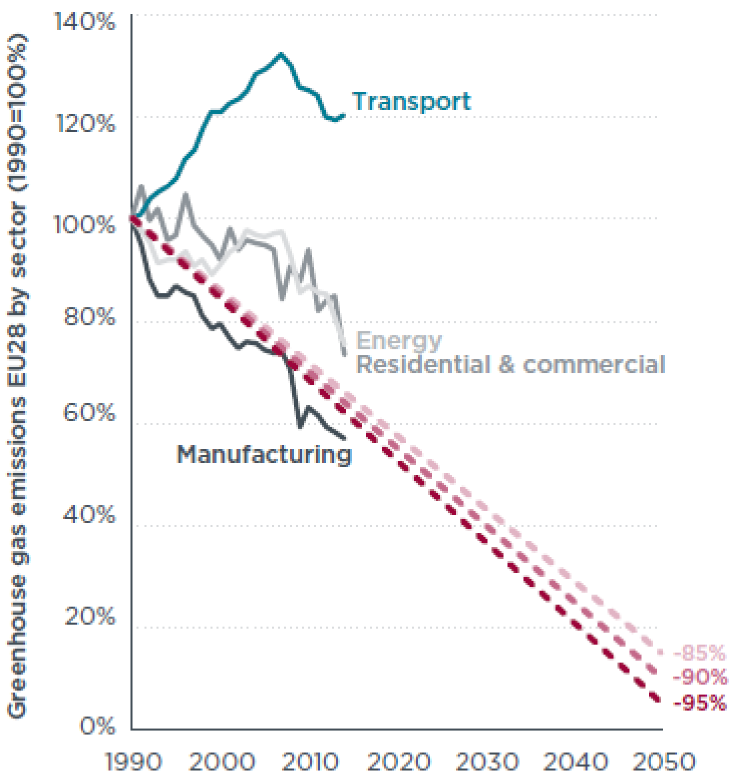

Figure 1.1 GHG emissions in the EU by sector and target range for reducing emissions by 85-95% by 2050[6]

The road transport sector is one of the biggest source of Greenhouse gases in EU, where it contributes for about 20% of the emissions. It is second only to the power generation sector which produces about 50% of GHG emissions [10]. Even if a lot of effort has been put for more than twenty years in improving vehicles efficiency and reducing road transport impact on emissions, this is still one of the few sectors in which Greenhouse gases emissions are increasing every year.

Improvement in vehicles efficiency and engines technology as well as use of less carbon intensive fuels (e.g. LPG) and biofuels couldn't yet counterbalance the growth of road traffic and the increasing demand of road transport.

1.1. CO_2 emissions regulation

By 2021 the average emissions from newly registered passenger cars in EU will have to be about 42% lower with respect to the levels of 2005, with a final binding target of 95 g CO_2/km.

Regulations and provisions carried out until today imposed a consistent investment to the automotive industry allowing the improvement of vehicles efficiency and the development of smart technologies. Such a high cost couldn't be undertaken by consumers and has been covered almost completely by manufacturers themselves.

In order to effectively keep the pace of reducing vehicles impact on emissions also in the next years, it is necessary to adopt measures not only relative to vehicle technology itself, but also to other factors which can influence overall CO_2 emissions such as fuel improvement (share of alternative fuels usage in PC including LPG, natural gas and electric vehicles is today less than 6%) , intelligent transport system, Eco-driving and fleet renewal (the average age of EU car fleet had reached nowadays the impressive record of 10.7 years old). [13]

1.1.1. Background

EU is one of the largest producer of passenger cars in the world. Recognizing the big impact that vehicles have on GHG emissions and climate change in the 1990s many manufacturers agreed on voluntary programs voted to develop industry commitment, inform consumers and promote fuel efficient cars in the market.

Mandatory targets were the following step in this strategy and in late 2009 European Commission defined Regulation 443 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles. The average specific emissions of the fleet of new passenger cars registered in EU had to be compliant with a limit of 130 gCO_2/km by 2015. Each manufacturer had a specific average fleet target according to the average weight of its fleet. Thus, manufacturers registering heavier than average cars were allowed to emit more and vice versa.

In late 2013 the previous Regulation was amended and a new target of 95 gCO_2/km was set to be reached in 2020 for 95% of vehicles and in 2021 for 100% of vehicles. The average fleet weight was again appointed as the main parameter affecting individual manufacturer targets.

In September 2017 WLTP (Worldwide harmonized Light-duty vehicles Test Procedure) has replaced the previous NEDC homologation cycle. This leaded to the need for an adjustment of 2020 targets through a NEDC-WLTP correlation in order to maintain the emissions reduction pace previously set. [5]

Table 1.1 reports the most interesting data about NEDC and WLTP test cycles to make a direct comparison.

		NEDC	**WLTP**
Distance	[km]	11.02	23.26
Duration	[s]	1180	1800
Duration of stops	[%]	24.8	13.4
Maximum speed	[km/h]	120	131.3
Average speed	[km/h]	33.6	46.5
Maximum acceleration	[m/s^2]	1.05	1.67
Maximum deceleration	[m/s^2]	-1.39	-1.50
Average acceleration	[m/s^2]	0.59	0.41
Average deceleration	[m/s^2]	-0.79	-0.44
Overall energy required over cycle[1]	[kWh]	1.25	2.44
Energy required over cycle[1]	[Wh/km]	144	105

Table 1.1 Main characteristics of NEDC and WLTC test cyles [7]

The WLTP test cycle is for sure more representative of real world driving condition with respect to NEDC. This is demonstrated by the fact that the stop time is now reduced to about 13%, whereas it was previously weighting for one fourth of the total time. Furthermore, the maximum speed is now set at 131.3 km/h, instead of 120 km/h as before.

[1] For a midsized EU C-segment vehicle

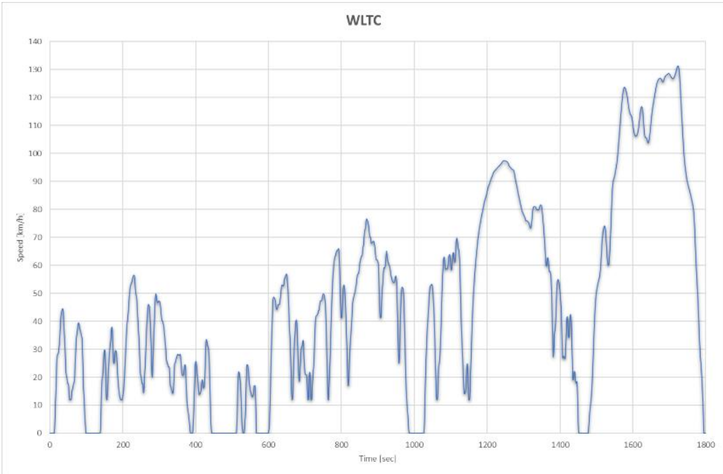

Figure 1.2 WLTP test cycle speed profile

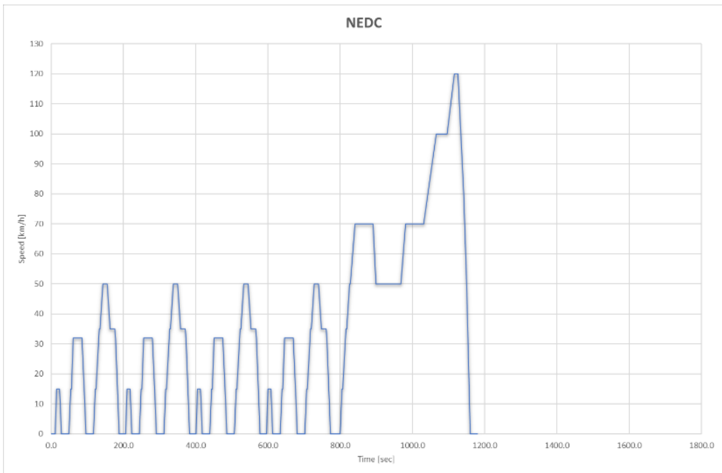

Figure 1.3 NEDC test cycle speed profile

Nevertheless, the most interesting values are those regarding accelerations and decelerations levels. Even if the maximum acceleration and the maximum deceleration are stronger than they were before, the average values are lower in module. This means that in WLTP a lot of softer decelerations have been introduced with respect to NEDC less frequent and steeper braking phases. Potentially the WLTP test cycle contains more phases in which idle coasting strategy can be actuated.

1.1.2. Post-2020

The European Commission is looking at cost-efficient ways to make the European economy more climate-friendly and less energy-consuming [8]. Its roadmap for more moving to a competitive low carbon economy in 2050 suggests that:

- By 2050, the EU should cut greenhouse gas emissions to 80% below 1990 levels;
- Milestones to achieve this are 40% emissions by 2030 and 60% by 2040;
- All sectors need to contribute;
- The low-carbon transition is feasible and affordable.

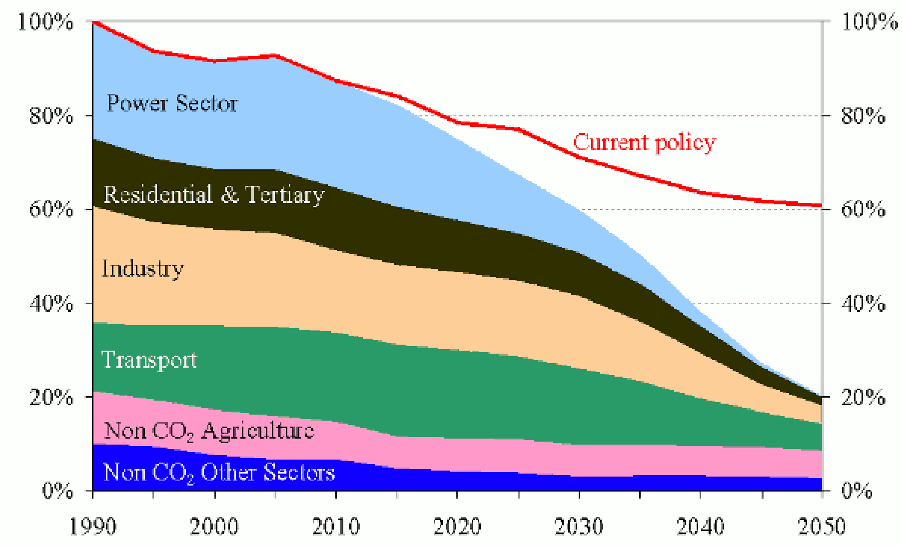

Figure 1.4 Possible 80% cut in GHG emissions in the EU with respect to 1990 levels [8].

On 8 November 2017 the European Commission presented a legislative proposal setting new CO_2 emissions standards for passenger cars and light commercial vehicles in the European Union for the period after 2020. The proposed targets are set for the EU-wide average emissions of new cars and vans in a given calendar year from 2025 on, with stricter targets applying from 2030. The proposed framework builds on the current Regulation (EC) No 443/2009 setting CO_2 emissions standards for light-duty vehicles which will be repealed on 1 January 2020.

Average emissions of the EU fleet of new cars in 2025 will have to be 15% lower than in 2021 and in 2030 30% lower than in 2021. As the WLTP test procedure has been introduced since September 2017 and will be phased in over the next years, the newly proposed targets are not defined as absolute values, but expressed as percentage reductions compared to the specific emission targets for 2021.

The resulting targets NEDC-based would be 80 g CO2/km in 2025 and 67 g CO2/km in 2030, in line with the recent global trend of emissions cutting as depicted in Figure 1.5.

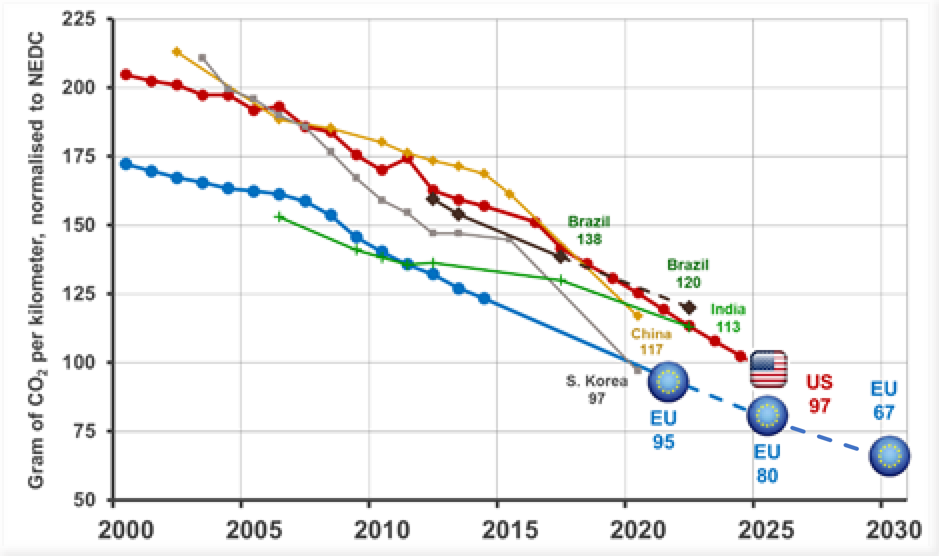

Figure 1.5 Passenger car CO_2 emissions historical trends and targets, normalized to NEDC (dashed lines are proposals at the moment) [9].

The proposed framework combines CO2 targets for 2025 and 2030 with a technology-neutral incentive mechanism for zero-emission vehicles (such as battery electric or fuel cell vehicles) and low-emission vehicles (such as plug-in hybrid vehicles) in order to give the market a clear signal for investment in clean vehicles.

Although in the next future electrification of vehicles will have a crucial role in contributing to OEM compliance to more and more severe CO2 targets, nowadays there are still lot of limitations hindering the development of ultra-low carbon vehicles, such as energy storage systems cost, lack of infrastructure for battery recharging, recharging time and range.

1.2. Eco-innovation

1.2.1. Regulation framework

According to Regulation (EC) 443/2009 setting emission performance standards for new passenger cars as part of the European Community's integrated approach to reduce CO_2 emissions from light duty vehicles a new target of 95 g CO_2/km is to be phased in from 2020 and fully applicable from 2021 (after the previous target of 130 g CO_2/km set from 2015 onwards). Specific emission targets are assigned to each manufacturer, based on the average specific emissions for each new passenger car registered in the preceding calendar year.

