POLITECNICO DI TORINO

MSc degree in Automotive Engineering

Final Thesis

Model based evaluation of the most suitable approach to achieve the CO_2 targets on an urban car

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Contents

Table of abbreviations and Symbols

AFV Alternative Fuel Vehicle

ASL Aggressive Shift Logic

AT Automatic Transmission

AMT Automatic Manual Transmission

A/C Air Conditioner

BISG Belt Driven Integrated Starter Generator

BMEP Brake Mean Specific Pressure

BSFC Brake-Specific Fuel Consumption

CAFE Corporate Average Fuel Economy

CAFC Corporate Average Fuel Consumption

CARB California Air Resources Board

CCP Couple Cam Phasing

CCPS Couple Cam Phasing on SOHC

CDPF Canalized Diesel Particulate Filter

COP Conformity Of Production

CNG Compressed Natural Gas

CPS Cam-Profile Switching

CVT Continuously Variable Transmission

CVVL Continuous Variable Valve Lift

DEAC Cylinder Deactivation

DEACS Cylinder Deactivation for SOHC

DEACO Cylinder Deactivation for OHC

DCP Dual Cam Phasing

DCT Dual Clutch Transmission

DI Direct Injection

DOC Diesel Oxidation Catalyst

DOHC	Dual Overhead Camshaft
DOT	Department of Transport
DPF	Diesel Particulate Filter
DVA	Digital Valve Actuation
DVVL	Discrete Variable Valve Lift
DVVLS	Discrete Variable Valve Lift for SOHC
DVVLD	Discrete Variable Valve Lift for DOHC
EC	European Commission
ECU	Electronic Control Unit
EFR	Engine Friction Reduction
EGR	Exhaust Gas Recirculation
EHPS	Electro Hydraulic Power Steering
EPA	Environment Protection Agency
EPS	Electronic Power Steering
EUDC	Extra Urban Driving Cycle
ETCL	Early Torque Converter Lookup
EV	Electric Vehicle
FC	Fuel Consumption
FE	Fuel Efficiency
FEAD	Front Engine Accessory Drive
FFV	Flex Fuel Vehicle
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GHG	Green House Gas Emission
GWP	Global Warming Potential
HDV	High Duty Vehicles (i.e. trucks and buses)
HEV	Hybrid Electric Vehicle

HPS Hydraulic Power Steering

H/C Hydrogen Carbon ratio (molecular structure of a fuel)

IATC Improved Automatic Transmission Control

ICCT International Council on Clean Transportation

ICE Internal Combustion Engine

ICP Inlet Cam Phasing

IMEP Indicated Net Mean Effective Pressure

IPI Tax on Industrial Products (in Portuguese)

ISG Integrated Starter Generator

LDB Low Drag Brakes

LDT Light Duty Truck

LDV Light Duty Vehicle

LED Light Emitting Diode

LNT Lean NOx Trap

LPG Liquid Petroleum Gas

LUB Low friction Lubricant

MPG Miles Per Gallon (US)

MR Mass Reduction

MT Manual Transmission

MY Model Year

NA Natural Aspirated

NEDC New European Driving Cycle

NHTSA National Highway Traffic Safety Administration

NMEP Net Mean Effective Pressure

NVH Noise Vibration and Harshness

OHC Overhead Camshaft

PC Passenger Car

PFI Port Fuel Injection

PHEV Plug In Hybrid Vehicles

RPM Revolutions per Minute

SAX Secondary Axle disconnect

SCR Selective Catalytic Reduction System

Sf Square feed

SGDI Stoichiometric Gasoline Direct Injection

SGDIO Stoichiometric Gasoline Direct Injection in OH

SHEV Strong Hybrid Electric Vehicle

SIDI Spark Ignition Direct Injection

SOHC Single Overhead Camshaft

SUV Sport Utility Vehicle/Suburban Utility Vehicle

TA Type Approval

TW Track width

UF Utility Factor

UNECE United Nations Economic Commission for Europe

US United States

USA United States of America

VVA Variable Valve Actuation

VVL Variable Valve Lift

VVT Variable Valve Timing

WB Wheel Base

WLTC Worldwide harmonized Light vehicles Test Cycle

ZEV Zero Emission Vehicle

List of figures

List of tables

Introduction

There is strong evidence that most of the global warming observed in the past years is attributable to human activities and that the greenhouse gas making the largest contribution from human activities is carbon dioxide (CO_2). It is released by the burning of biomass or fossil fuel as gasoline, diesel or natural gas used, among others, to power vehicles (1).
With the aim to reduce such source of greenhouse gases (GHG), worldwide policies on emissions reduction have been created over the pasts 20-30 years. The stringencies of these regulations regarding the emissions limits have risen in an exponential way during the last years and are expected to continue like this in the following decades.

Such regulations strongly influence automobile manufacturers, who have to ensure that their vehicles meet GHG regulations corresponding to the markets where their vehicles are sold. While at the same time, giving optimal customer value in terms of price, safety, performance, drivability, comfort, roominess, convenience…Pursuing maximum company profits[1].

Although it seems that automobile manufacturers have an immense amount of options when designing and projecting a car, in practice there are many constrains from market acceptance which reduce automatically such amount of possible choices. For example, a car without power steering will emit fewer emissions but will be unmarketable. Therefore, the real available options are limited and can be listed, classified, featured and used to elaborate alternative scenarios, as will be done in this Thesis.

Regulations vary from region to region and the competitiveness in such a global market, lead companies to work in highly challenging conditions. Standards are very complex and so it cannot be assumed that a specific emission limits from one regulation is more stringent than another. As a consequence if a vehicle meets what apparently is the more stringent regulation, it will not automatically meet any other. Case per case study has to be done since differences in regulations procedures are huge and heterogenic among types of vehicles (petrol vehicles, diesel vehicles,

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[1] Such word will be used along the document to refer the car manufacturer revenue or turnover

Flex Fuel Vehicles FFVs, automatic/manual transmission vehicles, EVs, PHEVs...). As an example, Alternative Fuel Vehicles AFVs emissions limits are quite different among regulations because not clear and absolute effectiveness on GHG reduction is found in such class of vehicles, as CNG and LPG vehicles: While tank-to-wheel emissions are quite well known (cleaner combustion), well-to-wheel emissions strictly depend on fuel production and transport methods which are considered in some studies to counteract the beneficial effect of a cleaner combustions due to spills and leakages (2).

There are several ways to reduce emission but some of them may worsen vehicle features as performance. Consequently, customers are not willing to pay the same for a car with lower performance, leading most probably to a reduction in company profits. However, such reduction on price and profits may not happen if the customer finds that the save in fuel consumption overcomes the loss in performance.

The main work of this Thesis is to understand how regulations are stablished worldwide and to analyse the possible choices regarding low emissions technologies to meet such regulations (or not, if can be avoided) maximizing the companies' margin profit taking into account customer value and production costs.

The subject integrates engineering/scientific investigation with an economic evaluation and includes the development of two tools:

1. A tool that finds the best combination of low GHG emissions technologies that should be applied to a given car. This will be called "package model".
2. A tool that optimizes an automobile manufacturer fleet with the aim of obtaining the maximum revenue, in a business perspective. This will be called "fleet model".

This is done by associating to each technology a level of CO_2 reduction and cost, which may have synergies with other technologies and vary depending on the year as they become cheaper on the future. Emissions limits also vary along the years. Three coefficients assess the profit margin related to a technology package. All possible combinations are assessed and only the ones who best fit the criteria are automatically selected by the model and shown as a result.

The document focuses on the two main regulations of concern:

- European regulations and
- US CAFE regulations

However, some comment is given about other important regulations as Chinese, Brazilian and other US standards. Besides, only two reference cars will be taken into the "package model" study: Midsize[2] 1.4NA MT and Midsize 1.3T AT while the "fleet model" calculations will work as well on a limited number of combinations chosen previously as the best ones.

The content of the Thesis is divided in four main chapters where the two first chapters deal with the framework of the issue and the last two chapters describe the approach and the tools.

1. A hint to longitudinal dynamics and an analysis of the main sources of inefficiencies along with some explanation of simulation software.
2. An explanation of the regulations and their features. How to deal with every type of car and the flexibilities. Comparison among regulations.
3. The package model: A complete explanation of how the model will be developed in order to find the technologies that best-fit the needs. Cheapest package, most cost effective package, most profitable packages are the main optimization criteria. Results and conclusions are given along with more intuitive explanations of the entire subject and a detailed explanation of the technologies considered in the models.
4. The fleet model: The description of the model that figure out which is the best group of car models that should be marketed, *i.e.* the optimal fleet in terms of revenue.

The data used for the calculations are almost entirely taken from federal registers, official regulations and reports belonging to state agencies or agenizes that work for them. The most up-to-date information has been used since regulations, costs estimations and technologies are continuously being updated.

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[2] For confidentiality reasons, the model will be called "Midsize".

1. Hint to FC/CO_2 related to vehicles - review of longitudinal vehicle dynamics and FC/CO_2 simulations

This chapter, along with the second chapter, present a base knowledge to understand what is done in the chapter three and four. On one hand, explain the sources of tailpipe emissions and give the physical sense to the low FC technologies showed on the chapter three and, on the other hand give an overview of the simulation methods that can be used to asses emissions reduction depending on technologies applied and the driving cycle. Furthermore, indications on some other important remarks on the subject of the paper are given.

The link between FC and CO_2 emissions is explained in the chapter 2.2. Basically, when talking about one specific fuel, the relation between FC and tailpipe CO_2 emissions is usually simplified by a constant proportional relation.

1.1 Longitudinal dynamics

In order to understand the way in which energy (or power) is used in the car, longitudinal dynamics are useful. The equations of the longitudinal dynamics are exposed bellow so that the different contributing terms can be analysed.

$$\boldsymbol{F_{trac} - F_{res} = m_e \frac{dV}{dt}} \qquad \text{Equation 1-1}$$

Which multiplied by the speed of the car is:

$$\boldsymbol{P_{trac} - P_{res} = m_e V \frac{dV}{dt}} \qquad \text{Equation 1-2}$$

Where:

F_{trac}: Traction force available at the wheels

F_{res}: Running resistance force

m_e: Equivalent simplified inertia mass of the translating mass and all the rotating masses (*i.e.* wheels, shafts…)

$\frac{dV}{dt}$: Vehicle acceleration

V: Vehicle speed

P_{trac}: Traction power available at the wheels

P_{res}: Running resistance power

And:

$$\boldsymbol{P_{trac} = P_e - P_l} \qquad \text{Equation 1-3}$$

$$\boldsymbol{P_e = P_i\eta_f = P_i\eta_{a-f}\eta_\theta\eta_m} \qquad \text{Equation 1-4}$$

$$\boldsymbol{P_l = P_{gbx} + P_{dvl} + P_{brk}} \qquad \text{Equation 1-5}$$

$$\boldsymbol{P_{res} = P_{aer} + P_{roll} + P_{cmb}} \qquad \text{Equation 1-6}$$

Where:

P_e: Power supplied by the engine to the crankshaft axis.

P_i: Power delivered to the engine in form of fuel.

η_f: Fuel conversion efficiency. Composed by η_{a-f}, η_θ and η_m.

η_{a-f}: Air fuel efficiency. Evaluate the effects of the actual properties of the fluid on the performance which basically decreases with the increase of temperature

η_θ: Thermodynamic efficiency. Evaluate the effects of different aspects which summarised are: Incomplete combustion, head transfer to the walls, gas flow into crevice regions and leakage and exhaust blowdown loss.

η_m: Mechanical efficiency. Evaluate the effects of the pumping losses due to drawing of the fresh mixture through the intake, losses due to friction resistance between elements with relative motion in the engine and the power used to drive the car accessories.

P_l: Power losses through the driveline. Corresponds to the sum of P_{gbx} which is the power loss due to frictions in the gearbox, P_{dvl} which is the power loss due to frictions along the driveline and P_{brk} which is the power loss due to parasitic frictions in the brakes.

P_{aer}: Power needed to overcome the drag resistance of the air

P_{roll}: Power needed to overcome the rolling resistance due to the energy absorption of the tires.

P_{cmb}: Power needed to overcome the slope of the road.

Modifying the above equations we may get that the power delivered to the engine in form of fuel P_i is:

$$\boldsymbol{P_i = \frac{P_{gbx}+P_{dvl}+ P_{brk}+P_{aer}+P_{roll}+ P_{cmb}+m_e V\frac{dV}{dt}}{\eta_{a-f}\eta_{\theta}\eta_m}} \qquad \text{Equation 1-7}$$

The power P_i Has a direct proportional relation to the volume/mass of fuel consumed by the car per unit of time. Therefore, the equation expresses clearly the different terms which has a contribution on the resultant value of the fuel consumption or CO_2 emissions as stated in the chapter 2.2. Of course, the terms relating to the speed V , acceleration $\frac{dV}{dt}$ and climbing resistance P_{cmb} are terms that should not be considered because they depend only on external inputs (driver and road) which are given by the road circumstances and not modifiable by the Automobile manufacturer.

Any other element in the equation may be improved in order to lower the FC. It should be bear in mind that the terms $\eta_{a-f}\eta_{\theta}\eta_m$ account for many sources of losses, especially $\eta_{\theta}\eta_m$. In the following pages it will be commented in a greater extension.

1.2 Analysing the inefficiencies

Any of the elements seen on the previous section is analysed in order to give an overview a classification and the physical explanation of the low CO_2 technologies applied on the model in the chapter 3, where much specific explanation is given.

At this point a classification can be done between terms contributing to:

- A more efficient generation of the power needed to move the car. This is: Improvement of any of the terms linked to the fuel consumption efficiency $\eta_f = \eta_\theta \eta_m \, \eta_{a-f}$ defined before.
- A more efficient generation of the power needed to drive its auxiliary loads. This is: Improvement of η_m linked to auxiliary loads.
- Lower the energy needed to move the car, usually called vehicle energy demand.
- Other particular sources of CO_2 reduction.

1.2.1 A more efficient generation of the power needed to move the car

An exhaustive analysis of each one of the efficiencies making up the fuel consumption efficiency is out of the scope of this Thesis but a more practical, intuitive explanation will be given. To this purpose the BSFC map will be introduced.

The efficiency in the generation of the power to move the car is the fuel conversion efficiency $\eta_f$and its components which have been defined before $\eta_f = \eta_\theta \eta_m \, \eta_{a-f}$. The definitions given in the previous chapter tell by themselves how to improve any of the efficiencies $\eta_\theta \eta_m \, \eta_{a-f}$. So for example an injection system which enforces the complete combustion of the charge in the right time will raise the thermodynamic efficiency and an improved lubricant which lowers the friction between piston and liner will raise the mechanical efficiency.

Here the analysis will be focused on understanding the BSFC map, its relation to η_f and its link to vehicle FC.

The BSFC is defined as:

$$\boldsymbol{BSFC = \frac{1}{\eta_f H_L}} \qquad \text{Equation 1-8}$$

Where:

$BSFC$: Stands for Brake Specific Fuel Consumption which is the mass of fuel injected per unit of output energy in the crankshaft. [g/kW·h]. Called c_s in the following subchapters.

H_L: Is the specific energy of the fuel. In the given equation, in [kW·h/g]

Thus, $\eta_f$is inversely proportional to $BSFC$ which means, of course, that the greatest values of η_f the lowest values of $BSFC$.

Given an engine, the fuel consumption efficiency is not at all a constant value. It ranges among a great amount of values depending on the engine working point. So any engine has a fuel consumption efficiency map or rather, more commonly, a BSFC map.

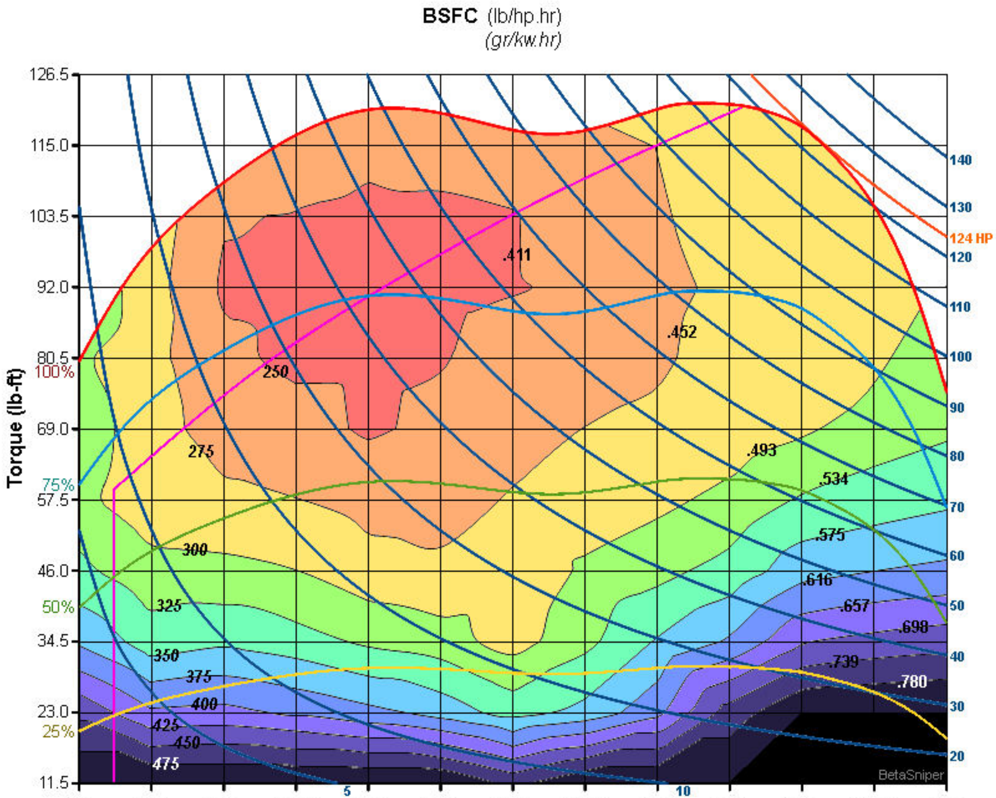


Figure 1-1 BSFC fuel map for a Saturn 1.9L (95 kW) DOHC SI engine **(3)**

The Figure 1-1 shows that two different engine working points with same output power may have absolutely different FC. The BSFC map gives the instantaneous FC of the car when the engine is working in a given conditions of torque and speed. Therefore, it is very important to minimise the values of the BSFC map by applying engine technologies or moving the working points to a more efficient working points. Therefore the labour of Automobile manufacturers to this concern is based on:

- Modify the de fuel consumption map in such a way that $BSFC$ values are lower in the most-probable working points improving $\eta_{\theta}\eta_{m}\,\eta_{a-f}$ by: Improved turbocharging (Higher pressures, dual stage turbocharging…); use of VVA; improved injection systems; higher compression ratios; lower frictions; cylinder deactivation; use of Diesel engines ; combination of an electric power source with the ICE…
- Modify the path that the working points follow in the BSFC map by: Modifying the transmission ratios; add more gears; stablishing an intelligent ECO-Schedule of gear

shifts when AT; using a fastest gear shifting mechanism when AT; using of Continuous Variable Transmission…

All the design improvements pointed out here are explained in greater detail in the chapter 3. Any of these design modifications involve not only a variation on the FC but also a variation on the performance, cost, NVH of the car and customer satisfaction; consequently the Automobile manufacturer must pursue a trade-off among FC performance and customer interests. Gearbox design has special influence on this.

1.2.2 A more efficient generation of the power needed to drive its auxiliary loads

Some power needs to be delivered by the crankshaft to accessories in mechanical or electrical ways (being the upstream source always mechanical):

- Mechanically: such as water pump, oil pump, valve train, A/C system, HPS and the alternator.
- Electrically: Accessories feed by the alternator such as lighting, EPS, ECU's and other loads that may be driven mechanically or electrically depending on the manufacturer's choice which has significant implications on terms of vehicles hybridization and FC.

The auxiliary loads have been considered in the past as a very small "loss" of energy and so there was not major concern on trying to improve its efficiency. However, with the newer more-stringent regulations on CO_2 tailpipe emissions, Automobile manufacturers have enter in a new path of FC reduction based on reducing these auxiliaries loads by:

- Lower friction components, with an obvious reduction on waste of energy and
- Using intelligent systems that do not waste energy if not needed, which may be performed by mechanical clutches or electrification of the system.
- Electrification of driving elements provide as well a higher range of driving working points adapted to the necessities. The introduction of electrified-driven auxiliary loads able the use of further electrification technologies as Start&Stop and beyond which further reduce both the losses of auxiliary loads and ICE loads by combination the action

of Electric motor when the ICE works on low efficiency points of the BSFC map or switching the engine off and disconnecting it when car is stopped or slowing down. Electrification in massive way leads to the possibility of ICE engine removal from the vehicle and therefore none tailpipe emissions. Furthermore, intelligent systems may aid a quick warm-up period.

1.2.3 Lower the energy needed to move the car. Introduction to Coast down coefficients.

Aerodynamic load: If the driving conditions as acceleration and climbing resistance are skipped, aerodynamic resistance is the main source of power that the engine has to overcome specially in high speed cycles. Only the frontal area S and the drag coefficient C_d may be improved by the Automobile manufacturer. To this concern, the frontal area is highly limited by the car size/segment, which is a customer/market requirement but the drag coefficient is something that can be improved.

$$\boldsymbol{F_{aer} = \frac{1}{2}\rho S C_d v^2} \qquad \text{Equation 1-9}$$

Where ρ id the air's density and v the speed of the car.

