POLITECNICO DI TORINO

Dipartimento di Ingegneria Meccanica e Aerospaziale

Corso di Laurea Magistrale in Ingegneria Meccanica

Tesi di Laurea Magistrale

Impact of WLTP homologation cycle on passenger cars cost and CO_2 compliance

Relatore:

Prof. Federico Millo

Tutor aziendali:

Dott. Carloandrea Malvicino

Ing. Elizabeth Julia Tettamanzi

Candidato:

Puliti Piero

IMPORTANT NOTICE:

Sommario

Nel settembre 2017 il ciclo omologativo NEDC (New European Driving Cycle) è stato sostituito con il nuovo WLTP (Worldwide harmonized Light duty Testing Procedure). Oggigiorno, le penali relative il superamento dei limiti sulle emissioni di CO_2 hanno spinto le case automobilistiche ad investire su tecnologie ibride. In questo contesto, i sistemi di elettrificazione micro-ibridi dall'elevato rapporto benefici/costi permettono di ridurre sensibilmente le emissioni di CO_2 a costi contenuti.

In questo lavoro di tesi un sistema micro ibrido 12V e un sistema start and stop vengono valutati su un automobile di segmento A, in termini di emissione di CO_2, su cicli guida regolamentati (NEDC e WLTP) e Real World, in condizioni di partenza a caldo e a freddo. In particolar modo, nel modello micro-ibrido sono state implementate le funzioni di frenata rigenerativa, torque assist (assistenza della macchina elettrica, attuato in accelerazione) e il sistema start and stop avanzato. Successivamente, è stata cambiata la logica di attuazione del torque assist simulando un avanzamento in puro elettrico sotto determinate condizioni esplicitate, per valutarne il beneficio comparandolo con l'attuazione in accelerazione.

Il sistema 12 V e il sistema start and stop sono stati, altresì analizzati in termini di costi benefici e confrontati con altri sistemi di riduzione delle emissioni di CO_2 come la diminuzione della massa e della resistenza aerodinamica. Questa analisi è stata condotta sui cicli prima menzionati.

Infine è stata effettuata un'analisi di tipo economico per valutare la convenienza per una casa automobilistica ad investire sulle tecnologie micro ibrido 12 V e start and stop ipotizzando una totale implementazione su tutta la flotta di veicoli di segmento A venduta in un anno.

Abstract

The European Union has recently substituted the NEDC (New European Driving Cycle) with WLTP (Worldwide harmonized Light duty Testing Procedure). Nowadays, penalties caused by exceeding the limits on CO_2 emissions have forced car manufacturers to invest in hybrid technologies. As a consequence, carmakers invest a huge amount of money on hybrid technologies that can give benefit in terms of CO_2 reduction.

In this context, the effect of the application of a 12 V micro-hybrid and start and stop on a city car have been investigated via a mathematical model. The cycles considered were NEDC, WLTP and a Real World driving cycle in hot and cold starting conditions. The fuel saving functionalities, such as regenerative braking, torque assist (in acceleration condition) and enhanced start and stop have been implemented in the model. The torque assist control strategy has been modified to explore the possibility of pure electric driving: two different strategies have been evaluated, and the outcomes are compared.

The simulation results regarding conventional start and stop and micro-hybrid solutions have been compared in a cost-benefit analysis, for NEDC, WLTP and Real World driving cycle. Moreover, mass and aerodynamic drag reduction have also been taken into account to evaluate CO_2 reduction benefit.

Finally, a simple business case has been evaluated to estimate the economic feasibility of this micro hybrid and, start and stop implementation in a city car's fleet from the car maker perspective.

Index

List of the figures

List of the tables

Acronyms

Abbreviations

AC Alternating Current

BAS Belt Alternator Starter

BEV Battery Electric Vehicle

BMS Battery Management System

BAS Belt Starter Generator

CD Charge Depletion

CS Charge Sustaining

DC Direct Current

ECU Engine Control Unit

EM Electric Machine

ESS Engine start and stop

EU European Union

EUDC Extra Urban Driving Cycle

EV Electric Vehicle

FC Fuel Consumption

FCEV Fuel Cell Electric Vehicle

GHG Greenhouse Gases

HEV Hybrid Electric Vehicle

ICE Internal Combustion Engine

MT Manual Transmission

NEDC New European Driving Cycle

OCV Open Circuit Voltage

PHEV Plug-in Hybrid Electric Vehicle

PID Proportional Integral Derivative

RW Real World

SOC State of Charge

TA Torque Assist

TMH Test Mass High

TML Test Mass Low

UDC Urban Driving Cycle

WLTC Worldwide Harmonized Light Duty Test Cycle

WLTP Worldwide Harmonized Light Duty Test Procedure

Chapter 1. Introduction

1.1 CO_2 Regulation framework in EU

1.1.1 History of regulation

After industry power generation, Road transport is the most important source of greenhouse gas emissions in the EU. Its contribution is around one-fifth of the EU's total emissions of carbon dioxide and in the last 20 years CO_2 emission have been rising [1].

In 1993, the United Nations Framework Convention on Climate Change required members to mitigate climate change [2]. In 1998, the ACEA (European Automobile Manufacturers 'Association) made a proposal for the reduction of greenhouse emissions from new cars sold to 140 g CO_2/km by 2008. One year later, also, JAMA (Japanese Automobile Manufacturers' Association) and KAMA (Korean Automobile Manufacturers' Association) also took the same decision to reduce emissions to 140 g CO_2/km by 2009, but it was a voluntary agreement. As a result, in January 2007 a mandatory plan was launched to fix emissions to 120 g CO_2/km from 2012 for new cars sold fleet.

One month later, the Commission noticed that efforts were made to achieve the target of 140 g CO_2/km by 2008/2009, but they were not enough to reach the Community objective of 120 g CO_2/km. Other measures are applied to achieve this goal. In fact, Commission proposed an integrate approach. Hence, the target was set to 130 g CO_2/km for average new car fleet by investing on engine technology. In addition, a further reduction of 10 gCO_2/km should be realized by the spread of the biofuels. Commission proposed to apply disposition since 2011 in order to achieve 125 g CO_2/km for 2015. Furthermore, the other part of the commitment is to set the target to 2020 to 95 g CO_2/km. From the point of view of manufacturers, they can find several solutions to meet their target.

1.1.2 Regulation

The average emissions over car fleet are based on mass: there is a linear correlation between this parameter of the vehicle and its allowed emission.

For passenger car, the allowed emission follows the following formula [3], [4]:

From 2012 to 2015:

Specific emissions of CO_2:

$$130 + a(M - M_0) \tag{1.1}$$

where:

M: Mass of the vehicle $[Kg]$;

M_0: 1372 $[Kg]$;

a: 0.0457;

From 2016:

The formula is the same but the value for M_0 is different: it is the average mass of the new cars calculated by considering three previous years.

From 2020

Specific emissions of CO_2:

$$95 + a(M - M_0) \tag{1.2}$$

where:

M: Mass of the vehicle $[Kg]$;

M_0: is the average mass of the new cars calculated by considering the average mass of the vehicles sold in EU in the three previous years, it will be adjusted annually. For example, today the European Average mass valid from 2019 until 2021 is 1380 $[Kg]$ [12].

a: 0.0333

The trend of the straight lines are shown in Figure 1.

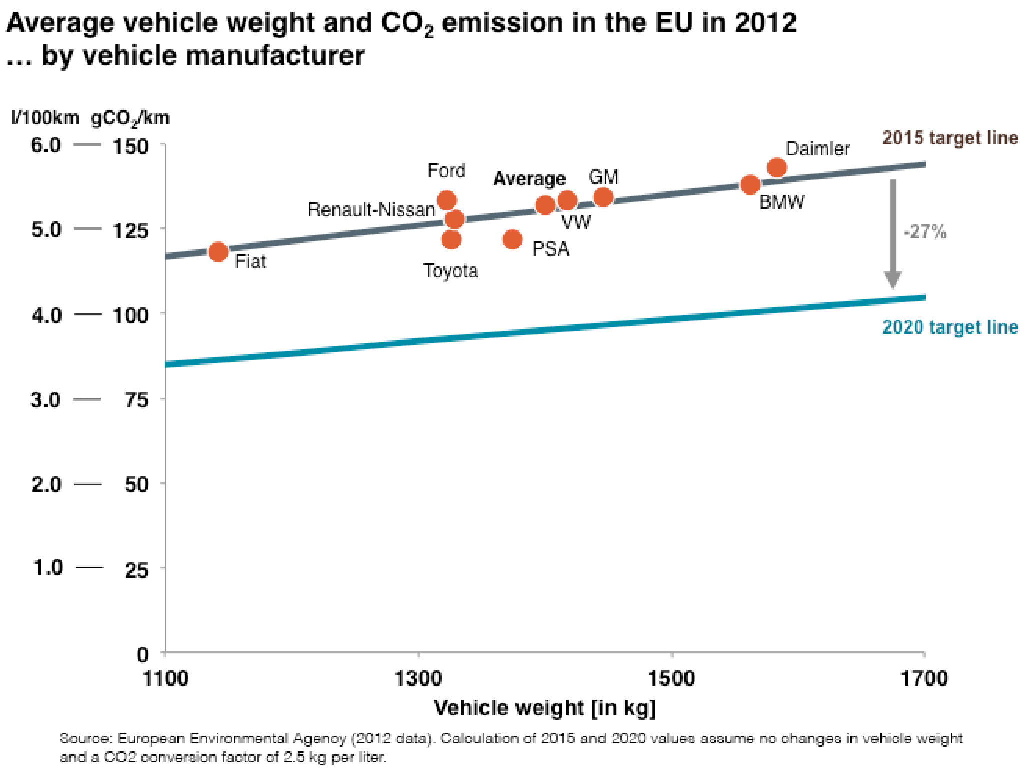

Figure 1: Trend of the CO_2 target in function of the mass [5].

The regulation claims that the average specific emission related to all new car should not exceed the average of the emission target. If it happens, carmakers have to pay a fine.

Respect to that, from 2012 Car makers have to pay a fine if their average specific emissions of CO_2 exceeds the target. The amount of the fine depends on the exceeded emission:

From 2012 until 2018:

- if carmakers exceed the target by more than 3 g/km the amount of fine is:

$$\left(\left(excees\ emission - 3\frac{g}{km}\right) * \frac{95€}{\frac{gCO_2}{km}} + 1\frac{gCO_2}{km} * 25\frac{€}{\frac{gCO_2}{km}} + \frac{1gCO_2}{km} * 15\frac{€}{\frac{gCO_2}{km}} + 1\frac{gCO_2}{km} * 5\frac{€}{\frac{gCO_2}{km}}\right) * number\ of\ new\ passenger\ cars \quad (1.3)$$

- if carmakers exceed the target of more than 2 g CO_2/km but less than 3 g CO2/km, we have:

$$\left(\left(excees\ emission - 2\frac{g}{km}\right) * \frac{25€}{\frac{gCO_2}{km}} + 1\frac{gCO_2}{km} * 15\frac{€}{\frac{gCO_2}{km}} + \frac{1gCO_2}{km} * 5\frac{€}{\frac{gCO_2}{km}}\right) * number\ of\ new\ passenger\ cars \quad (1.4)$$

- if carmakers exceed the target of more than 1 g CO_2/km but less than 2 g CO_2/km we have:

$$\left(\left(excees\ emission - 1\frac{g}{km}\right) * \frac{15€}{\frac{gCO_2}{km}} + 1\frac{gCO_2}{km} * 5\frac{€}{\frac{gCO_2}{km}}\right) * number\ of\ new\ passenger\ cars \quad (1.5)$$

- for exceed emission no higher than 1 g CO_2/km the formula is the following one:

$$\left(excees\ emissions * 5\frac{€}{\frac{gCO_2}{km}}\right) * number\ of\ new\ passenger\ cars \quad (1.6)$$

From 2019:

The amount of fine correspond to the following formula:

$$\left(excees\ emissions * 95 \frac{€}{\frac{gCO_2}{km}} \right) * number\ of\ new\ passenger\ cars \quad (1.7)$$

The goal of this fine is to stimulate car makers to invest money on innovative technologies in order to reduce CO_2 emissions.

On the other hand, small-volume manufacturers may form a pool among each other to jointly meet their CO_2 emission targets. However, it is important that average emissions of the pool as a whole do not exceed the target emissions. Furthermore, manufacturer that produce a number of new passenger cars lower than 10000, can ask a derogation to EU. In fact, they can have a specific emission target based on their economic and technological potential. Hence, this target takes into account the specific segment of the market where is collocated the vehicle.

1.1.3 Transition phase

As mentioned before, the regulation agreed in 2014 established a target value of 95 g CO_2/km from 2020 on NEDC. Meanwhile, in September 2017, WLTP has replaced the New European Test Cycle (NEDC), which is currently used. Consequently, WLTP is expected to provide different values for CO_2 emission and fuel consumption. This creates the following problem: existing target values for the NEDC should be "translated" to the WLTP. Therefore, CO_2 emissions measured in the WLTP has to be converted to NEDC equivalent emission values using correlation. That is why the European Commission has developed a specific tool: CO_2MPAS [6].

The CO_2MPAS is a CO_2 emission and fuel consumption calculator for light-duty M1 and N1 vehicles (cars and vans). This tool permits to obtain the CO_2 emissions value of a vehicle over the NEDC test, by using the results of an official WLTP test. On WLTC side, there are two type of WLTP test: WLTP-H (High), this test requires the highest cycle energy demand, on the other hand the WLTP-L (Low) requires the lowest cycle energy demand [7].

After the measure: if the NEDC equivalent (carried out by CO_2MPAS) is more than 4% above the manufacturer's declared value, the manufacturer can follow two ways. The first way is to accept the NEDC equivalent emission value, the other is up to retest vehicle three times on the chassis dynamometer. In this last case, if the CO_2 value measured is more than 4% above the value declared by the manufacturer, this last value applies.

In 2020, CO_2 emissions of new homologation vehicle will establish on the NEDC and WLTP procedure according to the correlation method. By monitoring these values with both procedures, it will have a series of data useful to establish target for CO_2 emissions on WLTP. This must be done because from 2021 onwards, CO_2 targets will be expressed in WLTP values and compliance will be checked using WLTP values. Given that, the CO_2 emissions will be higher on the WLTP than NEDC. In this context, WLTP CO_2 targets will be correlated to ensure that the stringency of those targets is comparable to the targets expressed in NEDC values. The changing of the specific CO_2 targets in the WLTP is foreseen for 2021. On the other hand, from 2018 will apply to all new car registrations.

1.1.4 Post 2020

For the period post 2020, the Commission prepared the following proposal [8]: from 2021 a manufacturer-specific reference target value will be determined using eq. (1.3).

$$\mathrm{WLTP}_{2021,\mathrm{target,reference}} = \frac{\mathrm{WLTP}_{2020}}{\mathrm{NEDC}_{2020}} * \mathrm{NEDC}_{2020,\mathrm{target}} \qquad (1.3)$$

$WLTP_{2020}$ and $NEDC_{2020}$ are the recorded average CO_2 emissions for 2020. On the other hand, the variables indicated with "target" are the NEDC target for that year resulting from the manufacturer's average vehicle mass and the WLTP reference target to be achieved for 2021. After 2020, the year-specific manufacturer target in the WLTP will be established by eq. (1.4).

$$\mathrm{WLTP}_{202x,\mathrm{target}} = \mathrm{WLTP}_{2021,\mathrm{target,reference}} + a * [(\mathrm{M}_{\mathrm{OEM},202x} - \mathrm{M}_{\mathrm{all},202x}) - (\mathrm{M}_{\mathrm{OEM},2020} - \mathrm{M}_{\mathrm{all},2020})] \qquad (1.4)$$

M represents the average masses particular manufacturer's car fleet (M_{OEM}) and of all new registrations in the particular year (M_{all}); the factor *a* is a constant.

The following timeline summarizes the changeover from NEDC to WLTC [9].

From September 2017

Cars type approved using NEDC before September 2017 can still be sold.

• WLTP type approval testing will be introduced for new car types.

• Some cars will have 'old' NEDC values, while others will already be certified under the new WLTP conditions.

• During the period of transition (up until the end of 2018), only NEDC values should be used on labels and information in dealerships to enable consumers to compare different cars.

• It is expected that national tax regulations will continue to be based on NEDC values.

From September 2018

All new cars must be tested according to the WLTP test, and no longer on NEDC.

From January 2019

• All cars in dealerships should have WLTP-CO_2 values only to avoid any confusion among consumers, in the view of the automobile industry.

• An exception will be made for end-of-series vehicles to allow for a limited number of unsold vehicles in stock that were approved under the old NEDC test to be sold for one more year.

• National governments should adjust vehicle taxation and fiscal incentives to WLTP values, respecting the principle that WLTP should not have a negative impact on consumers.

1.1.5 Super credit

For passenger car that emits CO_2 lower than 50 g/km, for the compliance of CO_2 is possible to count this vehicle as

- 3.5 cars in 2012,
- 3.5 cars in 2013,
- 2.5 cars in 2014,
- 1.5 cars in 2015,
- 1 car from 2016.

However, from 2020: it is possible to count vehicle that has a value of CO_2 emission lower than 50 g/km as

- 2 passenger cars in 2020,
- 1.67 passenger cars in 2021,
- 1.33 passenger cars in 2022,
- 1 passenger car from 2023.

There will be a cap on super-credits' contribution to CO_2 reductions of 7.5 g CO_2 /km per manufacturer over the entire period.

1.1.6 Eco-innovation and Off-cycle credits

In 2010, The Commission introduced the possibility to approve technologies, called Eco-Innovation, that shows a reduction of CO_2 emission not in homologation cycle, but in a real driving condition. The supplier is accountable for CO_2 savings and it has to fill a report where test the benefit. However, there are characteristics that technologies must own to be approved such as eco-innovations.

It is important that benefits have not been related on the behavior of the driver and they must be demonstrated by a comparison with and without technology on a testing procedure. This test should be verifiable, repeatable and comparable measurements. Hence, it could be used chassis dynamometer or simulation. The methodology chosen has to give in output accurate results. The technology to become an eco-innovation has to show at least a CO_2 reduction of 1 g/km. Hence, Commission will verify the certified CO_2 savings. The specific regulation for the methodologies is provided by the European Commission. The overall contribution of these technologies to reduce CO_2 emission for one carmaker can be at max no more than 7 g CO_2/km. The main eco innovation approved by EU are: high efficiency alternator, Led lighting, idle Coasting (only for specified segment of the vehicle), engine encapsulation, enthalpy storage tank and system for navigation for control of the SOC of the Li-ion battery, in fact it is a specific eco-innovation for hybrid vehicles.

Technologies such as Eco-Innovation exists also in other regions of the world, they are called Off-cycle credits. The regulation that explain the eligibility for them is different among the regions.

1.2 Homologation cycles

1.2.1 NEDC

Vehicle emission regulation was introduced for the first time in Europe in 1960 and 1970. The first homologation cycle had only urban part and the maximum speed was of 50 km/h. In that year CO_2 emission have not been measured because the problem of climate change was not important such as today. Accordingly in this historical period, there was not mandatory a CO_2 regulation. In 1990, an extra urban part with a maximum speed of 120 km/h was added to NEDC. In this way, it was born the actual NEDC [10].

The NEDC (New European Driving Cycle) is the homologation cycle used by the European Community. NEDC is constituted by a two different sub-cycles:

- The UDC (Urban Driving Cycle) that represent a classic urban path for vehicle in busy European cities. This part has a maximum speed of 50 km/h.
- The other part is constituted by EUDC (Extra Urban Driving Cycle). This last part simulates a path with higher velocity than the first mentioned. Finally, EUDC was added in 1990.

The UDC can be split in four ECE urban driving cycles. In this sub-cycle, there are three "ramps" of acceleration and deceleration. In the first "ramp" of acceleration, vehicle reaches a speed of 15 km/h and cruises for 8 s. In the second one it achieves 32 km/h, it cruises for 24 s. Finally, in the last "ramp" vehicle accelerates until to achieve 50 km/h, it cruises for 12 s, decelerates to reach 35 km/h. After that, velocity maintains constant for 13s until decelerates to stop of the vehicle.

EUDC is constituted by two "ramps": in the first "ramp" of acceleration, the vehicle reaches a speed of 70 km/h, it cruises for 30 s. After that, vehicle decelerates until achieving the speed of 50 km/h. Hence, car should accelerate in 2 "ramps" in order to reach the max speed of 120 km/h and cruises for 20 s. The final step is to decelerate in order to stop the vehicle.