Article 12 of the same legislative act allows manufacturers to take into account CO_2 savings from the adoption of innovative technologies, so-called 'eco-innovations', in order to meet their specific CO_2 emissions targets [1]. For example: if a manufacturer fits in 300 000 cars an eco-innovation which gives 2 g CO_2/km savings and registers in the same year 1 000 000 cars, its fleet average emissions are reduced of

$$2*300\,000/1\,000\,000 = 0.6 \text{ g CO2/km}$$

The maximum savings that a manufacturer may take into account for reducing its average fleet emissions in a given calendar year is 7 g CO_2/km.

This incentive is given to new technologies with a CO_2 reducing potential with the aim of facilitating their introduction and penetration into the market and with the purpose of helping OEMs to reach their specific emission targets.

The European Commission defines eligibility criteria and other additional information on how to prepare the application; in particular the innovative technology:

- Must not be already fitted in more than 3 % of all new passenger cars registered in 2009
- Should improve the energy use of the vehicle serving for either performance or safety
- Must provide a minimum of 1 g CO_2/km saving

The Commission assesses those applications for the approval of innovative technologies as 'eco-innovations', drafted by either manufacturers or suppliers. After the approval decision is made, manufacturers can claim CO_2 savings as part of the type approval process. Testing methodologies for an eco-innovation approved by the Commission is available to other manufacturers that are willing to obtain the certification of a vehicle fitted with a technology corresponding to the approved eco-innovation.

The manufacturer should provide a verifiable demonstration of CO_2 savings effect given by the innovative technology through testing on dynamometer and calculations/models and should demonstrate that the minimum saving is exceeded in a statistically significant way. The reference type approval test should be used as a reference, however when the CO_2 reducing effect cannot be adequately demonstrated with the NEDC speed/time profile a deviation from the standard cycle can be requested if properly justified.

1.2.2. CO_2 savings calculation

As shown below, CO_2 savings are evaluated from several tests under modified testing conditions through the difference between baseline and innovative vehicle; the corresponding CO_2 savings are weighted by a usage factor.

$$\Delta CO_{2MC} = (B_{MC} - E_{MC}) \cdot UF_{MC} \quad 1.1$$

Where $\Delta {CO_2}_{MC}$ is the CO2 saving given by the eco-innovation under modified conditions; B_{MC} is the CO_2 emission of baseline vehicle under modified conditions and E_{MC} is the CO_2 emission of innovative vehicle under modified conditions; UF_{MC} is the usage factor for the modified conditions.

When the innovative technology is active under type approval, the innovative and baseline vehicles must be tested again (a usage factor is multiplied to corresponding CO_2 savings) and the resulting CO_2 savings should be subtracted from the previous.

$$\Delta CO_{2TA} = (B_{TA} - E_{TA}) \cdot UF_{TA} \quad 1.2$$

$$C_{CO_2} = \Delta CO_{2MC} - \Delta CO_{2TA} \quad 1.3$$

In order to better clarify the meaning of the usage factors it is important to underline that CO_2 savings of an eco-innovation must be accountable to manufacturer (or supplier) only. This means that all other possible influencing parameters should be excluded to ensure a constant rate of activation. However, technologies which can be switched on and off, but are normally activated and deactivated because of changing ambient conditions to ensure safe operation of the vehicle could be eligible, provided that relevant statistical data can support the actual CO_2 reducing effect of the technology (usage factor). In general, the driver should not be conscious of the existence of the technology.

1.3. Approved Eco-innovations

Table 1.2 reports a list of the technologies already approved as Eco-innovations by the European Commission.

Applicant	*Technology*	*Eco-innovation code*
Audi AG	LED Lamps	1
Valeo Equipments Electriques Moteurs SAS	Efficient alternator	2
Daimler AG	Engine compartment encapsulation	3
Robert Bosch Car Multimedia GmbH	Navigation based battery charge for hybrid vehicles	4
Automotive Lighting	Low power consumption LED Low Beam module - E-LIGHT	5
Denso Corporation	DENSO efficient alternator of the output class of 150A, 180A, 210A	6
Webasto Roof & Components SE	Battery charging Webasto solar roof	7
Robert Bosch GmbH	High efficiency alternator (HED)	8
Robert Bosch GmbH	High efficiency alternator (SAR)	9
Daimler AG	Efficient exterior lighting with the use of LED	10
asola Technologies GmbH	Charging solar roof	11
MITSUBISHI ELECTRIC COROPORATION (MELCO)	High efficiency Gxi alternator	12
Porsche AG	Coasting	13
Denso Corporation	Efficient alternator	14
Toyota Motor Europe	LED lightings	15
MITSUBISHI ELECTRIC COROPORATION (MELCO)	Motor generator	16

Robert Bosch GmbH	High efficiency alternator (MGD)	17
Valeo Electrical Systems	High efficiency alternator (high efficiency diodes)	17
MAHLE Behr GmbH & Co. KG	MAHLE Enthalpy storage tank (EST)	18
Honda Motor Europe Ltd	LED lightings	19
Mazda Motor Corporation	LED exterior lightings	19
Toyota	LED lightings for Non Externally Chargeable Hybrid Electrified Vehicles	20
A2-solar	Automotive solar roof	21
Valeo Electrical Systems	12V iSTARS belt-driven starter-alternator	22
BMW	Engine Idle Coasting Function	23

Table 1.2 List of approved Eco-innovations

The list is updated to 25 January 2018. The code on the third column is the code to be entered into type-approval documentation as specified in the Implementing Decision of the corresponding innovative technology.

1.4. Idle coasting

Coasting is the dynamic condition in which the vehicle keeps on moving because of its own kinetic energy with the wheels disconnected from the engine (it is also known as "free-wheeling") and slows down because of external resistances only, the so-called coast-down forces. This behaviour in some conditions brings benefits in terms of fuel consumption because it allows to avoid useful vehicle kinetic energy dissipation due to engine frictions and to cover a longer a distance than a similar vehicle travelling with engine connected to wheels.

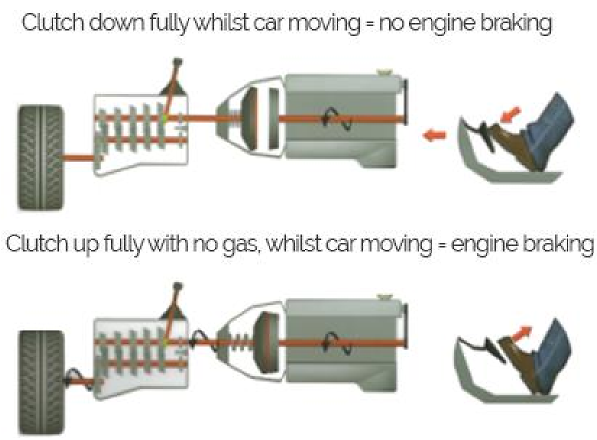

Figure 1.6 Engine braking and coasting in neutral working principle in a Manual transmission

Such a situation can be practically experienced on a moving car with Manual transmission putting the gearshift in neutral and keeping the brake pedal released. However, for driveability and safety reasons coasting should be activated automatically and not by the driver himself. For this reason, it is applicable to automatic gearbox or manual gearbox with electronic clutch.

1.4.1. History

Free-wheeling techniques have a quite long history. In 1958, the Trabant 500, "the car of East Germany", was equipped with a mechanical free-wheeling function. Initially in all gears, this free-wheeling mechanism was implemented into the 4th gear only for later models.

In order to address the second oil crisis, Volkswagen developed the so called "Schwungnutzautomatik" (SNA) in the late 1970s. Based on a manual transmission, SNA combined an automated clutch with an engine Start/Stop system. This allowed to automatically decouple the engine and transmission during coasting conditions, to stop the combustion engine and to restart it as soon as the accelerator pedal was depressed. Different techniques were considered: starting the combustion engine via starter motor (SNA-1) and also using a flywheel to restart the engine (SNA-2). This flywheel was positioned between the transmission clutch and a second clutch separating it from the engine. For this second technique the starter motor was only needed for the initial start and for restarts after long stop-phases. In 1980 Volkswagen planned to implement the SNA-1 concept into the Golf I for the American market. However, the end of the oil crisis stopped this project due to a lack of demand.

In 1994 Volkswagen adopted the SNA-1 idea for the Golf III Ecomatic. This 1.9L SDI diesel car was equipped with an electro-pneumatically actuated automatic gearbox. There was a manual gearshift lever, but no clutch pedal, which made the handling of the car rather unique. As a result vehicle was never really accepted by the market. To meet the increased technical requirements, an improved brake vacuum monitoring system was implemented, including a larger vacuum storage with a mechanically operated vacuum pump. To avoid voltage drops induced by the starter motor, a larger battery and alternator as well as an additional small backup-battery for lights were added. Free-wheeling could be turned off by an extra switch in the dashboard.

The next step was made in 1999 with the VW Lupo 3L TDI. An automated manual transmission was used, with hydraulically actuated clutch and gear selector. During coasting conditions, the clutch would open and the engine would be operated at idle speed.

With the introduction of parallel hybrid vehicles that use an additional clutch between the combustion engine and the drivetrain, coasting engine off has lately made its way into various series applications like the Porsche Cayenne Hybrid introduced in 2010. Non-hybrid vehicles like the 2010 VW Passat 1.4L TSI Bluemotion also apply this fuel-saving technique. For non-hybrid vehicles, the first development step of coasting technology is with the combustion engine operated at idle speed in order to drive accessories that are nowadays still coupled to the engine. With more and more accessories being driven alectrically, the next development step will be towards turning off the combustion engine duting coasting. [12]

1.4.2. Physics principle

Engine frictions due to mechanical and pumping losses can be significant especially with increasing engine displacement and increasing engine speed. The on road real benefit of coasting is based on the fact that in this phase the energy waste due to those losses is eliminated, because the engine is decoupled from the wheels. Figure 1.7 shows the behaviour of frictions with respect to engine speed [14].

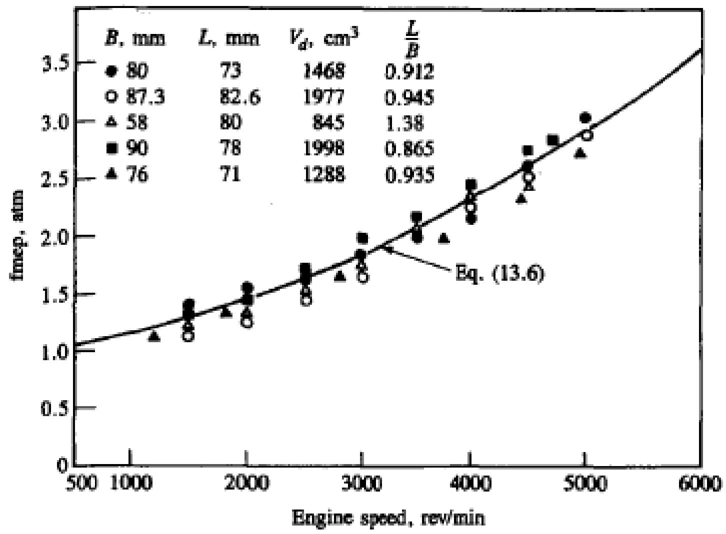

Figure 1.7 Frictions Mean Effective Pressure under motored conditions at wide-open throttle for several 4 cylinder SI engines. (L = stroke, B = bore, V_d = engine displacement)

In modern vehicles it is widely applied the strategy of Fuel Cut-Off during decelerations. The fuelling is switched off when the vehicle is slowing down and the wheels are dragging the engine, leading practically to no fuel consumption during decelerations. The idle coasting would cut down this benefit as the engine would continue to run at idle speed in those situations. But when the vehicle is freewheeling decoupled from the engine it can cover a greater distance with respect to the same vehicle with the gear engaged, allowing in certain conditions to more than compensate the lost benefit of FCO. Figure 1.8 shows vehicle speed in engine braking and coasting condition.

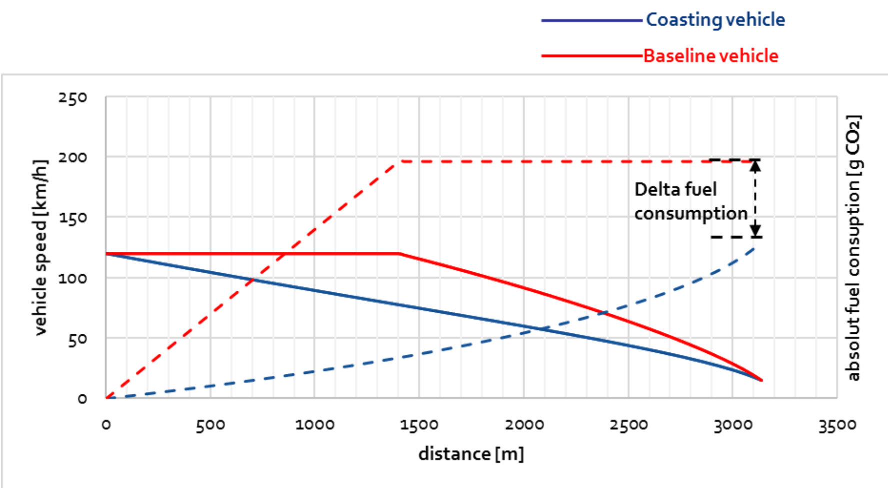

Figure 1.8 Rolling distance of a midsized vehicle in engine braking and in coasting deceleration modes

1.4.3. Idle coasting as an Eco-innovation

In real world coasting is possible in different situations depending on road and traffic conditions, for example approaching a roundabout or a traffic light or travelling on the highway on a slight descent.

In the NEDC homologation cycle the speed profile is simplified and standardized: it contains constant accelerations, constant decelerations, stops and constant speed phases. Furthermore, a unique profile is defined for every existing passenger car. With this boundary conditions it is not possible to perform coasting while following NEDC speed profile.

To determine in an objective way the CO_2 benefits of coasting a modified speed profile has been created, starting from the NEDC homologation cycle and substituting part of the deceleration phases with coasting phases. It is important to underline that one modified NEDC cycle must be built for each test vehicle, because each vehicle has its own coast-down parameters.