Rolling resistance load: It is not negligible at all, this loss belongs to the hysteresis cycle of the tires and tire companies are working very hard to improve the rolling resistance coefficients B_0 and B_2.

$$\boldsymbol{F_{roll} = B_0 + B_2 v^2} \qquad \text{Equation 1-10}$$

Driveline Resistance load and brake resistance load: They are far less important as the previous but Automobile manufacturers are already projecting new designs to improve these losses. The driveline resistance coefficients are T_0 and T_2. T_{brk} is the resident brake toque.

$$F_{dvl} = T_0 + T_1 v \qquad \text{Equation 1-11}$$

$$F_{brk} = 4\frac{T_{brk}}{R} \qquad \text{Equation 1-12}$$

Gearbox resistance load: Usually considered as part of the engine efficiency. High efficiency gearboxes are being projected by Automobile manufacturers which may include ultra-finishing of the surfaces, high efficiency bearings, and improved gear packages. Higher-number of gears gearboxes may be detrimental due to an increase number of steps.

$$F_{gbx} = (1 - \eta_{gbx})F_e \qquad \text{Equation 1-13}$$

All them (removing the F_{gbx}) are usually summed up and calculated in an experimental way which is called Coast Down method that is the actual procedure to find the driving resistance that the test bench has to simulate during the emissions measuring test driving cycles procedures. The test is especially useful because is an easy way to measure these inefficiencies and see consequences on changes in the design. It is used as well for computer simulation as shown in the (4)Figure 1-2.

$$F_{cd} = F_{aer} + F_{roll} + F_{dvl} + F_{brk} \qquad \text{Equation 1-14}$$

The coast down method is performed to obtain the coefficients of the Equation 1-15. There are different methodologies to obtain the values but all they are based on a free slowdown of a car from a given high speed to a lower speed and measure speed and time. Later the curve can be plotted and coefficients obtained.

$$F_{cd} = F_0 + F_1 v + F_2 v^2 \qquad \text{Equation 1-15}$$

Finally, the resistance due to the inertia of the car: It is very important to bear in mind that vehicle mass is the most important contributing term on m_e but not the only one. All rotating elements contribute to an increase of this equivalent mass m_e.

$$\boldsymbol{F_a = m_e \frac{dV}{dt}} \qquad \text{Equation 1-16}$$

1.2.4 Other particular CO$_2$ reduction sources

Some FC reduction sources are not clearly specified in the equations described up to now. Some comments on them are given here.

1.2.4.1 Brake regenerating

Besides the elements given in the Equation 1-7, there is an extra term which accounts for the FC: The braking. Braking is a source of loss of energy, actually braking is defined as the loss of vehicle's kinetic energy. Although braking (as the speed or the climbing resistance) is a factor given by the external conditions, Automobile manufacturers can take advantage of this source of energy loss by regenerating it. Reducing thus the amount of power lost during braking by keeping it and using it when more convenient.

There are several regenerating levels associated to the technology used as electrification/hybridization of the car. Mild and Micro hybrid vehicles just recover a small amount of energy while Strong hybrids (P2Hybrids, PowerSplit, PHEV..) and EV recover much more but it always depends on the specific technology applied and the braking level. To this it should be said that the recovering capacity of the batteries is limited and thus, beyond a specific braking level (which is rather low) and given a SOC and other battery conditions, the power delivered to the batteries remains below the amount of kinetic power dissipated. Adding the fact that the charging/discharging efficiency of the batteries is around 80% to 90% in li-ion and 50%

to 92% in Pb-Acid batteries and the conversion to mechanical or other electrical forms has an associated efficiency, the energy regenerating level is limited (5).

Micro hybrid vehicles do not have a specific starter-generator as all the other HEV but instead, an intelligent alternator which charges the 12-24V common Pb battery only when more convenient (*i.e.* during braking or when working in the most efficient BSFC map points). On the other hand, from Mild hybrids to EV there is a specific starter-generator that besides charging the batteries has a launch function helping the ICE in an amount of power related to the degree of Hybridization. Further information on this issue can be found on the chapter 3.

1.2.4.2 Start and Stop Technology

It is based on the switch off of the engine when the engine is at idle and the car is stopped. In this way, a great amount of the energy is spent to maintain the engine on idling is suppressed and only energy for electric devices as EPS, lighting…is used. Of course this technology has a greater potential as the percentage of time on which the vehicle is stopped increase, as in city driving cycles.

1.2.4.3 Special technologies

Other FC reduction sources that are neither showed directly nor implicit in any of the parameters of the equations described up to now:
Solar reflective paint, Active Seat ventilation, Passive cabin ventilation: They are based on the reduction of the A/C system by conditioning the car in a more efficient way.
Solar panels: Based on the charge of batteries thanks to the sun, a both cost free and emissions free source of energy.
Waste head recovery: Based on the recovery of tailpipe head gases by using usually a Rankine cycle.
Active engine/gearbox warm-up: It reduces the period of time that the engine works in cold conditions by warming it.

1.2.4.4 Tailpipe CO_2 emissions reduction due to use of cleaner fuel

The use of a different fuel may improve the fuel conversions efficiency, giving more energy per mass of fuel burned, as Diesel engines. However, such concept doesn't take into account how clean the fuel burns; fuels differ on compositions and chemical structure. Such fact leads to cleaner combustion of some fuels *i.e.* a fewer emissions of CO_2 per unit of energy delivered when burned.

Diesel engines emit a higher amount of GHG per unit of energy delivered. Nevertheless it is more than outweighed by the higher efficiency.

The table 1-1 shows how clean is each fuel in terms of tailpipe emissions of CO_2. If fuel efficiency is considered constant, NG vehicles are by far cleaner than others. Followed by LPG vehicles, gasoline engines and lastly, diesel engines. Nevertheless fuel efficiency is not maintained constant and therefore not further conclusions can be made with just this information.

Since fuel properties change among production methods, estimates on their characteristics do vary among countries. In this case, EPA estimates are showed and so they are mainly valid in US. Whereas probably well approximated for other regions.

Table 1-1 Tailpipe emissions per unit of energy delivered of different fuels **(6)**

	gCO_2/kwh
CNG	180,3
Gasoline	239,9
Diesel	248,3
LPG	214,6

Nevertheless, upstream emissions, which are related to the production and transport methods of every type of fuel, may counteract the beneficial of cleaner combustions. Furthermore, emissions on harmful gases do vary among different fuels. Those facts give rise to many differences on regulations among regions because not clear and "universal" evaluation on all this items can be done.

1.3 CO_2 Emissions variation due to driving conditions and test cycle conditions

As said, the driving conditions are external factor given by the road and the driver and therefore they cannot be modified by the Automobile manufacturer. Neither the homologating test cycles can be modified apparently (in practice, they are modified in some way, see chapter 2.4.3). However, different regulations use diverse driving cycles, which gives rise to variant FC results as can be deduced by the Equation 1-7 *e.g.* higher number of accelerations lead to more FC.

The driving conditions do influence both the final FC and the contribution of each source of FC to the total FC. For example, high speed driving cycle will carry a high FC due to aerodynamic losses and a cycle with high transitory working conditions will be highly influenced by the kind of injection (port or direct injection) resulting in a greater FC the port injection due to major difficulty to control film thickness on intake ducts (4).

Therefore Automobile manufacturers should do a great effort to understand and asses the several FC sources and its behaviour to the different driving cycles in order to invest on them for regulations compliance and customer satisfaction. Furthermore, more discussion about test cycles is given on the chapter 2.3.3, 2.4.1and 2.7.

1.4 Hint to low FC reduction technologies simulation software – Ricardo Data Visualization Tool DVT

1.4.1 FC and CO_2 emissions simulation procedures

The BSFC map has been introduced in the chapter 1.2. It is a powerful tool to forecast by simulation the FC and CO_2 emissions of any car. If the BSFC map of an engine is known, given a car and a driving cycle (speed vs time and gear vs time in the case of MT), the working point for any instant (Torque and engine speed) is known and the total or cumulative FC on the whole cycle can be calculated as integrating the instantaneous FC values over the time (4).

$$\boldsymbol{c_t[g] = \int_{t1}^{t2} c_s \left[\frac{g}{kWh}\right] \cdot P_e[kW]dt} \qquad \text{Equation 1-17}$$

Where BSFC (c_s) is found from the engine torque T_e , the engine speed ω_e , the reference cycle and car characteristics' (Coast down coefficients, gear ratios…). On the other hand, P_e is the torque times the engine speed. The figure 1-2 depicts it:

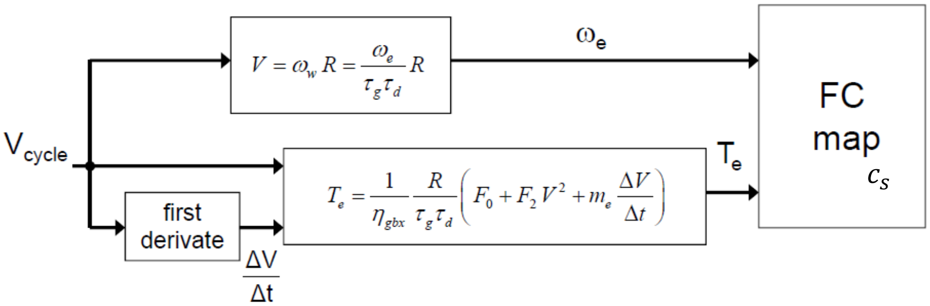


Figure 1-2 Simplified schematic model to calculate FC by simulation methods **(4)**

Where:

ω_w: Angular speed of the wheels

τ_g: Selected gearbox ratio (depending on the gear)

τ_d: Driveline ratio

R: Wheel actual radius

Therefore, more in detail, any of the parameters in the figure do modify the working point and so, the FC. Special attention to the gear ratios should be taken because it varies depending on the selected gear.

Of course, the cumulative fuel consumption can be expressed in many units by simple unit conversion. So, if volume of fuel is the desired output, $c_t[g]$ should be divided by the density of the fuel used. In the case that the FC should be given in terms of range so for example [l/100km], the cumulative FC of the cycle should be divided by the total running distance. Besides, it can be converted to CO_2 emissions. More discussion on this issue is given in the chapter 2.2.

In addition to this procedure, in which the reference driving cycle is supposed to be exactly the same as the actual driving cycle, there are other methods to assess the fact that driver cannot follow exactly the reference cycle and therefore an error is introduced. They are based in an integral proportional control.

Furthermore, it is important to bear in mind that if the warm up period has to be taken into account (to best-match real world), then the BSFC map can be modified or multiplied by a enrichment coefficient during the warm-up period to assess the increase of FC during that period. Furthermore, since BSFC maps are built in steady state conditions, transients are not taken into account neither the effect of engine temperature or climatic conditions. However, different approaches may be made to include them in some degree.

Finally, the effects of transitory power loss to accessories and the use of hybrid technologies and intelligent controls can also be taken into account but the model becomes more and more complex. However, many agenizes have developed very complex models in order to assess the FC improvement of certain technologies in certain vehicles in order to save money by avoiding making expensive real tests. An example of these models is the DVT which includes a metric performance module apart of FC/CO_2 module. This software has been used during the development of this Thesis for academic purposes and it is introduced in the chapter 1.4.2.

Thanks to the several agencies who have developed very complex models to asses improvement on FC due to present and future technologies, information could be gather to the purpose of the development of this paper.

1.4.2 Ricardo Data Visualization Tool DVT

The Data Visualization Tool allows the user to efficiently assess the effects of various combinations of future technologies on GHG emissions and other vehicle performance metrics. The Data Visualization Tool design space encompasses many combinations of vehicle class, engine, transmission, and other design parameters. It uses the Response Surface Model (RSM) set generated by the Complex Systems approach to represent the vehicle performance simulation results over the design space studied for light duty vehicles in the 2020–2025 timeframe (7).

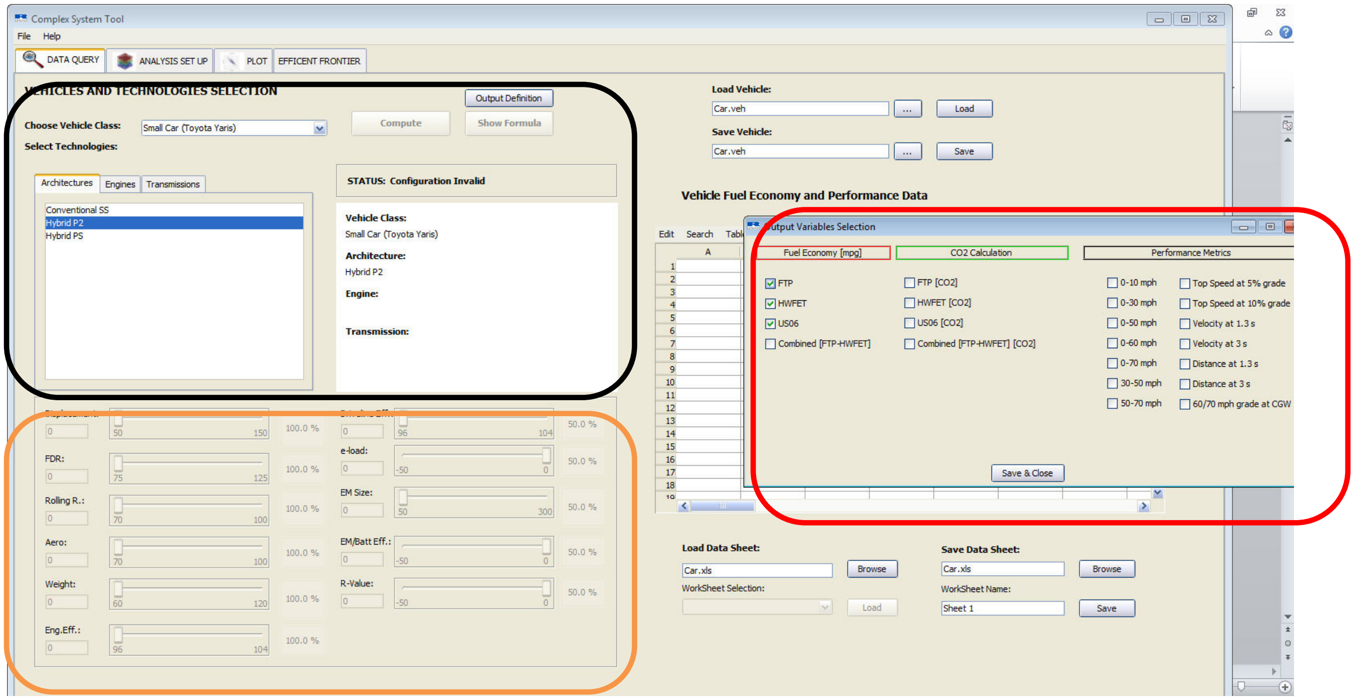
Many companies and agenizes as NHTSA, ICCT have worked with this tool for many purposes. Actually according to ICCT (8), the regression equations used in this Thesis for CO_2 emissions conversion among different test cycles (see chapter 3.7.4.3), were obtained thanks to this tool. Furthermore many of the data used for modelling technologies CO_2 reduction in this document, were obtained from studies which used DVT as a base. Therefore, Data Visualization Tool as well as other software developed by Ricardo has become well-known among professionals on this issue.

For this reason, it has been considered interesting to download the tool and play with it by doing some model runs. Unfortunately the free license does not include a lot of possible packages and it does not include costs, which made not possible to take data for the analysis of this Thesis, nevertheless it was a great experience.

It is a quite intuitive interface and so only some pictures will be used to explain its functioning. Of course the scope of this Thesis is not to show how this software works but rather a quick review of the tool utility and its potential so if more detailed information is required, see (8).

Data query

Three areas have been highlighted in the figure 1-3. They are: Vehicle and technology selection, highlighted in black. Output variables selection, highlighted in red. Reference Car tuning, highlighted in orange.



Choose Vehicle Class: Small Car (Toyota Yaris)

STATUS: Configuration Invalid

Vehicle Class:
Small Car (Toyota Yaris)
Architecture:
Hybrid P2
Engine:
Transmission:

Load Vehicle: Car.veh

Save Vehicle: Car.veh

☑ FTP
☑ HWFET
☑ US06
☐ Combined [FTP-HWFET]
☐ FTP [CO2]
☐ HWFET [CO2]
☐ US06 [CO2]
☐ Combined [FTP-HWFET] [CO2]
☐ 0-10 mph
☐ 0-30 mph
☐ 0-50 mph
☐ 0-60 mph
☐ 0-70 mph
☐ 30-50 mph
☐ 50-70 mph
☐ Top Speed at 5% grade
☐ Top Speed at 10% grade
☐ Velocity at 1.3 s
☐ Velocity at 3 s
☐ Distance at 1.3 s
☐ Distance at 3 s
☐ 60/70 mph grade at CGW

Load Data Sheet: Car.xls

Save Data Sheet: Car.xls

WorkSheet Name: Sheet 1

Figure 1-3 DVT Interface. Data query window.

Vehicle and technology selection; the user has to specify the reference car (or reference class) and its technologies:

- The vehicle class: Small car (Toyota Yaris), Standard car (Toyota Camry), Full size car (Chrysler 300)…
- The architecture: Conventional SS, Hybrid P2 and Hybrid PS.
- The engine: Stoich_DI_Turbo, Lean_DI_Turbo, EGR_Diesel, 2020_Diesel…
- The transmission: 6AT_2010, 8AT_2020, 8Dry_DCT…

The potential packages are however just a few because many of the combinations of these technologies are not valid (at least for the version used, which probably includes a reduced amount of input data).

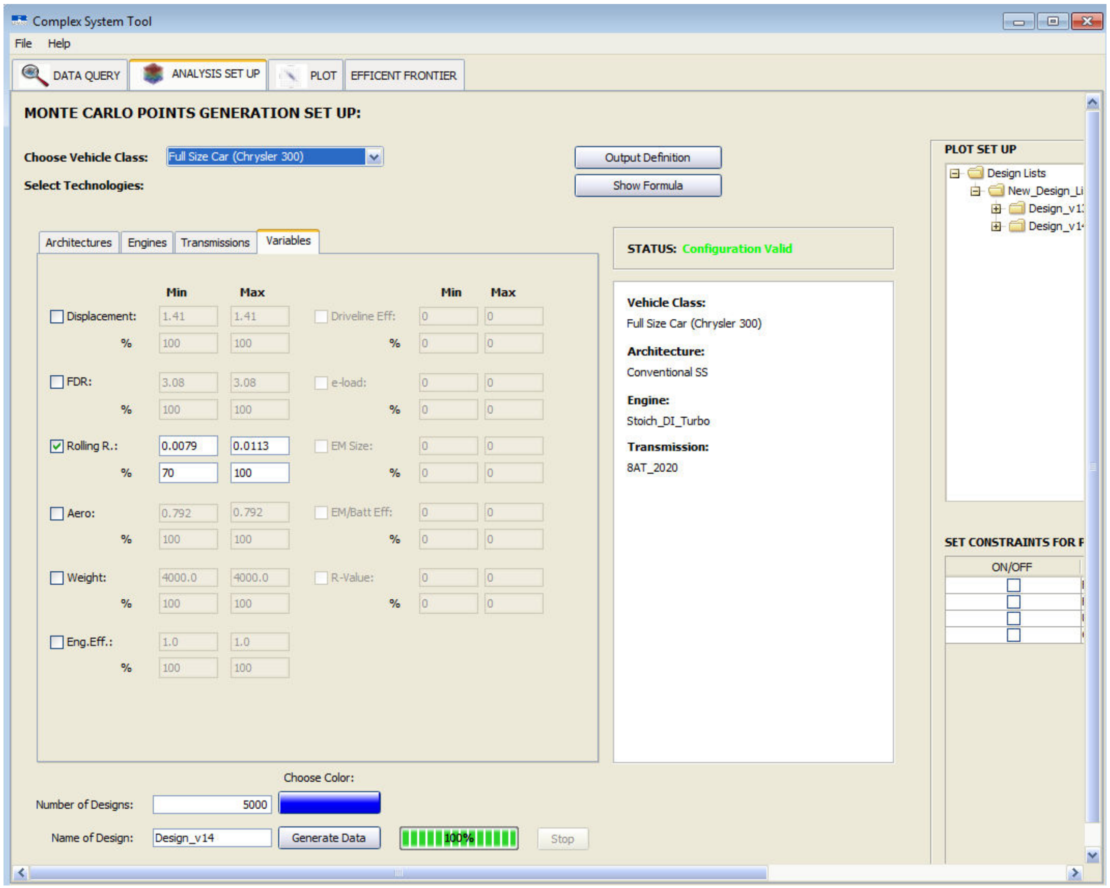
Output variables selection: The user has to simply select which outputs are desirable for his analysis, as can be seen in the Figure 1-3 many performance metrics can be calculated as well as CO_2 calculations for several test cycle. Unfortunately in this version only CO_2 emissions according to EPA regulations can be calculated.

Reference Car tuning: The selected vehicle and technologies may be tuned by varying the displacement, driveline efficiency, aerodynamic resistance and so on, as shown.