The gearshift of that vehicle is fixed, the temperature where the test takes place has to be between 20°C and 30°C. The electric load is very low, because the vehicle during the test use the minimum of the auxiliaries loads [11] (air conditioning is switched OFF, the same for the exterior lighting, except for mandatory exterior lights. The speed profile is shown in Figure 2. On the other hand, the main characteristics of this cycle are represented in Table 1.

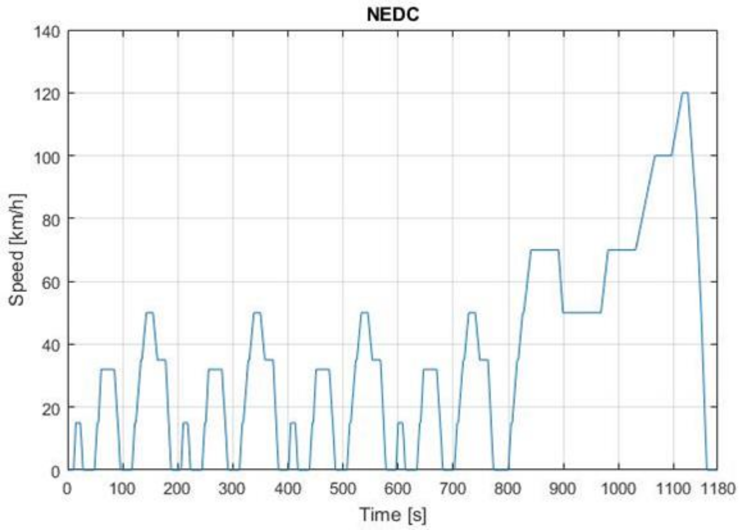

Figure 2: NEDC speed profile.

Characteristics	Unit	ECE 15	EUDC	NEDC
Distance	km	0,99	6,95	10,93
Total time	s	195	400	1180
Idle (standing) time	s	57	39	267
Average speed (incl. stops)	km/h	18,35	62,59	33,35
Average driving speed (excl. stops)	km/h	25,93	69,36	43,1
Maximum speed	km/h	50	120	120
Average acceleration	m/s^2	0,60	0,35	0,51
Maximum acceleration	m/s^2	1,04	0,83	1,04

Table 1: Characteristic table for NEDC.

1.2.2 WLTP

In 2007 a technical working group began to think about a different cycle where test vehicle. That is why NEDC does not reproduce in a better way the real driving condition. In this way WLTP was born.

There are three types of classes in function of power-to-mass (PWr in kW/Tonne) ratio:

- Class 1: low power vehicles with $\mathrm{PWr} \leq 22$;
- Class 2: vehicle with $22 \leq \mathrm{PWr} \leq 34$;
- Class 3: high power vehicle with $\mathrm{PWr} > 34$;

The test mass considered in WLTP is higher than in NEDC.

The tolerance between the actual speed and the target speed has to have a maximum upper limit of 2 km/h higher than the target velocity at given point at -1 s. Lower limit has to be maximum of 2 km/h below the target value of the point situated at +1 s respect to the given point [12]. In this case temperature of the test, it has to be 23 ± 5°C (for Type-1 test), there is also an Ambient Temperature Correction Test (ATCT). The value of CO_2 calculated on WLTP has to be modified by FRF (Family Correction Factor), it is defined as follow:

$$FRF = \frac{CO_{2RC}}{CO_{2Type_{-1}}}$$

CO_{2RC}: is the CO_2 emission for WLTC at regional condition (14°C)

$$CO_{2ATCT} = CO_{2Type_{-1}} * FRF$$

This is valid for all vehicles in one family. As regards, ATCT family is a group of the vehicles which have identical specified characteristics (for example: powertrain, type of cooling system, catalytic converter, etc.).

For each classes there are type of cycle with different characteristic in function of class (duration, shape,…). In the majority part of wide world vehicles belongs to class 3 (they has a power-to-mass ratio > 34). As shown in the figure 3, WLTC is divided in four parts: low, medium, high and extra high. For each phases, the main characteristics are represented in Table 2.

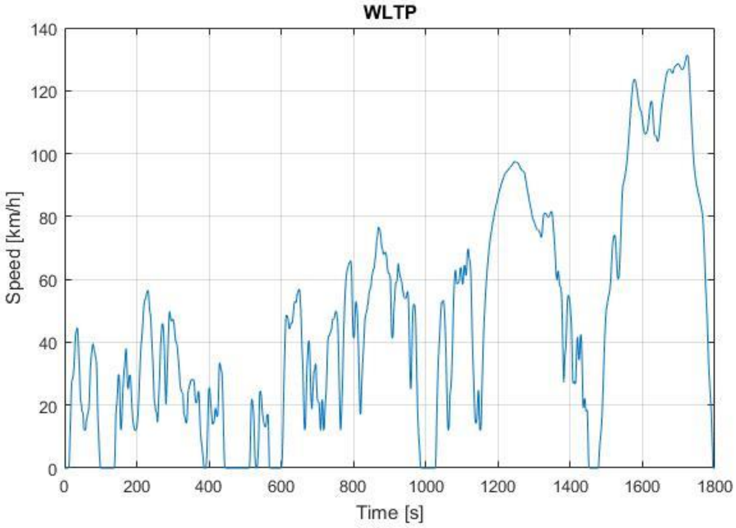

Figure 3: WLTC class 3 speed profile.

	Low	**Medium**	**High**	**Extra High**	**Total**
Duration [s]	589	433	455	323	1800
Stop duration [s]	150	49	31	8	235
Distance [m]	3095	4756	7162	8254	23266
% of stops	26,5%	11,1%	6,8%	2,2%	13,4%
Maximum speed [km/h]	56,5	76,6	97,4	131,3	
Average speed [km/h]	18,9	39,4	56,5	91,7	46,5
Minimum acceleration [m/s^2]	-1,5	-1,5	-1,5	-1,44	
Maximum acceleration [m/s^2]	1,61	1,61	1,67	1,06	

Table 2: Characteristic table for WLTC Class 3.

1.2.3 Main Differences

The most important differences between NEDC to WLTC are:

- **The path of driving cycle**

As mentioned before WLTP has a different shape than the NEDC. In fact, the "ramps" that characterized the WLTP are sharper than NEDC. Hence, acceleration in WLTP are higher than in NEDC. WLTP is a more "aggressive" cycle.

The main differences related the path are shown in Table 3.

	Units	**NEDC**	**WLTC**
Start condition	[-]	cold	cold
Duration	s	1180	1180
Distance	km	11,03	23,27
Mean velocity	Km/h	33,6	46,5
Max. velocity	Km/h	120,0	131,3
Stop phases	[-]	14	9
Durations:			
Stop	s	280	226
Constant driving	s	475	66
Acceleration	s	247	789
Deceleration	s	178	719
Shares:			
Stop	%	23,7	12,6
Constant driving	%	40,3	3,7
Acceleration	%	20,9	43,8
Deceleration	%	15,1	39,9
Mean positive acceleration	m/s^2	0,59	0,41
Max. positive acceleration	m/s^2	1,04	1,67
Mean positive 'vel*acc' (acceleration phases)	m^2/s^3	4,97	4,54
Mean positive'vel*acc' (whole cycle)	m^2/s^3	1,04	1,99
Max. positive 'vel*acc'	m^2/s^3	9,22	21,01
Mean deceleration	m/s^2	-0,82	-0,45
Min. deceleration	m/s^2	-1,39	-1,50

Table 3: Differences between NEDC and WLTC [9].

- **Cold start**

WLTP is longer than NEDC (1800 s and 23 km compared to 1180 s and 11 km) the impact of cold starts are reduced in WLTP. In fact, engine works in operating temperature for a longer time in WLTP than in NEDC that achieve its operating temperature. Cold engine causes higher CO_2 emission than warm engine, because cold engine has to win higher mechanical friction and works with cold lubricant (higher viscosity). That is why cold-start has higher impact on NEDC respect WLTP.

- **Vehicle load**

The WLTC is formed by higher engine speeds and mass than NEDC (131.3 km/h compared to 120 km/h) and also accelerations are higher. Then, this will increase the inertial force.

- **Gearshift**

In WLTP, gearshift can be adapted to the individual characteristic of the vehicle. For example, CO_2 emission decreases by using a gearshift that allow engine to work at lower engine speed and high load. This is due to the higher mechanical efficiency.

- **Stop share**

In NEDC there are more points where vehicle stops and starts again (23.7% compared to 12.6%). Start and stop technology gives better results on CO_2 emission in NEDC than in WLTP.

- **Test mass**

NEDC uses the lowest mass of the vehicle model, WLTP test cycle is divided in 2 cases: the first consist to consider vehicle without optional devices (WLTP-L), lowest rolling resistance and lowest aerodynamic drag. The other configuration considers the highest mass (WLTP-H) due to the application of all optional, higher rolling resistance and greatest aerodynamic drag. To summarize, in the first case, the vehicle required the lowest energy demand and in the other case, the vehicle required the highest energy demand. For each of these vehicles it is performed WLTP test in order to find CO_2 emission.

- **Engine temperature**

The temperature for the WLTP is 23 ± 5°C (for Type-1 test). In NEDC test it has to be in the interval between 20 and 30 °C.

- **Interpolation family**

As mentioned before, under the WLTP a vehicle Low (WLTP-L) and a vehicle High (WLTP-H) will be tested. The first is the vehicle with lowest CO_2 emission, on the contrary, the second vehicle is the highest. These two vehicles cover all of the possible configuration. All of the vehicles that are between the high and the low configuration form an interpolation family. Hence, CO_2 emissions are calculated by interpolating the straight line between the high vehicle and the low over the test cycle. Furthermore, an interpolation family is formed by vehicles that have the same characteristics/elements: ICE, the operation strategy of all CO_2 mass emission for all influencing components, transmission type, ratio between engine rotational speed and vehicle speed, number of powered axles and ACTC family.

Chapter 2. Hybrids systems

2.1 Hybrid systems overview

Pollutant emission limits, global warming and CO_2 emission reduction needs have caused the appearance of hybrid vehicles on the global market.

Hybrid vehicles have two or more sources of power that provide propulsion: one is the chemical energy stored in the fuel, while the other derived from a variety of technology, such as electric (HEV: Hybrid Electric Vehicle), or fuel cell hybrid (FCEV: Fuel Cells Electric Vehicle). HEV usually have the following components:

- ICE: The engine in HEV has different characteristics with respect to conventional systems. It is generally smaller and emits less pollutant emissions. In fact, the purpose of the engine in conventional car is propulsion. In HEV this can be different: for example in range extenders the ICE recharges the battery.
- Fuel tank: stores the fuel.
- Electrical machine: there can be more than one, in which the power can go in two directions, from the brakes to the battery (for example when regenerative braking is used) or from the battery to the electrical machine and then to the wheels (for example in torque assist).
- Batteries: can provide the power to move the electrical machine and store the energy.
- Transmission: plays a key role in HEV architecture classification. Transmission system is required to transfer the power from power sources to the wheels.

On the powertrain side, these vehicles are in between BEV (Battery electric vehicle) and ICE conventional cars. Although BEV do not have an ICE, they are equipped with a heavy battery pack in order to move the vehicle [13]. As regards batteries, the market offers several kinds of technologies, among these Li ion battery is expected to become the most performance and it will be probably used for BEV and PHEV (Plug-in hybrid electric vehicle). Generally, this kind of battery has more power and lower cost compared with other battery technologies. Moreover, another advantage is a low self-discharging loss. Figure 4 shows the most popular batteries technologies and their specific power.

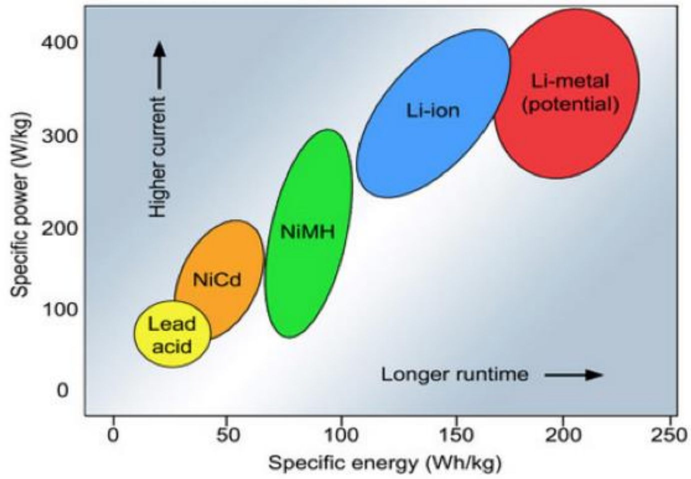

Figure 4: Energy density and specific energy for different type of batteries [14].

The main problem with BEV is the distance range: the energy density of the battery is very low then fuel density energy, as shown in Figure 5. It is clear that to travel the same distance, BEV needs an enormous number of battery cells compared to the conventional car. This causes the increase of the cost and the weight of the vehicle. In addition, another problem is the need of infrastructure to recharge. Examples of BEVs available in the market are: Renault Zoe and Nissan Leaf.

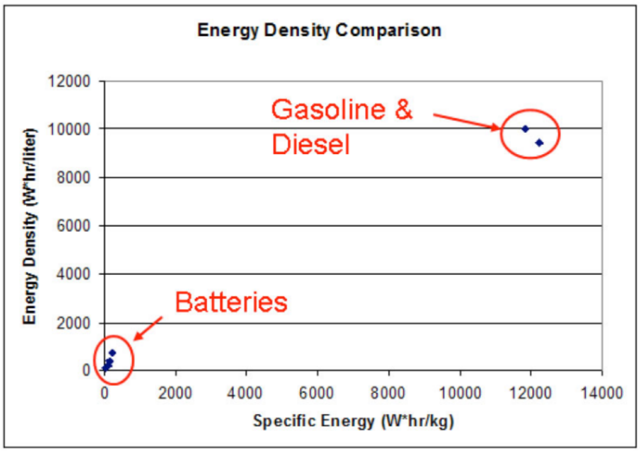

Figure 5 Comparison between batteries and hydrocarbon fuels, energy density and specific energy [14].

Plug-in Hybrid Electric Vehicle (PHEV)

Although PHEVs are equipped with electrical machine, they have also an ICE. In fact, they can travel in electric mode using batteries (in-charge depleting mode), or in conventional combustion-fueled driving (in charge-sustaining mode). Indeed, the high-energy battery can be charged from a power grid. Moreover, they are designed to travel longer distances. This eliminates the "range anxiety" because when batteries are depleted, the ICE can help the electrical machine. Chevrolet Volt in U.S. markets and Toyota Prius Plug-in Hybrid are two examples of PHEVs available in the market.

Classification

Nowadays, several kind of hybrid vehicles are present in the market. They differs each other on powertrain configuration. In Figure 6 is shown a classification of the hybrid vehicles based on the degree of the hybridization. The classification is based on the weight of the electrical power source with respect to the ICE. The main powertrain architecture are series and parallel. A brief description of the most important hybrid vehicles configuration is below.

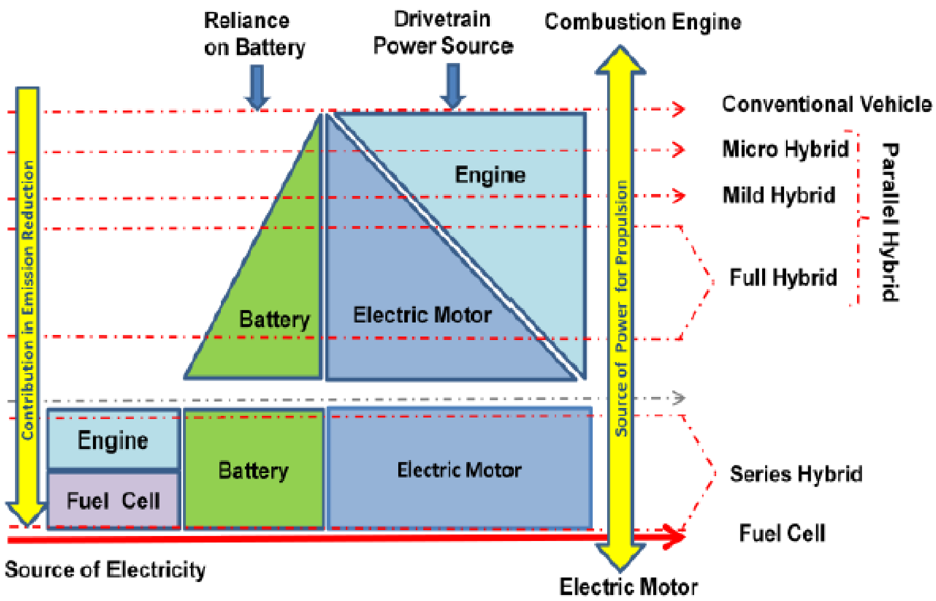

Figure 6: Classification of hybrid vehicles on degree of hybridization [15].

Series hybrid

In series configuration the electrical machine is the only component linked to the wheels, the battery pack provides power to electric machine. On the control strategy side, at low speed the power is drawn by the batteries to electrical machine. During acceleration phases, ICE drives the generator, in this way it compensate the power provided by the batteries [16].

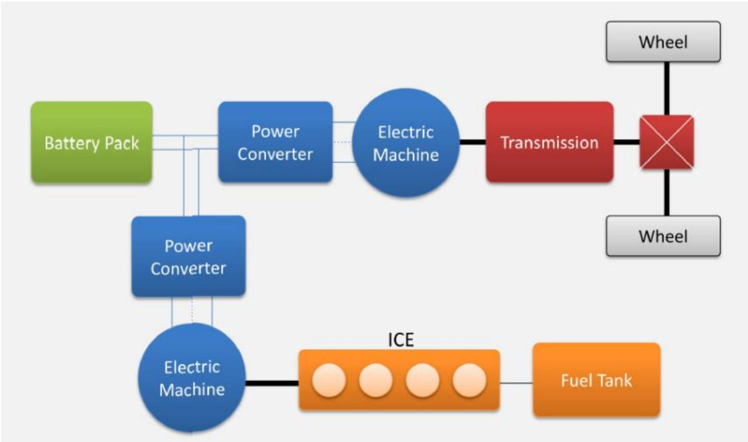

Figure 7: Series configuration for hybrid vehicle [2].

Parallel hybrid

In parallel configuration, ICE and electrical machine are linked to mechanical transmission, they can work together to power the vehicle. Furthermore, the electrical machine can enabled function such as start and stop, regenerative braking, e-motor assist.

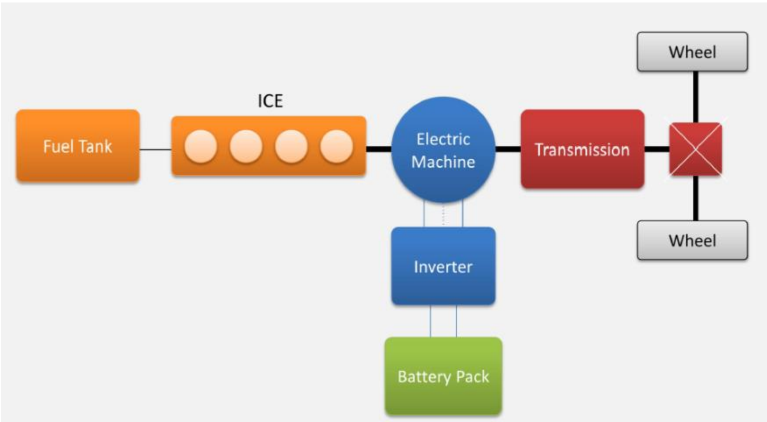

Figure 8: Parallel configuration for hybrid vehicle [2].

Combined hybrid

This kind of HEV shares features of both series and parallel configuration, this is allowed by power-split device. This system divides the power demand between ICE and electrical machine. Hence, in this hybrid car strategy to give benefit in terms of fuel consumption can be exploited. System works in series configuration when the speed is low, therefore the ICE works near optimum efficiency points; on the contrary the system works in parallel when speed is higher [17].

Input power-split system is an example of combined hybrid system, used by Toyota and Ford. This consists in two large electrical motors and a planetary gear system that replace the conventional transmission. Hence, this system has the benefit to make smoother the transition between the different power sources. On the other hand, the drawback is related to the cost.