For this reason, the coast-down curve of the vehicle shall be defined on the dynamometer, performing a deceleration from 120 km/h down to standstill or to the lowest speed possible with the engine disconnected from the wheels (clutch disconnected). Then the modified NEDC profile must be generated taking into account the following constraints:

1) The distance at the end of each deceleration phase of the mNEDC shall be equal to the distance at the end of each deceleration phase of the NEDC;
2) In cases where multiple coasting curve solutions are possible, the selection of solution should be made such that deviation from the NEDC profile is minimized;
3) During coasting phase the engine is decoupled from the wheels and no active correction of the vehicle trajectory is permitted;

Furthermore, the following boundaries shall be respected:

1) Lower speed limit for coasting; the coasting phase must be interrupted when the vehicle reaches a speed of 15 km/h, following from this point a speed profile parallel to the corresponding NEDC deceleration ramp.
2) Minimum stop time; after every deceleration to standstill 2 seconds of stop must be respected.
3) Minimum time for constant speed phases; after every acceleration 2 seconds of constant speed must be respected.

4) Minimum time between coasting phases; between two consecutive coasting phases 4 seconds must pass.

In general, accelerations, decelerations and constant speed levels must be equal to those of NEDC and speed and time tolerances must follow UN/ECE Regulation No. 101.

1.4.4. Porsche AG case

Idle coasting technology has been already exploited as an Eco-innovation in the recent past. The first example is the Commission Implementing Decision 2015/1132 approving Porsche AG coasting function as an innovative technology for reducing CO_2 emissions from passenger cars. The decision published on the Official Journal on 10 July 2015 regards Porsche S-segment M1 vehicles (sports coupé) and the technology is referred to as an automatic gearbox intelligent control strategy allowing the vehicle to run with the combustion engine decoupled from the wheels and idling.

The application has been approved by the Commission according to Implementing Regulation No 725/2011 mentioned in Chapter 3 and included the testing methodology used to evaluate CO_2 emissions reduction from the use of the coasting function. The methodology is defined as follows.

Two testing vehicles are provided:

Eco-innovation vehicle: a vehicle with innovative technology activated;

Baseline vehicle: a vehicle with innovative technology deactivated.

It is necessary to determine the CO2 emissions from the eco-innovative vehicle under modified testing conditions (E_{MC}) and the CO2 emissions from the baseline vehicle under modified testing conditions, i.e. hot start NEDC (B_{TAhot}).

A conversion factor is required for the calculation of potential CO_2 savings to take into account the difference between emissions from the NEDC test (B_{TA}) and those under modified NEDC test (B_{MC}) for the baseline vehicle. The factor c is defined as the ratio between B_{MC} and B_{TA} and it is set to a value of 0.96, even if it could slightly differ from this value depending on transmission characteristics and other vehicle parameters.

E_{MC} is measured from the vehicle with the idle coasting activated running along the modified NEDC speed profile (mNEDC, explained in Paragraph 4.3.1). One or more preconditioning test should be performed to reach the hot testing conditions of engine, motor and battery and the final CO_2 emissions value is the arithmetic mean of at least three repetitions. B_{TAhot} is measured from the vehicle with the idle coasting deactivated running along the NEDC type approval speed profile. Again, the preconditioning test and the mean of at least three repetitions shall be made to obtain the final value.

Finally, the formula used to calculate CO_2 savings of the eco-innovation is the following:

$$C_{CO2} = (c \cdot B_{TAhot} - E_{MC}) \cdot UF \qquad 1.4$$

Where

C_{CO2} : CO_2 savings in g CO_2/km;

c : conversion parameter equal to 0.96;

E_{MC} : arithmetic mean of CO_2 emissions along mNEDC for eco-innovative vehicle;

B_{TAhot} : arithmetic mean of CO_2 emissions along NEDC (hot start conditions) for baseline vehicle;

UF : usage factor equal to 0.8 for Porsche S-segment vehicles, reduced to 0.4 where cruise control is present;

In order for the idle coasting to be awarded as eco-innovation it has to be demonstrated that the statistical error of the total CO_2 saving is not exceeding 0.5 g CO_2/km and that the total CO_2 saving is exceeding the minimum threshold with a statistic relevance through the following formula:

$$MT = 1\ gCO_2/km \leq C_{CO_2} - s_{C_{CO_2}} \qquad 1.5$$

Where:

MT : minimum threshold equal to 1 g CO_2/km;

C_{CO_2} : CO_2 savings in g CO_2/km;

$s_{C_{CO_2}}$: standard error of total CO_2 savings;

1.4.5. BMW AG case

Commission Implementing Decision 2017/1402 approved BMW AG engine idle coasting function as eco-innovation on 28 July 2017. BMW extended the application to all its M1 vehicles with conventional powertrain and automatic transmission. A value of 0.7 has been proposed to the Commission, but a more conservative 0.62 was recognized. The rest of the application is almost equivalent to Porsche’s.

2. Case study

2.1. Experimental campaign

The fleet is made up of a homogeneous population of cars. Indeed, they are of the same brand and of the same model, sharing also the powertrain architecture and specifications. The main difference among them is the driver, with its own driving style and intentions. By the way this is not a factor of secondary importance, because fuel consumptions are strongly affected by the driving style.

The fleet analysed is composed by 19 users, each recording a daily mileage ranging from 34 to 163 km per day and an overall average speed ranging from 35.9 to 74.6 km/h. The total mileage is almost 64000 km in about 800 days of recording. Table 2.1 lists the most relevant statistics for each driver.

Vehicle ID	**Distance [km]**	**Duration [hrs]**	**Days**	**Average daily mileage [km/day]**	**Average speed [km/h]**
318	4952	84	59	84	58.9
732	8005	107	49	163	74.6
733	5397	92	50	108	58.8
766	4083	74	44	93	55.0
767	3086	46	41	75	66.5
768	2030	48	40	51	42.5
770	2859	57	42	68	49.8
771	1629	35	26	63	46.4
772	1258	35	37	34	35.9
920	2958	72	51	58	41.3
318a	3044	65	35	87	46.6
732a	2401	57	46	52	42.1
733a	1919	31	26	74	61.1
766a	4279	76	41	104	56.1
767a	2444	41	32	76	59.5
768a	2849	49	25	114	58.0
771a	3495	70	39	90	49.8
772a	4721	90	45	105	52.6
920a	2497	67	51	49	37.5
Overall	**63908**	**1198**	**779**	**82**	**53.4**

Table 2.1 Main statistics of each user

2.1.1. Data acquisition

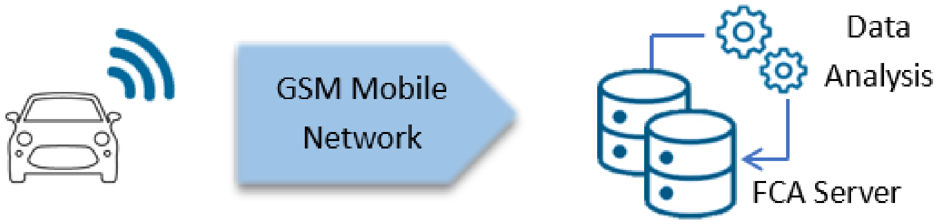

Figure 2.1 Working scheme of the data acquisition system

The experimental data have been acquired through a telematics box installed in the vehicles. This device allows to acquire data from the vehicle and send them live on GSM network to a server. The data have been post-processed and analysed by FCA.

The acquisition box is easy and fast to install and it is connected directly to OBD diagnostic port. The data acquired consists of CAN messages and are related to vehicle status (vehicle speed, engine speed, battery state of charge, accelerator pedal position, etc.) and to external conditions (intake air temperature, road slope, etc.). Once the device is installed on the vehicle it is possible to upgrade it remotely, for example adding or removing the acquired CAN messages or modifying the acquisition frequency.

It is possible to use this system on prototypes, during the development phase or for specific acquisition campaign for performances characterization.

2.1.2. Statistical analysis

Two different classes have been defined depending only on the average speed during the driving mission: a low-speed class (between 18 and 25 km/h) and a high-speed class (between 70 and 80 km/h). Further criteria have been used to make the samples more uniform: driving missions with very low mileage (< 5 km) and with relative braking distance out of the range 5-20% have been excluded. Then each speed class has been divided into two samples, one with a higher relative coasting distance (more than 3%) and the other with a lower relative coasting distance (less than 3%), representing respectively those who make a consistent use of idle coasting function and those who do not. The relative coasting distance is defined as the ratio between the distance travelled in coasting mode and the total distance covered in the mission. Looking at the average fuel consumption along the driving mission it is possible to notice a reduction of 8% for the low-speed class, which rises up to 11% for the high-speed class. Figure 2.2 shows the fuel consumption of every user selected in the analysis, plotted as a function of the average speed; each point represents a daily driving mission and the points are divided between those who use more frequently and those who use less frequently the idle coasting feature.

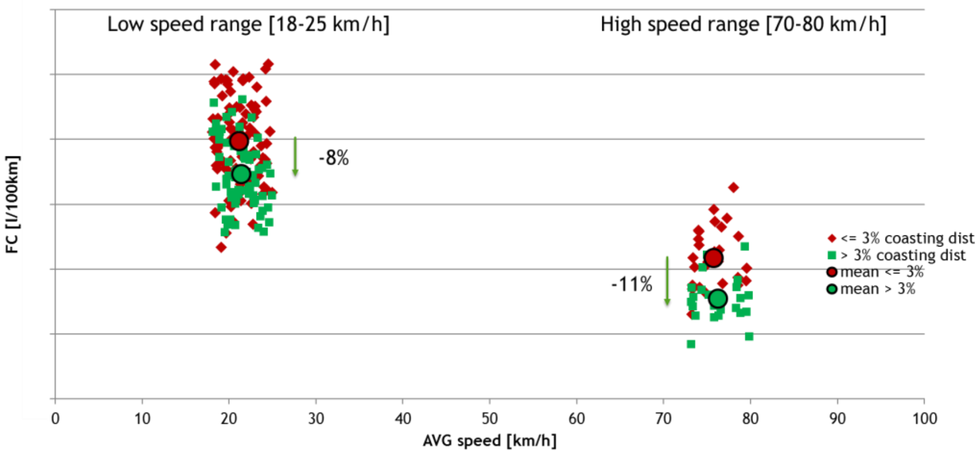

Figure 2.2 Fuel consumption of the driving mission acquired. Green: relative coasting distance higher than 3%; Red: relative coasting distance equal or lower than 3%

In order to assess the statistical significance of the analysis, a Student t test has been made on the mean fuel consumption values of the two samples. Applying Equation 2.1 it is possible to calculate t parameter for each of the two speed classes.

$$t = \frac{|\mu_1 - \mu_2|}{\sqrt{\frac{(n_1 - 1)\cdot\sigma_1{}^2 + (n_2 - 1)\cdot\sigma_2{}^2}{n_1 + n_2 - 2}\cdot\frac{n_1 + n_2}{n_1 n_2}}} \qquad 2.1$$

Where

t : Student t variable

μ_i : mean of sample i

n_i : number of elements of sample i

σ_i^2 : standard deviation of sample i

Subscript i refers to sample (1 is the green sample, 2 is the red sample)

Student t distribution returns a significance level more than acceptable, as it the probability of null hypothesis is lower than 0.01. Table 2.2 and Table 2.3 report the main statistics of the samples, together with their significance level.

Low speed	*n*	*Std deviation [l/100km]*	*DOF*	*Delta FC [%]*	*P*
RCD<3%	84	1.3	153	**8**	**0.000**
RCD>3%	71	0.9			

Table 2.2 Statistics of low speed range samples

High speed	*n*	*Std deviation [l/100km]*	*DOF*	*Delta FC [%]*	*P*
RCD<3%	27	0.8	42	**11**	**0.001**
RCD>3%	17	0.7			

Table 2.3 Statistics of high speed range samples

2.2. Numerical model

The calibration and optimization of modern hybrid powertrain utilization strategies require a virtual model to simulate the behaviour of each component of such a complex system. It is impossible to handle the interactions between so many subsystems and to evaluate their sensitivity with respect to fuel efficiency performance through the analysis of on field experiments only. Indeed, this type of approach turns out to be extremely time consuming and ineffective not only with complex HEVs but also with simpler powertrain control strategies such as idle coasting. At the same time, the need to simulate fuel economy and CO_2

emission performances over an entire homologation cycle or long driving missions often lead to choose a map-based model of the entire vehicle rather than to develop detailed models of each component.

Even with a simplified vehicle model, it is now preferable to adopt an approach able to capture the system transients, which are becoming more and more relevant on dynamic driving cycles, such as WLTC. In the following paragraphs a general overview of the most used simulation approach will be given to point the most suitable for the purpose of this project.

2.2.1. Kinematic approach

It is also known as backward method because it retrieves the vehicle speed and the road load form the driving mission given as an input. The engine speed is obtained through simple kinematic relationships: from the rotational speed of the wheels knowing the transmission ratios of the final drive and of the gear engaged it is possible to calculate the engine rotational speed at each instant. The engine torque is evaluated starting from the torque required at the wheels to move the vehicle: from the given speed profile the tractive force is calculated based on longitudinal dynamic equilibrium using the vehicle coast-down parameters estimated through its main characteristics (mass, tyre rolling resistance, aerodynamic resistance, etc.). Once both the engine speed and the engine torque are known the interpolation of steady state maps gives the instantaneous fuel consumption and the total value over the driving mission is obtained through a simple integration of instantaneous values. Figure 2.3 depicts a scheme of the logic behind the kinematic approach.

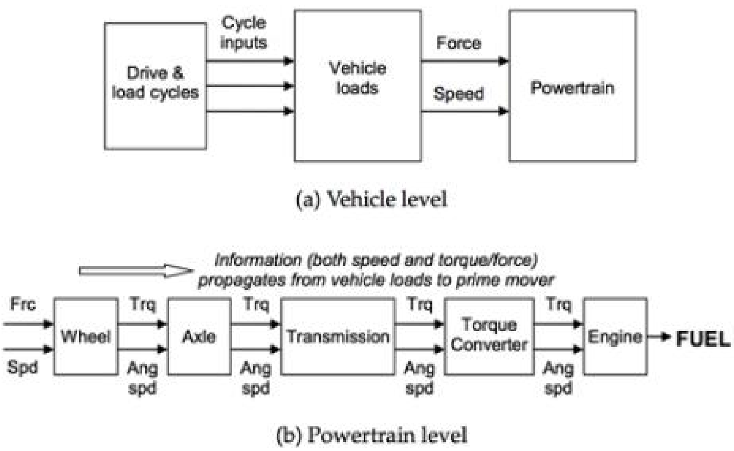

Figure 2.3 Information flow in a kinematic model (backward method)

This method is very effective for the preliminary feasibility study of a new technology, but it has some limitations: it represents the simulation as a sequence of stationary states neglecting the dynamic behaviour of the whole system; moreover, it assumes that the speed trace is reproduced exactly, which is not true both in test cycles and in real driving missions. Figure 2.4 shows the principle of a map-based backward model.