At this point, if compute button is set, the software will show the output variables selected for the reference car just created. If the user wants to see the effect of different vehicle parameters on CO_2 and FC as the variation of displacement and so on, he/she needs to follow the next step “set up”.

Set up

The user may define a variable and its minimum and maximum limits. The DVT will calculate the selected outputs for “any” value of the variable.



MONTE CARLO POINTS GENERATION SET UP:

Choose Vehicle Class: Full Size Car (Chrysler 300)

Select Technologies:

	Min	Max		Min	Max
☐ Displacement:	1.41	1.41	☐ Driveline Eff:	0	0
%	100	100	%	0	0
☐ FDR:	3.08	3.08	☐ e-load:	0	0
%	100	100	%	0	0
☑ Rolling R.:	0.0079	0.0113	☐ EM Size:	0	0
%	70	100	%	0	0
☐ Aero:	0.792	0.792	☐ EM/Batt Eff:	0	0
%	100	100	%	0	0
☐ Weight:	4000.0	4000.0	☐ R-Value:	0	0
%	100	100	%	0	0
☐ Eng.Eff.:	1.0	1.0			
%	100	100			

STATUS: Configuration Valid

Vehicle Class:
Full Size Car (Chrysler 300)
Architecture:
Conventional SS
Engine:
Stoich_DI_Turbo
Transmission:
8AT_2020

Choose Color:

Number of Designs: 5000

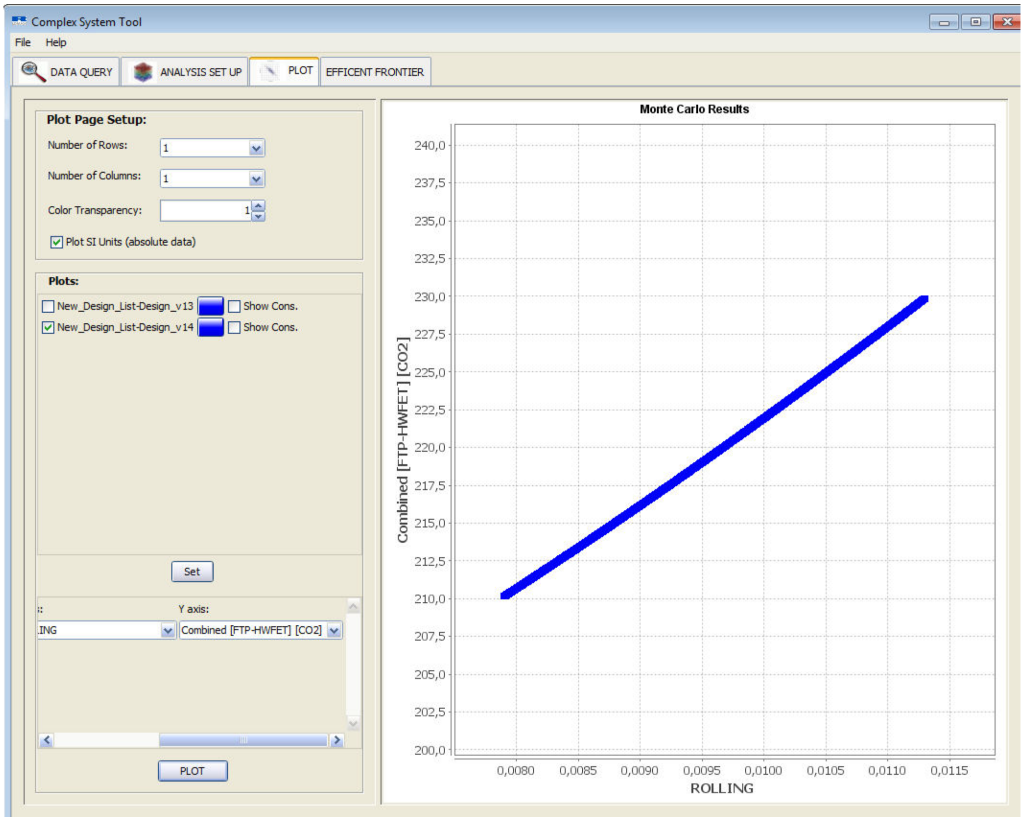
Name of Design: Design_v14

Figure 1-4 DVT Interface. Analysis setup window.

The figure 1-4 shows how the user has chosen the rolling resistance to range from 0,0079 to 0,0113. Thus, a shift from 100% to 70% of rolling resistance with reference to the base car. The base car, as shown in the white window, is a Chrysler 300, conventional SS, and Stoichiometric Direct Injection Turbo with a 8 gears Automatic Transmission.

Plot results

The user may choose to plot many different outputs in several windows in the screen by selecting the number of rows and columns. The user can freely choose the axis of each plot and can, if previously selected in the set up phase, show the effects of several variables on the same plot. In the example the only variable is the rolling resistance and just one plot is shown in the figure 1-5.



Plot Page Setup:

Number of Rows: 1

Number of Columns: 1

Color Transparency: 1

☑ Plot SI Units (absolute data)

Plots:

☐ New_Design_List-Design_v13 ☐ Show Cons.

☑ New_Design_List-Design_v14 ☐ Show Cons.

:: ING

Y axis: Combined [FTP-HWFET] [CO2]

Figure 1-5 DVT Interface. Plot window.

As an example, a reduction of 20g/mi is achieved when reducing 30% rolling resistance in the combined cycle. Such percentage of rolling resistance is out of the possibilities nowadays and in a near future but, as said in the technologies definitions in the third chapter, agencies believe that a 20% reduction in rolling resistance could be achieved from 2017. Supposing that the assessed vehicle doesn't use low rolling resistance technology, a 20% of rolling resistance reduction would improve in some 13g/mi the combined cycle test.

Conclusions

Although the showed example is quite simple, the potential of this tool is huge. The tool may be used to asses: Specific vehicle design on terms of emissions, FE and performance and to explore the effect of vehicle design parameters and technologies in different vehicle architectures and baselines on terms of emissions, FE and performance.

Therefore it helps the user to find the best trade off among the different performance metrics, test cycle emissions and FE for a given vehicle architecture. First by making possible to build comparative plots (superposing or overlapping) the results of different analysis in the same plot which may include different vehicle architectures and baselines, secondly by making possible to choose many different axis (any of the 22 output variables and 11 vehicle parameters) to see the most relevant vehicle characteristics and third and last, by making possible to show many plots at the same time in different windows to compare in a global way one study or different studies.

As an example of what just said the Figure 1-6 has been created:

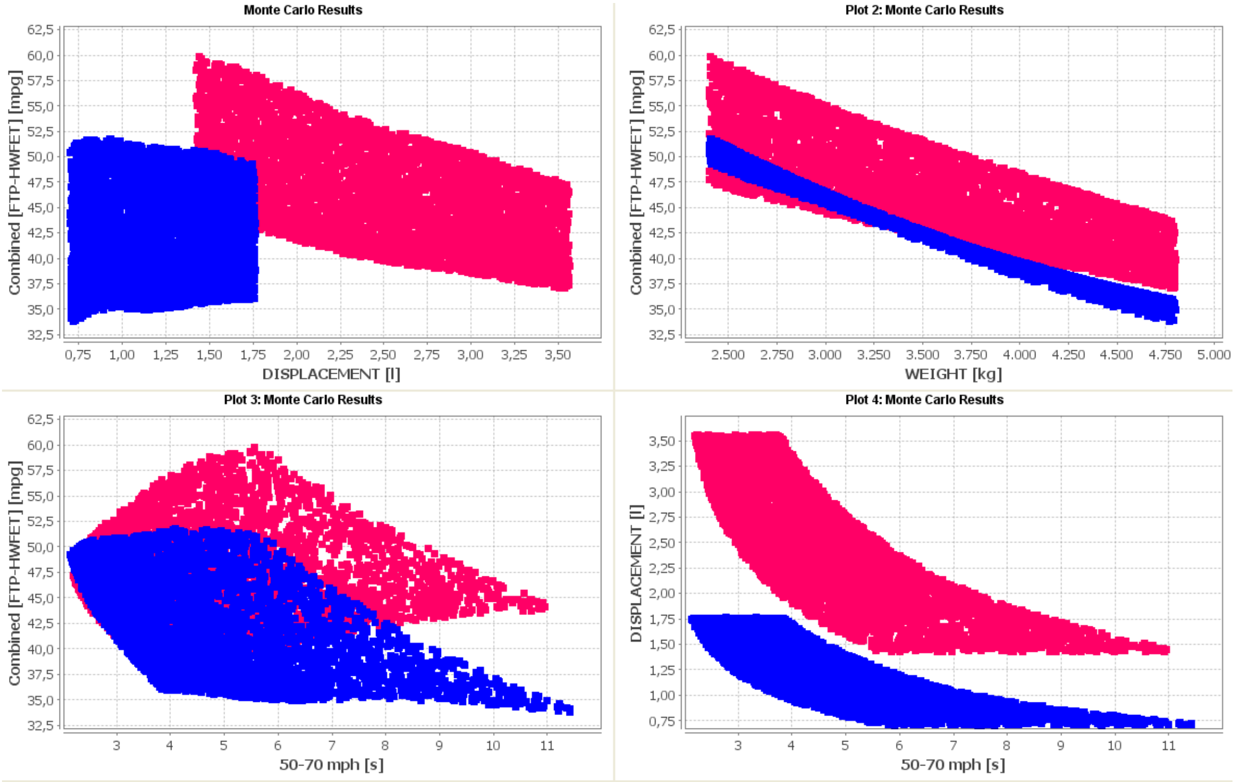


Figure 1-6 Plot results of a comparison of two different powertrains in a Chrysler 300 with weight and engine displacement ranging.

The Figure 1-6 shows a comparison among a MY 2020 Diesel engine with 8 gears automatic transmission MY2020 (pink spots) and a gasoline stoichiometric DI turbocharged engine with 8 gears gearbox DCT dry clutch (blue spots). The selected car is a Chrysler 300. The weight and the displacement of the engine range among 60-120% and 50-125% respectively.

2. Worldwide CO_2 emissions regulations

2.1 Introduction

Transport is, along with electricity production and industrial processes sector, one of the sectors with highest GHG emissions and, without any significant policy changes, is forecast to remain so for the next decades.

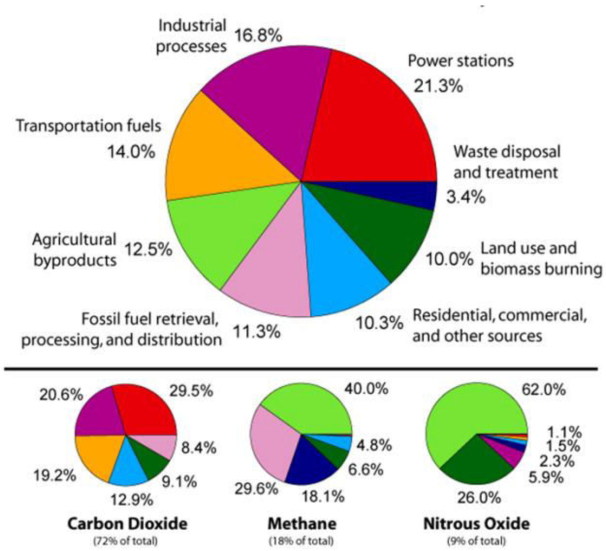


Figure 2-1 Annual GHG emissions by sector, as estimated in **(9)**

This figure shows the relative fraction of man-made greenhouse gases coming from each of eight categories of sources, depending on the sources it may vary but as can be seen in the Figure 2-1, 72% of the total GHG comes from CO_2 emission, which is a product of the combustion of fuels. Therefore it can drop only if combustion of fossil fuels lowers: by improving energy conversion efficiency, by using cleaner fuels or by lowering the energy demand. The other two main greenhouse gases are methane and nitrous oxide with about a 18% and 9% of the total GHG, respectively. Because carbon dioxide emissions account for nearly 95 percent of total GHG emissions that result from fuel combustion during vehicle use, agencies focus mainly in changes in emissions of CO_2 (10).

Recommendations and regulations are already in place or are incoming focus on road transport and including policies on improving energy efficiency, fuel economy standards for both light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs).

Government entities worldwide are asking for a huge effort to reduce the vehicle fuel economy to promote the achievement of lower level of emissions and reduce the dependency from fossil fuels (de-carbonization of road transport).

A number of different test procedures, formulas and approaches to regulating fuel economy and GHG emissions have evolved over the last several decades. The policy objectives of these regulations vary depending on the priorities of the regulating body, but most standards are applied to new vehicles in order to reduce either fuel consumption or GHG emissions (i.e. CO_2, CH_4, N_2O, H_2O, SF_6, CFC…).

There are important differences between these two approaches:

Fuel economy (FE) standards seek to reduce the amount of fuel used by the vehicle per distance driven. Methods to do so may include more efficient engine and transmission technologies, improved aerodynamics, hybridization, or improved tires.

GHG emission standards target either CO_2 or the whole suite of GHG emissions from the vehicle, such as refrigerants from the air conditioning system or nitrous oxide (NO_x) from the catalytic converter. GHG emissions standards may even extend beyond the vehicle to encompass the GHG emissions generated from the production of fuels.

Moreover, both types of standards may be less stringent to specific vehicles/fuels or technologies in order to promote its use for interests that go beyond the GHG emissions *i.e.* political/economic reasons.

Mainly FE standards will be dealt in this work.

The largest automobile markets (North America, European Union, China, Japan and Brazil) approach these new vehicle standards quite differently.

The most relevant regulations, will be described without entering in unnecessary details and focusing if possible only on the MY 2018+ (period of major concern in this work). Once they are described, a rough comparison between the main procedures is done.

2.2 Fuel Consumption (FC), Fuel Economy (FE) and tailpipe CO_2 Emissions

First to enter in detail about the regulations, it is useful to notice de difference between the terms that are being used along the document and that may cause some confusion.

The three terms are equivalent. Thus, simple unit conversions differentiate them, in principle. While FE and FC are the inverse (ratio between the distance travelled/fuel consumed and ratio between fuel consumed/distance travelled, respectively), the CO_2 emissions (measured in grams per unit of distance) depend upon the type of fuel burned and so an additional conversion unit is needed. This is because same volume of fuel may have different carbon content and so different CO_2 emissions as a product of the combustion.

Note that GHG final indicator is concerned to CO_2 emissions rather than FC or FE . However, FC and FE is commonly used at consumer level because it is more convenient for cost calculations. Furthermore FE is used for CAFE regulations and CO_2 emissions for EPA GHG and EU regulations. Whereas some regulations use FC as indicator.

FC is commonly used in Europe and It is expressed as [l/100km] while FE is more common in America and is normally expressed in [mpg] ([mi/gal]). Whereas the conversion between [km] and [mi] is straightforward (1 mi = 1.609344 km), in the conversion among [l] and [gal] it should be specified whether imperial gallons or US gallons are used. Thus, 1l = 0.264US gallons and 1l = 0.219 Imperial gallons.

For what concerns CO_2 emissions, they are expressed in [gCO_2/km] or [gCO_2/mi] depending on the region. After performing some chemical relationships for the combustion process (6) (11) (12). the agencies have stablished a common values of the grams of CO_2 emitted when 1l or 1kg (case of CNG) is burned:

Table 2-1 Tailpipe emissions of carbon dioxide per unit of volume or mass (in the case on CNG) **(6) (11) (12)**

Region	**Fuel type**	**[gCO_2/l] ([gCO_2/kg] for CNG)**
EU	Gasoline	2330
	Diesel	2640
	LPG	1528
	CNG	2669
USA	Gasoline	2400,8
	Diesel	2667,6
	LPG	1528
	CNG	2669

Which vary upon the region because fuel properties depend on the source and on the calculation hypothesis.

The second paragraph of this explanation has shown some uncertainty when suggesting that FC, FE and CO_2 tailpipe emissions are equivalent. On the precedent paragraphs, the physical meaning of such variables has been explained and their equivalent demonstrated. However, any of these variables (FC, FE…) can be measured in several ways according to the different procedures existing worldwide (NEDC, EPA GHG, EPA Labelling, CAFE and so on). All of them may show unlike values of such variables. As an example, EPA Labelling and CAFE are measured in FE (MPG) but they result in different values (about 20-25% difference (13)). Therefore it has to be specified under which circumstances they have been calculated.

However, many times it is not specified in the literature and specially in non-official sources as newspapers or magazines and therefore the reader needs to make assumptions. Of course, knowing the regulations will help the reader.

2.3 United States

In USA, EPA regulates Label and GHG standards while NHTSA and DOT regulates CAFE standards. The Label, GHG and CAFE standards are related to each other, but are separate programs. Compliance is evaluated for each program separately *i.e.* for GHG and CAFE. GHG legislation is more severe in terms of CO_2 targets; Manufacturers must comply with the GHG standards while they can pay fines if not compliant with CAFE standards.

The United States has regulated fuel economy in cars the longest with the Corporate Average Fuel Economy (CAFE) standard, which was introduced in 1975. The CAFE system was updated, or “reformed”, and enhanced in 2009 so that it became a function of vehicle size or “footprint” from 2011. On the other hand GHG emissions standards were first enacted on 2012.

In addition there is also in place the fuel economy label to enhance the customer sensitivity on Fuel Economy and promote the diffusion of more efficient light duty vehicles. The Labelling of vehicle fuel economy and associated costs has also been a requirement in the United States for more than 30 years. Canada has recently switched from a voluntary to mandatory fuel economy system and these standards are aligned with the United States’ revised CAFE standards.

The U.S. federal government has relied on CAFE (Corporate Average Fuel Economy) standards requiring each manufacturer to meet specified fleet average fuel economy levels for cars and light trucks. The standards are based on vehicle footprint and separate car and light-truck standards have been formulated. The scenarios represent 3 to 6 percent annual decrease in GHG levels from the MY2016 fleet-average.

Following the direction set by President Obama on May 21, 2010, NHTSA and EPA have issued joint Final Rules for Corporate Average Fuel Economy and Greenhouse Gas emissions regulations for model years 2017 and beyond. Which have been used as input data for this Thesis.

Figure 2-2 Logotypes of the National Highway Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA)

2.3.1 Corporate Average Fuel Economy (CAFE)

The Corporate Average Fuel Economy (CAFE) intended to improve the average fuel economy of cars and light trucks (trucks, vans and sport utility vehicles) so CAFE has separate standards for "passenger cars" and "light trucks", despite the majority of "light trucks" actually being used as passenger cars. Historically, it is the sales-weighted harmonic mean fuel economy, expressed in miles per U.S. gallon (mpg), manufactured for sale in the United States.

The CAFE standards are expressed as mathematical functions depending on vehicle "footprint" that is determined by multiplying the vehicle's wheelbase by its average track width while a simple formula with cut-off values is adopted to determine the threshold to be achieved. CAFE footprint requirements are set up such that a vehicle with a larger footprint has a lower fuel economy requirement than a vehicle with a smaller footprint.

For example, passenger car with a footprint of 42,3sf will have an associated FE MPG target of some 44mpg on 2018 and 57mpg on 2024. The Figure 2-3 shows the MPG limits for CAFE regulations.

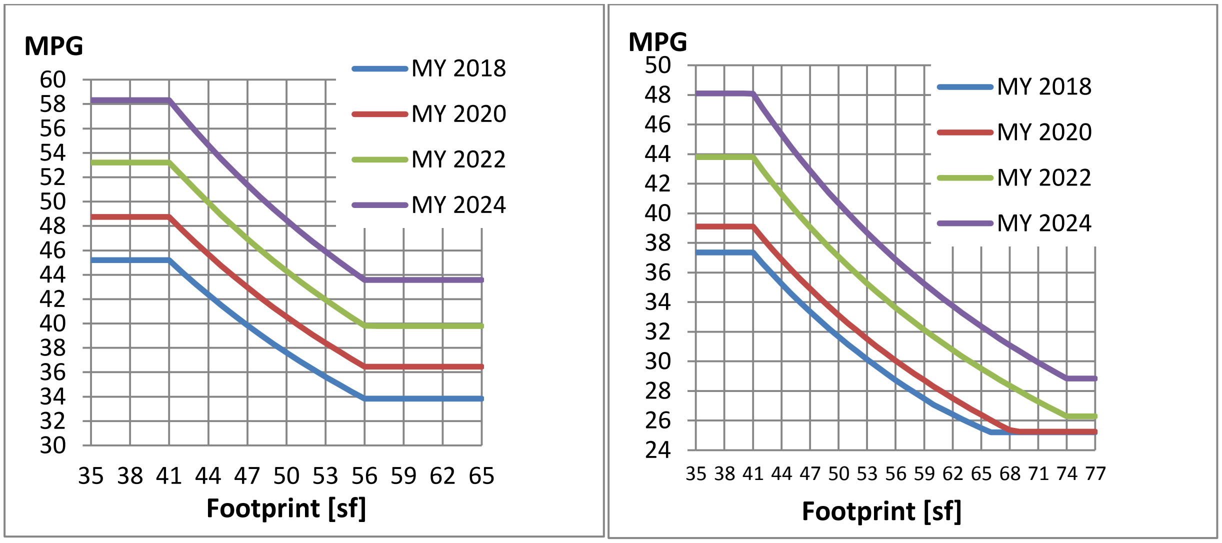


Figure 2-3US passenger car CAFE limit (left) and US light trucks CAFE limit (right) depending on MY

The Figure 2-3 has been created from the equations and coefficients given by EPA (10).