Inside the parallel configuration, it can be found:

Full hybrid

In full hybrid system, ICE and electrical machine can move the vehicle. In these vehicles, it could be useful to define a strategy to optimize the fuel economy. For example when the power demand to motion is low (at lower mechanical efficiency), the system switch to electrical mode, this is generally used in city driving.

Mild/Micro hybrids

In micro-hybrid, electrical machine does not provide enough power to move the vehicle. However, EM can give an assist in acceleration phases.

These vehicles enabled functions such as regenerative braking, torque assist and start and stop. Furthermore, the key difference between micro and mild hybrid vehicles is the power supplied by the EM: from 3 to 5 kW for micro-hybrid and from 7 to 12 kW for mild-hybrid.

Hydrogen fuel cells electric vehicle

HFCEVs are vehicles powered by electricity, which is generated by a fuel cell using hydrogen and air. The main advantage of these vehicles with respect to conventional ICE system is the higher conversion efficiency. In addition, the refueling is faster than charging battery in BEV. HFCEVs are very expensive. Toyota Mirai and Hyundai Tucson, both available in US market, represent two examples of HFCEVs.

2.2 CO_2 Reduction Technologies

If the power of the hybrid system is increased, there will be an increase in the number of the functions that the hybrid system can enable. This is shown in Figure 9. The main technologies usually used in hybrid vehicles are start and stop, regenerative braking, e-motor assist, EV-Drive.

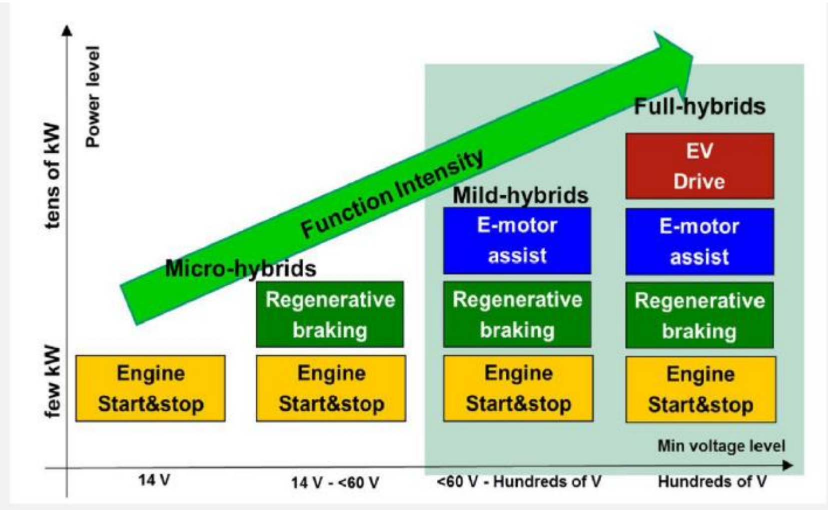

Figure 9: Hybrid functions and classification [2].

Start and stop

This technology switches off the engine when the vehicle is stationary (for example in front of a red traffic light). This mechanism also occurs in coasting mode (when the internal combustion engine is decoupled by transmission). There are variables that decide when to enable start and stop mechanism: the most important are battery SOC and engine temperature.

This system is disabled until a catalyzer achieves the light-off temperature. [18].

Regenerative braking

Regenerative braking exploits electric machine to convert a part of kinetic energy to electric energy (generator mode). The advantage is to use energy, otherwise dissipated to heat in the friction brakes. Obviously the maximum energy that can be converted depends by the maximum regenerative power of the electrical machine. In order to exploit all the potential of regenerative braking, friction brakes should be activated only when the braking power overcome the maximum power that can be recovered. This could be allowed by using a particular control system.

E-motor assist (Torque assist)

EM can help ICE to provide the power assist, mainly during fast acceleration request. Hence, this function can reduce the engine transient. The application of the e-motor assist depends by several variables: the capability of the battery to provide electric energy to the EM, the maximum discharge power, SOC.

EV Drive

This function is enabled only in full-hybrid vehicles, as shown in Fig. 9. EM is more powerful than mild hybrid in order to allow the pure electric drive.

Other technologies

Fuel cut off cuts the fuel injection when the engine speed is higher than a threshold. The injection is re-activated only when engine speed drop below a lower threshold [19].

The implementation of cut off system could create a problem when it is used a catalyzer, because the efficiency of the catalyzer falls down when the injection is cut. In fact, the catalyzer is filled of oxygen.

Chapter 3. Case Study

3.1 BSG 12 V Architecture

BSG is an example of micro/mild hybrid system. This solution has gained popularity in the last years due to the low cost and high benefit. BSG consists in a compact electrical machine more powerful than conventional alternator. This hybrid system works as generator and motor. In generator mode, the electrical machine recharges the battery (regenerative braking). On the other hand, EM provides an assist to the engine (motor mode).

The thesis focus on the implementation of BSG 12V in a city car. In this system regenerative braking, torque assist and start and stop are also enabled. The most important characteristics of the analyzed vehicle are listed in Table 4.

Vehicle	
Segment	A
Curb weight NEDC	1100 Kg
Curb weight WLTP TMH	1180
Tyre rolling radius	292 mm

Table 4: Vehicle's characteristics.

On the other hand, in Table 5 and Table 6 are shown the energy demand and coast down factors for NEDC and WLTC.

Coast down factors for NEDC	
F_0	86,7 N
F_1	0,193 N/km/h
F_2	0,0317 $N/(km/h)^2$
Vehicle demand power at 100 km/h	12 kW

Table 5: Coast down factor for NEDC.

Coast down factor for WLTP TMH	
F_0	116 N
F_1	-0,065 N/km/h
F_2	0,0358 N/(km/h)^2
Vehicle demand power at 100 km/h	13 kW

Table 6: Coast down factor for WLTC.

The global hybrid architecture of the city car is sketched in Fig. 10.

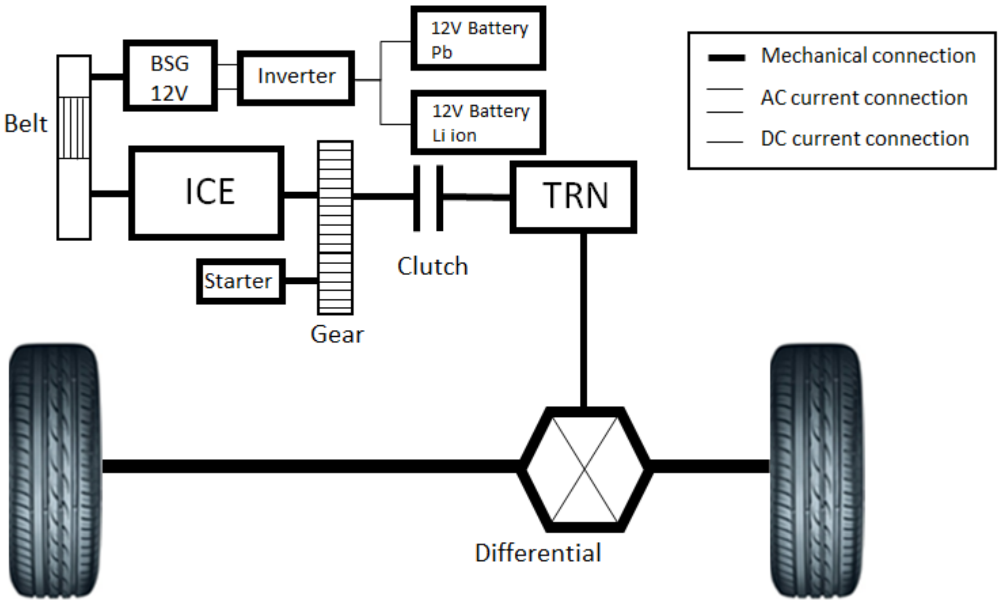

Figure 10: Architecture of BSG 12V.

Starter

Starter is used for starting from a stand still condition when engine is cold. It is linked to the crankshaft by means gear system.

Transmission (TRN)

The transmission gearbox has 5 gears, the main characteristics are shown in Table 7.

Transmission	
Gearbox type	MT – 5 speed
Gear ratio	1st 3,91
	2nd 2,174
	3rd 1,46
	4th 1,121
	5th 0,897
Final drive ratio	3,438
Final drive efficiency	95%

Table 7: Characteristics of the transmission.

ICE (Internal Combustion Engine)

The engine is a four cylinders natural aspired type; the most important features are shown in Table 8.

Engine	
Fuel	Gasoline
Displacement	1242 cm3
Peak Power	51 kW @ 5500 rpm
Peak Torque	102 Nm @ 3000 rpm
Idle speed	800 rpm
Inertia	0,25 Kg m^2

Table 8: Characteristics of the engine.

BSG 12 V

The EM used in this vehicle is BSG 12V. This is linked to crankshaft by belt drive and to the inverter by AC connection. The data of the electrical machine is shown in Table 9. On the other hand, in Fig. 11 is shown the characteristic of the EM normalized, in motor and in generation mode.

BSG 12V	
Type	Belt Starter Generator
Peak Power	Motor and Generation mode: 3kW
Maximum speed	20 000 rpm
Transmission ratio	2,2

Table 9: Characteristics of the BSG 12V.

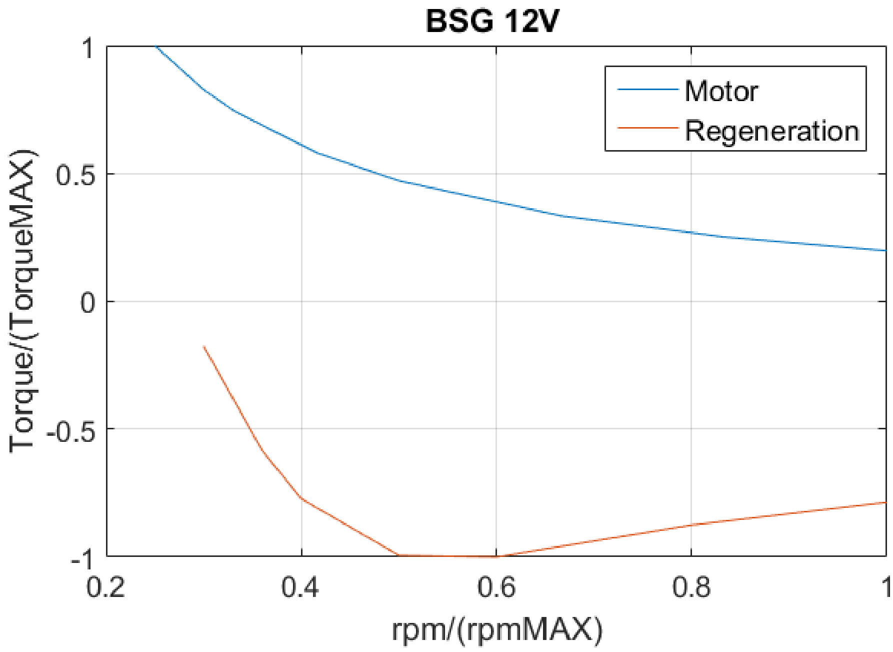

Figure 11: Characteristic of the EM normalized.

Inverter

Inverter is the device that transform AC from electrical machine, providing DC to batteries (lead acid Pb battery and Li-ion battery), and vice versa (in motor mode). This device links batteries to electrical machine.

12 V Battery Pb

Lead acid Pb battery is the usual battery used in all conventional vehicles. The main important parameters are listed in Table 10.

Battery Pb	
Capacity	63 Ah
Voltage	12 V
Maximum current discharge	500 A
Maximum current charge	34 A

Table 10: Characteristics of Pb Battery.

12 V Battery Li ion

This battery helps the Pb battery to provide electrical load to the vehicle request.

Li-ion battery characteristics are shown in Table 11.

Battery Li ion	
Capacity	11 Ah corresponding to 132 Wh
Voltage	12 V
Maximum current discharge	275 A
Maximum current charge	320 A

Table 11: Characteristics of the Li-ion Battery.

Both the batteries are in parallel configuration. As consequence, electrical load is covered in a higher part by Li-ion battery. In fact, the resistance of this battery is lower than lead acid.

An example of BSG available in the market is Suzuki Baleno. Mild hybrid system provided by Suzuki, called SHVS (Suzuki Hybrid Vehicle System), enables the following functions: regenerative braking, start and stop and assist the engine during acceleration phases. Belt drive system restart quieter and smoother with respect to conventional start and stop system. Furthermore, like the system in case study, this system has two batteries: lead acid and li-ion battery. The SHVS, in generation mode is shown in Fig. 12 Suzuki called this system ISG (Integrated Starter Generator).

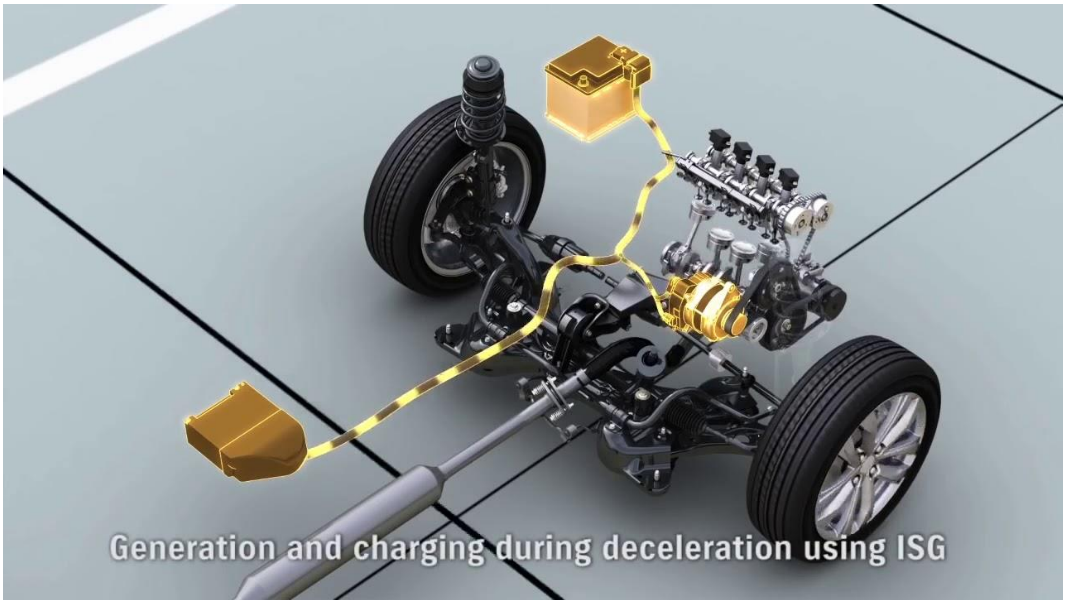

Figure 12: SHVS system in generation mode.

GM's mild hybrid system was introduced in 2007 with the Saturn Vue Green Line, this system had 36v NiMH battery pack and an electrical motor of 5 HP. In 2012 was introduced an improved system that allow also e-assist. It was implemented on Buick LaCrosse.

In this context, Mazda produced micro-hybrid system (i-ELOOP). This technology has an alternator that capture energy as soon as the driver release the accelerator pedal. Recovery energy is stored by a capacitor because this last accumulate energy faster than battery.

3.2 Mathematical model baseline and BSG 12V

The purpose of the model is to estimate CO_2 emissions. In order to do that, literature provides different methodologies based on the degree of detail for the model. The most common approaches are kinematic, quasi-static and dynamic approach.

Kinematic approach

This is the simplest methodology and is based on backward approach. The flux diagram followed by this approach is shown in Figure 13.

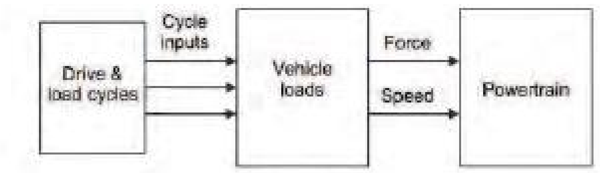

Figure 13: Flux diagram in a kinematic or backward simulator [22].

As it shown the input data is the vehicle speed of the driving cycle. The first step is the calculation of vehicle engine speed by using information of driving cycle and transmission ratios. On the other hand, information about vehicle such as vehicle mass and inertia of the engine are useful to calculate the traction power.

To calculate the engine speed, it can be used Eq. (3.1).

$$rpm = \frac{v * 60}{2 * \pi * R_0 * 3{,}6} * \tau_d * \tau_g \tag{3.1}$$

where: v is vehicle speed $\left[\frac{km}{h}\right]$, R_0 is the radius of the wheel $[m]$, τ_d is the transmission ratio of the differential and τ_g is the transmission ratio of the gear.

The next step is to calculate the vehicle load. There are three components: rolling resistance, aerodynamic drag and the road slope contribute. These components are taken into account by coast down factor as it shown in eq. (3.2)

$$F_{res}[N] = F_0 + F_1 * v + F_2 * v^2 \tag{3.2}$$

Hence, it has to be added to the inertial force. Therefore, it is necessary to introduce the equivalent mass m_a. This parameter takes into account vehicle inertia and energy losses that derives from rotational components of driveline.

$$m_a[Kg] = m_v + \frac{J_{wheel}}{R_0^2} + \frac{J_{engine}\ \tau_d^2\ \tau_g^2}{R_0^2} \tag{3.3}$$

where, m_v is the vehicle mass $[Kg]$, J_{wheel} is the wheel inertia $[Kg\ m^2]$ and J_{engine} is the engine inertia $[Kg\ m^2]$.

The power demand is computed as contribution of two forces: resistance eq. (3.2) and inertial, by using equation (3.4):

$$P_d[kW] = P_m \eta_T = F_{res} * v + m_a * \frac{dv}{dt} * v \tag{3.4}$$

By having: η_T is the transmission efficiency, P_m is the engine power [kW]. Bmep can be computed using eq. (3.5)

$$bmep[bar] = 1200 * \frac{P_m}{rpm * V} \tag{3.5}$$

where V is the displacement of the engine $[dm^3]$.

The final step is the calculation of fuel consumption and CO_2 emission with the eqs. (3.6) and (3.7).

$$Fuel\ consumption\ \left[\frac{l}{100km}\right] = 100 * \frac{f_c}{L} \tag{3.6}$$

f_c is the cumulate fuel $[g]$ and L is the distance $[km]$.

$$CO_2 emission\left[\frac{g}{km}\right] = \rho_{fuel} * \frac{\left[\frac{l}{100km}\right]}{0,0315 * 1000} \tag{3.7}$$

where ρ_{fuel} is the density of the fuel $[g/l]$.

Limits of this approach:

- This approach does not take into account the driver, in fact this methodology supposed that driver follows in a perfect way the driving cycle.
- There are not control system that limits the capabilities of the components. In other words, the model does not take into account if components can satisfy the load requests.
- This approach does not consider dynamic phenomena. In fact, the simulation is assessed as continuous series of stationary states.

Quasi static approach

Quasi static is a more detailed approach than the kinematic. Figure 14 shows how it works.

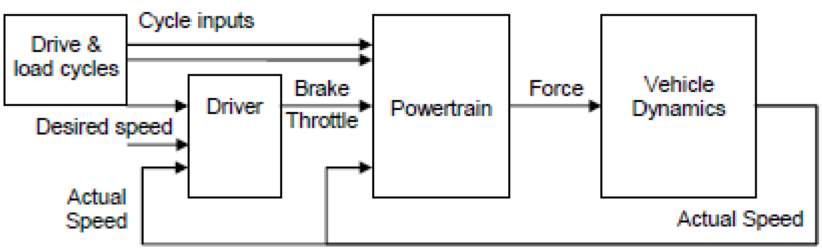

Figure 14: Flux diagram in a quasi-static approach simulator [22].

Driver tries to follow the driving cycle (input data). As consequence, actual vehicle speed is compared with respect to the target vehicle speed. This generates a power demand signal related to the variation between actual and target speed. Furthermore, driver (PID speed controller) sends brake or throttle signal to powertrain system. By knowing torque and engine speed, the vehicle dynamic equation are solved. While, CO_2 emission and fuel consumption are calculated using maps by following kinematic approach. The main components such as ICE, batteries and electrical machine are described by using performance maps.

This approach does not take into account the thermal transient behavior of driving cycle, and dynamic phenomena that can influence the emissions (for example turbo lag).

Fully dynamic approach

This methodology is the most complex. In fact, this model solves dynamic equations also for the components. Fully dynamic compared with respect to the quasi static approach, is able to take into account internal combustion engine behavior though 0D or 1D fluid-dynamics model.