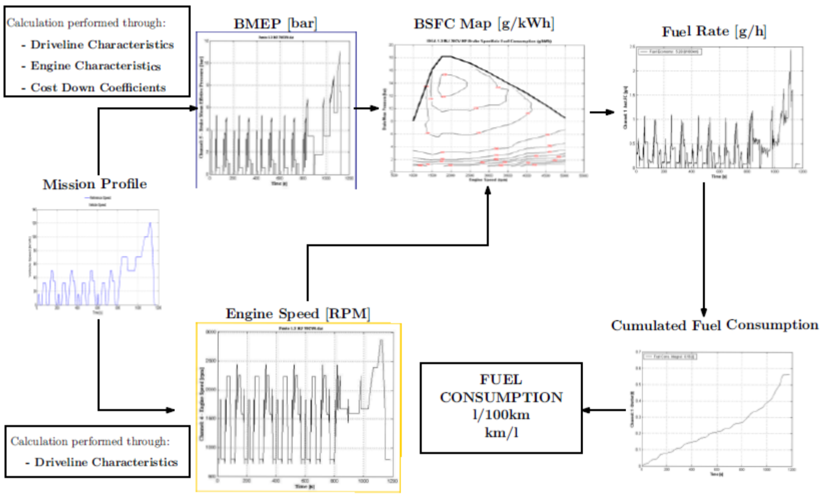

Figure 2.4 Information flow in a backward model for motor vehicles' fuel consumption calculation

2.2.2. Quasi-static approach

Contrary to what happens with the kinematic approach, in this method the driving mission is the not the only input, because it is filtered by the action of a driver (typically modelled as a PID controller). The driver acts on the vehicle through a power request (converted in accelerator and brake pedal position) depending on the difference between the actual vehicle speed and the speed defined by the driving mission. From the power requested it is possible to obtain the instantaneous fuel consumption and the cumulated value with the same methodology explained in the kinematic case. Figure 2.5 depicts a scheme of the logic behind the quasi-static approach.

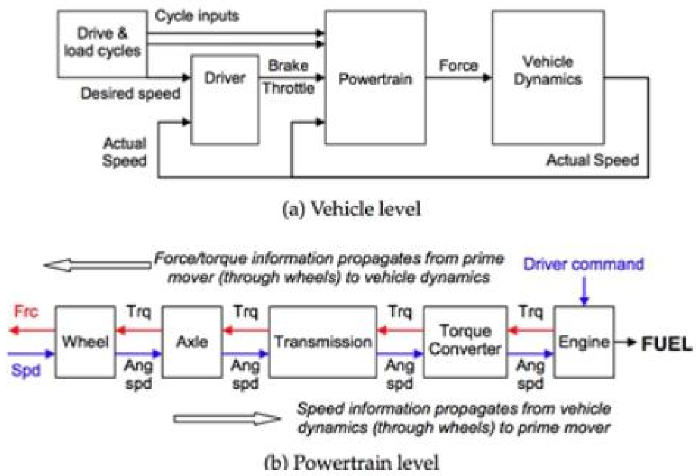

Figure 2.5 Information flow in a quasi-static model

This method still model the main components of the system through steady state maps, without reproducing the effects of transient phenomena, but it introduces the driver action leading to a more realistic dynamic behaviour of the system. For the purpose of this project a quasi-static approach has been considered sufficiently accurate, providing a reasonable accuracy on test cycles such as NEDC and WLTC.

2.2.3. Dynamic approach

A dynamic approach is modelling the fluid dynamic of internal combustion engine and of other subsystems to provide a detailed characterization of transient. It is particularly suitable for the performance evaluation of components such as turbochargers and it can adequately simulate manoeuvres such as strong tip-in and accelerations.

2.3. Control strategy

The most important parameter in powertrain control system is the accelerator pedal position, because it is a physical quantity strictly related to driver-vehicle interface. Translating the pedal position into a torque request it is possible to correlate directly the driver torque demand with the vehicle response. A good correlation of this kind leads to good level of driveability.

Therefore, it is appropriate to adopt a control strategy based on torque request. Considering a vehicle moving with a certain speed and acceleration it is possible to define the power the engine has to provide for motion (Equation 2.1) and consequently the corresponding torque (Equation 2.2).

$$P_{ICE} = (F_{aer} + F_{rr}) \cdot V_{veh} + m_V \ddot{x} V_{veh} \qquad 2.1$$

$$n_{ICE} T_{ICE} = n_W (T_{RL} + m_v \ddot{x} r_W) \qquad 2.2$$

It is important to notice that the torque requested by the driver through the accelerator pedal (T_{REQ}) is not equal to the torque needed for motion (T_{ICE}), because of the engine friction ($T_{motoring}$).

$$T_{ICE} = T_{REQ} - T_{Motoring} \qquad 2.3$$

To define the control strategy for coasting entry/exit it is possible to compare T_{REQ} with these two thresholds:

- T_{RL}: is the torque needed to proceed at constant speed (including aerodynamic resistance, rolling resistance and road slope).
- $T_{motoring}$: is the torque needed to overcome engine friction.

Therefore, 4 different areas are defined:

1. Area A: the torque requested by the driver is higher than the road load and the vehicle accelerates; here coasting cannot be enabled.
2. Area B: the torque requested by the driver is still positive (the accelerator pedal is slightly pressed), but the vehicle slightly decelerates; here coasting can be enabled, in fact the energy of the fuel in these conditions is used to overcome engine resistances and not to propel the vehicle.
3. Area C: the torque requested by the driver is negative, but it is still lower in module than the motoring torque and some fuel should be burned to overcome engine friction; here the coasting can be enabled again and the desired deceleration can be achieved using brakes.
4. Area D: the torque requested by the driver is negative and higher in module than the motoring torque; here coasting should be inhibited because the engine braking effect is helpful to decelerate the vehicle and the engine is running in FCO mode.

Figure 2.6 shows these 4 operating areas.

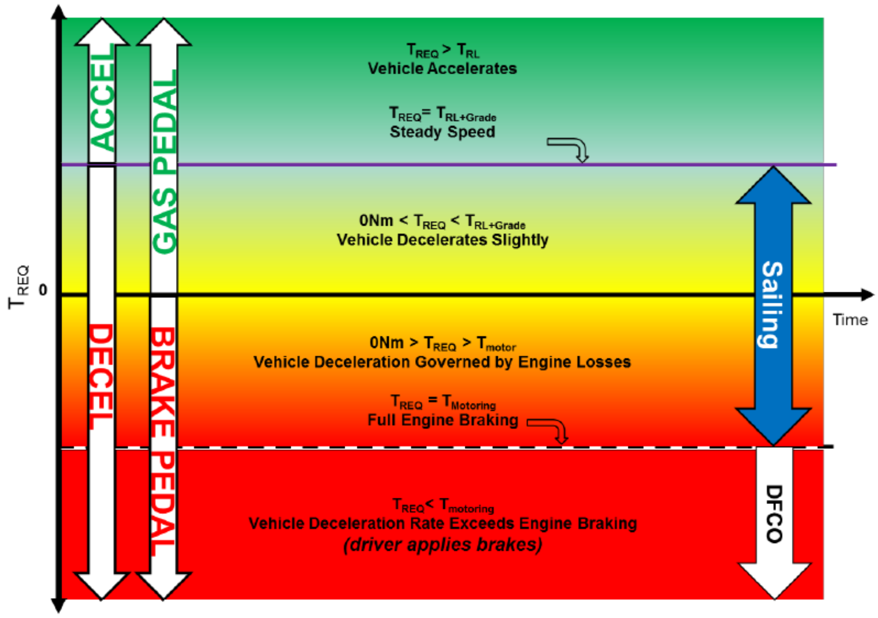

Figure 2.6 Sailing operating areas

For sake of simplicity, the two torque threshold values are considered to be constant over time. In actual working conditions those values are varying during the driving mission.

2.4. GT model description

In order to perform some simulations of fuel consumption performances a GT-Suite v2017 model of the vehicle was used. It is based on several blocks which represent the main parts of the vehicle/driver system relevant to the energy consumptions evaluation.

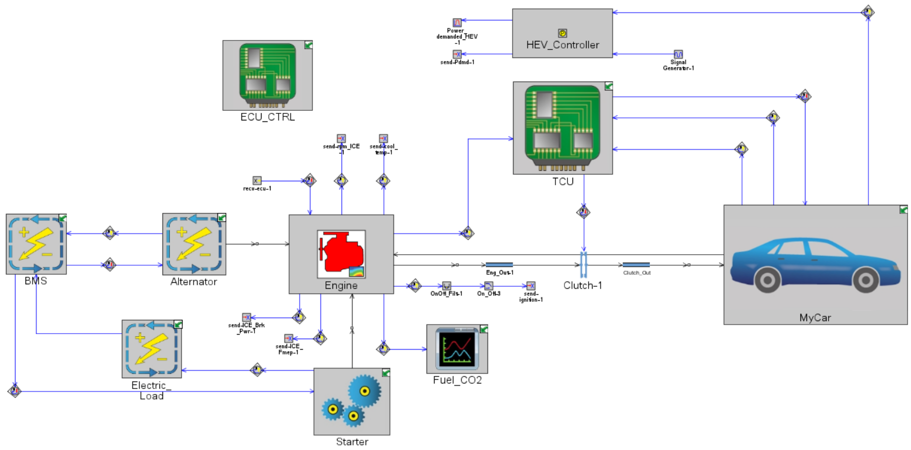

Figure 2.7 GT-Suite vehicle model overview

In particular, a *ControllerHEV* template in speed-targeting mode is used to allow the development of quasi-static approach in the driving cycle simulation. It calculates the necessary tractive power for a targeted vehicle speed, i.e. the cycle speed profile of the driving mission, and correct the demanded power through a PI control in order to minimize the error between the target and instantaneous vehicle speed values. The power demanded is then sent to the driver subassembly which operates the accelerator, clutch and brake pedals.

2.4.1. Vehicle characteristics

The vehicle chosen for the numerical simulations is a D-segment passenger car, equipped with a 2.2 liter diesel engine and an Automatic Transmission (AT). Main characteristics of the powertrain and vehicle system are reported in Table 2.4, Table 2.5 and Table 2.6.

Vehicle	
VDE at 100 km/h	13.9 kW
Mass	1445 kg

Table 2.4 Vehicle characteristics

Engine	
Displacement	2143 cm^3
Fuel	Diesel
Max Power	132.5 kW
Max Torque	450 Nm

Table 2.5 Engine characteristics

Transmission	
Type	Automatic
Speeds	8
Gear ratio	**1**st 5.0 **2**nd 3.2 **3**rd 2.143 **4**th 1.72 **5**th 1.314 **6**th 1 **7**th 0.822 **8**th 0.64
Final Drive ratio	2.62

Table 2.6 Transmission characteristics

2.4.2. Vehicle subassembly

The vehicle subassembly contains the main blocks modelling a conventional vehicle, such as vehicle itself (*VehicleBody*), axles (*Axle*), tires (*TireConnRigid*), brakes (*Brake*), transmission (*Transmission*) and differential (*Differential*), as well as road (*Road*) and external environment (*VehicleAmbient*).

2.4.3. Engine, Transmission and Clutch

The internal combustion engine is modelled through the *EngineState* template; it is map-based model of a conventional engine which describes engine performances, fuel consumption and emissions based on maps defined as function of load and engine speed. The engine is directly controlled by the *IceController*, which manages conditions such as idling and fuel cut-off.

In the *Transmission* template each gear ratio and in gear efficiency are defined, whereas the clutch is modelled through the *ClutchConn* template.

2.4.4. Transmission Control Unit

In the TCU block the control logic explained in Section 2.3 is implemented by means of look-up tables and logic operators. Four different vehicle parameters are taken as input to verify that the coasting event can be enabled:

- Vehicle speed; the vehicle speed must be lower than the maximum threshold and higher than the minimum threshold in order for the coasting to be activated. Those thresholds can be set depending on the feature specifications. At the same time the vehicle speed must remain in the tolerance band of +/- 2 km/h defined by the legislation.
- Gear engaged; an ad hoc look-up tables reporting the vehicle speed on one axis and the gear engaged on the other can be defined in order to inhibit or permit the activation of coasting in different conditions.
- Accelerator pedal position; a maximum threshold can be set, above which the coasting event is inhibited. A further parameter can be tuned in order to allow some hysteresis.
- Brake pedal position; a maximum threshold can be set, above which the coasting event is inhibited. A further parameter can be tuned in order to allow some hysteresis.

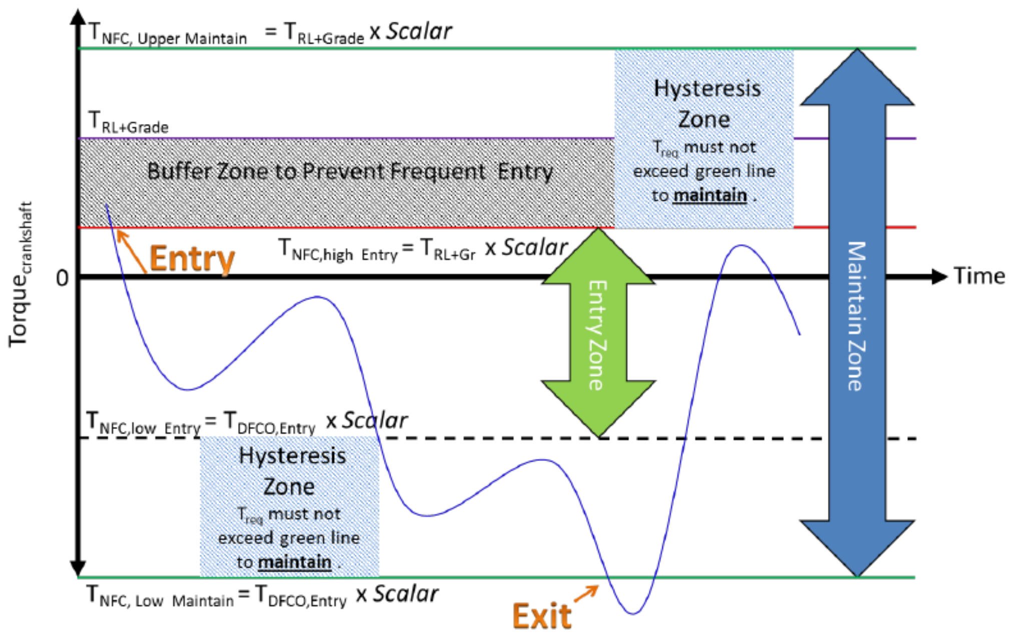

Figure 2.8 Coasting activation example: blue line shows the demanded torque behaviour and each Scalar assumes a different value according to calibration of entry/exit thresholds

If all the above conditions are respected at the same time the possibility to perform coasting is verified. At this point the power required by the vehicle to follow the targeted speed profile is sensed and it is compared to the thresholds defined in the control strategy. Two scalars are pre-multiplied to each threshold, defining the actual entry and exit thresholds and avoiding too frequent and consecutives entry/exit events. Figure 2.8 shows how the thresholds works and an example of the possible pattern followed by the power required.