While the limit curve in EU is a simple linear equation, the CAFE regulation stablishes a quite complex curve.

2.3.2 Labelling

The Fuel Economy and Environment Labels provides the public with information on vehicles' fuel economy, energy use, fuel costs, and environmental impacts so to enable an easy and fair comparison among different type of vehicles including advanced technology vehicles such as hybrid and electric cars.

The labels are required to be placed in all new passenger cars and trucks both conventional gasoline or other fuels powered and "next generation" cars, such as plug-in hybrids and electric vehicles.

EPA DOT Fuel Economy and Environment
Gasoline Vehicle
Fuel Economy
26 MPG
Small SUVs range from 16 to 32 MPG. The best vehicle rates 99 MPGe.
combined city/hwy
22 city
32 highway
3.8 gallons per 100 miles
You save $1,850 in fuel costs over 5 years compared to the average new vehicle.
Annual fuel cost $2,150
Fuel Economy & Greenhouse Gas Rating (tailpipe only)
7
1
10 Best
Smog Rating (tailpipe only)
6
1
10 Best
This vehicle emits 347 grams CO_2 per mile. The best emits 0 grams per mile (tailpipe only). Producing and distributing fuel also create emissions; learn more at fueleconomy.gov.
Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs $12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $3.70 per gallon. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.
fueleconomy.gov
Calculate personalized estimates and compare vehicles
Smartphone QR Code™

EPA DOT Fuel Economy and Environment
Electric Vehicle
Fuel Economy
99 MPGe
Midsize cars range from 10 to 99 MPGe. The best vehicle rates 99 MPGe.
combined city/hwy
103 city
95 highway
34 kW-hrs per 100 miles
Driving Range
When fully charged, vehicle can travel about...
0 20 40 60 80
99 miles
Charge Time: 8 hours (240V)
You save $9,600 in fuel costs over 5 years compared to the average new vehicle.
Annual fuel cost $600
Fuel Economy & Greenhouse Gas Rating (tailpipe only)
10
1
10 Best
Smog Rating (tailpipe only)
10
1
10 Best
This vehicle emits 0 grams CO_2 per mile. The best emits 0 grams per mile (tailpipe only). Does not include emissions from generating electricity; learn more at fueleconomy.gov.
Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs $12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $0.12 per kW-hr. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.
fueleconomy.gov
Calculate personalized estimates and compare vehicles
Smartphone QR Code™

Figure 2-4 US Fuel Economy Labels (At left: ICEV, at right: EV)

The Label reports:

Fuel Economy: Miles per gallon (MPG) estimates. The combined City/Highway estimate is the most prominent to allow quick and easy comparison to other vehicles. However, such values are adjusted in order to better reflex the real FE.

Fuel Economy and Greenhouse Gas emissions: one-to-ten rating comparing the vehicle's fuel economy and tailpipe carbon dioxide emissions to those of all other new vehicles, where a rating of 10 is best on CO_2 emissions.

Smog rating: A one-to-ten rating based on exhaust emissions that contribute to air pollution.

Fuel Costs: an estimate of how much more (or less) the vehicle will cost to fuel over five years relative to the average new vehicle, as well as its estimated annual fuel cost. (10)

2.3.3 Test Driving Cycles

The procedure adopted in US to assess the vehicle label fuel economy and CO_2 is based on 5 cycles to be performed on a chassis dynamometer while the two test procedure is used for CAFE purposes.

EPA Federal Test Procedure (FTP-75): the "city" driving simulates an urban route of 12.07 km (7.5 mi) with frequent stops. It has of two phases: "cold start" phase of 505 s over a projected distance of 5.78 km at 41.2 km/h average speed, and "transient phase" of 864 s. A "hot start" cycle which repeats the "cold start" cycle is then performed after 10 minutes pause at the end of "transient" phase.

Highway Fuel Economy Driving Schedule (HWFET) represents highway driving conditions under 60 mph.

US06 is a high acceleration aggressive driving schedule that is often identified as the "Supplemental FTP" driving schedule.

SC03 Supplemental Federal Test Procedure (SFTP) represents the engine load and emissions associated with the use of air conditioning units in vehicles certified over the FTP-75 test cycle.

FTP-20: the FTP cycle is performed at 20 °F (-6.7 °C) with the heating and de-icing system activated.

The difference among the two-cycle procedure and the five-cycle procedure is around 20-25% (14) due to the use of two adjusting factors (1,1 and 1,22 (13)) and the differences coming from the unlike driving cycles. The FTP-75 and HWFET cycles also called combined cycle or two-cycle procedure is used to assess the vehicle fuel economy CAFE and therefore, the ones that apply for the purpose of this work. Fuel economy is calculated as follows:

$$FuelEconomy_{CAFE} = \frac{1}{\frac{0.55}{FE_{city}} + \frac{0.45}{FE_{Highway}}} \qquad \text{Equation 2-1}$$

Where $FE_{city,highway}$ are calculated from the concentrations of CO_2 and other pollutants found using the bags procedures, depending on the fuel used. For further information about the other cycles see the annexes.

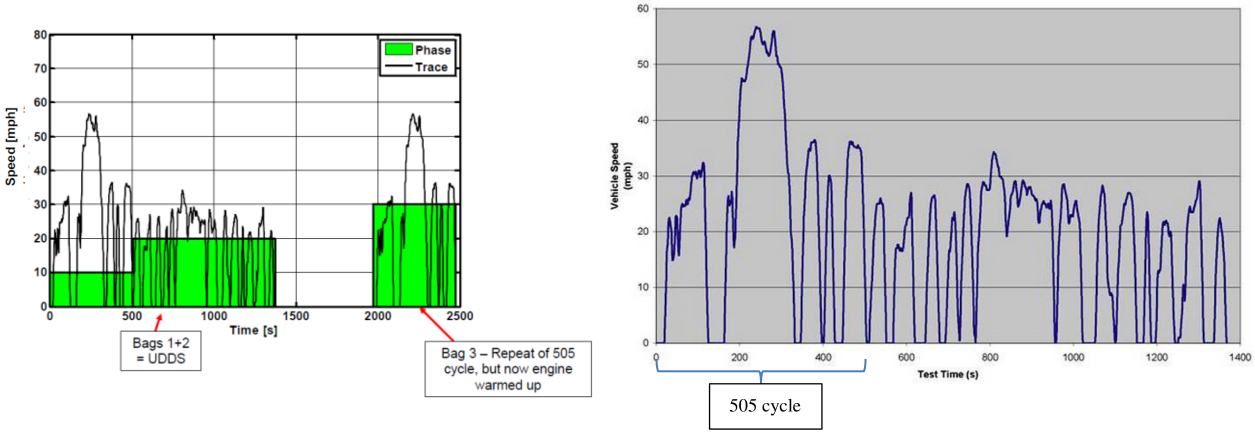


Figure 2-5 At left complete FTP 75 Driving Cycle. At right, UDDS driving cycle and “505” driving cycle. After the Hot start phase there is still for HEV another phase which is not illustrated above.

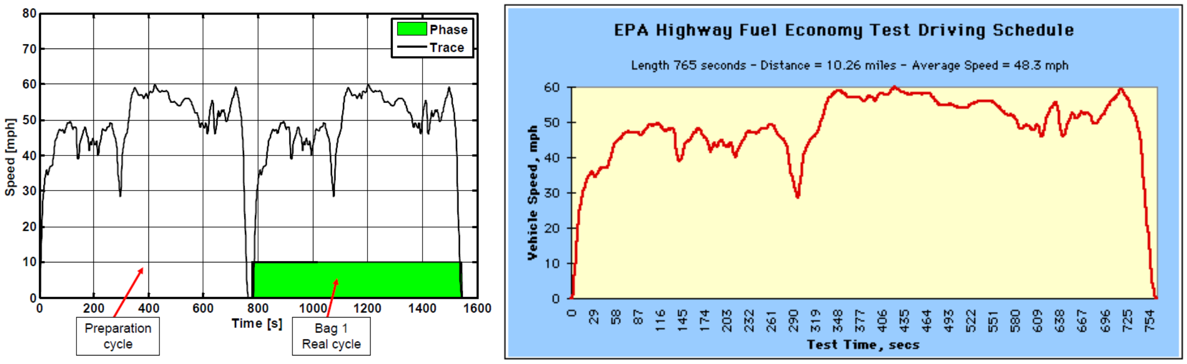


Figure 2-6 At left, complete HWFET Driving Cycle, at right only the part that is repeated.

Four bags are collected and used to estimate emissions and FE for regulation purposes. Such procedures and estimations may vary depending on the type of vehicle.

2.3.4 Flexibilities

EPA’s final program includes provisions that offer compliance flexibility to auto manufacturers. Together these flexibilities are expected to provide sufficient lead time for manufacturers to make necessary technological improvements and to reduce the overall cost of the program, without compromising overall environmental objectives. The flexibilities also provide incentives to facilitate market penetration of the most advanced vehicle technologies. Furthermore, even if no incentives were given to advanced vehicle technologies (as use of cleaner fuels…), a specific procedure to calculate their FE and CO_2 emissions is needed. As an example, how FE (MPG) in CNG vehicles is approached? It is clear that gallon of gasoline and a “gallon” of CNG are totally unlike and incomparable. Such provisions are explained bellow .Flexibilities may be GHG regulations applicable or CAFE applicable (or both). Flexibilities can be a source of loopholes or opportunities from where manufacturers may take advantage of. Therefore, Automobile manufacturer’s strategies are quite legated to such provisions.

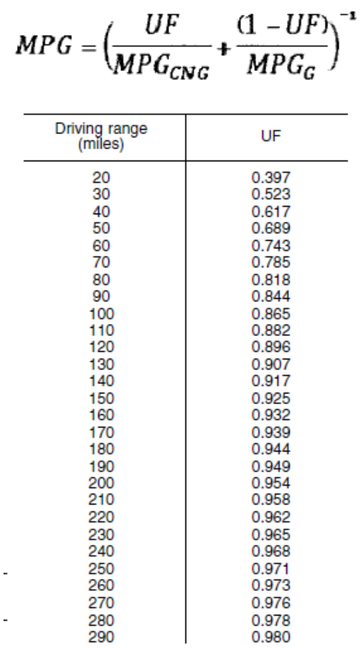
Credit banking and trading

These provisions help manufacturers in planning and implementing the phase-in of GHG and CAFE-reducing technology in their production, consistent with typical redesign schedules. Credits may be carried forward, or banked, for five years, or carried back three years to cover a deficit in a previous year. A manufacturer may transfer credits across all vehicles it produces, both cars and light trucks. Trading of credits between companies is also permitted. To facilitate the transition to the increasingly more stringent MYs 2017-2025 standards, EPA is finalizing under its Clean Air Act authority a one-time CO_2 credit carry-forward provision beyond 5 years, allowing credits generated from MYs 2010 through 2016 to be used through MY 2021.

However, such provision is not used for the calculations of this Thesis.

Treatment of Compressed Natural Gas (CNG), Plug-in Hybrid Electric Vehicles (PHEVs), and Flexible Fuel Vehicles (FFVs)

EPA is finalizing a methodology for determining CO_2 levels for plug-in hybrid electric vehicles (PHEVs) and dual fuel compressed natural gas (CNG) vehicles. This methodology assumes how much of the time these vehicles will operate using the alternative fuel, and how much on gasoline. This methodology (called a “utility factor”) assumes that owners of these vehicles will use the cheaper non-gasoline fuel most of the time, since that was a main reason for purchasing the vehicle.



$$MPG = \left(\frac{UF}{MPG_{CNG}} + \frac{(1 - UF)}{MPG_G}\right)^{-1}$$

Driving range (miles)	UF
20	0.397
30	0.523
40	0.617
50	0.689
60	0.743
70	0.785
80	0.818
90	0.844
100	0.865
110	0.882
120	0.896
130	0.907
140	0.917
150	0.925
160	0.932
170	0.939
180	0.944
190	0.949
200	0.954
210	0.958
220	0.962
230	0.965
240	0.968
250	0.971
260	0.973
270	0.976
280	0.978
290	0.980

Figure 2-7 CAFE FE regulations. Utility factor for CNG vehicles **(10)**

From 2019 the utility factor for CNG vehicles will be taken from the Figure 2-7. Most of the cars have a CNG tank able to provide range of about 220mi which correspond to a utility factor of 0,962. So the final MPG is quite well approximated the combined fuel economy for operation on natural gas (in mpg gasoline equivalent) divided by 0,15. There is still no utility factor data for PHEV and others FFV.

For liquid alternative fuels, this methodology generally counts 15 percent of the volume of fuel used in determining the mpg-equivalent fuel economy. For gaseous alternative fuels (such as natural gas), the methodology generally determines a gasoline equivalent mpg based on the energy content of the gaseous fuel consumed, and then adjusts the fuel consumption by effectively only counting 15 percent of the actual energy consumed.

So for CNG and LPG cars, CAFE MPG is 6,7 times higher than a conventional gasoline vehicle if the MPGe are the same, which is not the case. MPG for LPG engines and MPGe for CNG engines are usually lower than MPG of conventional gasoline for two reasons: First, for LPG (that is comparable as it is liquid fuel as well), the energetic density is lower and so more gallons are used to run the same range even if the fuel efficiency is the same. Second, in order to obtain maximum efficiency in both operating modes (gasoline/diesel and LPG or CNG) the engine has a much higher cost due to technologic complexity so most of times no one of the operating modes is 100% optimized but rather a trade-off among cost, FC and performance. Even though, this MPG multiplier (6,7) is a great advantage for alternative fuel vehicles CAFE compliance calculation. Note that LPG and CNG engines show some 10% and 20% of tailpipe CO_2 reduction respectively, which is much lower than the 6,7 multiplier when comparing MPG to CO_2 emissions. Even taking into account the lower energy content of LPG, the final MPG is much higher than the real. Thus, values of 200-300MPG (for compliance calculation) for those types of cars are common.

In the case of FFVs fuelled with E85 and gasoline (customer's choice), the resultant MPG is divided by 1,39(because of the lower energetic content) and by 0,15. This gives a total multiplier of 4,8 if considering a fuel efficiency equal to a conventional gasoline engine. Besides, the incremental cost of these cars is about 100$. These conditions give rise to a perfect "loophole" to which Automobile manufacturers can take profit to accumulate credits for CAFE compliance.

EVs

In the CAFE program, for EVs, the methodology generally determines a gasoline equivalent MPG by measuring the electrical energy consumed, and then uses a petroleum equivalency factor to convert to a mpg equivalent value. The petroleum equivalency factor for electricity includes an adjustment that effectively only counts 15 percent of the actual energy consumed. Counting 15 percent of the fuel volume or energy provides an incentive for alternative fuels in the CAFE program.

In the GHG regulation for EVs, PHEVs and FCVs, EPA is setting 0 g/mi as the tailpipe compliance value for EVs, PHEVs (electricity usage) and FCVs for MYs 2017-2021, with no limit on the quantity of vehicles eligible for 0 g/mi tailpipe emissions accounting. For MYs 2022-2025, 0 g/mi will only be allowed up to a per-company cumulative sales cap. For sales above these thresholds, manufacturers will be required to account for the net upstream GHG upstream (fuel production and distribution) emissions for the electric portion of operation, using accounting methodologies set out in the rule.

Off-cycle credits

For MY 2017+ EPA proposed and is finalizing provisions allowing manufacturers to continue to generate and use off-cycle credits to demonstrate compliance with the GHG standards. These credits are for measureable GHG emissions and fuel economy improvements attributable to use of technologies whose benefits are not measured by the two-cycle test. The sum of these values for all technologies would be the amount of CO_2 credit generated by that vehicle, up to a maximum of 5.0 g/mi for car. These technologies and their features are clearly depicted in the Figure 3-18 and the chapter 3.5.8.

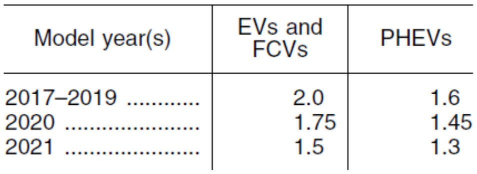
EPA and NHTSA are finalizing a proposal for stablishing fuel economy off-cycle credits for the CAFE regulation compliance from the MY 2017+. The actual value of on the FE improvement of each technology will not be a simple conversion from g/mi to MPG but the general procedures will be the same as used in MY's 2014-2016. It is still not known what technologies will generate off-cycle credits for CAFE compliance.

Penalties

If the average fuel economy of a manufacturer's annual fleet of vehicle production falls below the defined standard, the manufacturer must pay a penalty, currently $5.50 USD per 0.1 MPG under the CAFE standard, multiplied by the manufacturer's total production for the U.S. domestic market. In the case of GHG regulations no flexibility is allowed.

Incentive multiplier

In order to provide temporary regulatory incentives to promote the penetration of certain ‘‘game changing’’ advanced vehicle technologies into the light duty vehicle fleet, EPA is finalizing, as proposed, an incentive multiplier for CO_2 emissions compliance purposes for all electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs) sold in MYs 2017 through 2021. This will lower the manufacturers average emissions, making it easier to meet the target.



Model year(s)	EVs and FCVs	PHEVs
2017–2019	2.0	1.6
2020	1.75	1.45
2021	1.5	1.3

Figure 2-8 US GHG standard incentive multiplier for EVs, FCVs and PHEVs **(10)**

NHTSA did not propose and is not including incentive multipliers comparable to the EPA incentive for CAFE compliance. Instead, CAFE uses the 0,15 divisor for MPG calculation in EVs, LPG vehicles and CNG vehicles from the gasoline equivalent MPG.

2.3.5 Other North American and US State specific Regulations

In California, as directed by the statute, the California Air resources Board (CARB) issued a regulation in 2004 to establish year-by-year GHG emissions targets for two vehicle class categories separately from MY 2009 to 2016, giving automakers a 5-year lead time.
In late 2009, EPA granted a waiver to California to implement its GHG standard for model year 2009-2011 vehicles. California subsequently revised its program to allow manufacturers to show compliance with California's standards by complying with the federal standards.

In addition the State of California adopted a ZEV (Zero Emission Vehicle) program as part of the regulations, and originally included standards and requirements which specify ZEV percentages of 1998 and subsequent model passenger cars and light-duty trucks with a loaded vehicle weight of 0-3750 lbs.

Beginning in 2018, through 2025, large-volume manufacturers (LVMs) must produce an amount at least equal to the "minimum ZEV floor" percentage requirement and may fulfil the remaining ZEV requirement with credits from PHEV (i.e. Transitional Zero-Emission Vehicles or TZEV)

In Canada, in October 2010, the Government finalized the regulation to limit GHG emissions from passenger cars and light trucks from model year 2011 to 2016. The standards will adopt the footprint based structure proposed in the US latest rule making.

2.4 The European Union

In 2009, the European Parliament and the Council adopted a Regulation (EC) No 443/2009 setting CO_2 emission performance standards for new passenger cars. The EU Regulation is the first main measure of the EU Strategy to reduce CO_2 emissions from light-duty vehicles (cars and vans) and is directly applicable in the Member States not requiring any national law through national legal instruments to be transposed into.

Figure 2-9 European Commission logotype

The standard is based on vehicle mass and means that the passenger car fleet on average will emit 130 g CO_2/km by 2015 (compared with 161 g CO_2/km in 2005) and 95 g CO_2/km by 2021 measured over the New European Driving Cycle (NEDC). In a way that 95% of the cars MY 2020 has to account for the calculation in the year 2020 and the whole fleet accounts from 2021 onwards. The regulation is applicable to passenger cars, vehicle category M1. The specific emissions target for each manufacturer in a calendar year is based on the vehicle mass. It is calculated as the average of the Specific Emissions of CO_2 (g/km) of each new passenger car registered in that calendar year, where: To comply with the regulation, a manufacturer will have to ensure that the overall sales-weighted average of all its new cars does not exceed the limit value curve. Otherwise and if the manufacturer doesn’t take any action as for example pooling, it will be fined.