3.3 Characteristics

Three models were built in order to evaluate benefit in terms of CO_2 and fuel consumption. The first is the baseline, the second is the baseline equipped with start and stop system, the last is the BSG 12V model.

All of the mathematical model are created using "quasi static" approach, with a dynamic driver that follows the cycle. In the following sections, details of the model are described.

The generic model is depicted in Figure 15.

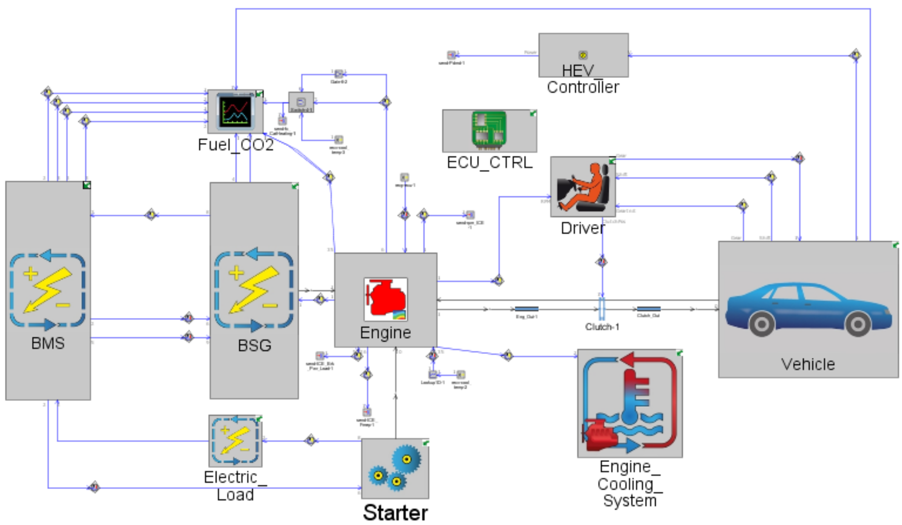

Figure 15: GT-Suite model.

Model is composed by the following subassembly:

- Vehicle
- Engine
- Engine Cooling System
- Driver
- Engine Control Unit
- Fuel CO_2
- Battery management system
- Alternator
- Electric Load
- Starter

In the following sections are analyzed each of these components.

3.3.1 Vehicle

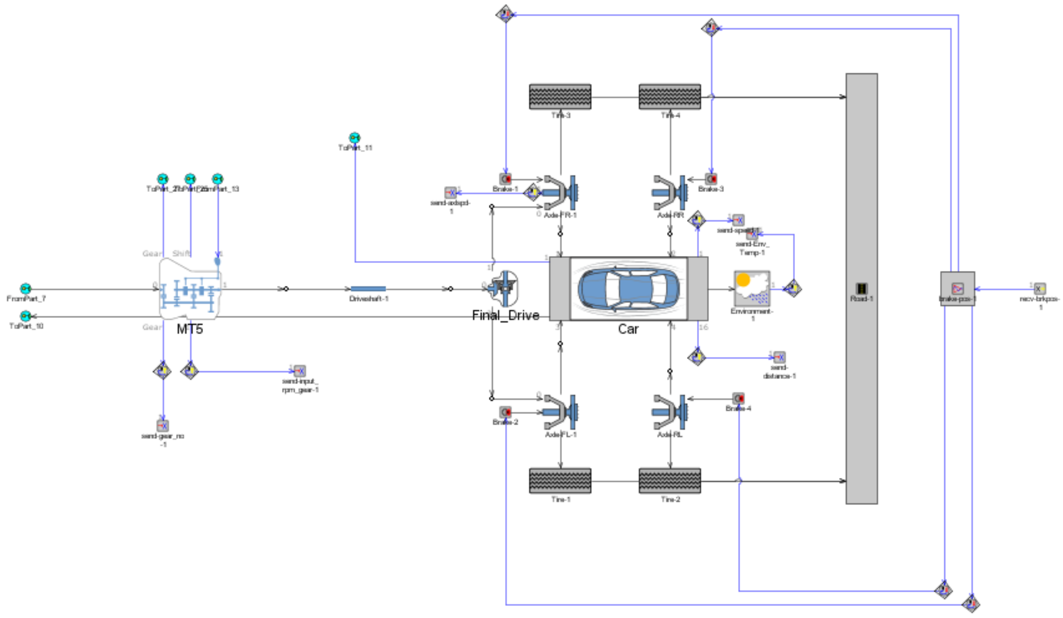

Figure 16: Vehicle subassembly.

In this section are represented all of the components that characterize vehicle model. Hence, all of the geometric parameters such as wheelbase, rolling radius, height of the vehicle are introduced. Furthermore, there are information related to the transmission such as: final drive ratio, the transmission ratio for each gear and their efficiency. The coast down coefficient are included in the car model: they represent the resistance force of the vehicle (rolling resistance, aerodynamic drag and road slope component).

3.3.2 Engine

Engine is modelled by means of stationary maps. Full load characteristic, fuel map, and the friction map are the input of the engine block. This block is linked to the ECU. This last sends the accelerator pedal signal to the engine. Pumping losses are not taken into account in the model.

3.3.3 Battery Management System

This section has only two blocks: the battery and the inverter. The SOC of the battery is calculated based on the power being drawn from or supplied to the electric circuit, depending on the direction of the current. The battery is considered an open circuit voltage in Fig. 17.

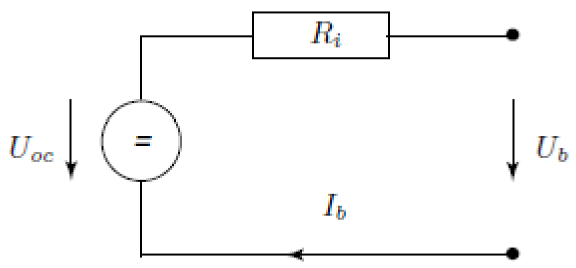

Figure 17: Open voltage circuit model, for the battery [17].

U_{OC}: is the OCV of the battery;

R_i: is the internal resistance of the battery;

U_b: is the voltage of the battery;

The voltage of the battery U_b is evaluated by applying Kirchhoff's law eq. (3.8):

$$Uoc(t) - Ri(t) * Ib(t) = Ub(t) \tag{3.8}$$

Battery is connected to the inverter, which limits the variables: current, voltage, the maximum discharge and charge power.

For the first two models (baseline and ESS) there is only lead acid Pb battery that supplies all of the electrical load. In BSG model there are also Li-ion batteries. In reality, batteries are in parallel configuration. The subassembly is shown in Fig. 18.

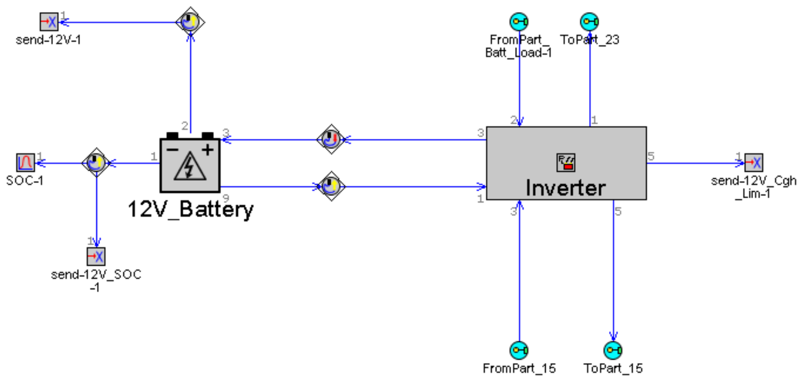

Figure 18: Battery subassembly for baseline and ESS model.

In the BSG model, electrical load are taken by Pb battery until its SOC achieve 80%. At this point, Li-ion battery recharges the other battery by taking its SOC constant to the mentioned value. Furthermore, Li-ion battery provides power to torque assist and recovery energy by regenerative braking. The subassembly is represented in Fig. 19.

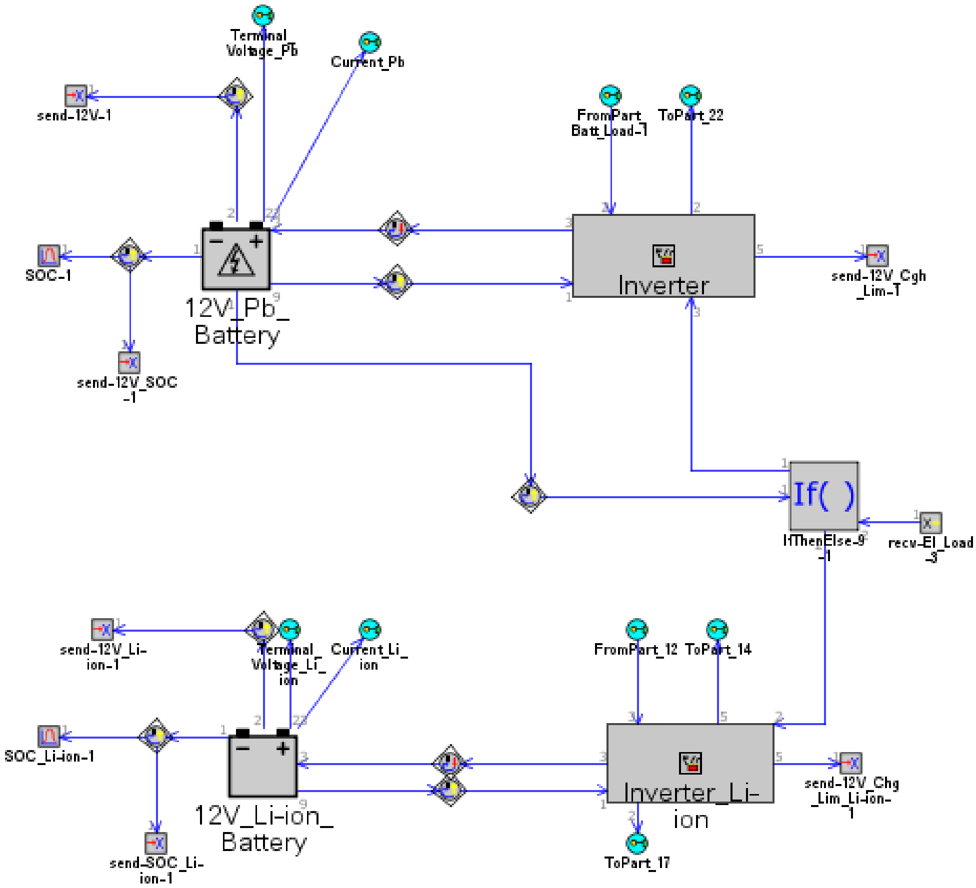

Figure 19: Battery subassembly for BSG model.

3.3.4 Electric Load

In this section the load required from cruise are grouped. Electrical load is supposed constant: 220 W for NEDC and 350 W for WLTP (engine on). When start and stop system is enable, electric load is supposed equal to 120W (engine off). The power related to the starter is added to electrical load.

3.3.5 Alternator

The control strategy of the alternator is here explained. In baseline and ESS model, alternator is controlled by an event manager, this last decides when recharge the battery. In fact, battery is recharged when SOC is lower than SOC minimum (75%) and it continues to charge until the SOC will be equal to maximum SOC value, set to 85%. The amount of the power provided for the battery charging is the maximum power charge calculated by the inverter plus the electrical load. When the vehicle is in deceleration condition is a little amount of regenerative power is recovered and stored in the battery.

In the model, alternator works in power-brake mode: the system input is mechanical brake power demand and computed output are electrical power and brake torque. Finally, the alternator is linked, with a transmission ratio of 2,41, to the belt drive.

In BSG model, alternator is replaced by EM. Hence, this last interfaces with also Li-ion battery. BSG recharges Li-ion battery only when its SOC is lower than 30%. In this case, EM recharges the battery until it reaches a SOC level of 33%. This threshold is chosen to avoid instability condition caused by recharged and discharged of the battery.

3.3.6 Starter

In baseline and ESS model, starter is used to switch on the engine. ECU sends the input signal every time after start and stop events. On the contrary, in BSG model if the engine is warm enough, BSG restarts the vehicle.

3.3.7 Driver

The driver block simulates a real driver that follow the driving cycle. Driver controls the three pedals (accelerator, brake and clutch pedal) on cruise condition. When the vehicle starts from stand still, driver is replaced by an event manager. During gearshift event the accelerator pedal is released until 50%, meanwhile the clutch is disengage. Gearshift occurs in this moment. After that the accelerator pedal will press until achieve the maximum stroke, and the clutch is released gradually.

3.3.8 Engine Control Unit

ECU system controls functions such as idling, fuel cut and start and stop. In fact, engine speed is higher than idle speed, for the first 50 s in order to speed-up the warm up of the engine. From 51 s until the end of the cycle, engine speed decreases until reaches 800 rpm. On the other hand, there is start-stop control logic. A delay for the acceleration pedal is also taken into account to consider the fluid dynamics transient.

3.3.9 Engine Cooling System

The Engine cooling system model is a first order differential system. This takes as input the mechanical power and give as outcome the coolant temperature. A simplified sketch of the engine cooling system is shown in Fig. 20.

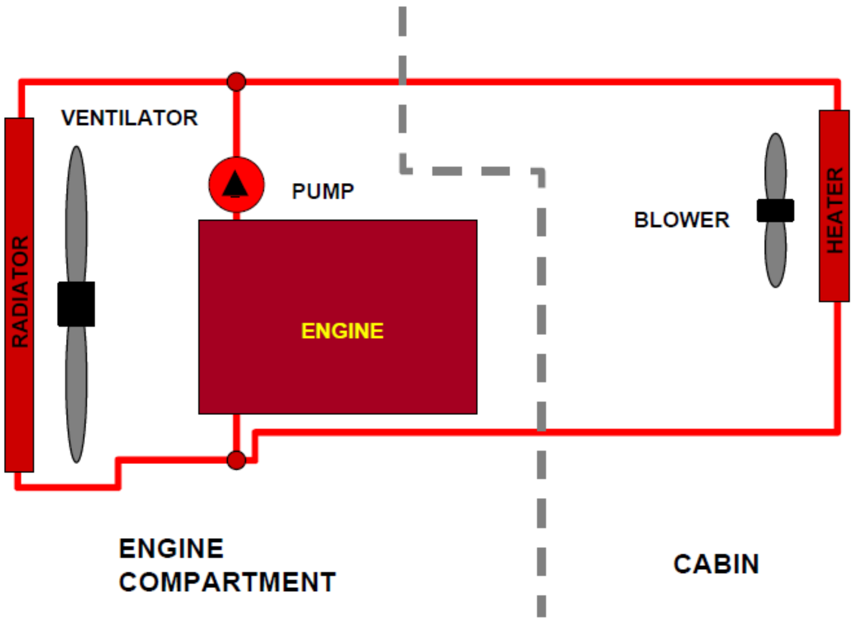

Figure 20: Scheme of the engine cooling system [23].

By applying the first law of thermodynamics:

$$C_T \frac{dT_{H_2O}}{dt} = W_{ENGINE} - W_{HEATER} - W_{REJECTED} \quad (3.9)$$

where:

T_{H_2O}: Coolant temperature $[°C]$;

W_{ENGINE}: mechanical power $[W]$;

W_{HEATER}: Power release by cabin heater $[W]$;

$W_{REJECTED}$: Power rejected by the front of radiator $[W]$;

$$C_T = C_{CF} + C_{ENGINE} + C_{OIL} \tag{3.9}$$

Where:

C_T: Total thermal capacity $[kJ/°C]$;

C_{CF}: Thermal capacity of the coolant fluid $[kJ/°C]$;

C_{ENGINE}: Thermal capacity of the engine $[kJ/°C]$;

C_{OIL}: Thermal capacity of the lubricant $[kJ/°C]$;

In the simulations it is supposed that conditioning system is disabled

$$W_{HEATER} = 0$$

For the calculation of $W_{REJECTED}$ it is used an experimental law. For further information, CRF Cabin model - Rapporto di lavoro [23].

3.4 Functions and strategy

In this section there will describe the strategy of functions on BSG model and start and stop system for ESS model.

3.4.1 Start and stop

For baseline and ESS models, start and stop is enabled when coolant temperature is higher than 50 °C and vehicle speed is lower than 1 km/h. Another condition is related to the catalyzer heating. In fact, ESS is enabled only after 190 s (time required for warm up of the catalyzer). Furthermore, this last condition, is also implemented in BSG model.

In BSG model, start and stop system is improved (it is called Enhanced ESS). This function takes place when vehicle speed is lower than 15 km/h.

3.4.2 Regenerative braking

This function is enabled only in BSG model. Regenerative braking takes place, when:

- Acceleration < 0;
- Clutch pedal and accelerator pedal are released;
- Brake pedal is pressed within 1.5 s after accelerator pedal is released;
- Engine speed > 1500 rpm, it will disabled when it falls under 1325 rpm (it follows an hysteresis cycle);

When regenerative braking is left, it is blocked during 2s to avoid re-entrance if conditions are still true. This is implemented to avoid instability condition.

3.4.3 Torque-assist

Torque Assist acceleration

Torque Assist is enabled when:

- Accelerator pedal > 30%;
- Brake and clutch pedals are both released;
- Engine speed achieves 2270 rpm, over 2270 rpm it is disabled. It is re-enabled when engine speed is lower than 2160 rpm (hysteresis cycle);
- Torque Assist power: 2 kW;

If SOC Li battery < 50%, this function is disabled. Furthermore, when torque assist is left, it is blocked off during 2 s to avoid re-entrance, if conditions are still true. This is implemented to avoid instability condition.

Torque Assist Plateau

It is implemented another torque assist condition. The idea was to use pure electric mode on the plateau of NEDC characterized by vehicle speed constant equal to 15 km/h and in deceleration phases. In this configuration ICE is shut-off.

Hence, the conditions put in the model are:

- Acceleration <0 OR vehicle speed < 16 km (Deceleration condition)
- Acceleration =0 AND T>70 °C AND vehicle speed < 16 km/h, it means that vehicle is driving on the plateau of NEDC at 15 km/h.
- Power demand <2 kW;

Enable until Power demand achieve 2 kW and stop when it drop below 1,5 kW (hysteresis cycle).

Chapter 4. Virtual Testing and Validation

In this section are reported the results coming from simulations NEDC, WLTC for hot and cold conditions (starting coolant temperature=90°C for hot and 23°C for cold). In addition, Real World driving cycle is considered.

4.1 Real world driving cycle's building

This last cycle is built in the following steps. WLTC was divided in its 4 parts: Low, Medium, High, Extra-High. For each part it was computed CO_2 emission. A sensitivity analysis on CO_2 emissions was performed by changing the percentage of each part on distance. In other words, each part (low, medium, high and extra high) is weighted on distance in a different percentage than standard configuration. In this context, Table 12 shows the standard percentage and the other chosen to create Real World driving cycles.

	LOW	**MEDIUM**	**HIGH**	**EXTRA-HIGH**
Standard	13%	20%	31%	36%
RW A	50%	25%	15%	10%
RW B	30%	20%	30%	20%
RW C	25%	25%	25%	25%

Table 12: Percentage of WLTC chosen for Real World driving cycles.

These values for RW have been chosen to weight in different part LOW phase. In fact, statistical analysis realized by Heinz Steven in Fig. 21 [24] has been analyzed. Fig. 21 represents the overall vehicle speed distributions for the different data sources. Around 50% (cum frequency) of the cases have been considering for Italy by taking the maximum speed of LOW phase (56,5 km/h as shown in Table 2). This means that by weighting LOW phase in more remarkable way it is possible to built RW cycle. In addition, the percentage of the cases are higher by considering other European countries such as Germany and France (70% for both of them).