From the instant in which the power enters the entry zone all the boundary conditions must be true for a minimum time (to be set arbitrarily), after which the coasting event actually begins. This is done to further reduce the possibility of too frequent on/off.

Coasting is shut off as soon as the power exceed the exit threshold or one of the conditions listed above are no more verified.

2.4.5. Engine Control Unit

The subassembly called Engine Control Unit (ECU) contains essentially the *ICEController* and the control logic of the activation of Start&Stop system, based on engine cooling temperature, vehicle speed and gear engaged.

2.4.6. Battery management system, Alternator and Starter motor

The battery is a modelled as a conventional automotive 12 V Lead-Acid battery with a capacity of 80 Ah. It is connected to an inverter, which limits the maximum charge and discharge current, as well as the maximum and minimum voltage. An alternator connected to the engine accessory pulley is modelled and the electrical loads are assumed to be constant, with the exception of the electrical power requested by the starter motor during engine cranking events.

2.4.7. Driver

The driver subassembly calculates the pedals position based on power demanded and other vehicle parameters and is made of four main blocks: the *VehDriver* template, the *EventManager* template, the *BrakeController* template and the *PowertoPedal* template.

The *EventManager* is a subset of logic statements and defines three events:

a) StandStill
b) DriveAway
c) Cruise

Each of these events corresponds to a combination of accelerator, clutch and brake pedal position. The purpose of this block is to better manage the driveaway event from a standstill condition.

For what the brake pedal is concerned in all the events its position is defined by the *BrakeController*. It calculates the brake pedal position based on the actual axle speed, the braking power demanded and the maximum torque deliverable by the brake.

Finally, the *PowertoPedal* is able to calculate the accelerator pedal position based on the power demanded, provided an engine map (bmep as a function of accelerator pedal position and engine speed) is given.

2.5. Model calibration

The control strategy of idle coasting feature has required a big effort to be calibrated. Each vehicle needs ad hoc calibration to avoid frequent entry/exit into coasting event, which result in deteriorated comfort and driveability as well as accelerated wear of driveline components. In fact, 11 parameters had to be tuned in order to obtain a satisfactory behaviour:

- Six parameters related to the power thresholds
- One constant defining time delay to activate the feature
- Four parameters defining accelerator and brake pedals levels to deactivate the feature

Several simulations have been carried with the aim to evaluate the sensitivity of each parameter on coasting event duration, coasting event frequency and CO_2 emissions along the driving mission. The best trade-off has been chosen to select the definitive values for the control parameters.

The calibration activity has been performed on the mNEDC in order to evaluate the CO_2 saving potential of idle coasting feature as Eco-innovation. The same calibrated parameters have been set for further considerations on other driving cycles.

2.6. Model validation

The numerical model has been validated with the aid of the time histories of data acquired and analysed. Two sets of data have been chosen to capture different driving conditions and driving behaviour. The first mission is

Comparing the vehicle speed simulated with the experimental vehicle speed it is possible to state that the driver/vehicle integrated system is able to reproduce almost perfectly the given mission profile. Figure 2.9 and Figure 2.11 report the speed profile and the coasting activation (when present) for both missions.

The simulated engine fuel consumption reported in Figure 2.10 and Figure 2.12 replicate faithfully the behaviour of the real world experimental data. The final discrepancy at the end of each mission can oscillate around 5 and 10%. The error is considered acceptable, taking into account that some external factors cannot be captured by the virtual simulation:

- External environment conditions, such as wind, road inclination, bumps and irregularity;
- Vehicle conditions, such as tyre pressure, actual load, possible accessories degrading aerodynamics;
- Gear shifting strategy, which can be significantly different as the transmission is automatic;
- Engine and transmission settings such as Start&Stop or Eco driving mode or other similar strategies affecting fuel consumption and driveability.

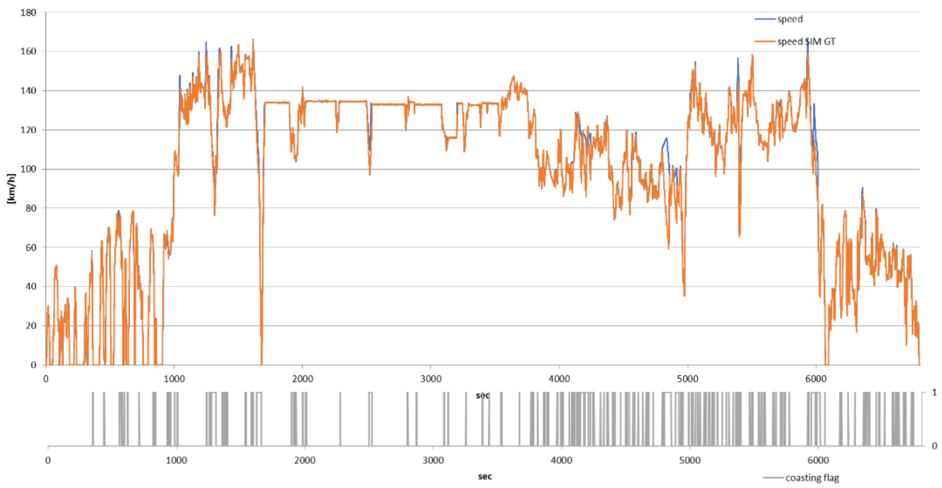

Figure 2.9 Experimental and simulated vehicle speed profile and coasting activation (mission 1)

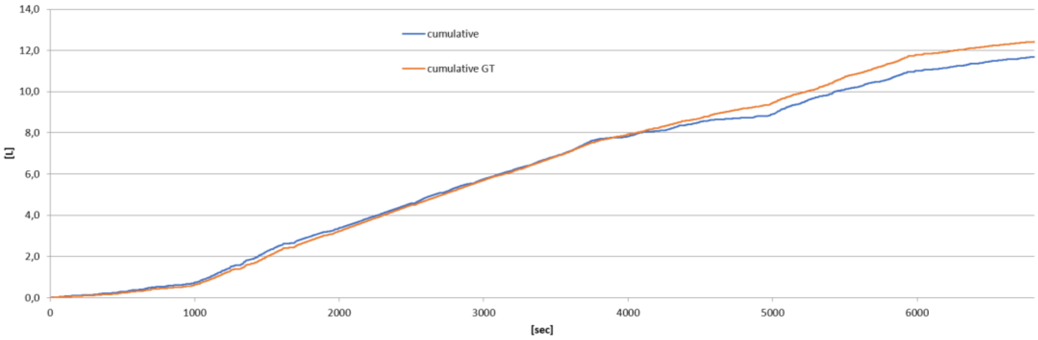

Figure 2.10 Experimental and simulated cumulated engine fuel consumption (mission 1)

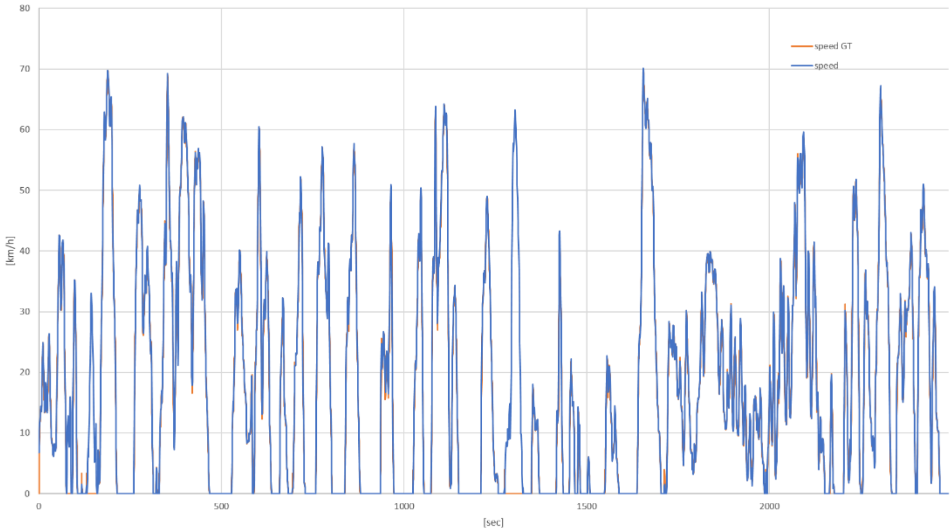

Figure 2.11 Experimental and simulated vehicle speed profile (mission 2)

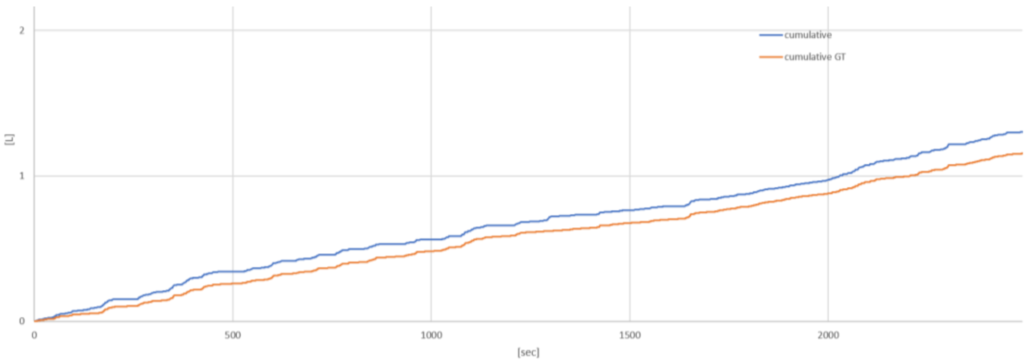

Figure 2.12 Experimental and simulated cumulated engine fuel consumption (mission 2)

3. Results

The simulations have been performed using the GT-Suite map-based model defined in Section 2.4 in order to compare fuel consumption and CO_2 emission levels in different situations.

Some reference driving cycles have been chosen to simulate the behaviour of idle coasting in a realistic mission. The comparison has been done between a standard baseline vehicle (idle coasting feature disabled) and with the same vehicle with the idle coasting feature enabled. The driving cycles chosen for the purpose are first of all a couple of actual homologation cycles such as NEDC (New European Driving Cycle) and WLTC (Worldwide harmonized Light-duty vehicles Test Cycle), and mNEDC (modified NEDC). The latter is the cycle specifically built in order to show the potential benefit along the NEDC of the correct usage of coasting feature in a real driving mission.

3.1. NEDC baseline

The baseline vehicle has performed the NEDC test simulation at hot start conditions; the initial coolant temperature in the engine block is 90 ºC and is set to be steady state for the whole cycle duration. Therefore, the engine Stop&Start system is enabled since the beginning of the cycle. The gear engaged is not imposed by testing procedure, since the transmission is automatic; therefore, a gear shifting strategy depending on engine rotational speed has been defined, upshifting at 1750 rpm and downshifting at 1100 rpm. Figure 3.1 illustrates the actual vehicle speed and the gear engaged over time as well as engine fuel consumption over the NEDC simulation of the baseline vehicle.

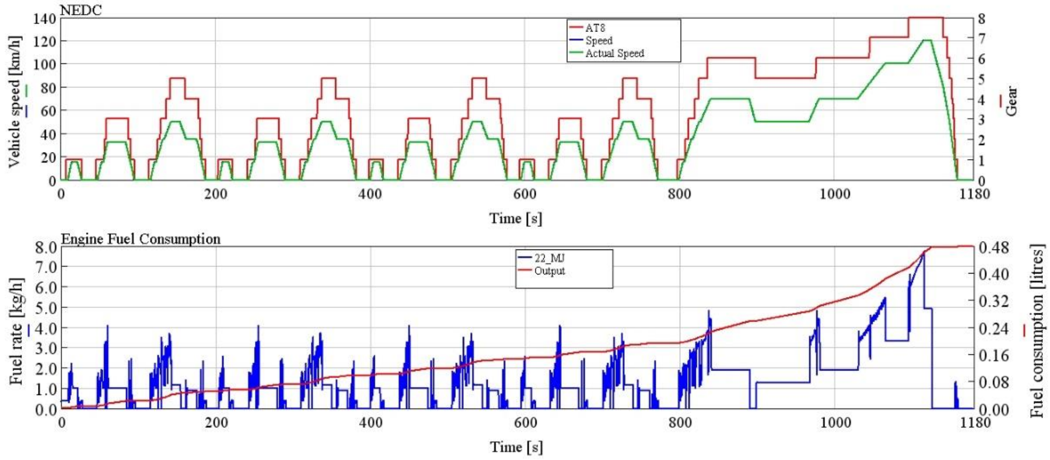

Figure 3.1 Upper) Target vs. actual speed and gear engaged; Lower) Instantaneous and cumulated fuel consumption of baseline vehicle on NEDC

Table 3.1 reports the most relevant statistics regarding NEDC simulation of the baseline vehicle.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative Coasting distance [%]*	*CO2 [g/km]*
NEDC	1180	11003	0	0	121

Table 3.1 NEDC baseline vehicle

3.2. NEDC with idle coasting

The same boundary conditions defined for the baseline vehicle has been adopted to perform the simulation along NEDC with idle coasting function enabled. Figure 3.2 illustrate the actual vehicle speed, the gear engaged and the coasting event flag over time

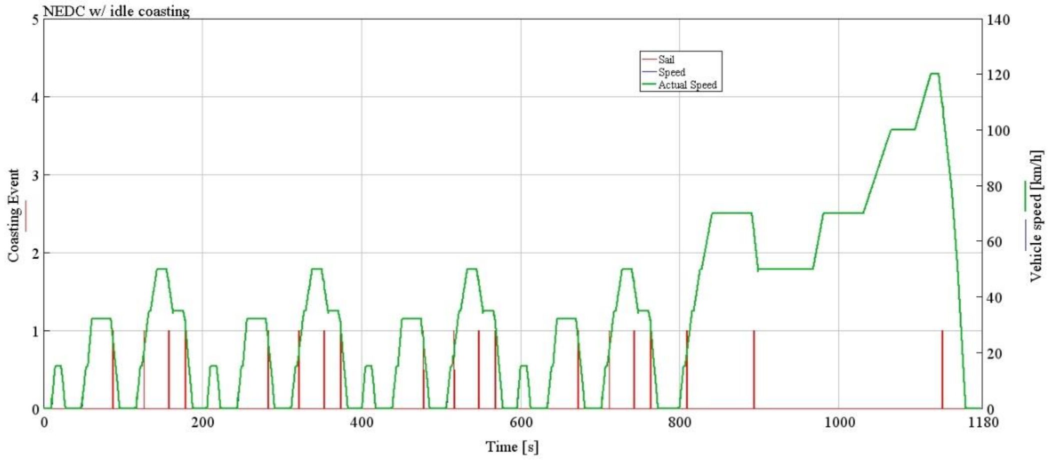

Figure 3.2 Target vs. actual speed and coasting activation of the vehicle w/ idle coasting enabled on NEDC

Running the model with idle coasting feature enabled along the NEDC it occurs occasionally that the coasting event is triggered few times and for very short durations (less than 1 second on average). Those events are immediately halted because the instantaneous actual speed of the vehicle exceeds the value set by the reference cycle. This happens because the decelerations in the NEDC are strong enough to require the activation of the brakes by the driver and are higher in module than the average vehicle coast-down deceleration.