Specific Limit Emissions will be calculated as:

$$\boldsymbol{SLE_{from\,2016}}\left[\frac{\mathbf{g}}{\mathbf{km}}\right] = \mathbf{130} + \boldsymbol{a_1} \cdot (\boldsymbol{m} - \boldsymbol{m_0}) \qquad \text{Equation 2-2}$$

$$SLE_{from\ 2020}\left[\frac{g}{km}\right] = 95 + a_2 \cdot (m - m_0)$$ Equation 2-3

Where:

m: is the curb mass of the car

m_0: “By 31 October 2014, and every three years thereafter, measures shall be adopted to adjust the figure m_0, referred to therein, to the average mass of new passenger cars in the previous three calendar years.” From January 2016, $m_0 = 1392kg$ (15)

a_1: 0,0457

a_2: 0,0333

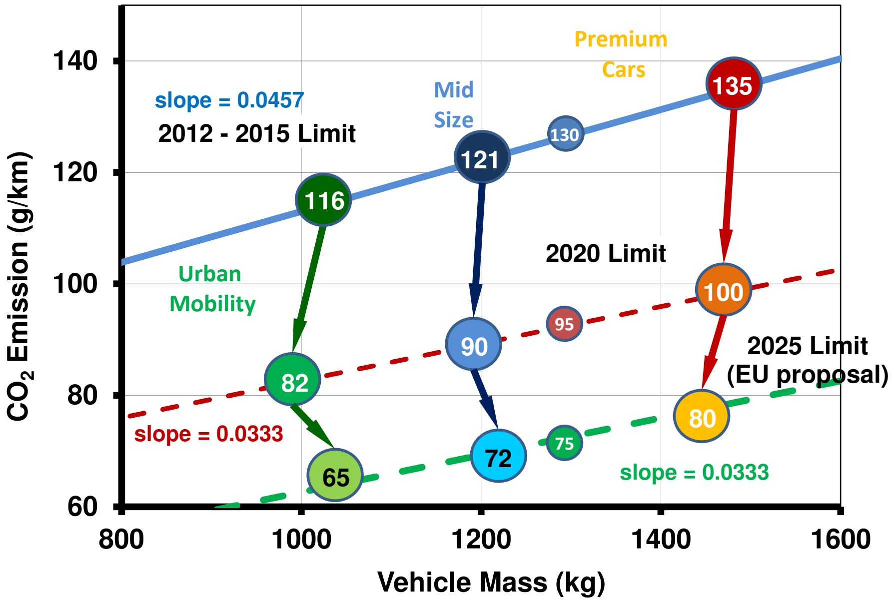


Figure 2-10 The EU Regulation on CO$_2$ emissions indicating the limit curve and a possible CO$_2$ reduction path per segment **(16)**

Car manufacturers have to ensure that the average of their new sales meets these levels. Individual car types can thus be above or below the limit, if car manufacturers exceed these limits they have to pay fines, as is explained in more detail in the next paragraphs.

The curve is also set in such a way that emissions from heavier cars will have to be reduced more than emissions from lighter cars, as can be seen by the shift in slope from 0,0457 to 0,3333. This result in an average CO_2 emissions reduction of 42,5gCO_2/km for PC with curb mas of 2000kg and 30,1gCO_2/km for PC with curb mass of 1000kg from MY2015 to MY2020.

It is 'desirable' indications of how the regulations are going to be provided for the period beyond 2020 in order to enable the automotive industry to carry out long-term investments and innovation. Special concerns arise from the fact that WLTC cycle may start to be applied and therefore Automobile manufacturers will have to make an additional effort to forecast which low FC technologies will be the most convenient for that type of cycle.

The current scenario foreseen under proposal a further reduction of the limit from 95 g/km to 75 g/km to promote a real technology change and asking for a deep review of the role of conventional powertrain.

2.4.1 Test Cycles

Light vehicles are subjected to a transient cycle named New European Driving Cycle NEDC. The NEDC is supposed to represent the typical usage of a car in Europe. It consists of four repeated ECE-15 urban driving cycles (UDC) and one Extra-Urban driving cycle (EUDC).

It is expected that, in the framework of the CO_2 Regulation, the NEDC test cycle will be replaced by the so called Worldwide harmonized Light vehicles Test Cycle (WLTC) that is considered more representative of the real world mission as has been demonstrated that NEDC not representative of the real world. Up to 38% difference among NEDC and real world has been detected while 25% for the CAFE combined cycle (17).

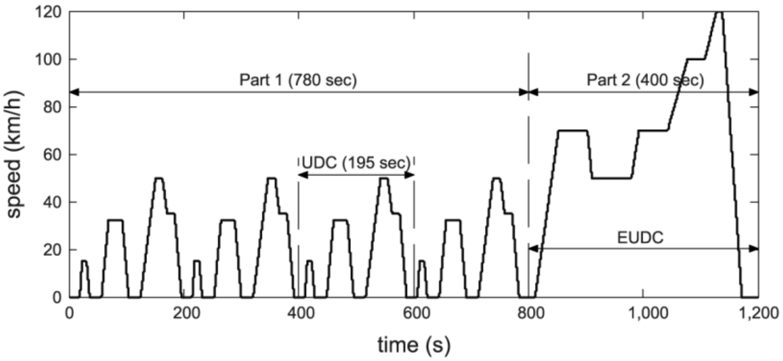


Figure 2-11 New European Driving Cycle NEDC

As well as the speed vs time, there is a gear shit even schedule vs time not represented in the Figure 2-11.

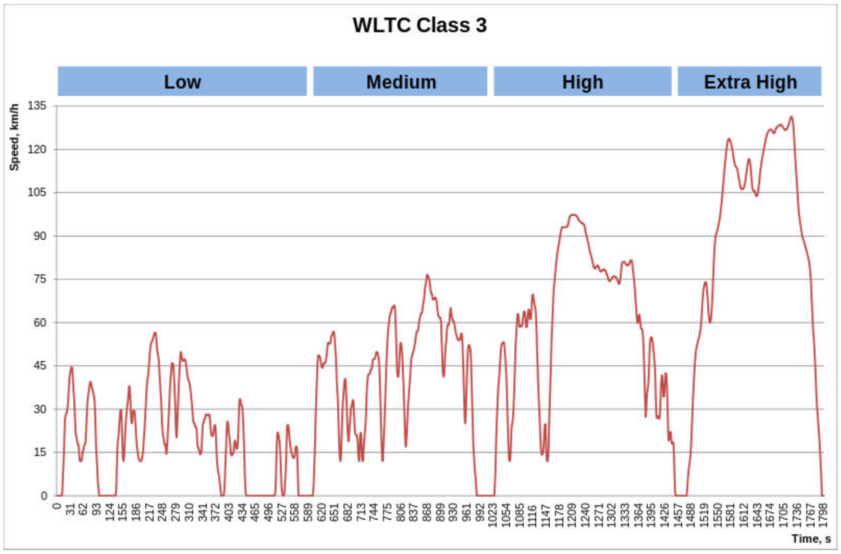


Figure 2-12 Worldwide Harmonized Light Vehicles cycle

The WLTC driving cycle will affect CO_2 emissions in many ways as many parameters of the procedure are redesigned to better adjust to real driving conditions and give less test procedure flexibilities. Thus, not only the driving cycle is more demanding but all the parameters as road load determination (tyre conditions, wheel alignment…), test temperatures, vehicle masses and others (17).

2.4.2 Flexibilities

As in US regulations, some flexibilities are available for manufacturers.

Super-credits

This legislation aims at encouraging the development of very low-CO_2 technologies, despite the high costs involved, by giving 'super credits' for cars that (tank-to-wheel) emit less than 50gCO_2/km. This will lower the manufacturers' average emissions as calculated by the Commission, making it easier to meet the target. For the 130 g CO_2/km the scheme spires in 2016, however from 2020 95 g CO_2/km target:

In calculating the average specific emissions of CO_2, each new passenger car with specific emissions of CO_2 of less than 50 g CO_2/km shall be counted as: 2 passenger cars in 2020; 1,67 passenger cars in 2021; 1,33 passenger cars in 2022; 1 passenger car from 2023.

Differently from CAFE regulations, in which a kind of well-to-wheel gasoline equivalent calculation is performed for EV (see chapter 2.3.4), EVs are currently counted as zero-emission vehicles in EU as they do not have tailpipe emissions.

Currently in practice super credits almost entirely relate to electric cars. Differently from what stablished in CAFE regulations (in which incentives are automatically applied for AFV), alternative fuel vehicles(EV, HEV, FFV, CNG, LPG, methanol compatible…) do not have incentives for compliance calculations as long as they have CO_2 emissions above 50g/km in the NEDC regulations.

Eco-innovations

Manufacturers may apply for credits for innovative CO_2 reducing technologies which are not accounted for in the current test cycle (Eco-innovations). Current examples of such eco-innovations are: solar roofs that provide power for auxiliary electrical systems; efficient lighting (e.g. LEDs); exhaust heat recovery (18).

Incentives can be granted to technologies whose CO_2 saving is not already covered by the CO_2 type approval test procedure. If the CO_2 reducing effect of an eco-innovation is only partially covered by the type approval procedure, the granted CO_2 saving is the difference between the CO_2 saving at modified testing modalities and CO_2 saving under type approval conditions *i.e.* any savings that can be demonstrated using the normal type.

Where basic technical features are not activated permanently during vehicle's operation, average usage factors should be derived from strong statistical data. Normally, such statistical surveys cannot be performed for new technologies before their market introduction.
In general, only technologies whose CO_2 saving effect is not under the influence of the driver's choice or behaviour would normally qualify. Some examples of potentially qualifying technologies are: Engine heat storage, LED lighting, battery charging solar roof. Other examples of potentially and non-potentially qualifying technologies are showed in the annexes.

The total contribution of eco-innovation credits is limited to 7 gCO_2/km in each manufacturers average specific target. Note that the recently published proposal on the 2020 targets for new passenger cars states that: "Eco-innovations are retained when a revised test procedure is implemented".

Differently form EPA GHG provisions on off-cycle credits, eco-innovations are not pre-approved and so the procedure for qualifying is quite more complex, leading Manufacturers to doubt about the worthiness of such provisions.

Joint pools

Manufacturers can group together to form a pool which can act jointly in meeting the specific emissions targets.

Low volume manufacturers

Manufacturers with fewer than 10000 new cars registered per year may apply to the European Commission for derogation from the specific emission targets. Several conditions apply.

Penalties

From 2012 to 2018, the penalties are €5 per vehicle for the first g/km of CO_2; €15 for the second gram; €25 for the third gram; €95 from the fourth gram onwards. From 2019, manufacturers will pay €95 for each g/km exceeding the target.

2.4.3 Test procedure flexibilities

Until now, flexibilities have referred to regulation parameters that have been created on purpose to ease regulation stringency under some conditions in order to make a more efficient, neutral and better approached emissions regulations. There is, however, a second approach of flexibilities (test procedure flexibilities) very different from the first one. Test procedure flexibilities have not been created on purpose from the regulations but rather, they are regulations loopholes from where manufacturers may take profit.

In other words and highlighting the implications of this fact: procedures contain flexibilities that could be exploited to achieve lower CO_2 emission values on the Type Approval test without applying technical improvements to the tested vehicle. Achieved by carefully selecting vehicle test conditions within, or possibly even outside, allowable bandwidths, manufacturers might be able to achieve reduced CO_2 emission levels on a given vehicle at homologation that do not correspond to an equivalent reduction in emissions for a given driving pattern on the road. Therefore, reductions in type approval CO_2 emissions obtained in such a way not only affect the net impact of the regulation in a detrimental way but also the costs of meeting the targets. So, final real life fleet emissions are higher than expected and cost of cars are reduced, which absolutely benefice profits of manufacturers by worsen air quality.

Some of the flexibilities are Automobile manufacturer's choice while others are not really modifiable since they depend upon the facilities used to carry the tests.

The TA process differs between the US and Europe. Utilisation of test procedure flexibilities appears to be more wide-spread in the EU than elsewhere. However, the new WLTC will remove some of the available flexibilities. Such flexibilities (that will be explained below in detail) can basically be applied to European regulations and not to USA regulations and therefore, it can be stated that USA regulations are better realised, without such loopholes. The reasons of such differences among regulations are the certificate of conformity tests (also called Conformity Of Production test COP) performed to the vehicles coming from the production line after Type Approval test have been successfully surpassed. These second tests are performed in order to check that prototypes tested on the TA test are actually representative to that vehicles coming from the production line and sold. In EU, such COP test can be performed with the same conditions than TA test so "loopholes" can still be exploited. However, USA regulations do not perform the "COP" test with same conditions which make manufacturers to not dare/risk to use flexibilities. Furthermore, customer can ask EPA to audit Automobile manufacturers if Label MPG is not coherent to real MPG. As an example Ford C-max was revised and it was found that Coast down coefficients were not representative and therefore EPA punished Ford.

A preliminary evaluation suggested that some 9 - 10% of the reductions observed in assessed vehicle models between 2002 and 2009 could not be attributed to additional technologies applied to the assessed vehicle models between 2002 and 2009.This sensitivity analysis indicated that a reduction in type approval emissions of 9- 10% due to increased utilisation of flexibilities would lead to around € 600 lower costs per vehicle for meeting the passenger car target of 95 g/km in 2020, which is about one third of the costs estimated with cost curves based on application of headline technologies only (8).

Key flexibilities fall into two categories, firstly those that affect the coast down measurement test, secondly those that affect the type approval or NEDC test:

- For the road load determination test (coast down measurement) the main identified issues are:
  Wheel alignment, adjustment of brakes, transmission and driveline preparation
  Ambient conditions : temperature, pressure, wind, humidity
  Tyres: type, pressure, and wear
  Test track: surface type and slope

Vehicle weight as tested
Vehicle body type

- For the NEDC type approval test the main issues found are:
  Inertia class
  Factors affecting driving resistance on the dynamometer
  Influence of the driver: using the tolerances in the driving cycle
  Preparation of the test vehicle
  Optimised measurement
  Variation in gear shifting
  Battery state of charge
  Laboratory soak temperature

Also it is worth to mention that a portion of the theoretically available flexibilities may not be practical to implement in every vehicle and whilst some flexibilities reduce CO_2 they can have an adverse effect on other emissions (such as increasing NOx). Furthermore it should be clear that most of times the maximum level of CO_2 emissions reductions cannot be achieved for each item and that some items effects cannot be summed up.

A more detailed explanation of any flexibility has been summarized from (8) and is given in the following points, with some references to the regulations which can be found in (19).

2.4.3.1 Coast down method flexibilities

Let's explain more in detail the flexibilities in the coast down method which may sum-up up to 4,5% CO_2 reduction, in the best case:

Wheel and tyre specification

Manufacturers often have a range of wheel and tyre size options available within a family of vehicles. The legislation includes some flexibility in the choice of wheel and tyre used in both the coast down measurement test, and the NEDC test.

Regarding the tyre choice for coast down measurement, UNECE R83 – Annex 4a, Appendix 7, 4.1.2 states: “The widest tyre shall be chosen. If there are more than three tyre sizes, the widest minus one shall be chosen.”

Tyre specification has a significant effect on rolling resistance, and tyre width has an effect on aerodynamic drag. The flexibility in tyre choice may be used to optimize rolling resistance and drag for the coast down test, when in reality incentives could be used or be present to sell the majority of vehicles with different wheels and tyres. For example, it could be possible to specify very extreme tyres as the “widest minus one” in the range, therefore gaining significant benefit on the coast down test. However this may not be viable in practice, as the manufacturer would have to ensure no customers purchase vehicles with such extreme tyres due to the reduced grip. A more viable approach might be to specify reasonably low rolling resistance tyres as standard, and make other tyres available as an option for more performance oriented customers.

Tyre pressure

Tyre pressure is also a significant factor in rolling resistance, therefore coast down performance. For the coast down test, UNECE R83 – Annex 4a, Appendix 7, 4.3 specifies that “The following checks shall be made in accordance with the manufacturer's specifications for the use considered: Wheels, wheel trims, tyres (make, type, pressure), front axle geometry, brake adjustment (elimination of parasitic drag), lubrication of front and rear axles, adjustment of the suspension and vehicle level, etc.”

Tyre pressures are set when the tyres are ‘cold’, however the exact temperature is not specified. Therefore there is some flexibility in the change of pressure during the course of the coast down procedure. If the ambient temperature is low when pressures are set, any increase in ambient temperature during the day will be of benefit as increased tyre pressures will result.

In addition to the effect of ambient temperature, the vehicle operating temperature will also have an effect on tyre pressure. It is advantageous to get the tyres to the highest temperature possible during the preconditioning phase of the test, in order to further increase tyre pressure. This benefit is offset somewhat as the tyres become softer with increased surface temperature, increasing rolling resistance.

Brakes

Also mentioned in UNECE R83 – Annex 4a, Appendix 7, 4.3 on "brake adjustment (elimination of parasitic drag)," are adjustments that may be made to certain components. The adjustment of brakes to remove parasitic drag in particular is likely to improve coast down performance relative to a vehicle in service.

Preconditioning

Another flexibility in the legislation is the preconditioning of the vehicle prior to coast down testing. This is referred to in UN/ECE R83 – Annex 4a, Appendix 7, 4.4.4 "Immediately prior to the test, the vehicle shall be brought to normal running temperature in an appropriate manner." The temperature of vehicle components affects rolling resistance, therefore maximising the vehicle temperature at the start of the coast down test can further improve the coast down curve.

Running-in period

The legislation states the following regarding the condition of the vehicle used for the coast down test (UNECE R83 – Annex 4a, Appendix 7, 4.2): "The vehicle shall be in normal running order and adjustment after having been run-in for at least 3,000 km. The tyres shall be run-in at the same time as the vehicle or have a tread depth within 90 and 50 per cent of the initial tread depth."

This includes some flexibility in the running-in distance, and the tread depth on the tyres. It is advantageous to use tyres with minimum tread depth to reduce rolling resistance. It is also advantageous to cover enough distance to minimise friction losses throughout the vehicle.

Ambient conditions

This includes the influence on aerodynamic drag of ambient temperature and air pressure, wind direction and speed, and humidity. UNECE R83 – Annex 4a, Appendix 7, 3.1 states: “Testing shall be limited to wind speeds averaging less than 3 m/s with peak speeds of less than 5 m/s. In addition, the vector component of the wind speed across the test road shall be less than 2 m/s.” Also, UNECE R83 – Annex 4a, Appendix 7, 3.2 states that “Humidity: The road shall be dry.”, while in UNECE R83 – Annex 4a, Appendix 7, 3.3 the following is prescribed: “Pressure and Temperature: Air density at the time of the test shall not deviate by more than ±7.5 per cent from the reference conditions, P = 100 kPa and T = 293.2 K.”

In general a low ambient pressure and a high ambient temperature with low humidity are considered to be optimal for best coast down performance within the ranges specified above. However, the power determined from the coast down test is corrected by a formula given in UNECE R83 – Annex 4a, Appendix 7, 5.1.1.2.8, “The power (P) determined on the track shall be corrected to the reference ambient conditions (20 °C and 100 kPa).” Consequently the effect of altitude of a test track is assumed to be negligible. For humidity no correction is made. In reality, humidity does influence the density and viscosity of air, and in general may deserve consideration.

Test track design

Regarding the test track used for coast down testing, the following statement includes a tolerance for the slope of the track: UNECE R83 – Annex 4a, Appendix 7, 2 “Definition of the road: The road shall be level and sufficiently long to enable the measurements specified in this appendix to be made. The slope shall be constant to within ±0.1 per cent and shall not exceed 1.5 per cent.”

It may be possible to use this tolerance to gain advantage. It may also be possible to optimise track surface to minimise its contribution to the overall rolling resistance of the vehicle. For example, a smooth surface is expected to generate less resistance than a rough surface. Currently characteristics of the road surface are not specified in the test procedure.

The regulations require the coast down test to be repeated in opposite directions in order to account for the wind direction on the day of testing. This provision counteracts the effect of a slope and wind in the test track to a large extent but not entirely since it is not specified that the second test should be performed exactly in the same piece of track and the wind may change direction between the two runs.

In practice, most of the test coasts down procedures are performed in Idiada track in Spain, which is optimal.

2.4.3.2 NEDC test Flexibilities

Here some explanation is given to flexibilities concerning the TA test.

Reference mass

The reference mass is significant to cycle CO_2 as it determines the chassis dynamometer inertia setting used for the test. It is a benefit to use any flexibility in the legislation to claim a lower inertia class for achieving reduced CO_2 emissions. It also has a great effect of reducing road load in tests where cookbook loads are used because these loads are related to the reference mass.

UNECE R83 – Annex 1, 2.6, specifies the reference mass to be used as: "Mass of the vehicle with bodywork and, in the case of a towing vehicle of category other than M1, with coupling device, if fitted by the manufacturer, in running order, or mass of the chassis or chassis with cab, without bodywork and/or coupling device if the manufacturer does not fit the bodywork and/or coupling device" This statement allows to specify certain items as dealer fitted optional extras, therefore not fitted by the manufacturer, which may result in a reduced inertia class if the vehicle is close to the lower end of the class boundary.

Wheel and tyre specification

For the NEDC test, standard wheels, tyres, and tyre pressures are used, as specified by the manufacturer. However, there is some flexibility in the sense that low CO_2 wheels and tyres could be specified by the manufacturer as standard, but not used in practice due to strong incentives for customers to choose alternative options with higher performances and much lower prices but less fuel efficient.

The combination of wheel and tyre specification affects gearing, due to the effective rolling radius. Thus, the flexibility in wheel/tyre choice could potentially be used to optimise gear ratios for the NEDC test, if alternative wheels/tyres are offered as a dealer fitted option.

In general, it is anticipated that higher gear ratios are beneficial for CO_2 reduction due to the improvement in brake specific fuel consumption occurring at lower engine speeds. There is also a secondary effect of reduced drivetrain power losses.

Tyre specification can also be used to improve rolling resistance on the NEDC test, by specifying low rolling resistance tyres, and high tyre pressures, for the tyres that will be used.

When a twin roller chassis dynamometer is used, the tyre pressures are allowed to be higher: UNECE R83 –Annex 4a, 6.2.3 states that: “The tyre pressure may be increased by up to 50 per cent from the manufacturer's recommended setting in the case of a two-roller dynamometer.” However, twin rollers may increase rolling resistance due to the increased tyre deformation experienced, so it is not clear if this is a CO_2 benefit overall.