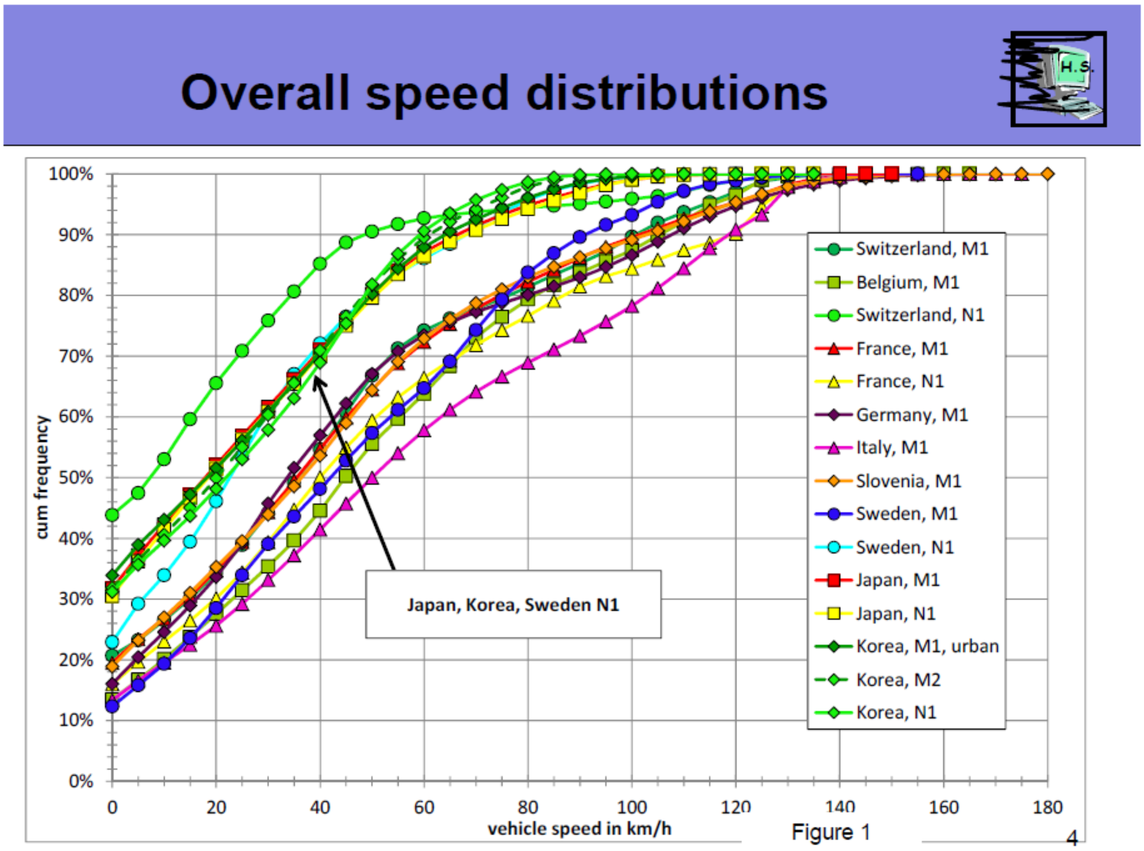

Figure 21: Overall vehicle speed distribution for different data sources [24].

For the calculation of CO_2 for RW driving cycles is used the eq. (4.1):

$$CO_{2_{RW}} = CO_{2LOW} * [\%_{LOW}] + CO_{2_{MEDIM}} * [\%_{MEDIUM}] + CO_{2_{HIGH}} * [\%_{HIGH}] + CO_{2EXTRA-HIGH} * [\%_{EXTRA-HIGH}] \quad (4.1)$$

4.2 CO_2 Results

The results in terms of CO_2 emissions along cycles and differences among model configurations, coming from the simulations, are shown in the Table 13.

CO_2 emissions [g/km]	Baseline	ESS	Δ CO_2 ESS vs baseline [%]	BSG	Δ CO_2 BSG vs baseline [%]	Δ CO_2 BSG vs ESS [%]
NEDC HOT	122	115	6	109	11	5
NEDC COLD	133	126	5	120	10	5
WLTC TMH HOT	138	134	3	128	7	4
WLTC TMH COLD	145	141	3	135	7	4
RW A	168	159	6	149	11	6
RW B	155	148	4	140	9	5
RB C	152	146	4	139	9	5

Table 13: Results from the simulations.

By analyzing results on cold NEDC, BSG allows a saving of 13 g CO_2/km. On the same cycle, ESS model gives as outcome a saving of 7 g CO_2/km. As results, technologies studied are environmental friendly because they reduce greenhouse gas emissions. On the other hand, the differences among the configurations are represented in Figure 22, in order to have a faster evaluation.

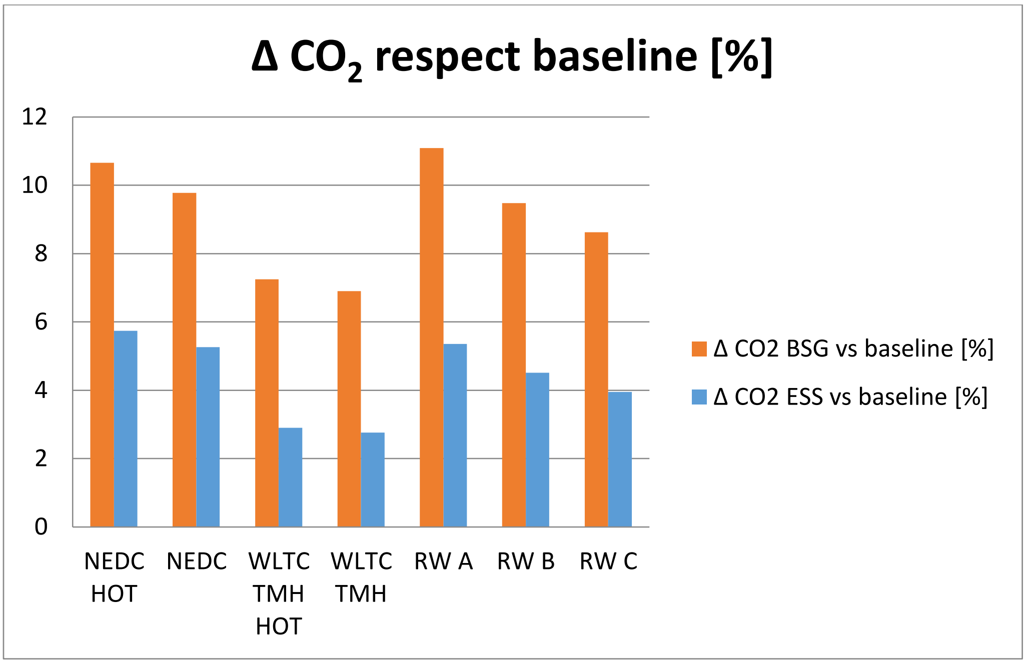

Figure 22: Differences in terms of CO2 of ESS and BSG respect baseline, for each cycle.

It is clear that BSG reduces greenhouse gas emission. By considering the homologation cycles NEDC and WLTC, reduction of CO_2 emissions is higher in NEDC than WLTC. By analyzing Real World driving cycles, BSG gives the best benefit in RW A. The reason regards the different weight of CO_2 emission given to LOW phase. In fact, BSG has higher benefit in LOW phase with respect to the other parts. This occurs because in LOW part, BSG can exploit better its functions. As consequence, by building RW in the way mentioned before, the saving on RW A is higher than in the RW B and RW C.

4.2.1 Baseline model

By considering baseline model on NEDC, it can be noticed that there are differences between the values of CO_2 emissions in hot and cold starting. Cat-heating is the responsible of this phenomena. In fact, in the first part of the cycle, it is mandatory to have an higher idle engine speed to warm up quickly the catalyzer. On the other hand, the impact of cold and hot condition on WLTC is lower with respect to NEDC (respectively 5% with respect to 8%). WLTC is longer than NEDC, cold starting has a lower effect because the majority part of the cycle is driven in hot condition.

In Fig. 23 SOC of Pb battery and vehicle speed are represented for baseline model. In deceleration phases, the alternator recharged the battery for a low amount of energy. In fact, SOC is constant or increases in those phases. In addition, the alternator does not recharge the battery because the SOC level is always higher than 75%. In fact, the battery works in depleting mode.

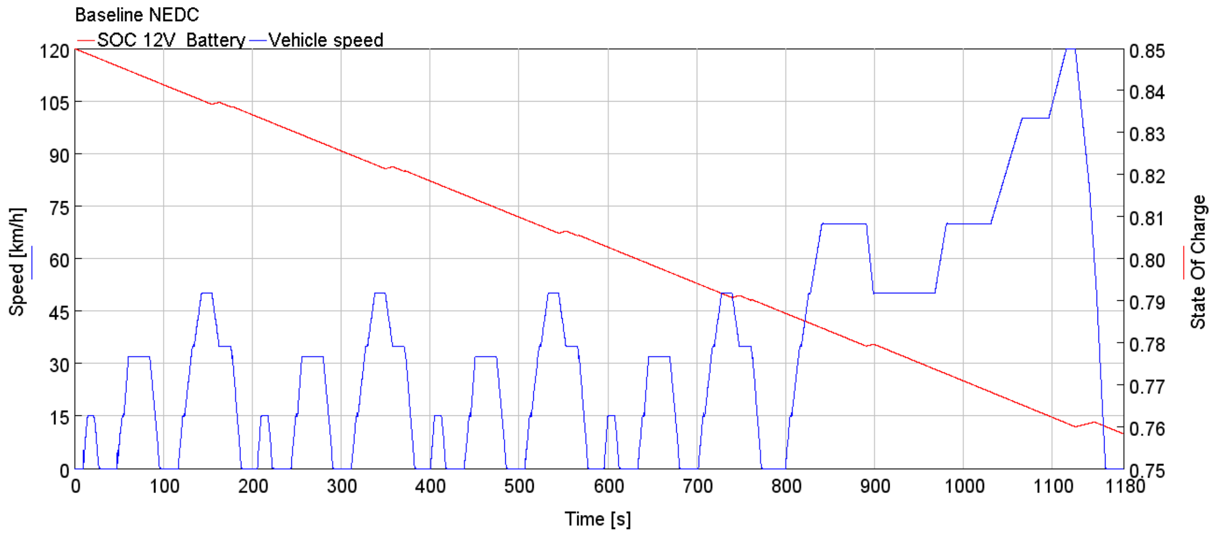

Figure 23: Vehicle speed and SOC for baseline model (NEDC).

In Fig. 24 is shown the SOC, vehicle speed and alternator signal for WLTC. During this cycle, at 791 s (dashed black vertical line), the SOC falls reaches the critical level of 75%. In fact, at this time step alternator recharges battery until SOC reaches 85% (as alternator strategy works). Fuel consumption increases due to the fact that engine has to provide power to move the vehicle but also to recharge the battery.

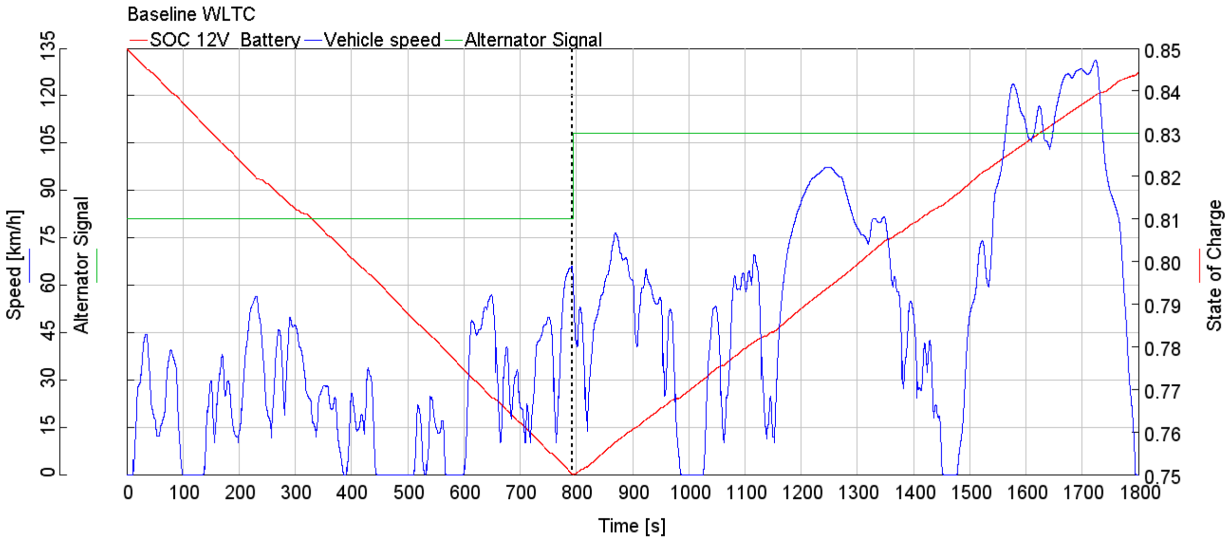

Figure 24: Vehicle speed, alternator signal and SOC for baseline model (WLTC).

4.2.2 ESS model

For ESS model, start and stop function is enabled after the first ECE-15 cycle for Catalyzer heating (only for NEDC cold). For hot NEDC, ESS function is enabled from the beginning of the cycle. For this reason, the difference in terms of CO_2 emissions between cold and hot NEDC is around 9%. By comparing savings on NEDC and WLTC, the benefit in terms of CO_2 emission in NEDC is higher than in WLTC. This happens because the first cycle has a higher number of stops (respectively 14 for NEDC and 9 for WLTC). When start and stop is enabled, electrical load is lower because the engine is switch-off. In this cycle, SOC battery does not drop below 75%, hence alternator does not recharge the battery. Fig. 25 and Fig. 26 show the trend of SOC, vehicle speed and start and stop phases for NEDC and for WLTC.

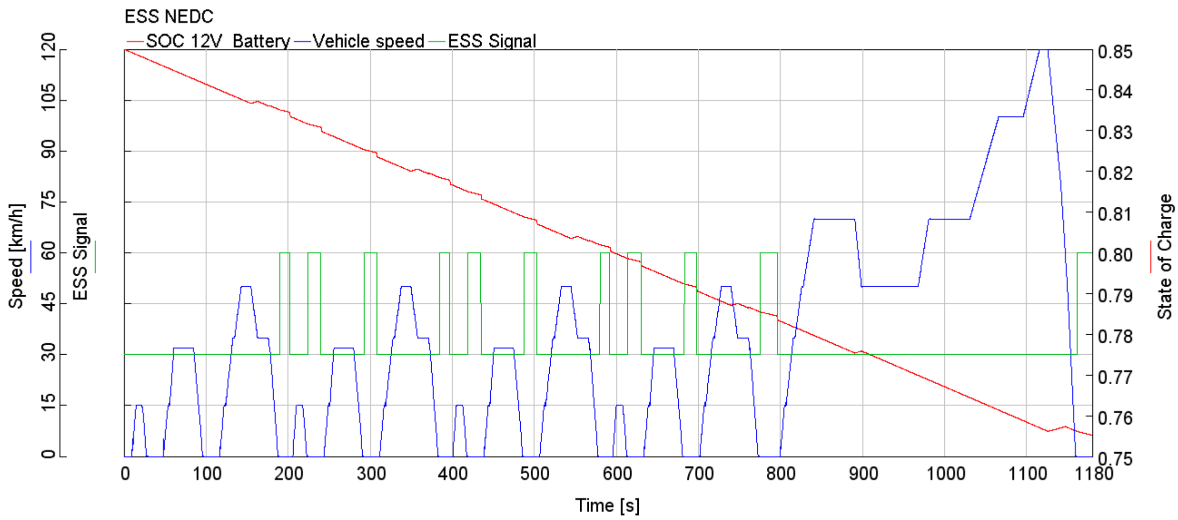

Figure 25: SOC, vehicle speed and ESS signal for ESS model (NEDC).

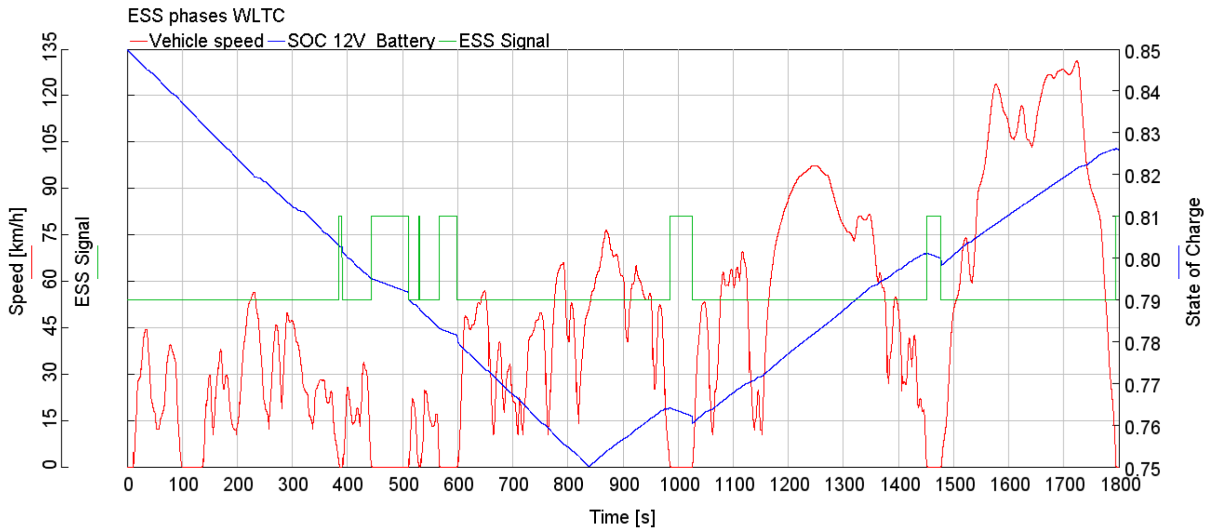

Figure 26: SOC, vehicle speed and ESS signal for ESS model (WLTC).

On the other hand, For WLTC the SOC of battery decrease below 75% (it occurs at 840s dashed line in Fig. 27). In this time step the alternator recharges the battery. This event occurs later than in baseline case because in start and stop phases the electric load is lower.

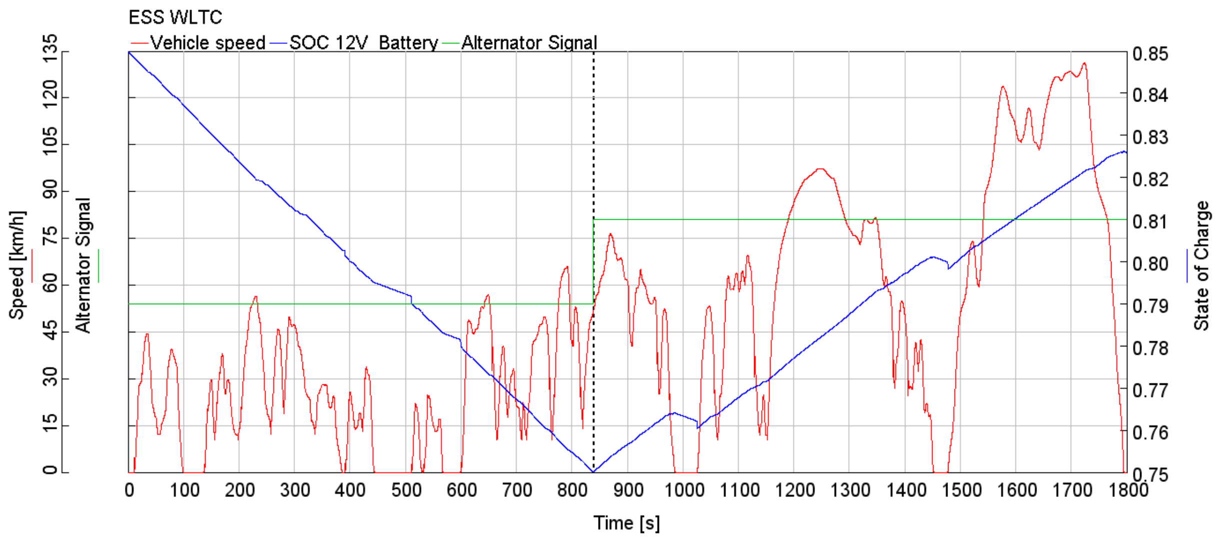

Figure 27: SOC, vehicle speed and alternator signal for ESS model (WLTC).

4.2.3 BSG model

BSG model shows higher benefit with respect to baseline and ESS model, as shown in Table 13 and Fig. 22. In fact, the higher benefit with respect to ESS model is due to the implementation of the enhanced start and stop and torque assist function.

For NEDC, electrical loads are supplied by Pb battery for all cycle. At 627 s (as shown in dashed line in Fig. 28) the Pb SOC reaches 80%. Li-ion battery recharges Pb battery, from this time step until the end of the cycle to maintain Pb SOC constant. Furthermore, the Li-ion battery does not drop below 30%, hence BSG does not recharge the battery.