This demonstrate clearly that a conventional driving behaviour such as the one reproduced in the homologation cycle wouldn't allow to take advantage of coasting potentials on road in the real world. Besides, it is widely agreed that the NEDC speed profile is not fairly reproducing real world driving conditions, which contains a wider range of acceleration and deceleration levels especially in extra-urban environment.

Table 3.2 reports the most relevant statistics regarding NEDC simulation of the vehicle with idle coasting function active.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative coasting distance [%]*	*CO2 [g/km]*
NEDC	1180	11007	19	1.6	123

Table 3.2 NEDC vehicle with idle coasting

It is worth to underline that the activation of idle coasting during the homologation cycle should be avoided through a fine and tuned calibration of the control strategy. In fact, unwanted activations could lead to worsening of CO_2 emissions.

3.3. WLTC baseline

Similarly to NEDC case, the simulation along WLTC cycle has been performed in hot start conditions. The main difference is that a different gear shifting strategy has been adopted; the upshift point has been set at 2000 rpm and the downshift at 1300 rpm. This has been done in order to assure the correct disengagement/engagement at the beginning and at the end of coasting events in the following simulations. In fact, the shifting strategy used for NEDC caused occasionally the engine to stall in the more dynamic WLTC. Figure 3.3 illustrate the actual vehicle speed and the gear engaged over time as well as engine fuel consumption over the WLTC simulation of the baseline vehicle.

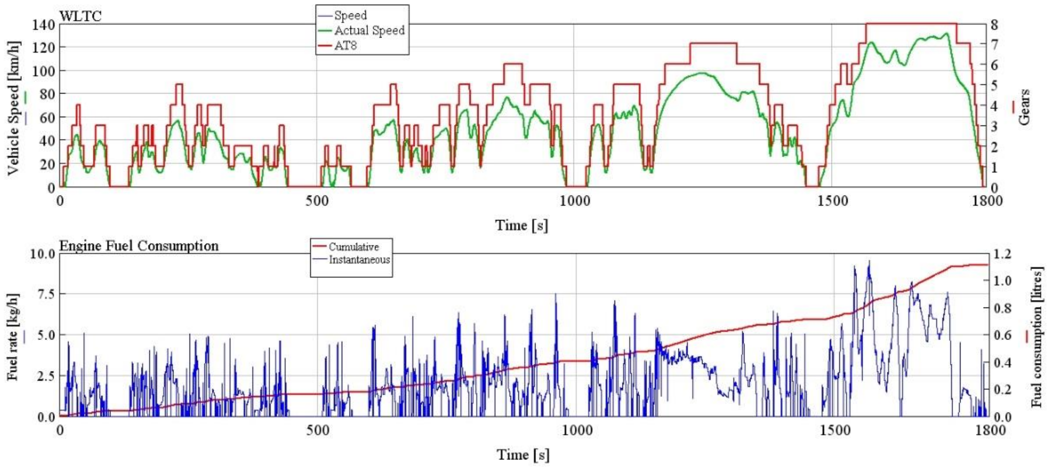

Figure 3.3 Upper) Target vs. actual speed and gear engaged; Lower) Instantaneous and cumulated fuel consumption of baseline vehicle on WLTC

Table 3.3 reports the most relevant statistics regarding WLTC simulation of the baseline vehicle.

	Total duration [s]	Total distance [m]	Coasting events	Relative Coasting distance [%]	CO2 [g/km]
WLTC	1800	23235	0	0	133

Table 3.3 WLTC baseline vehicle

3.4. WLTC with idle coasting

Simulations along the WLTC have revealed higher number of sections in which idle coasting activation is possible. This is due to the more dynamic nature of the new driving cycle which include a wider class of deceleration levels. For the same reason the average duration of coasting events turns out to be very short. Figure 3.4 shows the simulation on WLTC.

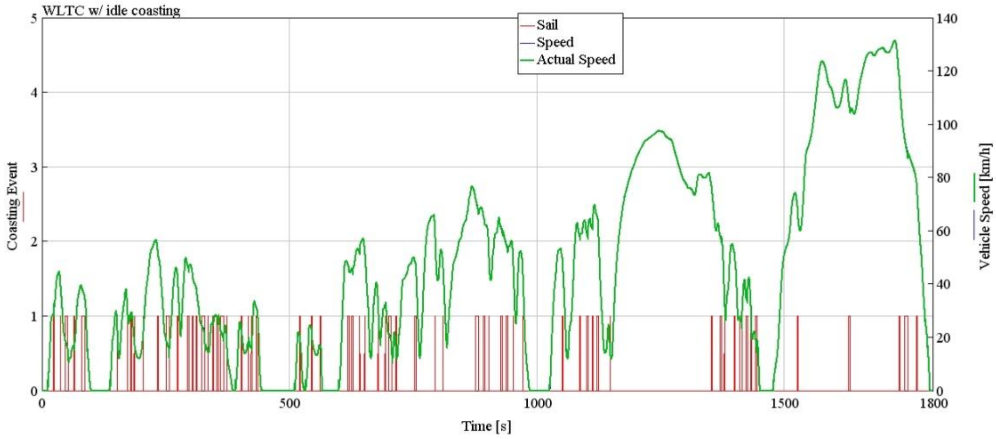

Figure 3.4 Target vs. actual speed and coasting activation of the vehicle w/ idle coasting enabled on WLTC

It is worth noticing that such a high number of idle coasting events one very close to the other it would be not acceptable from the driveability point of view. For the purpose of the thesis the control calibration adopted is satisfactory, but for a real world application higher effort is demanded to meet consumer requirements. Table 3.4 reports main statistic of WLTC simulation for the vehicle with idle coasting function enabled.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative Coasting distance [%]*	*CO2 [g/km]*
WLTC	1800	23228	66	7.7	132

Table 3.4 WLTC vehicle with idle coasting

3.5. mNEDC baseline

The testing conditions considered in the simulations along modified NEDC are those of the NEDC case, except for the speed profile. The idle coasting function is disabled; hence the virtual driver is following the imposed speed profile also in the deceleration phases where the coast-down curve has been introduced. To do so the accelerator needs to be slightly depressed in those phases.

Figure 3.5 illustrates the actual vehicle speed and the gear engaged over time as well as engine fuel consumption over the mNEDC simulation of the baseline vehicle.

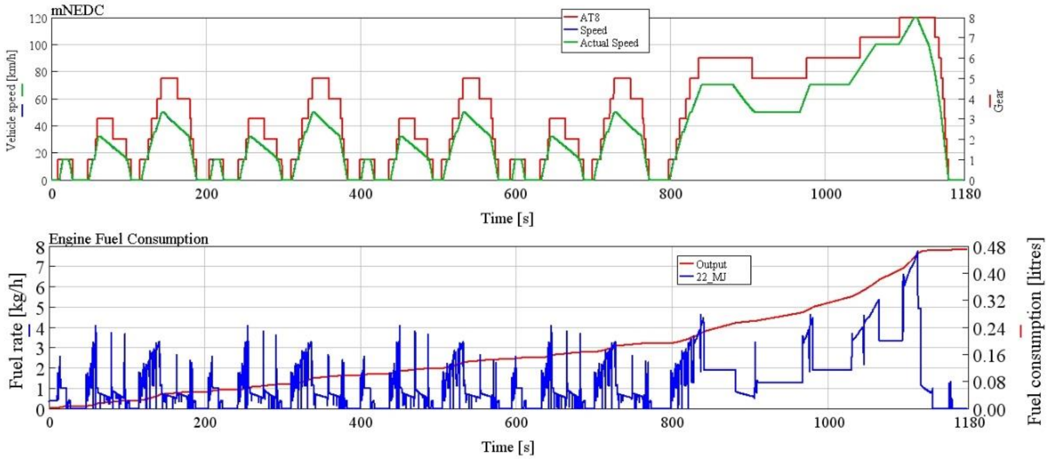

Figure 3.5 Upper) Target vs. actual speed and gear engaged; Lower) Instantaneous and cumulated fuel consumption of baseline vehicle on mNEDC

Table 3.5 reports the most relevant statistics regarding mNEDC simulation of the baseline vehicle.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative Coasting distance [%]*	*CO2 [g/km]*
mNEDC	1180	10991	0	0	118

Table 3.5 mNEDC baseline vehicle

3.6. mNEDC with idle coasting

Figure 3.6 illustrates the actual vehicle speed over time as well as engine fuel consumption over the mNEDC simulation of the vehicle with idle coasting activated.

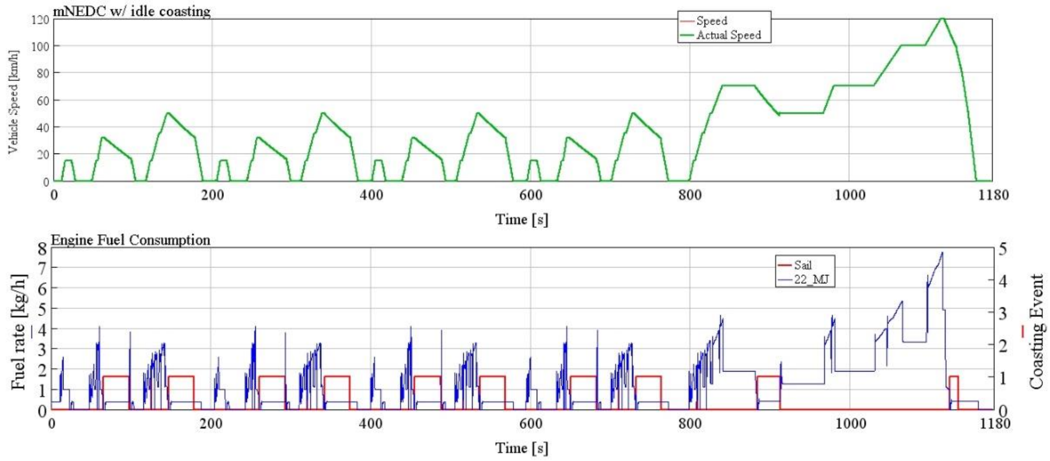

Figure 3.6 Upper) Target vs. actual speed; Lower) Instantaneous fuel consumption and coasting activation of the vehicle w/ idle coasting enabled on mNEDC

Running the model along mNEDC a significant part of the cycle is travelled in coasting mode following the coast-down speed profile of the vehicle. This allows to obtain a fuel consumption reduction with respect to the standard NEDC. Figure 3.7 shows the comparison between a standard deceleration phase of the homologation cycle and its corresponding modified coasting phase.

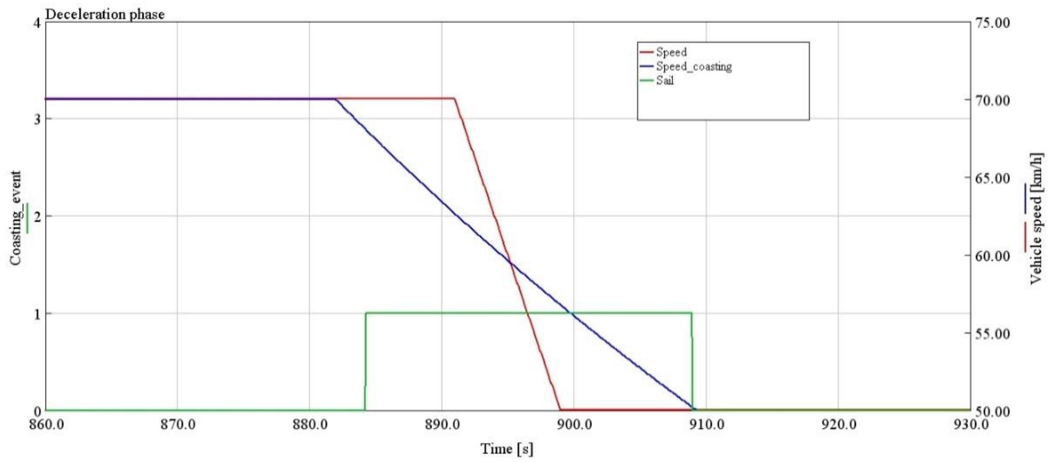

Figure 3.7 Vehicle speed during a deceleration phase: mNEDC vs NEDC

The significant benefit in terms of fuel consumption reduction is given by the fact that in mNEDC the accelerator pedal is released in advance with respect to NEDC in order to perform the coasting manoeuvre and cover the same distance at the end of each deceleration phase. Such a significant saving is partially reduced by the fact that the engine is running at idle also during phases in which in the standard homologation cycle it would burn no fuel at all thanks to fuel cut-off strategy. Fuel consumption would be for sure lower if the engine was shut off during coasting (Engine off coasting), because the fuel needed to overcome engine frictions and losses at idle speed would be saved. To better explain the phenomena, one phase is reported in detail in Figure 3.8: the phase corresponding to the deceleration from 70 to 50 km/h in the extra-urban section of NEDC cycle.