Other factors also affect rolling resistance on the chassis dynamometer, including: tension of tiedown straps holding the vehicle to the floor, weight and weight distribution of vehicle and occupants. The optimal arrangement is one which minimises weight acting on the driven wheels, but keeps the drive shafts alignment as straight as possible.

The result of increased gear ratios is lower engine speed, higher engine load. This generally reduces CO_2 but increases NOx in both diesel and gasoline engines. It could be argued that any increase in NOx emissions may require the engine calibration to be modified to compensate. These modifications may then increase CO_2 again. However, the overall effect is anticipated to be a reduction in CO_2.

Running-in period

Regulation UNECE R83 – Annex 4a, 3.2.1 specifies a minimum distance is to be recorded before the NEDC test: “The vehicle shall be presented in good mechanical condition. It shall have been run-in and driven at least 3,000 km before the test.” However, there are potential flexibilities in this running-in period in order to achieve the minimum possible friction losses in the engine and vehicle.

For a vehicle that has been run-in over a distance of 15,000km compared to a vehicle run-in over 3,000km the CO_2 benefit can be significant. The actual benefit may vary depending on factors including the design of affected components such as bearings, and the speed/load profile of the running-in cycle.

Laboratory instrumentation

The legislation covers measurement accuracy and tolerances for a range of instrumentation equipment. If the true accuracy of instrumentation lies well within the allowable tolerance band, then it may be possible to deliberately utilise some of that tolerance band to reduce the measured CO_2 result.

Fuel specifications

Fuel consumption and emission tests for type approval purposes are carried out with European reference fuels. This fuel has a very tight specification and a very narrow band of tolerance but they can still use a cleaner fuel which leads to some improvement on CO_2 emissions.

Laboratory altitude (air density)

The density of the intake air used during the NEDC test is largely dependent on laboratory altitude. This varies between facilities and may have some impact on CO_2 directly or indirectly.

Diesel engines in particular can be sensitive to altitude regarding the way they control NOx emissions, and depending on the control strategy used these may have a knock-on effect on CO_2 emissions as a result. Depending on engine hardware, it may not be possible to compensate for reductions in ambient air density through boost control (especially at the low load levels typical of the NEDC), which may result in reduced combustion efficiency and thus increased CO_2 emissions. In general, diesel NOx emission limits are perceived to be more challenging at higher altitudes, therefore it is likely to be preferred to choose a test facility located at sea level. For gasoline engines the lower air density at high altitude will tend to increase engine efficiency slightly due to wider throttle openings.

Temperature effects

Regulations governing the Type 1 (NEDC) test procedure state the following:

UNECE R83 – Annex 4a, 3.1.1 "During the test, the test cell temperature shall be between 293K and 303K (20°C and 30 C)."

UNECE R83 – Annex 4a, 6.3.1 "After this preconditioning, and before testing, vehicles shall be kept in a room in which the temperature remains relatively constant between 293 and 303K (20°C and 30°C).

This clearly shows flexibility in temperature within the specified range. There is a CO_2 benefit from higher vehicle soak temperature due to the reduced friction in the engine and vehicle components. Furthermore warm-up period is reduced thus reducing FC and CO_2 emissions. However, at the same time, it may be possible to improve combustion efficiency by setting the air temperature to the minimum (20 C). In general the best option would be to perform the test at 30°C. Starting the test at a higher temperature is likely to reduce aftertreatment warm-up times, which may give a benefit in other emissions.

Coast down curve or cookbook load terms

The NEDC test can be performed with chassis dynamometer load controlled in one of two ways: Road load simulation matched to a coast down curve based on real test data or load governed by 'cookbook' load factors or 'table values' according to the reference mass of the vehicle.

This flexibility in the legislation may be used for CO_2 benefit as the two methods will not result in identical load during the NEDC test. The method that produces the lowest CO_2 result depends on several factors which are not going to be discussed. Normally, Coast down method is the one chosen for PC.

Battery state-of-charge

The state-of-charge of the battery at the start of the NEDC test has a significant effect due to the additional electrical load placed on the alternator as it charges the battery during the test. If the battery is fully charged prior to the test the load will be reduced compared to a test starting with a battery in a low state-of-charge requiring more alternator charging during the NEDC. However, vehicles with intelligent alternators may not notice the difference since battery is charged when braking.

State of charge also affects the ‘stop/start’ strategy employed on some vehicles, for example, the engine control system may disable the stop/start strategy if the battery is not sufficiently charged at the start of the test, leading to increased CO_2.

Gear change schedule

Gear number and change points are pre-defined in the NEDC cycle. However, some flexibility exist: UNECE R83 – Annex 4a, 6.1.3.1 “If the maximum speed which can be attained in first gear is below 15 km/h, the second, third and fourth gears shall be used for the urban cycle (Part One) and the second, third, fourth and fifth gears for the extra-urban cycle (Part Two). The second, third and fourth gears may also be used for the urban cycle (Part One) and the second, third, fourth and fifth gears for the extra-urban cycle (Part Two) when the manufacturer's instructions recommend starting in second gear on level ground, or when first gear is therein defined as a gear reserved for cross-country driving, crawling or towing.”

If higher gear ratios are used, cycle CO_2 is reduced by two mechanisms. Firstly, the engine operates in a more efficient region of the BSFC map, due to the lower engine speeds associated with higher gearing. Secondly, the power losses in the drivetrain reduce as the overall ratio approaches 1:1.

Driving technique

Speed/time tolerance bands apply to the NEDC target cycle. UNECE R83 – Annex 4a, 6.1.3.4, "A tolerance of ±2 km/h shall be allowed between the indicated speed and the theoretical speed during acceleration, during steady speed, and during deceleration when the vehicle's brakes are used." UNECE R83 – Annex 4a, 6.1.3.5, "The time tolerances shall be ±1.0 s. The above tolerances shall apply equally at the beginning and at the end of each gear-changing period for the urban cycle (Part One) and for the operations Nos. 3, 5 and 7 of the extra-urban cycle (Part Two). It should be noted that the time of two seconds allowed includes the time for changing gear and, if necessary, a certain amount of latitude to catch up with the cycle."

It may be possible to use these tolerance bands to achieve a lower CO_2 result. This may be achieved by reducing the rate of acceleration as much as possible, making smooth transitions between start and end of each acceleration phase, and minimising the time taken to change gear.

DPF related Ki factor (distance between DPF regenerations) for calculating total cycle CO_2

For vehicles fitted with a diesel particulate filter (DPF), the total CO_2 result includes an additional factor to take into account emissions whilst regenerating the DPF. The weighting factor applied to the regeneration test relative to the standard test (known as the Ki factor) is dependent on the expected interval between DPF regenerations. It is likely that the CO_2 will be higher during the regeneration test; therefore, a shorter interval between regenerations will increase total CO_2. The flexibility in the legislation relates to the definition of this interval. It is advantageous to choose the method giving the longest interval between regenerations.

Declared CO_2 value

Once the CO_2 test result is known, the manufacturer can decide what value to declare, taking into account the margin required to pass conformity of production checks, and in service testing. The declared value can be up to 4% lower than the actual measured result:

UNECE Regulation No. 101, 5.5.1 "The CO_2 value or the value of electric energy consumption adopted as the type approval value shall be the value declared by the manufacturer if the value measured by the technical service does not exceed the declared value by more than 4 per cent."

2.5 China regulations

Although China is the biggest vehicle manufacturer of the world, China's first-ever fuel consumption standards for passenger vehicles were adopted in 2004 (National Standard GB 19578-2004). The standard established “Phase I” and “Phase II” fuel consumption standards, which were phased-in[3] from 2005-2006 and 2008-2009, respectively. The China Automotive Technology and Research Center (CATARC), a semi-governmental organization, drafted the regulations during a two-year process involving multiple agencies of the Chinese government. China uses the NEDC test procedure.

The Phase I and II standards required that each individual vehicle model comply with fuel consumption regulations prior to entering the market. This contrasts with policies in the US, the EU, and Canada, which permit auto manufacturers to meet targets by averaging emissions over their entire fleet of models.

In August 2009, China announced the development of Phase III of its fuel consumption regulation program, to be phased-in from 2012 to 2015. The Phase III program has some important differences to Phase I and Phase II. Most importantly, in addition to specific fuel consumption limits by weight class, the Phase III standards establish a corporate-average fuel consumption (CAFC) target which manufacturers are required to comply with.

In 2012, China's State Council released the Energy-Saving and New Energy Vehicle Industrialization Plan, which states an expected fleet average target of 6.9L/100km by 2015 5.0L/100km by 2020 under Phase 4 standards, which start to be phased in on 2016 and from 2020 100% cars have to be assessed. In March 2013, five government departments issued the Corporate Average Fuel Efficiency Accounting Method for Passenger Cars, which confirm the expected fleet fuel consumption targets.

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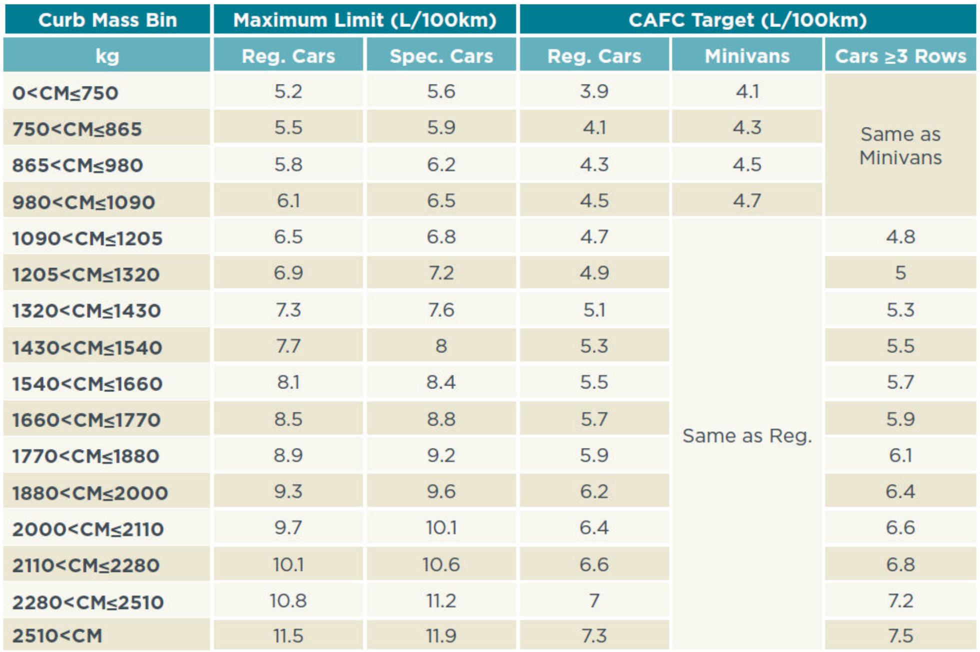
[3] Phase-in refers to the process of smooth introduction of new limits. In china regulations when a new limit is set, the percentage of cars which have to be considered for the CAFC calculations raises from the starting year to the last year in which the whole fleet have to be considered. This way, only the most efficient cars may be accounted during the first years. This is an actual flexibility, as credit banking and trading which is also used in US CAFE and GHG regulations.

The Phase 4 CAFC proposal is based on the same 16 vehicle curb weight classes defined in the Phase 3 standard. The numerical target for each bin is lowered between 25% and 37% from Phase 3, with greater reductions for the heavier weight bins. The CAFC standard also sets separate targets for regular vehicles and two types of special-feature vehicles, which in this case are defined as: vehicles of curb mass less than or equal to 1,090 kilograms with three or more rows of seats; all other vehicles with three or more rows of seats. The first specialty car type mainly refers to a type of mini-sized cargo van unique to China that is usually built on a mini-car platform. The market for these vehicles is mainly lower-income individual consumers or small-business owners in suburban or rural areas. The second refers to small vans, large SUVs and multi-purpose cross-style vehicles generally. Fuel consumption targets for each curb mass bin for the two special-feature vehicle types are 5% and 3% higher, respectively, than those for regular cars. Fuel consumption in l/100 km is calculated from the emissions of HC, CO and CO_2 measured over the combined European Drive cycle (NEDC), as in Europe (20).



Curb Mass Bin	Maximum Limit (L/100km)		CAFC Target (L/100km)		
kg	Reg. Cars	Spec. Cars	Reg. Cars	Minivans	Cars ≥3 Rows
0<CM≤750	5.2	5.6	3.9	4.1	Same as Minivans
750<CM≤865	5.5	5.9	4.1	4.3	
865<CM≤980	5.8	6.2	4.3	4.5	
980<CM≤1090	6.1	6.5	4.5	4.7	
1090<CM≤1205	6.5	6.8	4.7	Same as Reg.	4.8
1205<CM≤1320	6.9	7.2	4.9		5
1320<CM≤1430	7.3	7.6	5.1		5.3
1430<CM≤1540	7.7	8	5.3		5.5
1540<CM≤1660	8.1	8.4	5.5		5.7
1660<CM≤1770	8.5	8.8	5.7		5.9
1770<CM≤1880	8.9	9.2	5.9		6.1
1880<CM≤2000	9.3	9.6	6.2		6.4
2000<CM≤2110	9.7	10.1	6.4		6.6
2110<CM≤2280	10.1	10.6	6.6		6.8
2280<CM≤2510	10.8	11.2	7		7.2
2510<CM	11.5	11.9	7.3		7.5

Figure 2-13 Chinese regulations phase 4 FC limits for individual cars (left) and fleet average (right) according to weight bin. **(20)**

The proposed Phase 4 standard provides three types of credits: for new-energy vehicles battery-electric, fuel cell and plug-in hybrids); for other ultra-low fuel consumption vehicles, i.e., those with fuel consumption less than or equal to 2.8L/100km on the combined urban and extra-urban cycle; and for vehicles equipped with innovative technologies leading to real-world fuel saving (so-called off-cycle technology credits).

New energy vehicles are counted as multiple vehicles towards manufacturers' CAFC calculation for compliance. The multiplier is set at 5 in 2016–2017, falling to 3 in 2018–2019, and then to 2 in 2020. For the CAFC calculation, the energy consumption of battery-electric vehicles, the electric-drive part of plug-in hybrid vehicles and fuel cell vehicles are counted as zero. Other ultra-low fuel consumption vehicles with combined fuel consumption no more than 2.8L/100km will be counted as 3 vehicles in 2016–2017, 2.5 in 2018–2019, and 1.5 in 2020.

The proposed Phase 4 standard offers compliance credits to manufacturers that install innovative technologies with justifiable real-world fuel saving on their vehicles. Currently the regulatory agency is considering four types of technologies eligible for the credits: tire pressure monitoring system; high-efficiency air-conditioning system; start-stop system; and transmission gear shift reminder. Manufacturers that install one or more of these technologies with demonstrated fuel-saving are eligible for up to 0.5 L/100km credit towards their CAFC standard compliance.

The Phase 4 standard proposal did not specify whether a manufacturer can bank compliance credits and carry over the credits to future years. However, the *Passenger Car Corporate-Average Fuel Consumption Accounting Method* released in March 2013 (to guide the Phase 3 standard CAFC implementation) allows manufacturers to over-comply and carry forward the credits for future compliance for up to three years. It is possible that this rule also applies to the Phase 4 standard implementation (20).

2.6 Brazil regulations

In October/2012, the Brazilian government approved by decree a new program to encourage vehicle technology innovation called Inovar-Auto. Inovar-Auto fosters industry competitiveness and provides incentives like this: It first increases a tax on industrialized products (IPI) by 30% for all light-duty vehicles (LDVs) and light commercial vehicles and it imposes a series of requirements for automakers to qualify for up to 30% discount in the IPI. In other words, IPI taxes will remain unchanged for those manufacturers that meet the requirements. The requirements include automakers to produce more efficient, safer, and technology-advanced vehicles while investing in the national automotive industry thus incentivizing investments in vehicle efficiency, national production, R&D, and automotive technology.

The program is limited to vehicles manufactured between 2013 and 2017, after which IPI rates return to pre-2013 levels unless modifications to the decree are made. Because automakers must meet a minimum corporate average vehicle efficiency target to qualify for the 30% discount on IPI taxes, Inovar-Auto will likely result in efficiency improvements of new LDVs of at least 12% between 2012 and 2017, assuming that the program is well implemented, enforcement and compliance is effective (i.e., penalties for non-compliance are high enough to encourage automakers to meet efficiency targets), and there are no loopholes. Automakers can also qualify for an additional 2% discount on IPI taxes by meeting more aggressive efficiency targets (up to 19% improvement over 2012 levels).

This target was based on Europe’s 2015 target for new LDVs of 130 gCO_2/km, and adapted to Brazil based on differences in driving cycle, vehicle, fuel, and road specifications. Average vehicle efficiency, in megajoules/kilometers (MJ/km) and measured on the combined (urban/highway) CAFE cycle, needs to be calculated by Equation 2-4. To qualify for an additional IPI reduction of 1% and 2%, automakers need to meet average vehicle efficiency calculated by Equations 2-5 and 2-6 by October/2016, which would result in average improvements in new vehicle efficiency of about 16% and 19%, respectively. (21)

$$\boldsymbol{VE = 1{,}155 + 0.000593 \cdot M} \qquad \text{Equation 2-4}$$

$$\boldsymbol{VE = 1{,}111 + 0.000570 \cdot M} \qquad \text{Equation 2-5}$$

$$\boldsymbol{VE = 1,067 + 0.000547 \cdot M} \qquad \text{Equation 2-6}$$

VE: Corporate average vehicle efficiency (MJ/km).
M: Average mass in kilograms (curb weight) for all vehicles commercialized in Brazil, and weighted by vehicle sales in the 12 months preceding the calculation.

Notice that in Brazil the limits are provided by the vehicle general efficiency in terms of energy per unit of distance travelled and not to actual emissions or FE. Therefore, it is clear that high efficiency engines is the target while at the same time Brazilian market asks for engines compatible with many types of fuels and blends. FFVs in Brazil accounted for 87% of the sales and E22 and Diesel for the remaining 13% on equal parts in 2013 approx. No pure gasoline cars are commercialized in Brazil. Efficient FFVs are a challenge since maximum efficiency in all conditions is costly to achieve (22) (23).

Automakers must comply with Brazil's Vehicle Labeling Scheme (PBEV – Programa Brasileiro de Etiquetagem Veicular).

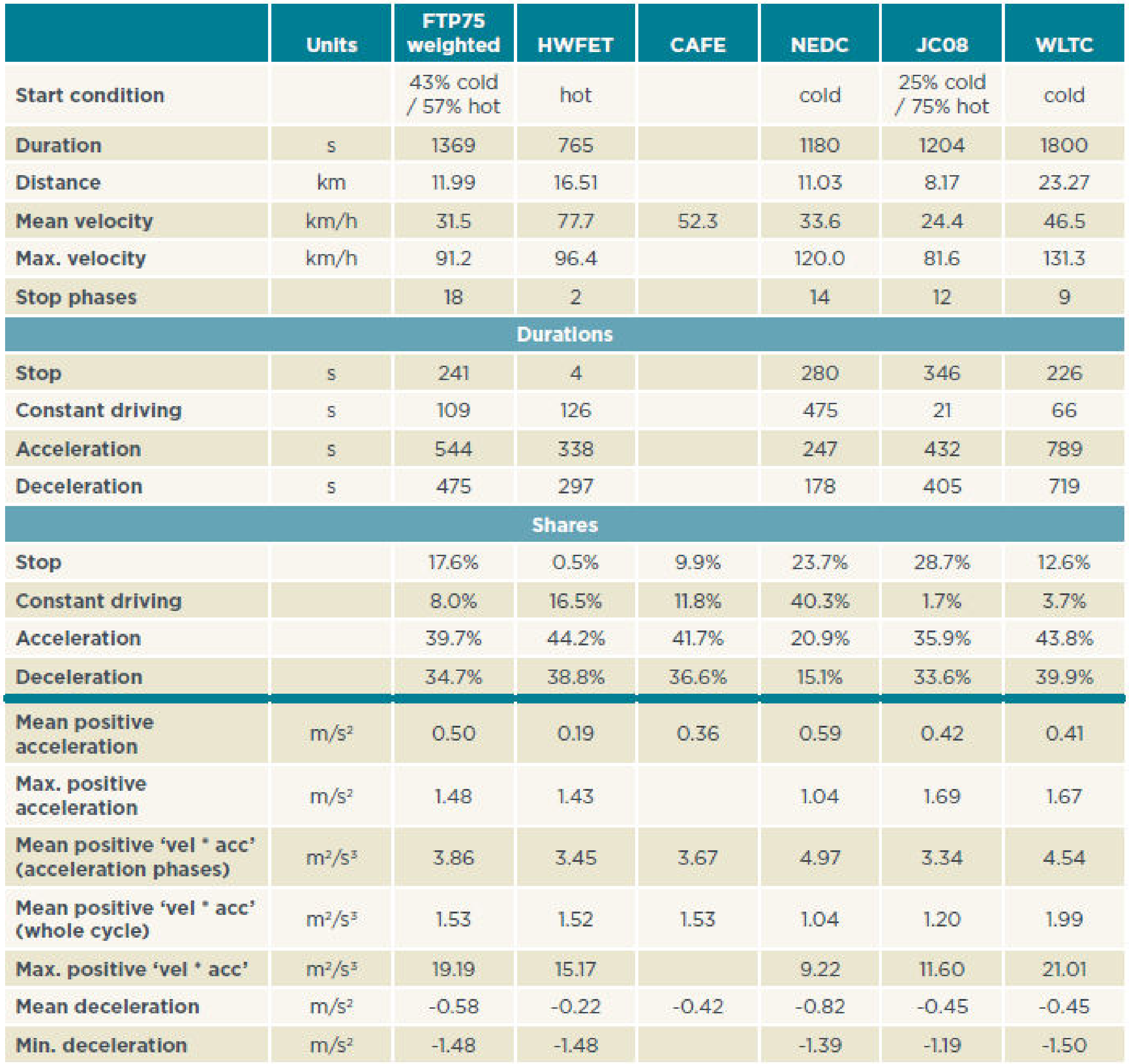
2.7 World regulations comparison

It has been showed that there are many regulations around the world. Fuel consumption, fuel economy and carbon dioxide (CO_2) emission standard are implemented worldwide and they are quite differently approached. The stringencies of the different regional standards and values measured under different boundary conditions are not directly comparable. While the unit conversion is clearly defined and straightforward (*e.g.,* from miles per gallon to gCO_2 per km), the different testing conditions, flexibilities and limits raise high uncertainties within the conversion process between different standards.