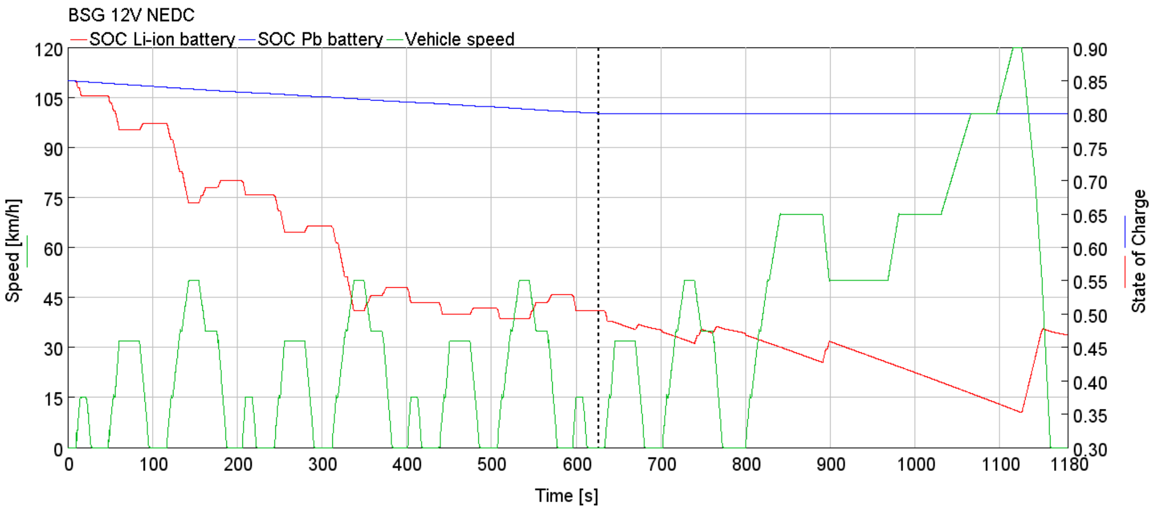

Figure 28: SOC, vehicle speed and alternator mode signal for BSG model (NEDC).

On the other hand, in Fig. 29 is represented the SOC of the two batteries for WLTC. Li-ion battery recharges Pb battery from 360 s (dashed black line in Fig. 28). By comparing Fig. 28 and Fig. 29 it is possible to notice that, for WLTC, Pb SOC reaches 80% earlier than in NEDC. The reason depends on higher electrical load for WLTC with respect to NEDC. Li-ion battery from this time step recharges the other battery of the amount of power needed to supply electrical load. Furthermore, in WLTC simulation Li-ion battery SOC drops to 30% (dashed horizontal red line in Fig. 29). By following the alternator strategy, EM recharges Li-ion battery until reaches a SOC level of 33%, as represented in Fig. 29 by alternator signal.

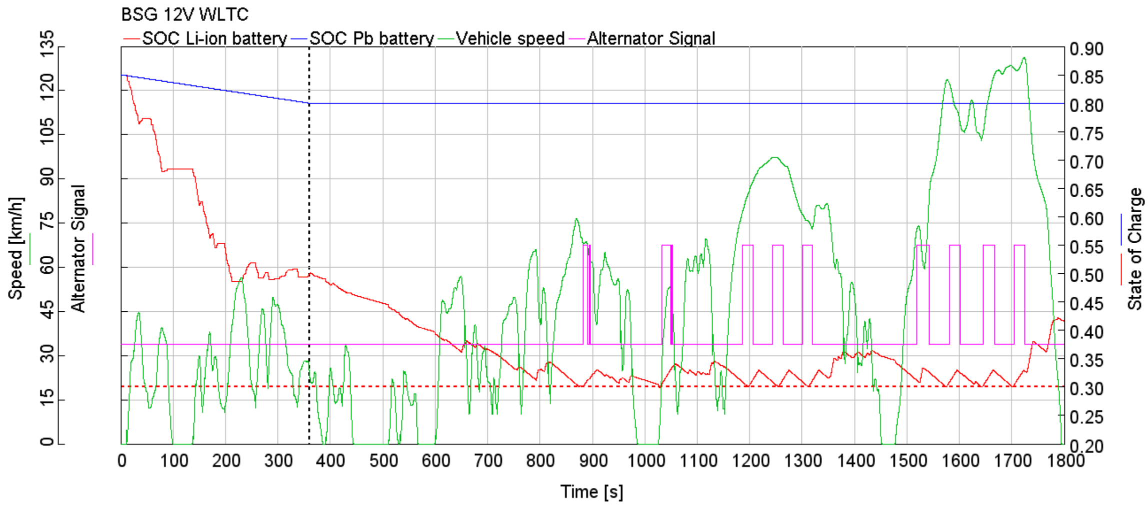

Figure 29: SOC, vehicle speed and alternator mode signal for BSG model (WLTC).

4.3 BSG functions

The benefit between ESS model and BSG model are due to Enhanced ESS and TA function. In this section, results for BSG functions have been analyzed.

4.3.1 Enhanced ESS

In Fig. 30 and Fig. 31 are shown the activation of the Enhanced ESS for NEDC and WLTC.

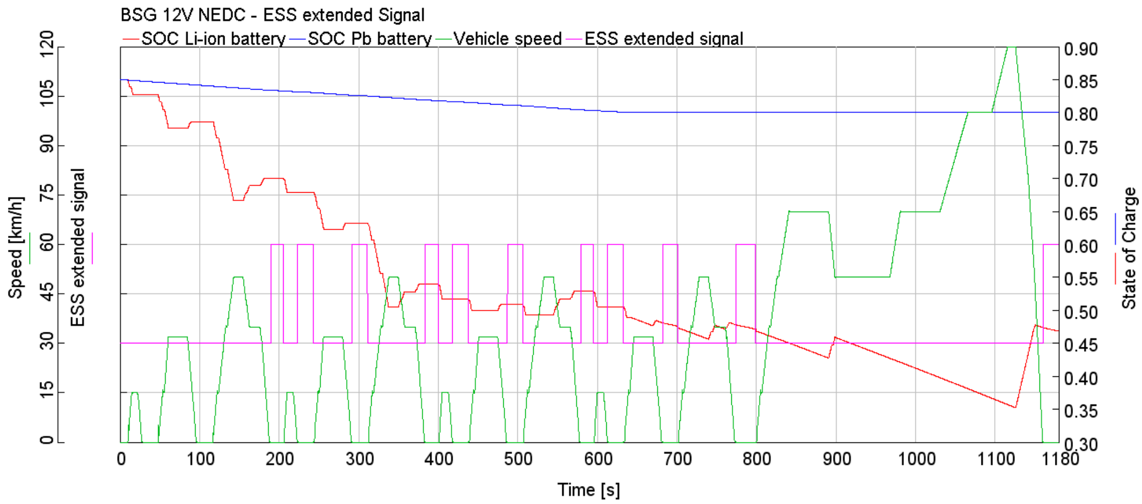

Figure 30: ESS events for BSG model (NEDC).

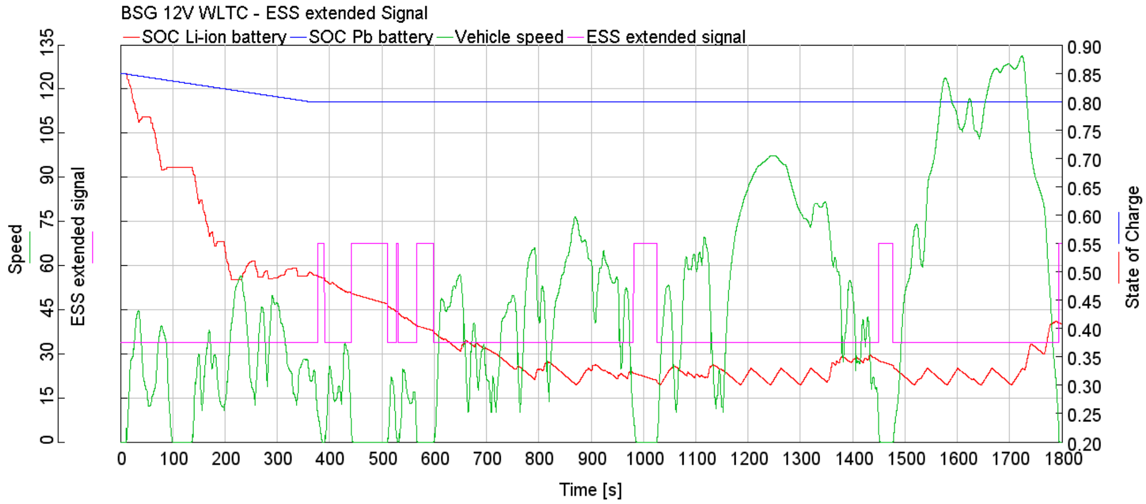

Figure 31: ESS events for BSG model (WLTC).

Extended ESS switches off the ICE when vehicle speed is lower than 15 km/h, enlarging start and stop phases durations with respect to conventional ESS system. In addition, the cranking occurs thanks to EM (when engine is warm up). EM takes the starting quieter with respect to the starter.

4.3.2 Regenerative braking

Regenerative braking events are shown in Fig. 32 for NEDC, and Fig. 34 for WLTC. In Fig. 33 is shown a detail for NEDC. When this function is enabled SOC of Li-ion battery increases. In the first deceleration of NEDC, RB conditions are satisfied, but SOC of Li-ion battery does not increase because power from braking is not enough to recharge battery.

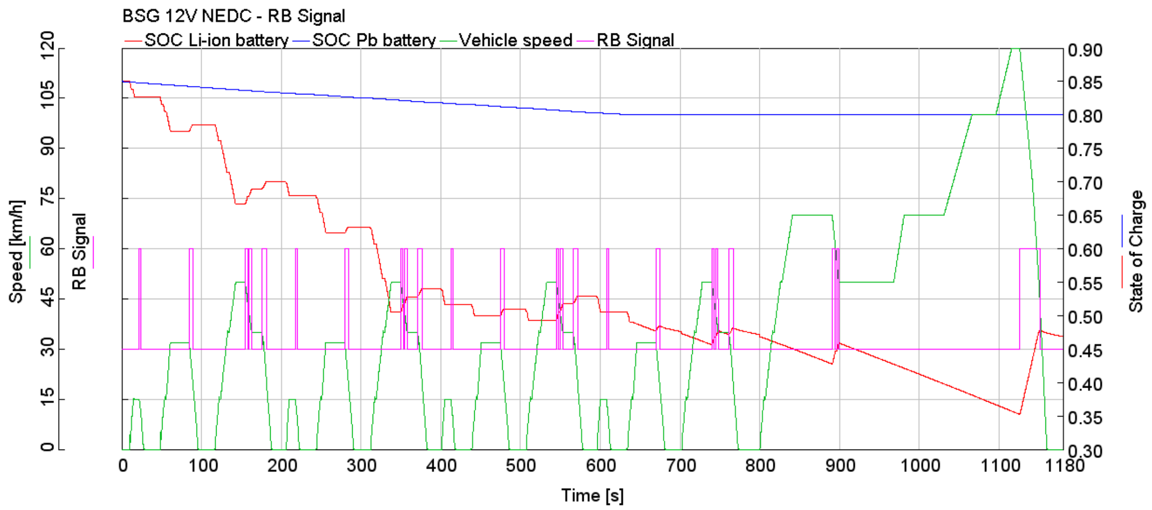

Figure 32: RB events for BSG model (NEDC).

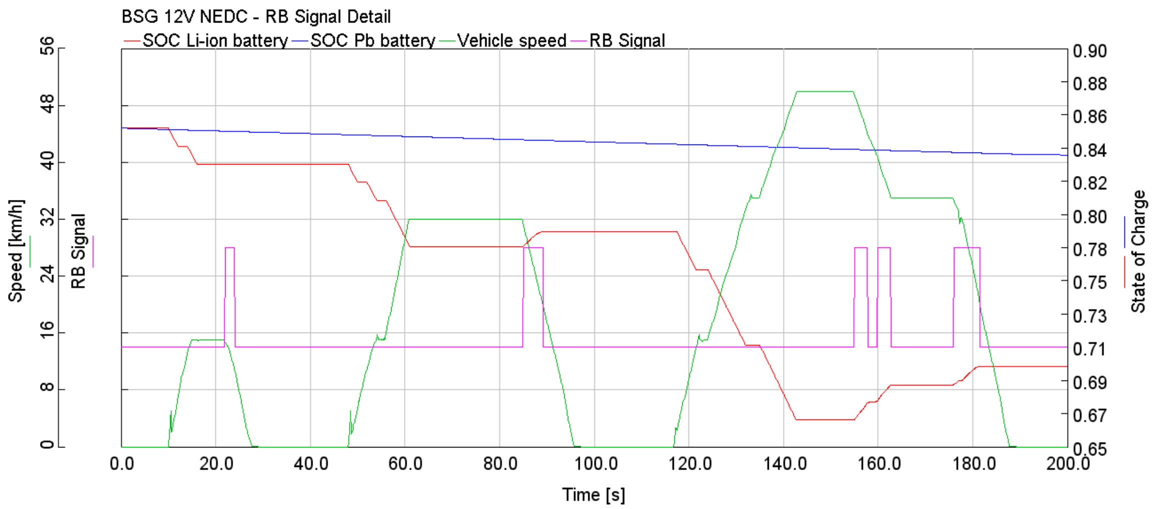

Figure 33: Detail for RB events for BSG model (NEDC).

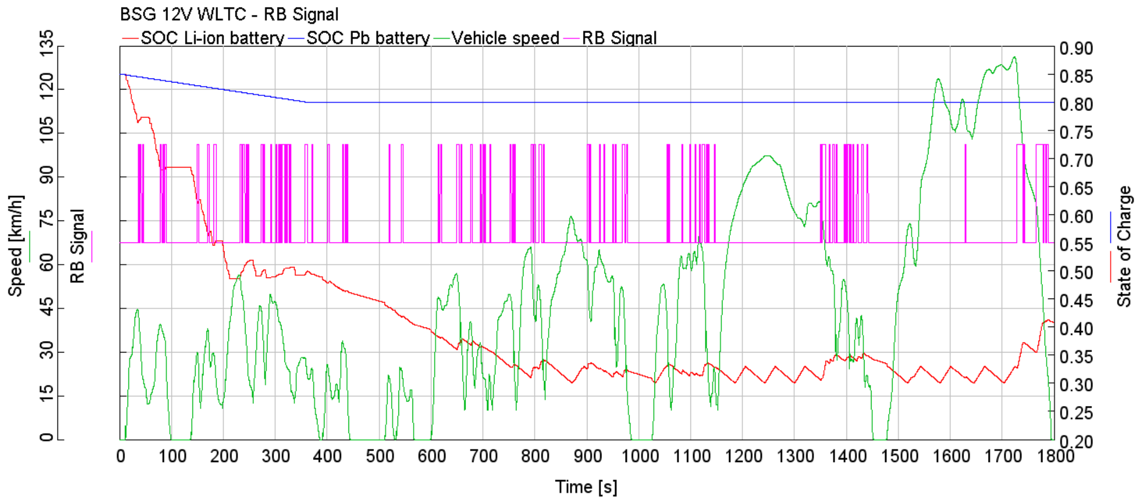

Figure 34: RB events for BSG model (WLTC).

An analysis for the regenerative braking has been performed. The purpose is to analyze how much of the available recovery energy can be stored in the battery. By remembering the architecture of the vehicle, the energy from the road passes through the transmission, engine, belt drive, inverter until arrive to the battery. Energy that can be recovered is reduced due to the mechanical friction (transmission, engine, belt drive connection) and electrical losses of the inverter.

NEDC

The results for NEDC are publishes in Table 14 and pie chart is shown in Fig. 35.

	Energy [kJ]
Total energy for braking	1065
Energy dissipated	756
Energy stored in the battery	235
Energy losses in inverter	74

Table 14: Energy braking path (NEDC).

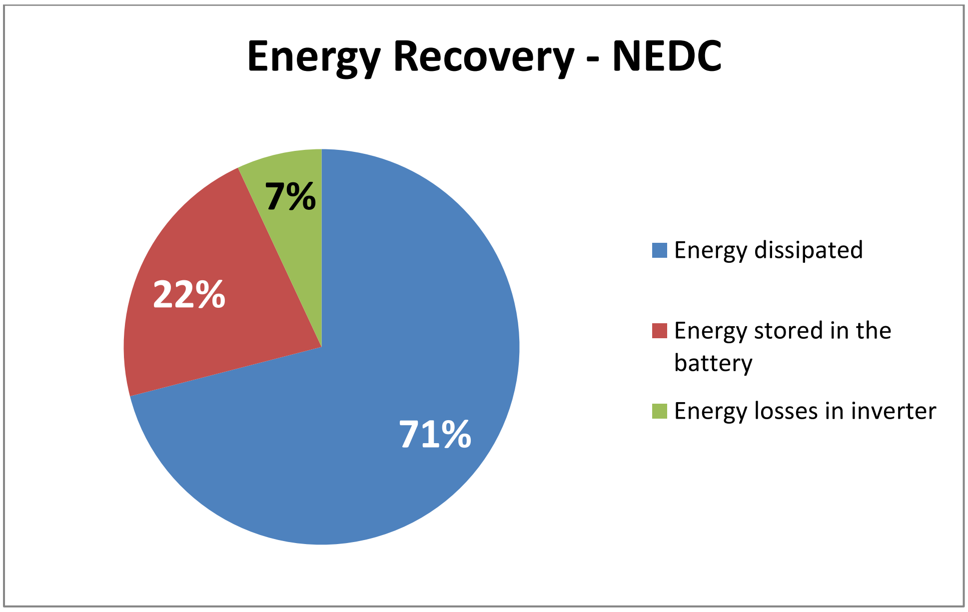

Figure 35: Pie chart of energy braking (NEDC).

WLTC

The results for WLTC are publishes in Table 15 and pie chart is shown in Fig. 36.

	Energy [kJ]
Total energy for braking	2773
Energy dissipated	2306
Energy stored in the battery	371
Energy losses in inverter	96

Table 15: Energy braking path (WLTC).

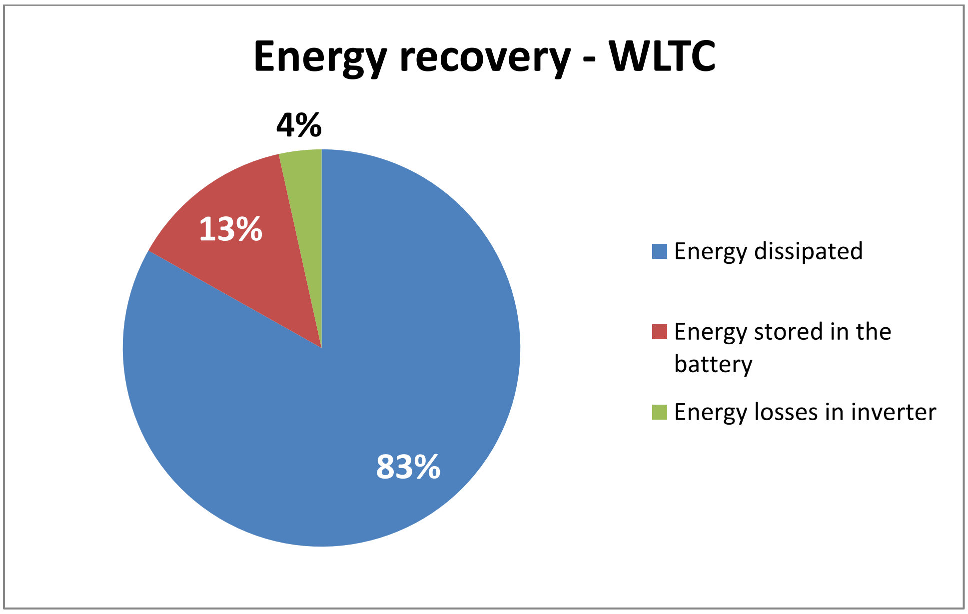

Figure 36: Pie chart of energy braking (WLTC).

Energy dissipated includes the part of energy wasted by braking and losses due to transmission and belt drive.

For NEDC the energy stored in the battery is higher than in WLTC (22% compared to 13%). This occurs because WLTC has phases where vehicle decelerates without braking (in high and extra-high part). In this way energy cannot be stored in the battery. By contrasting, in NEDC driver presses the brake pedal, for every deceleration phases. In this way for all of these phases the storage of the energy is allowed.

4.3.3 Torque Assist

The saving differences between ESS and BSG values of CO_2 emissions are also due to torque assist contribution.