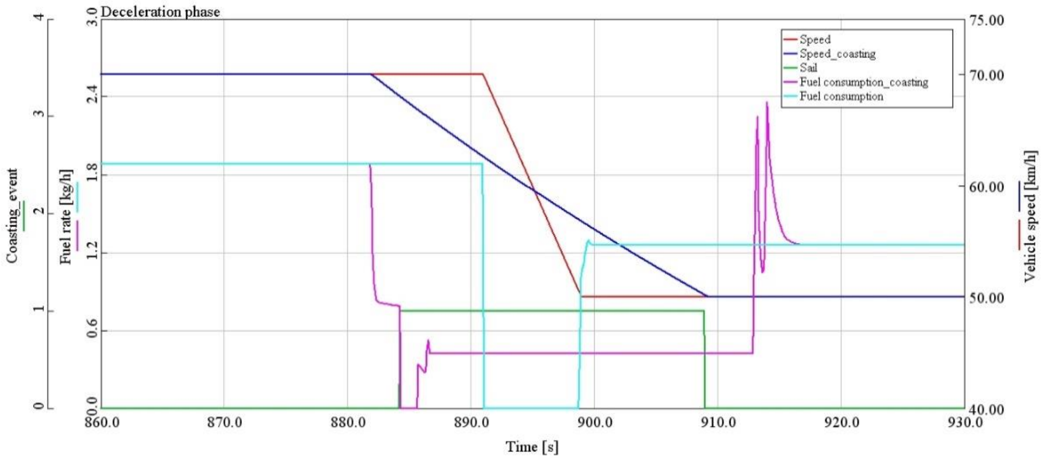

Figure 3.8 Vehicle speed and instantaneous fuel consumption during a deceleration phase: mNEDC vs NEDC

As soon as the idle coasting is triggered, engine fuel consumption drops to zero stabilizing to idle fuel consumption after a couple of seconds up to the end of coasting phase. In the corresponding baseline vehicle, engine fuel consumption remains at the constant speed level for a longer time, after which it drops to zero because of the fuel cut-off strategy; after the deceleration phase is over, engine fuel consumption rises again to a higher level.

Table 3.6 reports the most relevant statistics regarding mNEDC simulation of the vehicle with idle coasting enabled.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative Coasting distance [%]*	*CO2 [g/km]*
mNEDC	1180	10990	10	27.6%	112

Table 3.6 mNEDC vehicle with idle coasting

3.7. mWLTC (proposal) baseline

Fuel performance simulations have been performed also on a test cycle here called mWLTC (modified WLTC). It is derived from the WLTC speed profile of the new homologation procedure, to which coasting phases have been added. For each deceleration phase a coast-down curve has replaced the original deceleration curve, provided that some boundary conditions are fulfilled. Those limitations regard for example the minimum and maximum distance travelled during each coasting phase, the maximum vehicle speed deviation from the original profile during coasting phases, etc.

In particular, three situations have been defined, each corresponding in real world to an opportunity to perform coasting:

- Stationary obstacle ahead of the vehicle;
- Deceleration of preceding vehicle;
- Moving obstacle ahead of the vehicle.

The obstacle (or the preceding vehicle) virtually corresponds to a minimum in the vehicle speed profile of the original WLTC. All the coasting phase built from those three possible opportunities at the end have been synthetized, leading to the final modified speed profile. It is important to underline that such a speed profile at the moment is not useful for certification purposes and it is essentially a trial proposal to apply the methodology used nowadays to the WLTC procedure, which is going to replace permanently the NEDC in the next future.

Figure 3.9 illustrates the actual vehicle speed and the gear engaged over time as well as engine fuel consumption over the mWLTC simulation of the baseline vehicle.

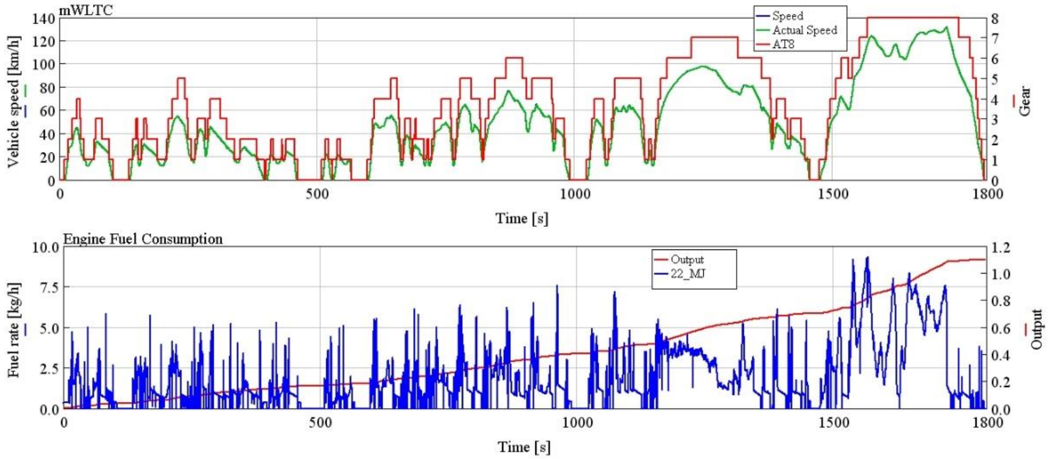

Figure 3.9 Upper) Target vs. actual speed and gear engaged; Lower) Instantaneous and cumulated fuel consumption of the baseline vehicle mWLTC (proposal)

Table 3.7reports the most relevant statistics regarding mWLTC simulation of the baseline vehicle.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative Coasting distance [%]*	*CO2 [g/km]*
mWLTC	1800	23199	0	0	131

Table 3.7 mWLTC baseline vehicle

3.8. mWLTC (proposal) with idle coasting

The coasting phases introduced by the ad hoc cycle modification allow to perform longer coasting manoeuvres and to better exploit the benefit of idle coasting.

Figure 3.10 illustrates the actual vehicle speed over time as well as engine fuel consumption and coasting activation over the mWLTC simulation of the baseline vehicle.

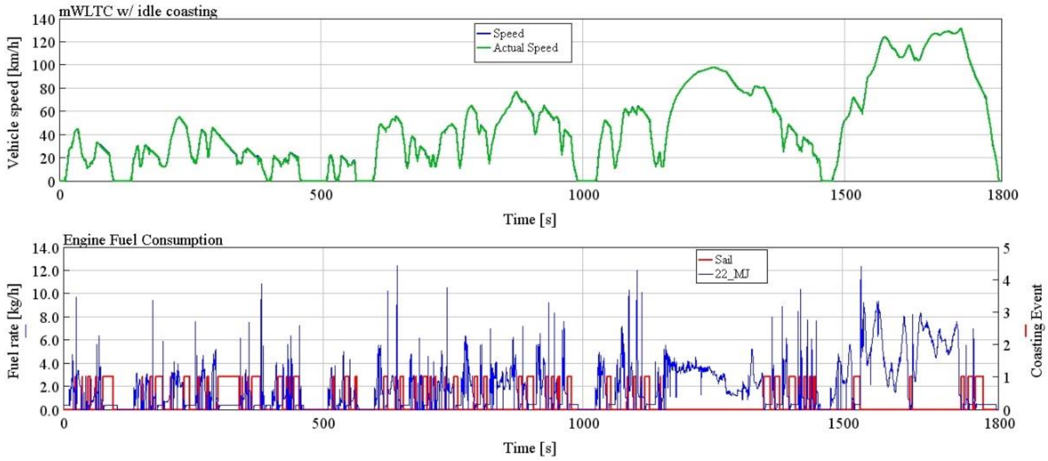

Figure 3.10 Upper) Target vs. actual speed; Lower) Instantaneous fuel consumption and coasting activation of the vehicle w/ idle coasting enabled on mWLTC (proposal)

Table 3.8 reports the most relevant statistics regarding mWLTC simulation of the vehicle with idle coasting enabled.

	Total duration [s]	*Total distance [m]*	*Coasting events*	*Relative Coasting distance [%]*	*CO2 [g/km]*
mWLTC	1800	23186	48	19.6	127

Table 3.8 mWLTC vehicle with idle coasting

3.9. Comparison

The comparison of the results of both the baseline vehicle and the vehicle equipped with the idle coasting function, expressed in g CO_2/km, are reported in Table 3.9.

	baseline	*w/ idle coasting*	*saving*
NEDC	120	122	+1.6%
mNEDC	118	112	-5.1%
WLTC	133	132	-0.8%
mWLTC (proposal)	131	127	-3.1%

Table 3.9 Test cycle CO_2 emissions comparison

The highest benefit is revealed in the mNEDC test case, on which the calibration activity has been carried out. In the NEDC type approval test case it results a degradation of CO_2 emissions. Whereas in the WLTC and mWLTC cases CO_2 emission reduction benefit turns out to be limited. The underestimation of the potential real world saving suggest for the need of a further investigation on testing methods to account for type approval certification purpose.

From the simulated values it is possible to evaluate the potential CO_2 savings accountable for the approval idle coasting as Eco-innovation as explained in Section 1.4.3, using Equation 3.1.

$$CO_2\ saving = (c * BTA - EMC) * UF = 1.9\ g \qquad 3.1$$

Where

EMC is the Eco-innovative modified conditions CO_2 emissions level

BTA is the baseline type approval CO_2 emissions level

c is the conversion parameter (set to 0.96)

UF is the usage factor (set to 0.6)

The overall CO_2 saving calculated is well above the threshold of 1 g CO_2/km imposed by the Commission for Eco-innovation purposes.

The same calculation has not been done with WLTC values because the modified cycle is just a first attempt to translate the present testing methodology into a future WLTP-based regulation. Still there is no official communication on how the Eco-innovation potential saving has to be proved after the NEDC will be put away.

3.10. Parametric analysis

In this section it is presented a brief analysis aimed at showing the model tuning versatility. The parameter V_{EXIT} has been varied evaluating its sensitivity with respect to the fuel consumption and CO_2 emissions along a driving mission. V_{EXIT} is the lower vehicle speed at which idle coasting function is disabled and it has been set to 4 different levels: 15, 40, 50 and 120 km/h. These simulations have been performed along mNEDC.

As explained in Section 2.4.4, the actual vehicle speed is compared instant by instant with V_{EXIT} parameter and as soon as it goes below this value the coasting function is disabled. A new speed profile has been created for each case, because below V_{EXIT} the coast-down curve has been truncated and replaced with the original NEDC deceleration profile. Figure 3.11, Figure 3.12, Figure 3.13 and Figure 3.14 show the respective speed profiles. It is worth underlining that the last case in which V_{EXIT} = 120 km/h the speed profile is actually corresponding to that of the original NEDC test.

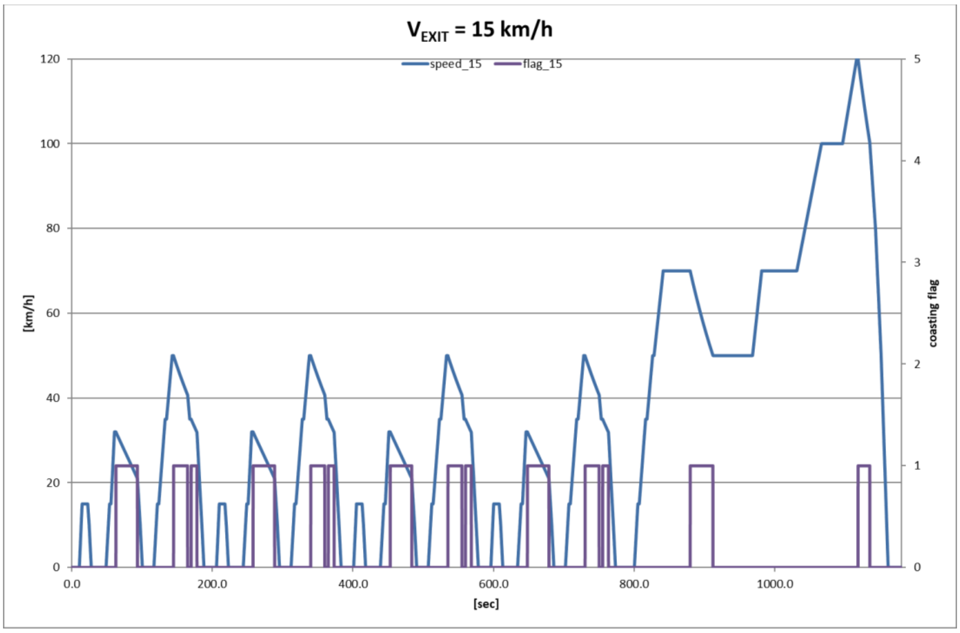

Figure 3.11 Vehicle speed and coasting activation on modified cycle with V_{EXIT} = 15 km/h