This issue has consequences of major concern for the automobile manufacturers due to the fact that low FC technologies may involve different reductions in terms of CO_2 emissions depending on the test procedure applied and the entire regulation. Thus, it generates confusion within manufacturers about how to approach the best trade-off to meet all the regulations with the most reduced cost and still offer good value to the customer.

The ICCT (24) have generated conversion factors package-based to face this issue. In the Table 2-2, many descriptive parameters of the main cycles are given including start conditions, durations, distances, mean velocities and accelerations. Nevertheless, differences on other regulation procedures and flexibilities are not given here.

Table 2-2 Descriptive parameters of the driving cycles City, Highway, combined, NEDC, JC8 and WLTC **(24)**

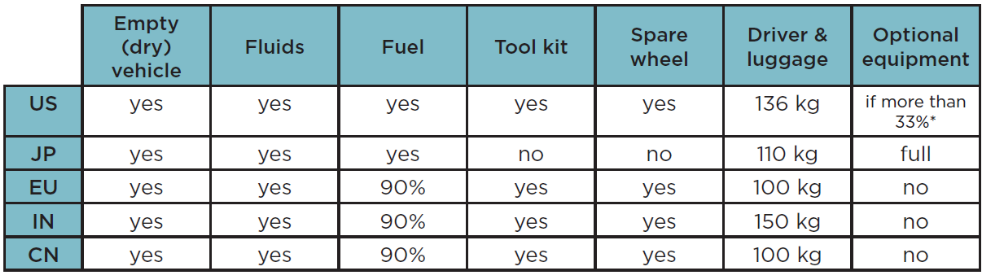


	Units	FTP75 weighted	HWFET	CAFE	NEDC	JC08	WLTC
Start condition		43% cold / 57% hot	hot		cold	25% cold / 75% hot	cold
Duration	s	1369	765		1180	1204	1800
Distance	km	11.99	16.51		11.03	8.17	23.27
Mean velocity	km/h	31.5	77.7	52.3	33.6	24.4	46.5
Max. velocity	km/h	91.2	96.4		120.0	81.6	131.3
Stop phases		18	2		14	12	9
Durations							
Stop	s	241	4		280	346	226
Constant driving	s	109	126		475	21	66
Acceleration	s	544	338		247	432	789
Deceleration	s	475	297		178	405	719
Shares							
Stop		17.6%	0.5%	9.9%	23.7%	28.7%	12.6%
Constant driving		8.0%	16.5%	11.8%	40.3%	1.7%	3.7%
Acceleration		39.7%	44.2%	41.7%	20.9%	35.9%	43.8%
Deceleration		34.7%	38.8%	36.6%	15.1%	33.6%	39.9%
Mean positive acceleration	m/s^2	0.50	0.19	0.36	0.59	0.42	0.41
Max. positive acceleration	m/s^2	1.48	1.43		1.04	1.69	1.67
Mean positive 'vel * acc' (acceleration phases)	m^2/s^3	3.86	3.45	3.67	4.97	3.34	4.54
Mean positive 'vel * acc' (whole cycle)	m^2/s^3	1.53	1.52	1.53	1.04	1.20	1.99
Max. positive 'vel * acc'	m^2/s^3	19.19	15.17		9.22	11.60	21.01
Mean deceleration	m/s^2	-0.58	-0.22	-0.42	-0.82	-0.45	-0.45
Min. deceleration	m/s^2	-1.48	-1.48		-1.39	-1.19	-1.50

There are significant differences among the relevant cycles regarding the resulting vehicle and engine loads. However it is quite difficult to get conclusions by comparing these values. Probably a cycle with higher accelerations will involve higher sensitivity to mass reduction technologies and a cycle with longer share of stop periods of time will be promoted by S&S technology, in addition, a vehicle with warm up technologies or a leaner engine cold starting will give higher improvements for cold start cycles than for hot or cold/hot weighted start cycles.

Adding that many other parameters as inertia class, climatic conditions, fuels used in the tests, reference mass… differ among regulations it definitely is a big challenge. The differences may even be greater when talking about hybrid vehicles, flex fuel vehicles and so on because regulations define specific procedures to perform tests that are absolutely different. However they all are performed with the aim of trying to forecast real world emissions.

Table 2-3 Reference mass definitions for US, Japan, EU, India and China **(24)**



	Empty (dry) vehicle	Fluids	Fuel	Tool kit	Spare wheel	Driver & luggage	Optional equipment
US	yes	yes	yes	yes	yes	136 kg	if more than 33%*
JP	yes	yes	yes	no	no	110 kg	full
EU	yes	yes	90%	yes	yes	100 kg	no
IN	yes	yes	90%	yes	yes	150 kg	no
CN	yes	yes	90%	yes	yes	100 kg	no

The Table 2-3 shows how reference mass may change depending on the region and so emissions would shift even if the test driving cycle was the same. As seen, the reference mass is not exactly the curb weight but rather curb weight plus driver weight. However, by mistake sometimes it is called as curb/kerb/unladed weight. Furthermore, the Figure 2-14 shows the diverse weight inertia class depending on the reference mass.

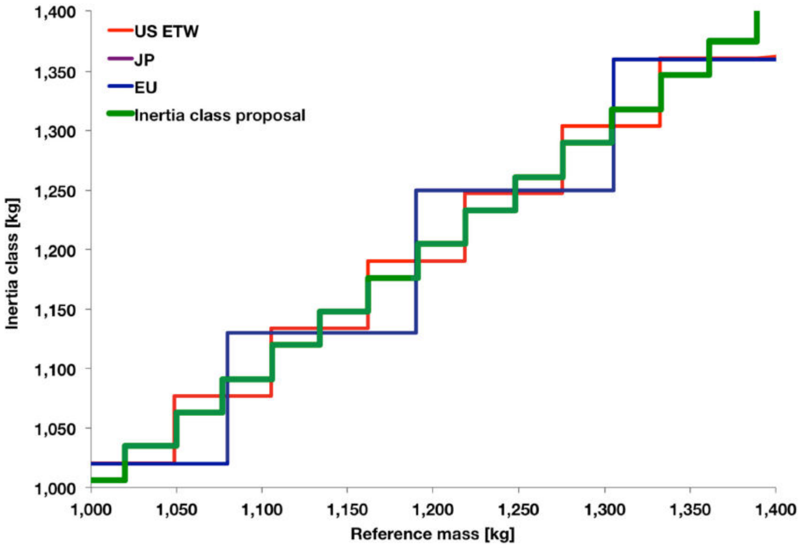


Figure 2-14 Weight class for US, JP and EU regulations. Green line is the proposal for the new WLTP procedure **(25)**.

The Figure 2-15 shows the main weight-based regulations limits. All of them converted to gasoline equivalent.

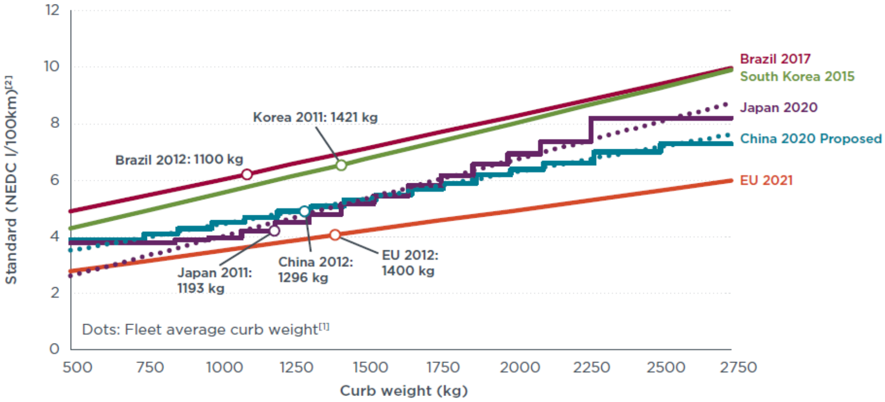


Figure 2-15 Vehicle weight-based equivalent FC limit for specific years and fleet-average vehicle curb mass across regions **(24)**

Note how manufacturers have to make efforts to maintain its vehicles in the step weight bin for Japan and China regulations, similarly to what happens regarding the inertia weight classes. It shows as well the average curb weight of the regional fleets on 2011 or 2012. Note how generally speaking EU limits are more stringent especially for higher curb weights. In Brazil most of the cars are FFV, which make them in general less efficient and therefore, even though the limit seems to be far less stringent than European one, it is not that much. However, the higher FC limits more than outweighs the smaller efficiency. In the case of CAFE regulations, the comparison is not as simple since limits are footprint based.

The ICCT have developed test cycle conversion factors among worldwide light-duty vehicle CO_2 emission standards. By using Data Visualization Tool from Ricardo (see chapter 1.4) they have compared the dynamics of the most important driving cycles and their impacts on fuel consumption and CO_2 emissions to produce an updated set of conversion factors for translating distance-based CO_2 emissions among the different driving cycles. The result is a number of equations package-based (used to create the model of this Thesis, see chapter 3.7.4.3) from which by assuming many hypothesis they have created the figure:

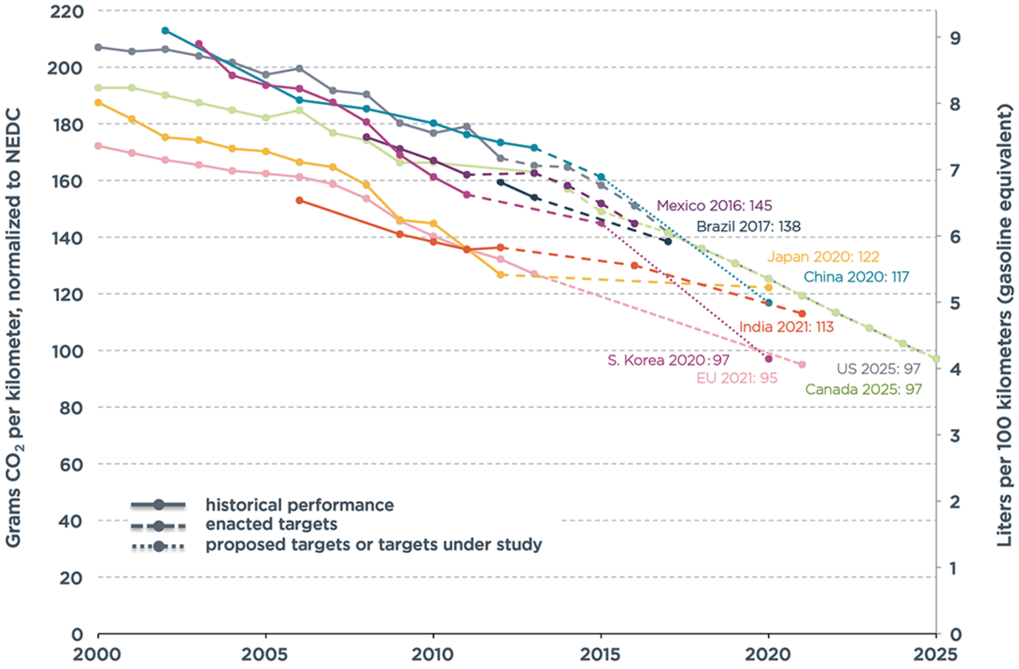


Figure 2-16 Time evolution of the most important CO_2 emissions/FC limits normalized to NEDC **(24)**

If someone assumes that if a car/fleet meets EU target it will automatically meet the rest of the limits he/she is wrong because the plot shows an average value and does not take into account mass and footprint based limits besides of many other hypotheses which do not take into account flexibilities and other items. Some of them are commented as follows. Notice as well that only the big dots indicate real limits where the lines that link them are just guideline values. So for example the limits for EU on MY in between 2015 and 2020 are not indicated.

In US, the average mass of the vehicle fleet was 1821kg in 2013 while 1400kg (23% less) in EU the year 2012 (26) (25). It is quite obvious then that the normalized target should be quite higher in US. By using the Equation 2-2 and Equation 2-3. The limit in EU if the average mass of the cars were the same than in US, will be: For the MY 2019, 149.6g/km and for the MY 2021, 109,3g/km. Far from the 130g/km and 95g/km.

Therefore, we can conclude that generally speaking, for the MY 2019 US regulations are more stringent than UE (a difference of about 15g/km). However, for the MY 2021 in which EU regulation makes a big step, US regulation becomes some 10g/km less stringent than EU. Particularly as a real example, a given car "model x" [4] that did comply with EU regulations was on risk of not being compliant with USA ones (16).

As a conclusion, case per case study has to be done since every type of car/fuel is assessed in unlike way and of course CAFE MPG-Footprint limits and NEDC CO_2-weight limits are not at all comparable.

Before, the regression equations developed by ICCT have been introduced. Furthermore, in the chapter 3.7.4.3 a detailed explanation of them and how to use them is given. The chapter 2.7.1 has been created with the purpose of comparing real CO_2 emissions in US and European regulations and verify the utility of the conversion regression equations.

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[4] Confidential information

2.7.1 Real case study – verify conversion equations

It may be interesting to compare real CO_2 measured over CAFE program and over the NEDC program. Of course, by comparing vehicles that has been marketed with the same characteristics *i.e.* same engine, in order to make an apples to apples comparison. This exercise has as a main purpose to validate the utility of the regressions equations used on the model of this Thesis to calculate CAFE FE from NEDC emissions and vice versa. Furthermore, the data on CAFE MPG and NEDC CO_2 will be plotted and compared.

To this purpose, CO_2 data of representative vehicles has been gathered. Unfortunately, to gather such data is not a straight process, nor the results will be accurate: First, most of the marketed vehicles with same body in US and EU, feature diverse engines, *i.e.* usually more powerful and less turbocharged engines are marketed in US, consistent with US customer preferences. Secondly, no data on CAFE FE or CO_2 emissions has been found because only data according to EPA Label FE regulations is available on public sources. Furthermore, not a negligible share of the vehicles marketed are FFVs which are addressed quite differently and that cannot be easily assessed only with the data found in public sources. Finally, even NEDC emissions found on public domain may be different from the actual CO_2 emissions since flexibilities allow homologate cars with a shift of up to 4% gap to the real emissions measured in the TA test (see chapter 2.4.3) plus other flexibilities and loopholes. However, some models have been compared and the regression equations have been used in order to check their utility unfortunately only in a rough way due to the just mentioned issues.

Thus, EPA Label FE data has been converted to CAFE FE in an approximatively way (14) and then converted to CO_2 emissions. According to EPA, Label MPG values are, in average about 20-25% lower than CAFE MPG values. Therefore and adjustment factor of 22,5% will be taken as a conversion.

The Figure 2-17 shows emissions of some car models that have been sold with same engines in Europe and US during the year 2014.

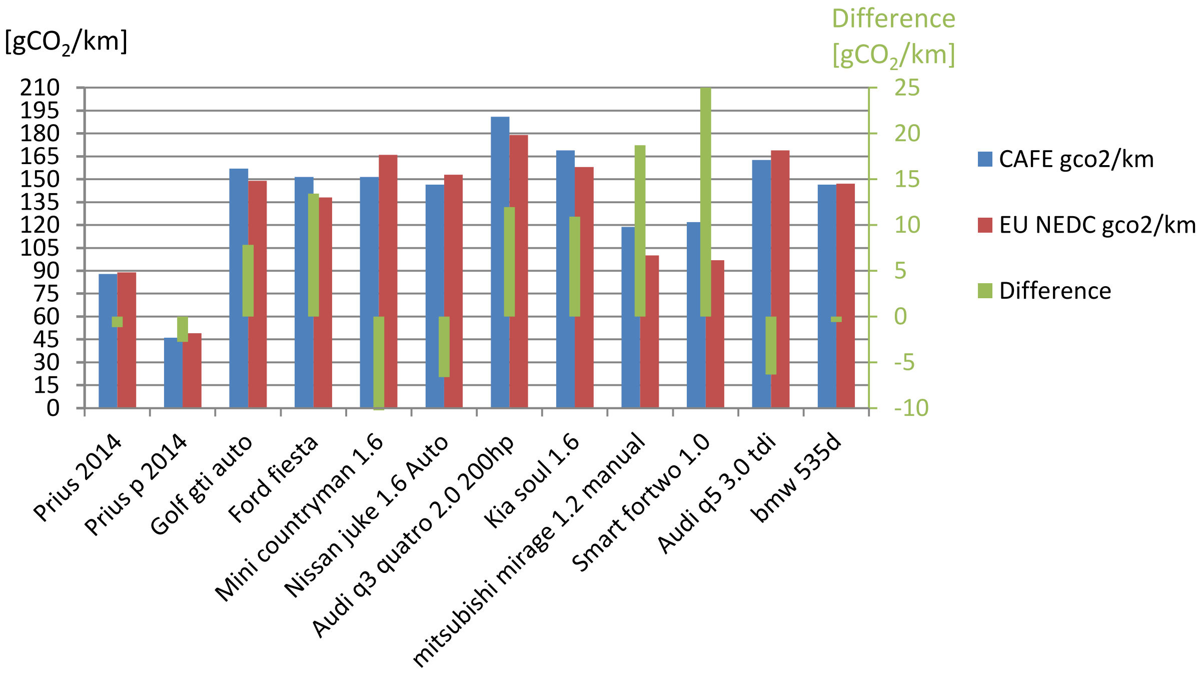

Figure 2-17 CAFE CO_2 emissions estimated from Label FE and NEDC homologated CO_2 emissions. Difference between them. **(27)** **(28)**.

The difference calculated in the Figure 2-17 seems to not follow a clear pattern since sometimes CAFE emissions are greater than NEDC and vice versa.

The Figure 2-18 shows the estimated CAFE emissions calculated from the NEDC emissions and compare it to the "real" CAFE CO_2 emissions shown in the Figure 2-16. The same procedure in the other way around is done and results are showed as well. The error is plotted.

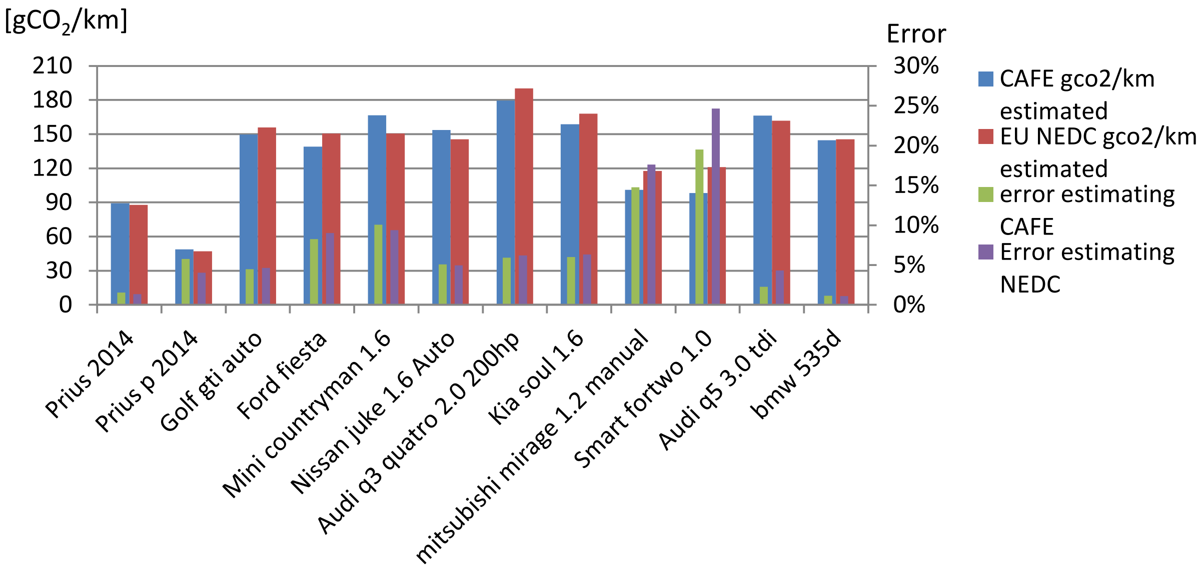

Figure 2-18 CAFE emissions estimated from NEDC and vice versa, by using the regression equations **(24)**. Different regressions equations according to the type of vehicle have been used. **(27)** **(28)**

Note how the error in absolute terms is quite high. On average 7-8% of error, which is far from the estimates of ICCT (24). See how error peaks for small cars as Mitsubishi mirage and Smart.