Torque Assist Acceleration

Fig. 37 shows TA activation for NEDC, this function is enabled until 637 s (black vertical dashed line). In fact, TA is disabled from this time step to the end of cycle because Li-ion battery SOC drops below 50% (TA disable condition red horizontal line).

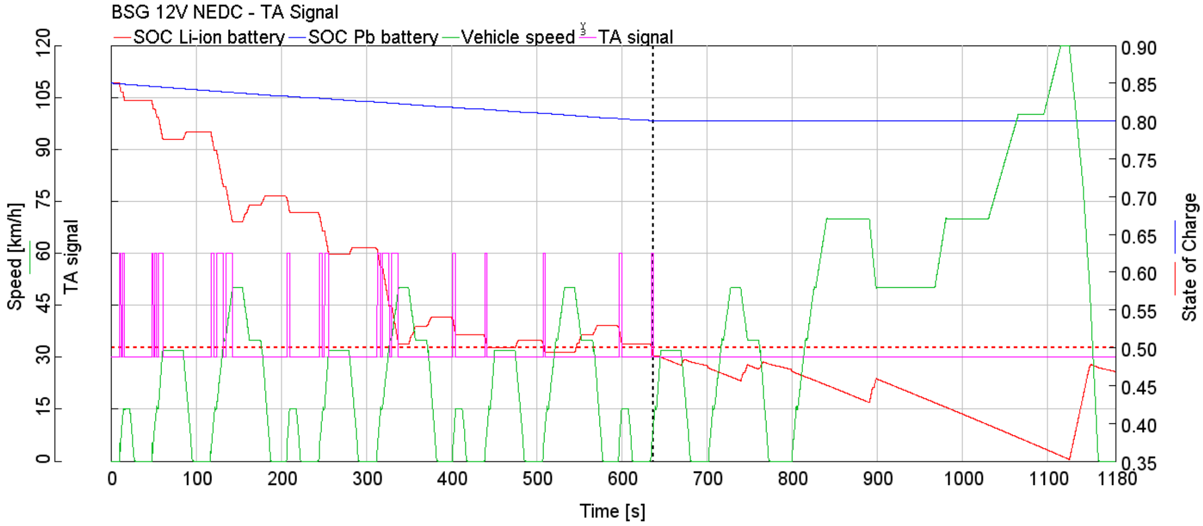

Figure 37: TA activation for BSG model (NEDC).

In order to see better when TA takes place, it is made a zoom of the Fig. 37. In Fig. 38 it is considered time values until 200s. In TA phases the power is provided by Li-ion battery. As consequence, it is possible to notice that Li-ion SOC decreases.

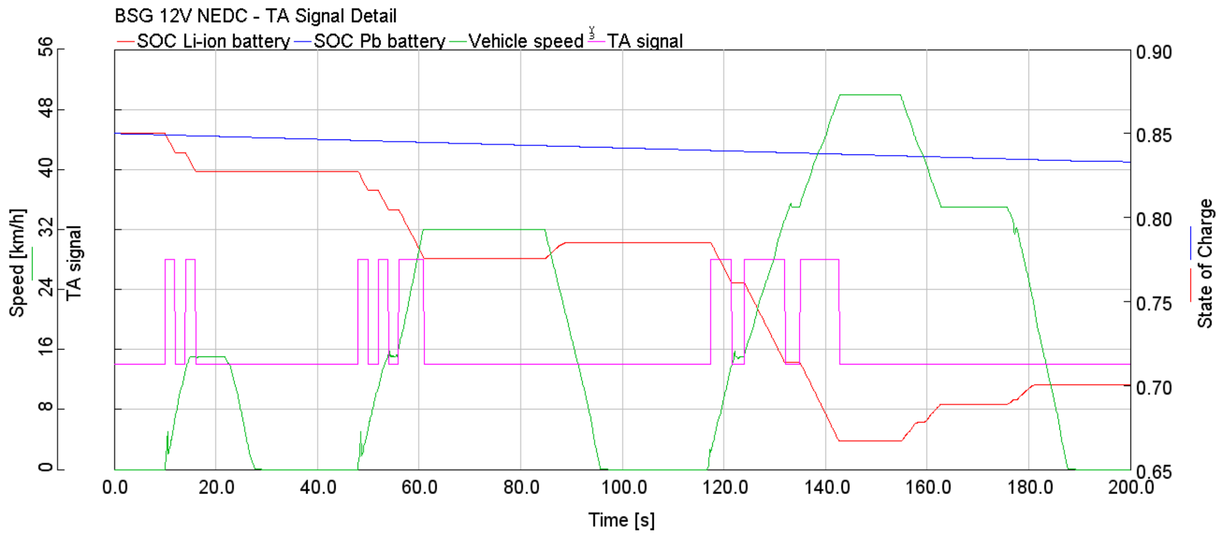

Figure 38: Detail for TA activation for BSG model (NEDC).

For WLTC, as the electrical load is higher than NEDC, the time point where TA is disabled is moved to the left. In this way for WLTC, TA is not enabled for all duration of the low phase. This behavior is shown in Fig. 39.

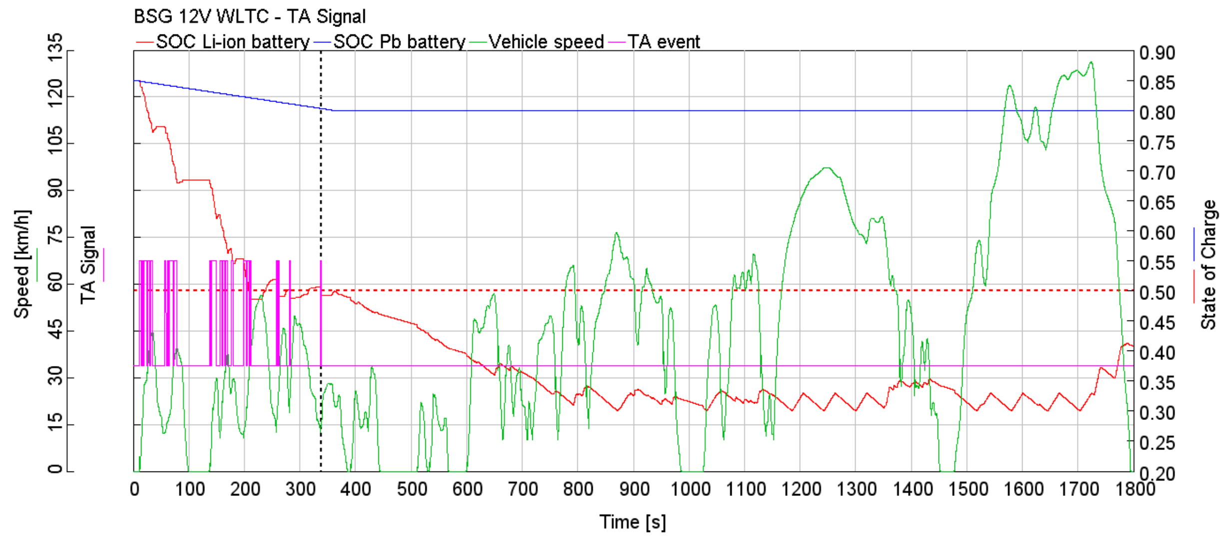

Figure 39: TA activation for BSG model (NEDC).

EM provides 4% of the total energy needed to run all cycle for NEDC and 1% for WLTC. This value is higher for NEDC because the NEDC is shorter than WLTC. In fact, the little amount of energy supplied by EM has an higher impact because the total amount of energy for NEDC is lower with respect to WLTC.

NEDC

The results for NEDC are publishes in Table 16 and pie chart is shown in Fig. 40.

	Energy [kJ]
Total energy for motion	4282
Energy provided by ICE	4130
Energy provided by EM	152

Table 16: Energy for motion (NEDC).

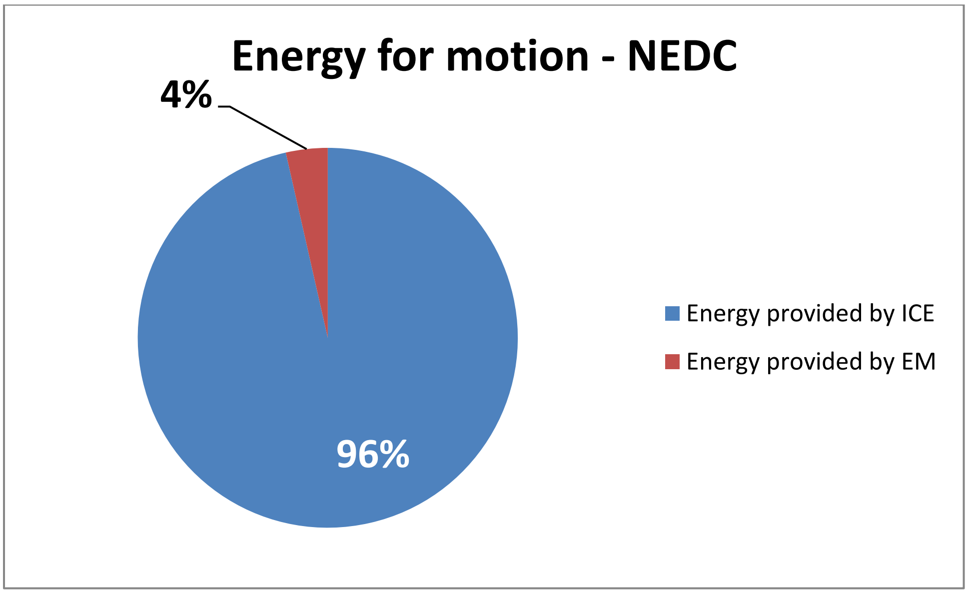

Figure 40: Pie chart for energy analysis (NEDC).

WLTC

The results for WLTC are publishes in Table 17 and pie chart is shown in Fig. 41.

	Energy [kJ]
Total energy for motion	12040
Energy provided by ICE	11895
Energy provided by EM	145

Table 17: Energy for motion (WLTC).

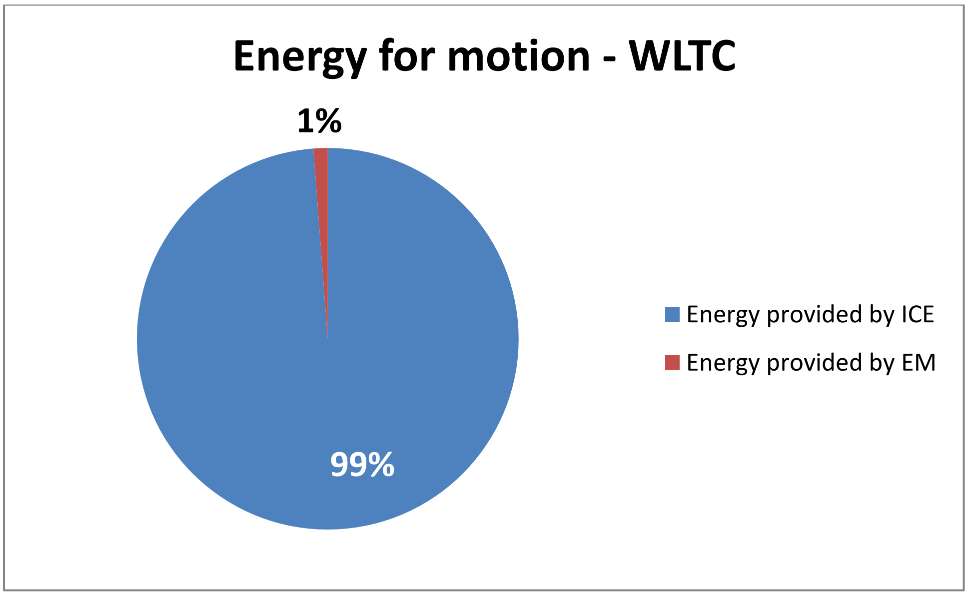

Figure 41: Pie chart for energy analysis (WLTC).

Torque Assist Plateau

In this section, results of Torque Assist plateau condition are described.

In NEDC, it is also considered a different way to apply TA function in order to have higher benefit with respect to the standard configuration. For example, it could be activated only when the speed is constant at 15 km/h. In NEDC cold, BSG cannot provide enough power for the motion until coolant temperature achieve 70 °C. In this condition the frictions becomes lower and system can switch in electric-mode. Fig. 42 shows the application in cold NEDC.

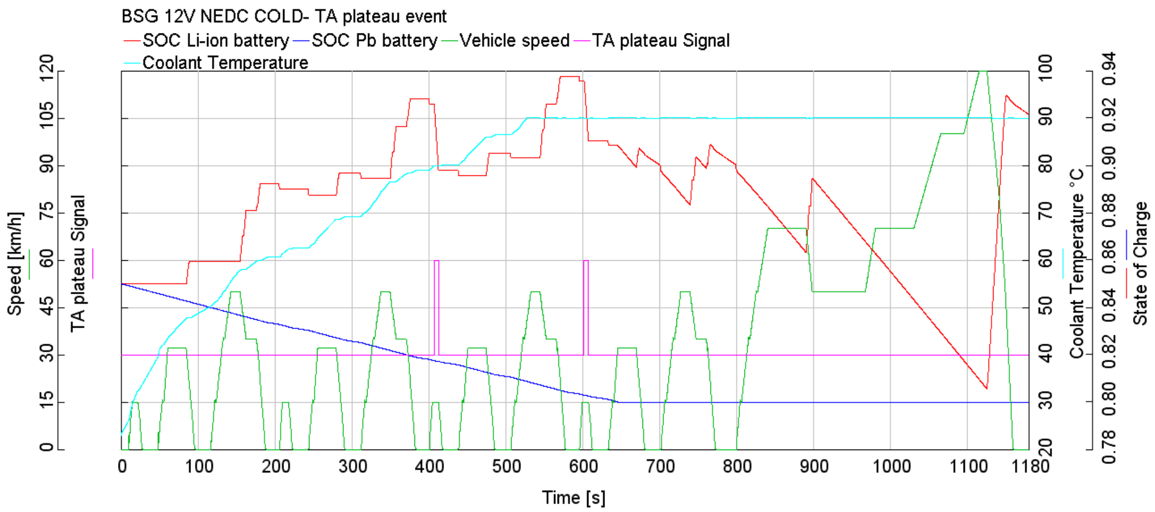

Figure 42: TA plateau event for BSG model in NEDC cold.

On the contrary, in hot condition vehicle enables Torque Assist plateau function immediately as represented by Fig. 43.

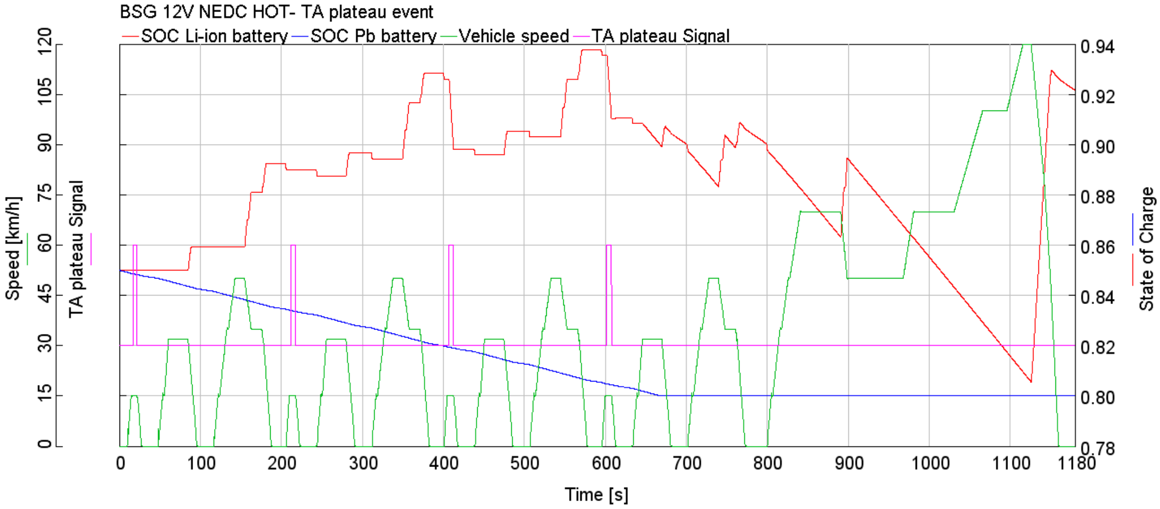

Figure 43: TA plateau event for BSG model in NEDC hot.

By comparing SOC of two different methodologies of TA (acceleration and plateau), it is clear that in TA plateau the power request is supplied only in phases at vehicle speed equal to 15 km/h. The number of these phases is much lower than acceleration phases. As consequence, Li-ion battery decreases less for TA plateau condition than for TA standard. Fig. 44 shows a zoom of Fig. 43.

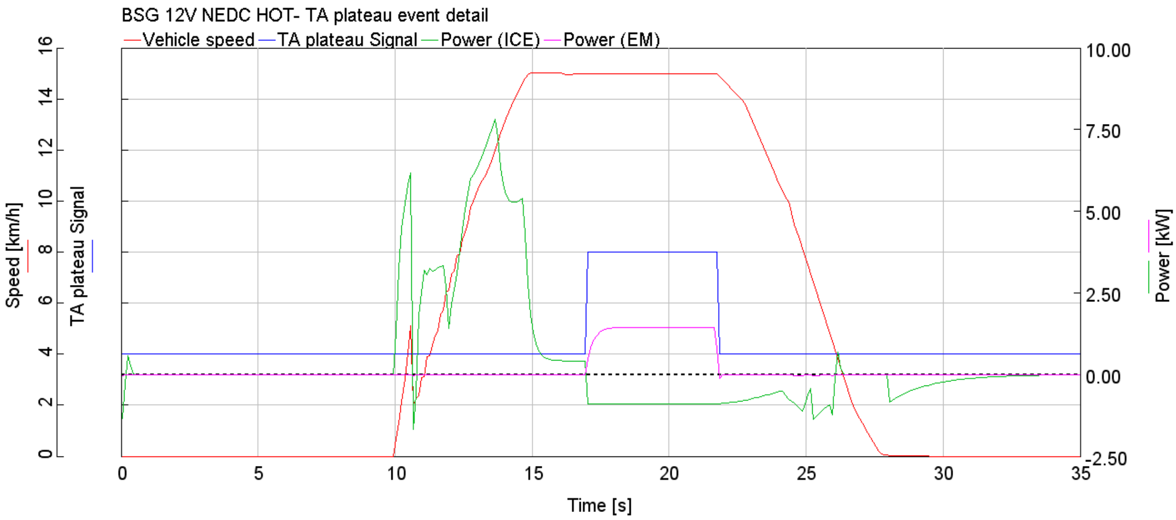

Figure 44: TA plateau event for BSG model in NEDC hot (detail).

In this figure are represented TA signal, SOC, and the power provided from EM and ICE. By looking Fig. 44 when TA plateau signal is switched on, ICE power is negative because ICE is dragged. EM has to win this dragged load to move the vehicle. Table 18 shows results between these different control logic. They are similar each other. Hence, the implementation of this control logic is not useful.

CO_2 emissions [g/km]	BSG (TA conventional)	BSG TA plateau
NEDC HOT	109	109
NEDC COLD	120	121
WLTC TMH HOT	128	127
WLTC TMH COLD	135	134
RW A	149	152
RW B	140	141
RB C	139	139

Table 18: Results for TA and TA plateau control logic.

4.4 Sensitivity analysis

A sensitivity analysis has been performed with respect to the mass reduction and aerodynamic improvement, for each configuration of the modelled vehicle.

4.4.1 Mild weight reduction

The weight of the vehicle is reduced by 10%. Such reduction is called mild weight reduction from now on. In this case, the reduction of the weight implies a modification of the coast down factors, and the steps are shown below.