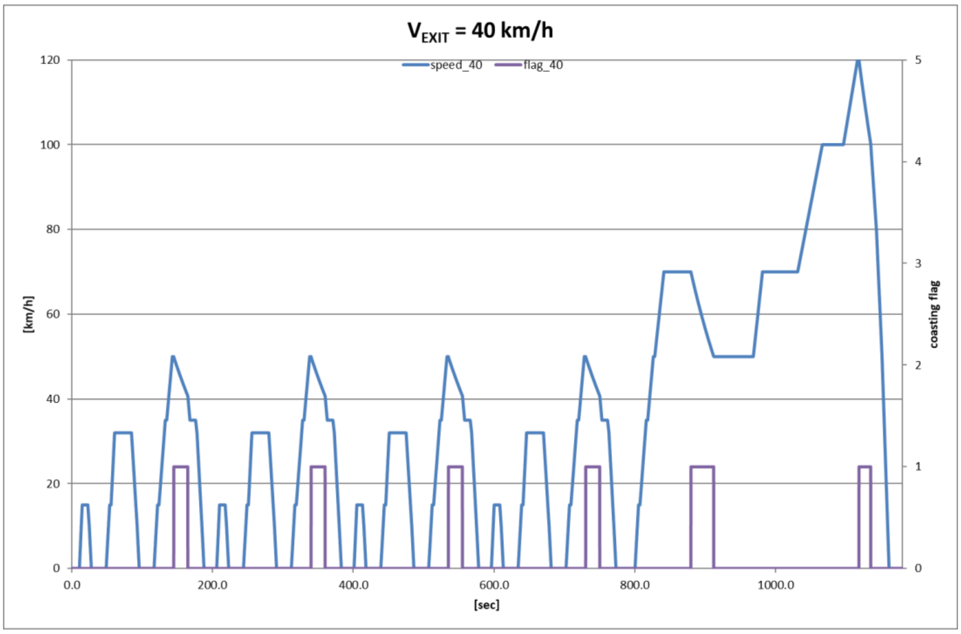

Figure 3.12 Vehicle speed and coasting activation on modified cycle with V_{EXIT} = 40 km/h

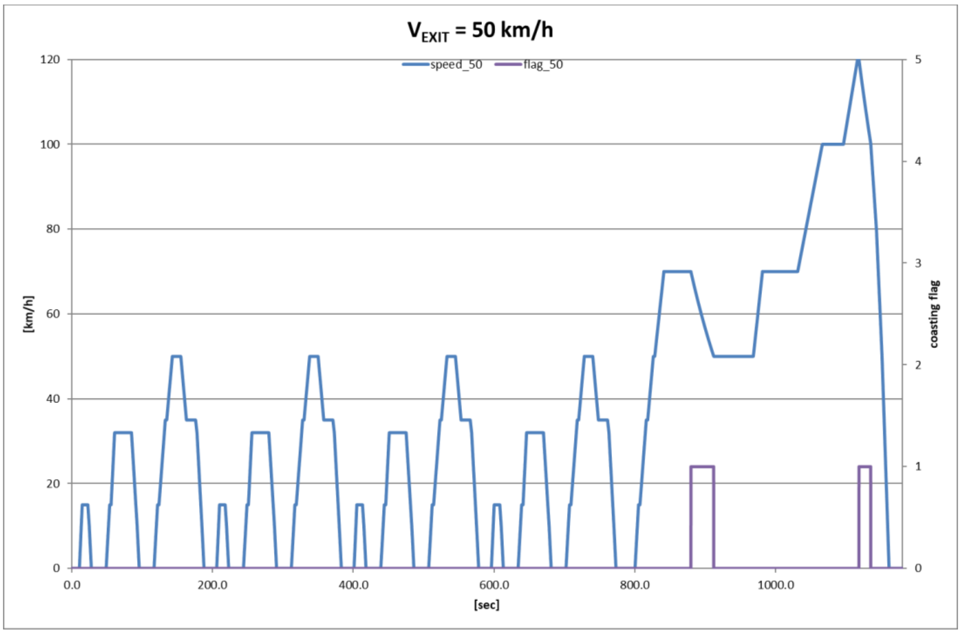

Figure 3.13 Vehicle speed and coasting activation on modified cycle with V_{EXIT} = 50 km/h

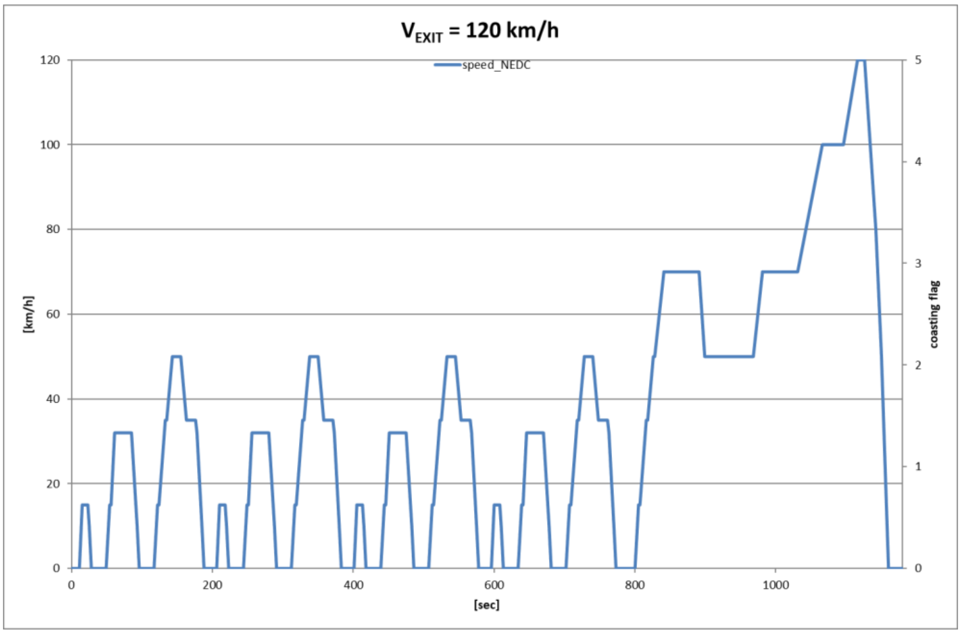

Figure 3.14 Vehicle speed and coasting activation on modified cycle with V_{EXIT} = 120 km/h

As expected the fuel consumption savings with respect to NEDC baseline decreased as the speed threshold increased, because coasting phases are shortened due to the more and more narrowed speed range in which coasting is allowed. Table 3.10 reports CO_2 emissions along the cycle opportunely modified.

	V_{EXIT}	CO_2 emissions [g/km]	Variation
Case 1	15 km/h	111	
Case 2	40 km/h	114	+2.7%
Case 3	50 km/h	116	+4.5%
Case 4	120 km/h	118	+6.3%

Table 3.10 CO_2 emissions at different values of V_{EXIT}

3.11. Engine off coasting

Idle coasting benefits in terms of CO_2 emissions and fuel consumption reduction can be significantly raised by the development of Engine off coasting. If the engine is shut off during coasting phases no fuel is required to burn and no CO_2 is emitted. The further improvement in fuel economy with respect to idle coasting could be easily estimated multiplying the instantaneous fuel consumption at idle speed for the coasting time during the given driving mission.

Figure 3.15 and Figure 3.16 show the simulations performed with the Engine off coasting along mNEDC and mWLTC (proposal).

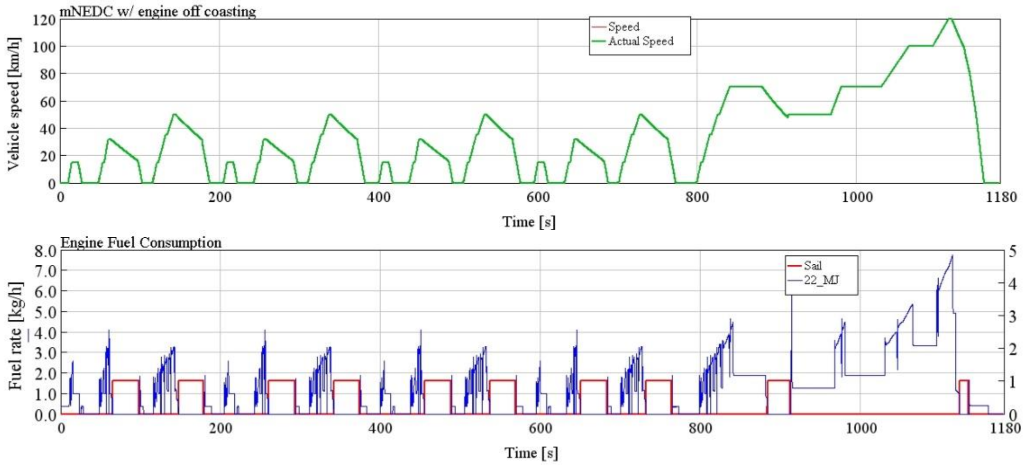

Figure 3.15 Upper) Target vs. actual speed; Lower) Instantaneous fuel consumption and coasting activation of the vehicle w/ engine-off coasting enabled on mNEDC

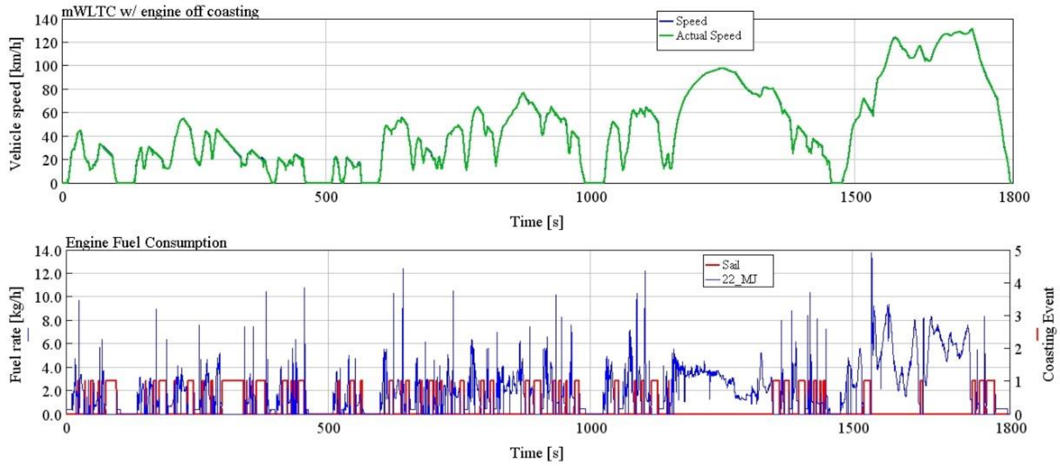

Figure 3.16 Upper) Target vs. actual speed; Lower) Instantaneous fuel consumption and coasting activation of the vehicle w/ engine-off coasting enabled on mWLTC (proposal)

CO_2 emissions from mNEDC and mWLTC (proposal) with Engine off coasting function are reported in Table 3.11, together with the comparison with Idle coasting and baseline configurations.

	baseline	*w/ Idle coasting*	*w/ Engine off coasting*
mNEDC	118	112	102
mWLTC (proposal)	131	127	122

Table 3.11 CO_2 emissions with engine off coasting

Engine off coasting leads to some technical issues related to the fact that the engine is turned off not only during stops (as in today's conventional vehicle with Stop&Start system), but also when the car is travelling at medium-high speeds. In these conditions all the safety systems must be available.

Three issues need must be pointed out:

1. Voltage drop during engine start;
2. Redundancy of energy supply;
3. Increased number of charging/discharging cycles for battery.

The voltage drop during engine start due to the power consumption of the starting device can detrimentally affect the power supply, causing a voltage drop. While in a normal Stop&Start system the voltage drop is "only" comfort relevant (like flickering lights), it is of higher importance for an Engine off coasting application. While driving, the functioning of systems like brakes or power steering must not be affected during engine start. Therefore an electrical system is to be designed to either cope with a certain level of voltage drop or to prevent any negative impact on the electrical system.

In the context of safety requirements, also the availability of the power supply system needs to be considered. State-of-the-art power net architectures represent redundant systems with two power supplies: the alternator and the battery. In case of a failure of either one, the vehicle can still be brought to a safe condition in a limp home type operation mode, based on the other power supply. With the combustion engine and therefore the alternator turned off during Engine off coasting, an additional power supply is essential for safety reasons.

The additional power supply would provide not only redundancy to the conventional vehicle battery in case the combustion engine is turned off, but also adds robustness to the electric energy storage system concerning an increased number of charging and discharging cycles. It is already known from conventional Stop&Start systems that the car battery's durability needs special attention in such applications because of this reason. This is currently being addressed by using an increased battery size or by using Absorbent Glass Mat (AGM) batteries, which are optimized for such applications. However, the increased number of charging and discharging cycles of Engine off coasting might require a technology step, suggesting power capacitors or LiIon battery technology.

3.12. Environmental assessment

In 2016, about 15 million passenger cars were registered in EU, which is the third market worldwide after Asia and America, accounting for more than 21% of motor vehicles sold. The market share is divided as follows:

- 30% A- and B-segment
- 26% SUV
- 22% C-segment
- 9% D-segment

Almost 50% of these cars run on diesel, 46% on petrol and the remaining 4% is equipped hybrid or full electric powertrains. The automatic transmission market share is around 40%: 20% AT, 16.5% DCT and the rest is composed by automated MT and CVT. The manual transmission vehicles weigh for 60% of the market instead. The average mileage of a passenger car is estimated to be 20 000 km per year.

Considering all the assumptions above, it possible to make a simple calculation to the regional impact of the introduction of idle coasting technology on passenger cars. If new passenger cars with conventional powertrain (not considering hybrid and electric) and with AT or DCT transmission are equipped with idle coasting technology, which allows a saving of at least 1,9 g CO_2/km, in the first year 0,22 Mton of CO_2 are saved globally. This corresponds to an impressive quantity of around 78 to 92 million of fuel unburned (depending if it is diesel oil or gasoline).

This latter analysis assumes that the technology is applied on every new passenger car in Europe, which is not that far from the reality given that ACEA is already moving towards the acknowledgment of idle coasting technology as Eco-innovation for all European car makers and all car segments. Furthermore, this calculation doesn't take into account that CO2 saving is likely to increase with time due to the improved driver skills in idle coasting feature efficient utilization [11].

4. Conclusions

The technological development of powertrain systems required for the compliance with next years CO_2 targets will lead for sure to the extensive deployment of already existing mild-hybrid solutions and to the introduction of more complex high voltage systems in the EU automotive market. The development of the strategies to make those technologies effective in CO_2 emission reduction could result to be time and sources consuming.

A cost effective solution can be the introduction of idle coasting feature in conventional powertrain systems. The proper usage of such function in real world driving allows to obtain fuel consumption savings in the range of 5-10%, depending on the driving mission. Furthermore, the European Commission allows this technology to be certified as Eco-innovation, helping the OEM who is applying idle coasting in its vehicles to reduce its average fleet CO_2 emission level.

The methodology available nowadays to test idle coasting Eco-innovation can grant more than 2 gCO_2/km of actual CO_2 saving NEDC based. Nevertheless, it seems to be necessary the development of such a methodology in order to properly point out the full potential of idle coasting.

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