The resistance force is:

$$F_{res}[N] = F_0 + F_1 * v + F_2 * v^2 \qquad (3.2)$$

and the three terms represent rolling resistance, aerodynamic drag and road slope contributions respectively. They are shown in eq (4.2):

$$F_{res}[N] = \frac{1}{2} C_X \rho A v^2 + (f_0 + f_1 v + f_2 v^2) mgcos\alpha \qquad (4.2)$$

where

C_X: is the drag coefficient;

ρ: is the density of the air $[Kg/m^3]$;

A: is the frontal area of the vehicle $[m^2]$;

v: is the vehicle speed $\left[\frac{m}{s}\right]$;

f_0, f_1 and f_2 are coefficients that describes rolling resistances and road slope contributions;

m: is the mass of the vehicle $[Kg]$;

g: is the gravity $\left[\frac{m}{s^2}\right]$;

α: is the angle that describe the slope of the road, in this case is equal to zero;

By solving a systems composed by eqs (3.2) and (4.2), eqs (4.3), (4.4) and (4.5) can be found. The three coefficients f_0, f_1 and f_2 are the unknown variables of this system.

$$F_0 = f_0 mg\ cos\alpha \tag{4.3}$$

$$F_1 = f_1 mg\ cos\alpha \tag{4.4}$$

$$F_2 = f_2 mg\ cos\alpha + \frac{1}{2} C_X \rho A \tag{4.5}$$

From the last three equations it is possible to obtain the values of f_0, f_1 andf_2.

The next step is to find the new coast down factors by changing the mass for NEDC and for WLTC.

Results for Mild Weight Reduction (MWR) are shown in Table 19.

CO_2 emissions [g/km]	Baseline with MWR	Δ CO_2 Baseline with MWR vs Baseline [%]	ESS with MWR	Δ CO_2 ESS with MWR vs ESS [%]	BSG with MWR	Δ CO_2 BSG with MWR vs BSG [%]
NEDC HOT	120	1,6	113	1,7	107	1,8
NEDC COLD	131	1,5	124	1,6	118	1,7
WLTC TMH HOT	136	1,4	132	1,5	126	1,6
WLTC TMH COLD	143	1,4	139	1,4	133	1,5

Table 19: Results for mass reduction.

This sensitivity analysis does not show differences among the three models. In fact, the CO_2 savings is almost equal for both NEDC and WLTC.

4.4.2 Aerodynamic improvement

For the following analysis, the coast down factor F_2 is the only variable (reduced by 10%), whereas F_0 and F_1 are maintained constant.

Table 20 highlights the results for Aerodynamic Improvement (AI).

CO_2 emissions [g/km]	Baseline with AI	Δ CO_2 Baseline AI vs Baseline [%]	ESS with AI	Δ CO_2 ESS with AI vs ESS [%]	BSG with AI	Δ CO_2 BSG with AI vs BSG [%]
NEDC HOT	119	2,5	112	2,6	107	1,8
NEDC COLD	130	2,3	124	1,6	118	1,7
WLTC TMH HOT	134	2,9	130	3,0	124	3,1
WLTC TMH COLD	141	2,8	137	2,8	131	3,0

Table 20: Results for aerodynamic drag reduction.

For WLTC, benefit are higher with respect to NEDC because in WLTC vehicle reaches higher velocity and the aerodynamic drag has higher impact with respect to NEDC.

4.5 Validation

BSG model has been validated by comparing simulation results with respect to experimental data. Fig. 45 shows the simulated engine speed trend along with the result obtained from a real vehicle equipped with a BSG 12V.

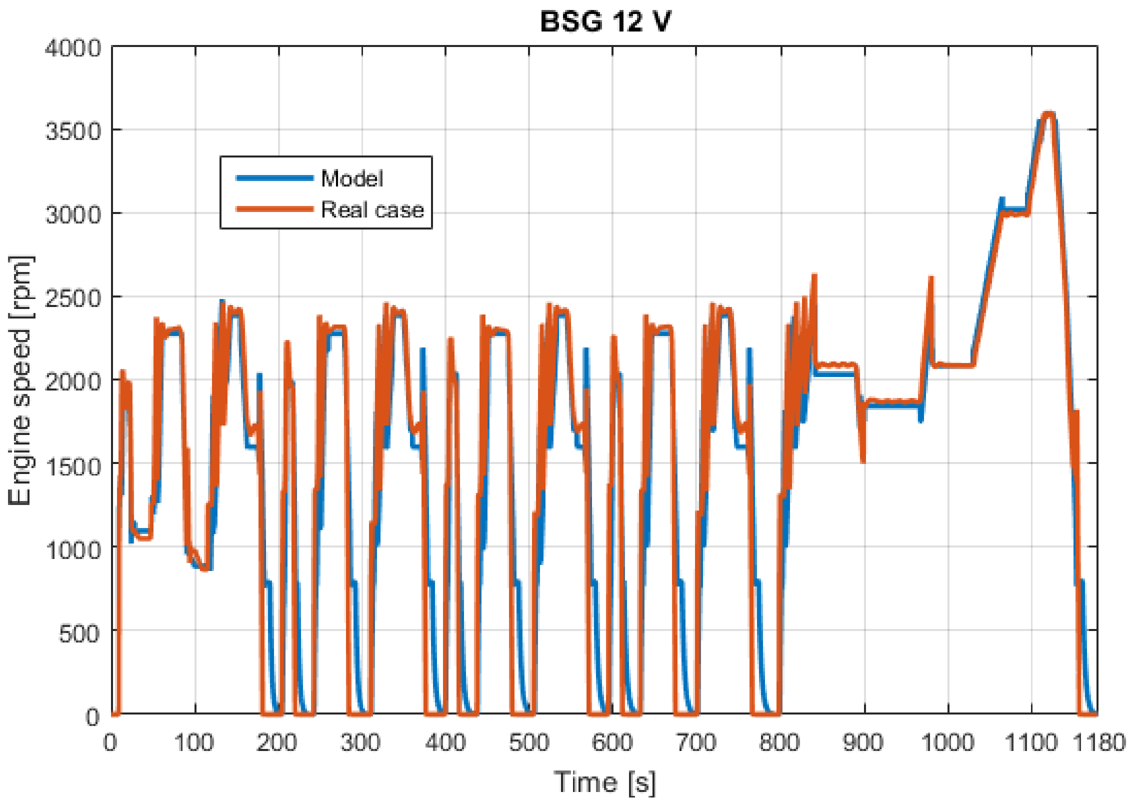

Figure 45: Engine speed real case and model for BSG (NEDC).

In the start and stop phases, the engine speed of the real case has a sharper decrease rate compared to the modelled one, and this occurs because pumping losses are not taken into account in the model.

Chapter 5. Cost vs benefit

According to the regulation, each gram of CO_2 above the limit equals to a potential fine of 95 € , that has to be multiplied by the number of new vehicles produced. These penalties would represent an important addition cost for the car maker, and in this regard solutions that allow to reduce the CO_2 emissions play a fundamental role. The cost of a technology depends on its complexity, but the fundamental parameter is the cost – benefit ratio. In fact, more expensive solutions, despite guaranteeing a more consistent benefit, might not be the most convenient. Hence, an analysis has been performed in order to evaluate the economic competitiveness of the simulated technologies. ESS and BSG solutions are compared also with mild weight reduction and the aerodynamic improvement. Costs for CO_2 reduction technologies have taken from the report "Improving understanding of technology and costs for CO_2 reductions from cars and LCVs in the period to 2030 and development of cost curves" [25]. For each technology analyzed, the typical total cost of manufacturing for low-medium car (SI ICE+HEV) has been selected. The cost considered , showed in Table 21, is the average between the cost for the year 2015 and 2020.

Technology	2015 [€]	2020 [€]	Average [€]
BSG	446	333	390
ESS	143	107	125
Mild weight reduction	48	41	45
Aerodynamic improvement	52	44	48

Table 21: Cost of technologies [24].

The ratio between the cost and the saving in terms of CO_2 emissions is calculated for NEDC, WLTC and RW A.

From the manufacture perspective, a technology is interesting if this cost/benefit ratio is lower than 95 €/g CO_2/km. Otherwise, car maker would not be motivated to invest, as the potential fine would be lower than the additional cost related to selected solution.

Results of this cost benefit analysis, respectively for NEDC, WLTC and RW A are shown in Fig. 46.

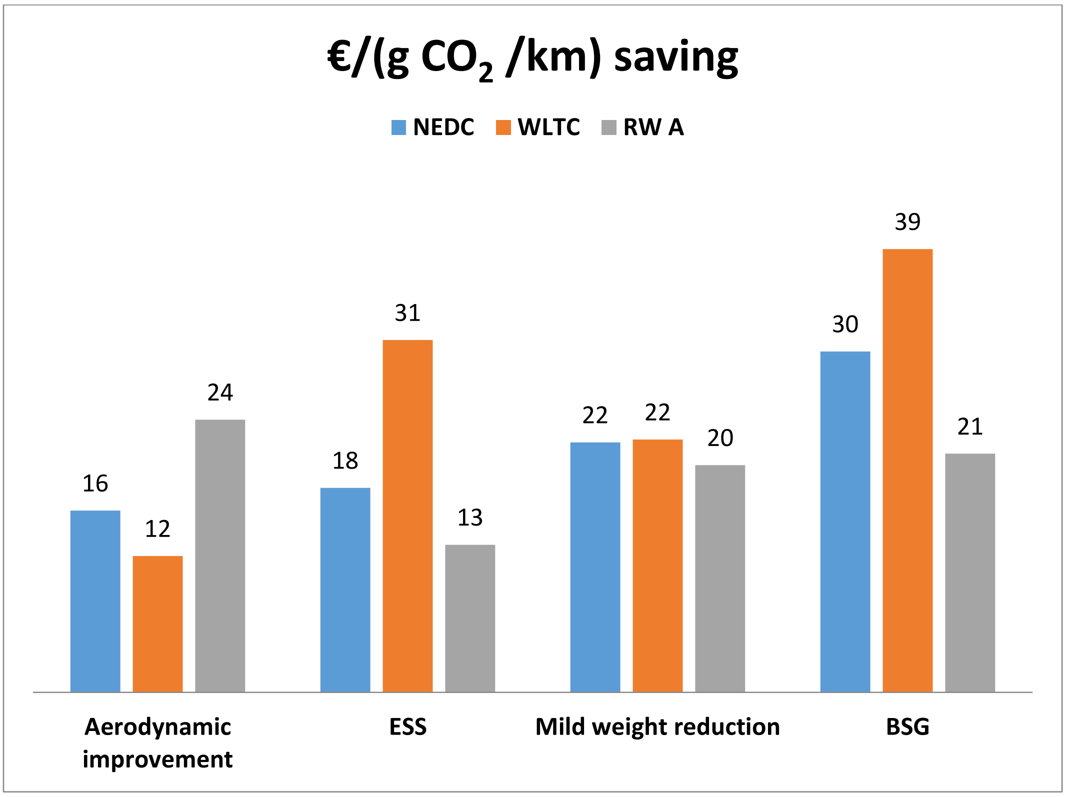

Figure 46: Cost benefit analysis results.

For WLTC aerodynamics improvement gives higher benefit because the cycle has longer part where vehicle drives at higher speed. Technologies on the left side of diagrams are better solutions. They have a lower price or high benefit, or both of them. Focusing on ESS, this technology has a cost/benefit ratio of 18 €/g CO_2 /km for NEDC, and 31 € /g CO_2 /km for WLTC. LOW part of WLTC has 4 phases where vehicle is stopped. In fact, this technology has lower cost benefit ratio for RW A. On the other hand, BSG seems to be among the least convenient because, for all of three cycles, is on the right side. However, its ratio is lower than 95 €/g CO_2 saving.

In addition, an economic analysis has been done to evaluate the convenience for a generic car maker to invest on BSG 12V and ESS system. In this context, cost of the technology, amortization cost for a plant to implement the technology on vehicle and the fines applied by European Commission for the exceeding the limit were taken into account in this analysis by considering baseline, ESS and BSG model on NEDC.

The first step was to find how many vehicles a generic carmaker has sold in one year: around 700.000 vehicles according to an Acea study [26]. From a statistical analysis, it is known that city cars cover the 40% of the cars sold (source: Acea [27]).

The number of city cars sold in one year is therefore equal to:

$$700.000 * 40\% \cong 280\ kUs$$

Baseline

For a city car of 1100 Kg, by applying (1.1), the limits in terms of CO_2 emission is 117 g CO_2/km. The baseline vehicle emits 133 g CO_2/km. By considering the fine calculated by using eq. (1.7), its amount is equal to 426 €Mio. Table 22 shows the analysis for baseline model.

Baseline		
Baseline CO_2 133 g/km ➔ Regulation limit 117 CO_2 g/km ➔ Penalty 95€ x 16 g/km = 1520 €/u		
Assumed investment	= 0 €Mio	0 €Mio
Additional cost	= 0 €Mio	0 €Mio
Penalty	= 1520 € x 280 kU	426 €Mio
Total cost		**426 €Mio**

Table 22: Results for baseline.

ESS

ESS model emits 126 g CO_2/km. It exceed of 9 g CO_2/km . Hence, by applying eq. (1.7) the amount of fine is 240 €Mio. In addition, it is supposed a cost for each start and stop device equal to 125€/units. As consequence, the cost due to supplier is: 35 €Mio. To implement this system it is mandatory to have a plant. It is supposed that this plant can be amortized in 5 years and that it has a cost of 10 million. Hence, the cost is 2 million (10 €Mio/5 years).

By summing all of these costs, from the car maker perspective the total cost is equal to 277 €Mio. Table 23 shows the analysis for ESS model.

ESS		
ESS CO_2 126 g/km ➔ Regulation limit 117 CO_2 g/km ➔ Penalty 95€ x 9 g/km = 855 €/u		
Assumed investment	= 10 €Mio amortized in 5 years	2 €Mio
Additional cost	= 125 € x 280 kU	35 €Mio
Penalty	= 855 € x 280 kU	240 €Mio
Total cost		**277 €Mio**

Table 23: Results for ESS.

BSG

BSG model emits 120 g CO_2/km. The emissions exceeded are 3 g CO_2 /km. The amount of fine is 80 €Mio. The cost for each BSG is equal to 390 €/unit. As consequence, the cost related to the total implementation on city car's fleet is equal to 109 €Mio. Also in this case a plant has to be built to implement the device in the vehicle. The cost for this plant is supposed 30 €Mio. In addition, it is supposed amortized in 5 years. As consequence the cost is 6 €Mio (30 €Mio/5 years).

By summing all of these costs, from the car maker perspective the total cost is equal to 195 €Mio. Table 24 shows the analysis for BSG model.

BSG 12V		
BSG CO_2 120 g/km ➔ Regulation limit 117 CO_2 g/km ➔ Penalty 95€ x 3 g/km = 285 €/u		
Assumed investment	= 30 €Mio amortized in 5 years	6 €Mio
Additional cost	= 390 € x 280 kU	109 €Mio
Penalty	= 285 € x 280 kU	80 €Mio
Total cost		**195 €Mio**

Table 24: Results for BSG.

As results, for car maker BSG is a great solution for future investment.

The result coming from this analysis is the convenience for a car maker to invest on micro-hybrid system.

Conclusions

Nowadays the problem of the fines related to CO_2 emissions can be solved by hybrid vehicle commercialization. In this context, this thesis analyzed the implementation of two different technologies: Start and stop and micro hybrid system. These solutions were chosen due to their low cost, and were applied to an A – segment gasoline car. The low cost of these devices is important because the higher the cost of technologies the higher the cost of the vehicle. In this way, customers can benefit from a series of fuel – saving functionalities without the need for a greater initial investment typical of full – hybrid vehicles.

The simulations have been performed and assessed with GT Suite, which is a powerful tool that allowed to estimate the fuel consumption and CO_2 emissions without testing physically the vehicle. The regulation framework is undergoing a transition phase, and this aspect forces carmakers to evaluate the CO_2 emissions on both NEDC and WLTC. Hence, another interesting aspect is to known which is the technology that can maximize the emissions reduction on each cycle. In this regard the BSG model's benefit in terms of CO_2 emission reduction was:

- 10% under NEDC condition
- 7% under WLTP condition
- 11% under Real World condition

In fact, this technology is able to reduce of 13 g CO_2/km on NEDC and 12 g CO_2/km for WLTC (with the before mentioned hypothesis). As results this technology has a strong impact on both the homologation cycles.

On the other hand, the ESS system enabled a benefit of 7 g CO_2 /km for NEDC and 4 g CO_2 /km on WLTC. This system gives better results on NEDC for the higher number of ESS phases (as mentioned before).

From the cost - benefit perspective, the implementation of both technologies is convenient. For NEDC and WLTC, the ESS gives better results due to the lower cost.

The improvement of the aerodynamic design and the reduction of the mass give also results that are not negligible. This happens because these solutions have a low cost.

In addition, the simple business case analyzed assessed the importance for a car makers to invest on micro hybrid technology for a city car.

Acknowledgements

First of all, I would like to thank Dr. Carloandrea Malvicino for giving me the opportunity of working in such important and challenging company as FCA Italy S.p.A., and most of all for his continuous supporting and enlightening and vital advice.

I would also like to thank Professor Federico Millo for his continuous guidance and patience during my thesis work.

Another special thanks goes to Ing. Elizabeth Julia Tettamanzi who always has been so kind with me and thanks for her limitless disposability and patience.

Thanks to Alessandro Zanelli and Claudio Cubito for their support.

Special thanks and gratitude to my beloved family which has given me the opportunity to study and achieve this important goal.

Least but not last, I would like to thank my friends with whom I shared my studying period here in Turin and have been my supporting everyday family.

Bibliography

[1] Road transport: Reducing CO2 emissions from vehicles, https://ec.europa.eu/clima/policies/transport/vehicles_en accessed on February, 1st, 2018.

[2] E. Spessa “Controllo delle emissioni inquinanti”, Slide for lessons, Politecnico di Torino, 2017.

[3] Regulation Commission (EU) 333/2014 of 11 March 2014.

[4] Regulation Commission (EU) 2017/1153 of 2 June 2017.

[5] P. Mock, “A midsummer night’s skullduggery”, ICCT (The International Council on Clean Transportation), 1 July 2013.

[6] CO_2MPAS: Vehicle simulator predicting NEDC CO_2 emissions from WLTP, https://co2mpas.io/ accessed on February, 1st, 2018.

[7] P. Mock, J. Kühlwein,U. Tietge, F. Vincente, A. Bandivadekar, J. German. The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU, ICCT (The International Council on Clean Transportation), 29 October 2014.

[8] WLTP Regulation Commission (EU) 2017/1502 of 2 June 2017.

[9] Acea,”Getting ready for WLTP”, 2017.

[10] Regulation Commission (EU) 443/2009 of 23 April 2009

[11] M. Ramprasad, “CO_2 Emission Reduction Strategies: Transition From NEDC to WLTP”, Politecnico di Torino, 2016.

[12] Regulation Commission (EU) 2017/1151 of 1 June 2017.

[13] P. Wolfram, N. Lutsey,”Electric vehicles: Literature reviews of technologt costs and carbon emissions”, 15 July 2016, ICCT.

[14] Electric Cars and Plug-ins, http://www.energyresourcefulness.org/Fuels/plug_ins.html, Accessed on 11thMarch 2018.

[15] Ganji B., Kouzani A.Z., Trinh H.M.: "Drive cycle analysis of the performance of hybrid electric vehicles", Life system modeling and intelligent computing, 2010, 434-444.

[16] M. Kebriaei, A. Niasar,"Hybrid Electric Vehicles: An Overview", 2015 International Conference on Connected Vehicles and Expo (ICCVE), 299-305.

[17] J. German,"Hybrid Vehicles, Technology Development and Cost Reduction", ICCT, Technical Brief No1, July 2015.

[18] Baldizzone S. "Performance and Fuel Economy Analysis of a Mild Hybrid Vehicle Equipped with Belt Starter Generator," Master thesis, University of Windsor, 2012.

[19] Gamma Technologies. GT-Suite User Manuals.

[20] Suzuki Ignis SHVS #truetest, https://www.youtube.com/watch?v=5HhTLIznaIQ, Accessed on 11thMarch 2018.

[21] F. Millo, L. Rolando, M. Andreata,"Numerical Simulation for Vehicle Powertrain Development". INTECH Open Access Publisher, 2011.

[22] L.Guzzela, A. Sciarretta,"Vehicle Propulsion System Introduction to Modelling and Optimization", Springer

[23] "Cabin model - Rapporto di lavoro", CRF.

[24] Heinz Steven, "Overview of in-use driving behaviour data from

different regions", 30-08-2010

[25] "Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves", https://ec.europa.eu/clima/policies/transport/vehicles/proposal_en#tab-0-2, Accessed on 12th March 2018.

[26] Consolidated Registrations - By Manufacturer – 2017 http://www.acea.be/statistics/tag/category/by-manufacturer-registrations, Accessed on 14th March 2018.

[27] Segments by Body, Country - 2017,
http://www.acea.be/statistics/tag/category/segments-body-country Accessed on 14th March 2018.