The target emissions and target MPG are plotted in the Figure 2-19 and the Figure 2-20 along with the data relating to each car. Again, CAFE MPG has been calculated from Label FE while NEDC CO$_2$ is the homologated one.

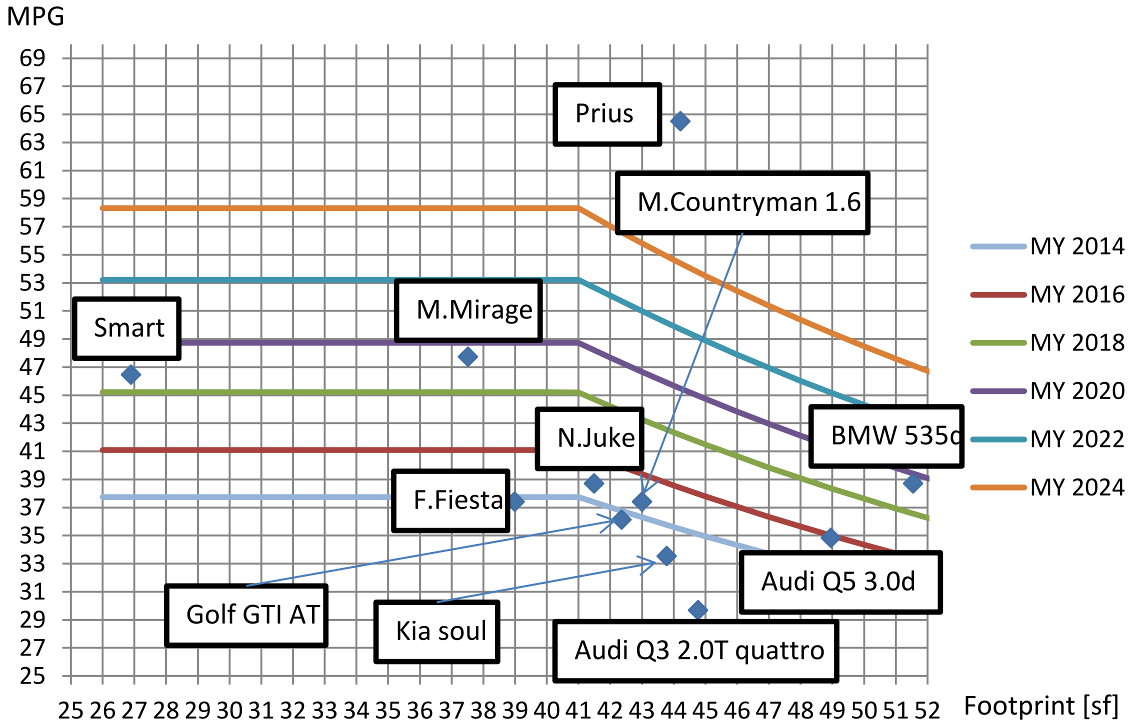

Figure 2-19 CAFE targets for MY 2014-2024 and FE examples of passenger cars. **(27)** **(28)** and Automobile manufacturer's website. Only limits every two years are plotted.

Notice that for very small cars, the limit curve becomes flat and so more relaxed in some way. Thus, Automobile manufacturers can produce smaller and lighter cars without having to improve MPG and therefore, with the possibility of removing some other less cost effective low FC technologies.

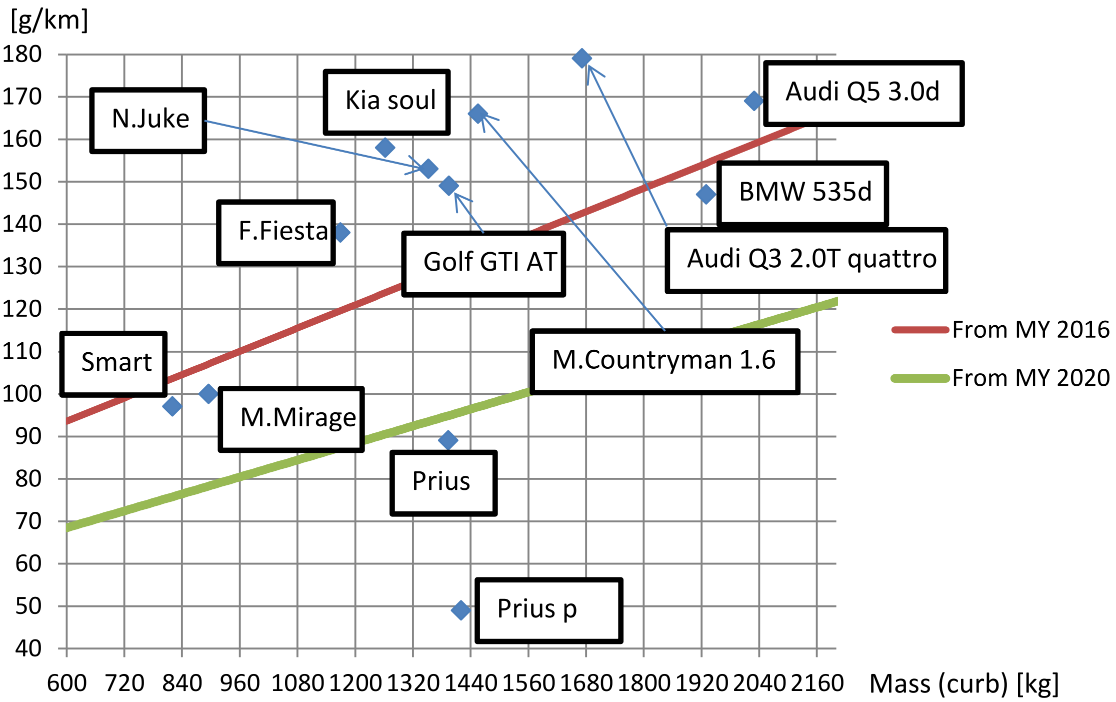

Figure 2-20 EU targets from MY 2016 to MY 2024 and emissions examples of passenger cars. **(27) (28)** and Automobile manufacturer's website.

The lines in the Figure 2-20 may change slightly every three years since $\boldsymbol{m_0}$ is readjusted. For MY 2015 the limit is as well the brown line with $\boldsymbol{m_0}$ of the previous three years.

2.7.1.1 Conclusions

The fact that data on CAFE CO_2 emissions could not be used and the "declared CO_2" flexibility along with other flexibilities, leads to a results of quite a high error. Giving an error of 7-8% on average for the estimation of CAFE CO_2 from NEDC and vice versa.

There are basically two sources of error in the estimation of CAFE CO_2 from Label FE. On one hand, as already pointed out, the fact that Label FE is about 20-25% lower than CAFE FE but the exact value is unknown. On the other hand, Label FE is given without decimals, either city FE, highway FE or the combined FE. Therefore, as an example a two different cars with 28MPG of city FE and 32MPG and 34 MPG of highway FE will have both a combined fuel efficiency of

30MPG while if decimals were considered it would be 30,4MPG and 29,6MPG of combined FE. In this case, the error introduced is around 3%.

Consequently no clear conclusion on the usability of the regression equations has been found. Nevertheless, the high error values for low emissions cars (Smart and Mitsubishi mirage) relatively to other models arise great suspicious on the validity of such regression equations when talking about very small cars as Segment A. Fortunately, the reference car is not a Segment A vehicle.

Even though, the regression equations made by ICCT (24) using simulation methods will be used on this work, as a gesture of trust in such an important agency.

Concerning the Figure 2-19 and the Figure 2-20, we can see how in general EU regulations are more stringent than CAFE regulations. However only Toyota Prius (2014) is compliant for MY 2020 with both regulations. See how in EU, limits are defined every five years while in US every year the limit is raised. Notice that the shape of the curve limits is so that mass reduction technologies and vehicle dimensions reduction is not an actual way to encourage compliance in general unless in the case of very small cars, where the CAFE curve becomes flat and so easier to meet. Note how the models Smart, Mirage and BMW 535d are the only ones who meet EU regulations from 2016 to 2019. Nevertheless it should be bear in mind that both regulations asses compliance as a fleet average and that the cars showed are MY2014 while enacted limits showed up to MY2024 limit. Therefore, it is clear that automobile manufacturer's will have to make a huge effort on FE policies to lower the average emissions.

3. Model calculation for the reference cars – Package model

3.1 Introduction

Only about 14%–30% of the energy from the fuel put in a conventional vehicle is used to move it down the road, depending on the drive cycle. The rest of the energy is lost to engine and driveline inefficiencies or used to power accessories. Therefore, the potential to improve fuel efficiency with advanced technologies is enormous. The Figure 4-1 shows how the energy content of a fuel is wasted along the vehicle systems in the US combined cycle.

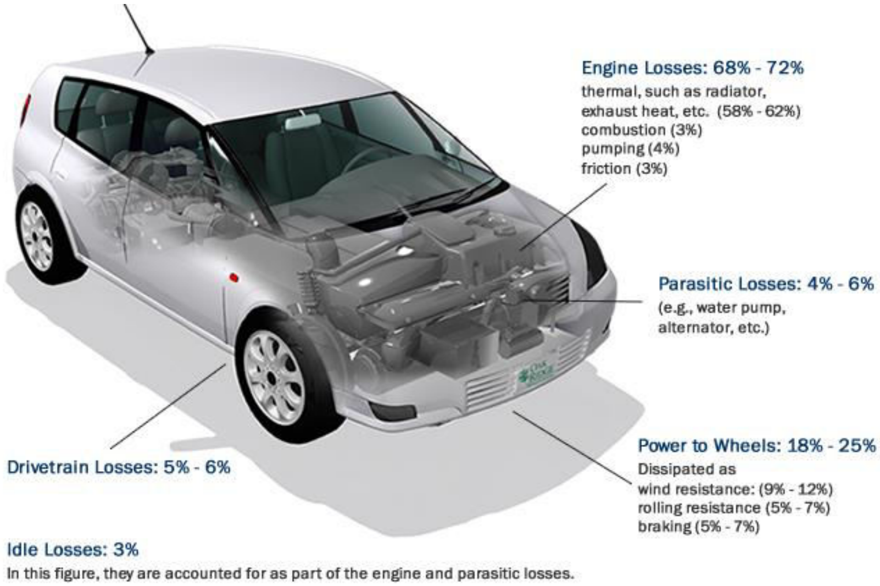

Figure 3-1 Energy requirements for Combined city/highway driving cycle **(29)**

Automobile manufacturers have to work hard to reduce such sources of losses in order to be compliant with regulations and still give value to the customer with the final aim of gain the maximum profit/revenue. The “package model” introduced in the section 3.2 will approach such challenge.

3.2 Algorithm fundamentals

It is known that many technologies can be applied to a given car in order to meet the CO_2 targets. Each one of these technologies has an incremental cost and a potential CO_2 reduction, which may change depending on other technologies already applied to the car, the type of car, and the year at which it is build.

The main target of this calculation is to find the best package of low CO_2 technologies that a given car needs in order to be compliant with its target CO_2 emissions for the MY 2018-2024. In detail, it is to find the best package of technologies according to three different criteria:

- Cheapest compliant package
- Most cost effective compliant package and lastly
- Most profitable compliant package in EU, USA or both regions at the same time (same car)

From the beginning it was clear that data about low fuel consumption technologies would be one of the most relevant pillars of this work. Therefore one of the main tasks has been to gather reliable data which could be useful to develop the model. The major amount of data, its definitions and its hypothesis have been taken from papers belonging to NHTSA (10) (30) (31). The way in which the problem is solved is strictly related to the characteristics of the data used and particularly to the hypothesis on which data values are based.

At a first glance, it may seem that the data found are just low CO_2 emissions technologies and its main characteristics: Cost of technology; CO_2 emissions reduction linked to the technology. However it is not only these two concepts which are well illustrated in Figure 3-6 to Figure 3-16. It has to be added the concepts of technology applicability and the synergies, which are quite complex. They are explained in detail in the chapters 3.2.1 to 3.2.3.

3.2.1 Applicability of a technology

The applicability of a technology means that a given technology may be conditioned by several factors such as:

- Other technologies: Thus, a specific technology may not be applicable to a given package if other technology (or group of technologies) does not belong to that package. For example: Start & Stop S&S cannot be applied if there is no Electric Power Steering EPS because when the engine turs off, the steering system would not work properly.
- The architecture of the car: Thus a given technology or a group of technologies may not be applicable if the architecture of the vehicle does not allow to. For example, Cylinder deactivation may only be applicable when the number of cylinders is higher than 4. Another quite simple but clear example may be that a MT car cannot be equipped with a shift optimizer.

  Besides, it may be possible that the reference car at which technologies are being applied in the model run, is already equipped by some low CO_2 emissions technologies (which cannot be applied twice, of course).

  Furthermore, there are different data values of a particular technology depending on the architecture of the reference car and engine. Small cars, midsize cars…small engines, midsize engines… All of them have different values for a given technology. Concerning this last point, only midsize cars data and small engines data has been used. Such choice is coherent with the reference body with four cylinders engine.
- Applicability worthiness: It means that according to the hypothesis of EPA, there is a sorting in the applicability of technologies. In the sense that first, the most cost effective technologies should be applied and later, the following ones that are less cost effective. The data is based on this idea and if not followed, the results worsen. For example, it is not worth to apply a second level of aerodynamic improvements if the first level is not applied. So first, AI Level1 is applied and secondly, AI Level2 and CO_2 reduction and costs are added.

The costs and the CO_2 reductions are well approximated if these rules are followed. Otherwise the accuracy worsens.

The Figure 4-2 shows in a comprehensive (but not exhaustive way) the applicability path (or sequence) for every car system. In order to see better how this system works, in the spreadsheets in the annexes, the row “incremental to” explain which is the precedent technology that must be in the package to be able to apply a given technology. To make it clear with an example: The fact that Low Friction Lubricants (LUB1) is in the beginning of the engine path does not mean that any other technology cannot be included in the package if LUB1 is not included. It simply means that LUB1 is the most cost effective and therefore the one that give the best ratio cost/FC reduction on this path. Furthermore LUB1 may be applied or not in whatever package because its applicability doesn’t depend on other technologies. However it doesn’t mind that the resultant cheapest compliant package will include the most cost effective technologies (as LUB1) because the model run will stop adding technologies when the compliance limit is surpassed.

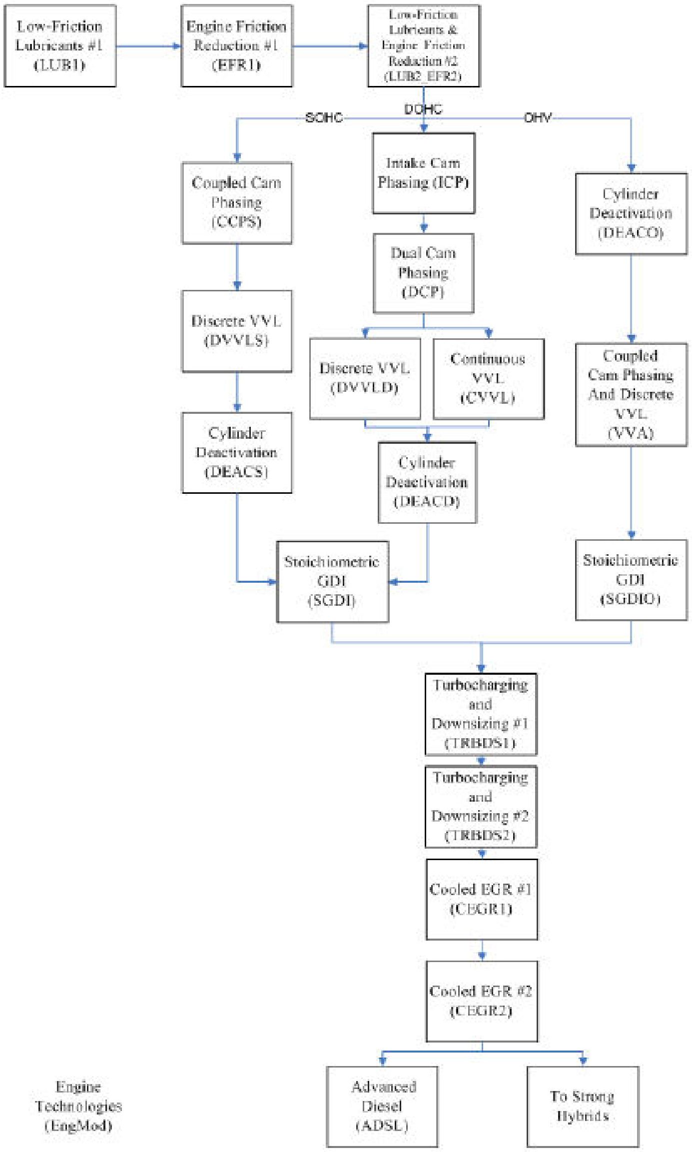

Figure 3-2 Engine technologies applicability path **(30)**

As depicted in the Figure 3-2, the paths splits in several branches depending on the engine architecture which have led to different technologies applicable to the two reference engines studied in this Thesis. Furthermore, bear in mind that the reference engines already use some of the technologies in the tree which means that they cannot be accounted. So they are skipped (just partially) because they may introduce synergies with new technologies.

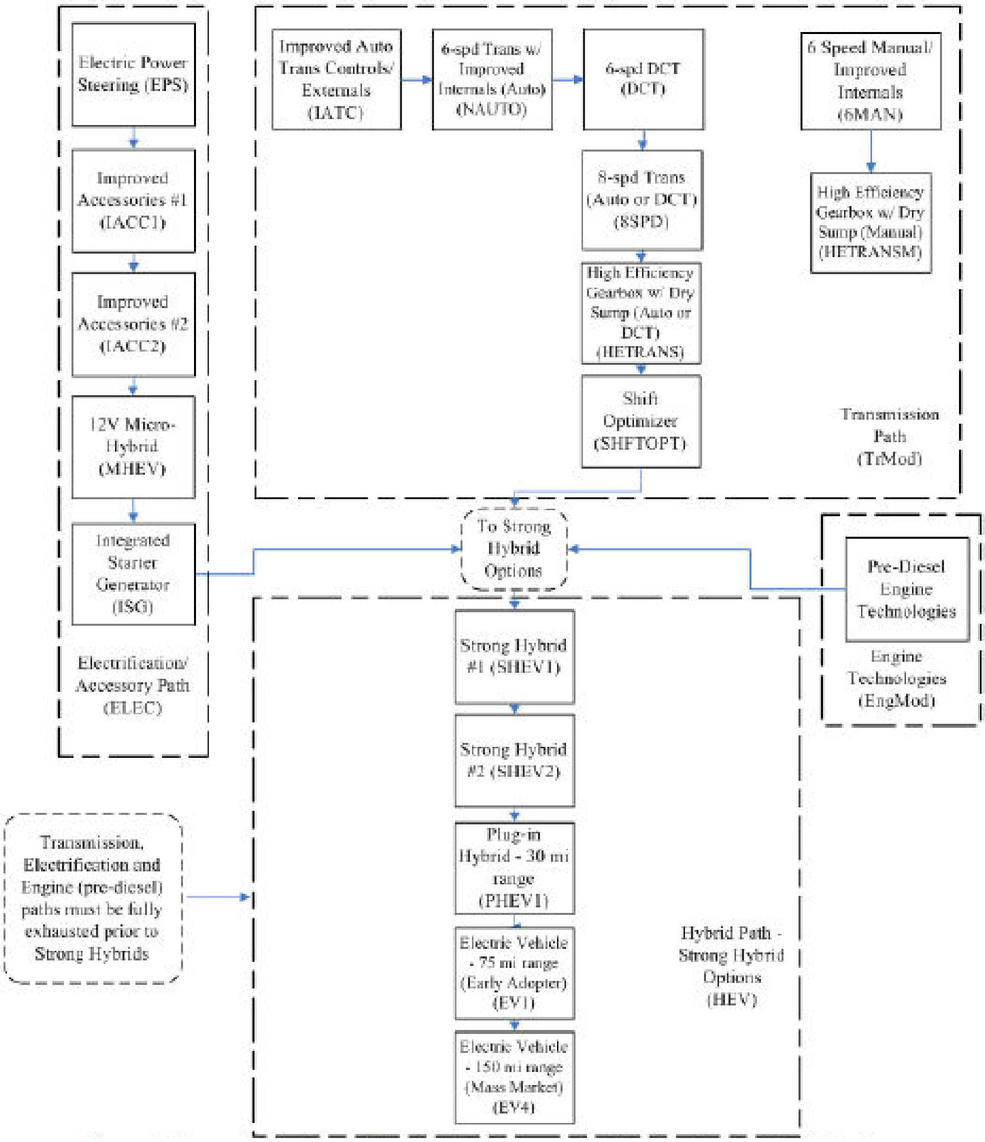

Figure 3-3 Light and strong electrification applicability paths and transmission applicability path **(30)**

In the Figure 3-3 many paths are showed, note that transmission paths split in two types of transmission MT or AT. Note how Strong Hybrid packages are only possible if other technologies belonging to other paths are already considered in the package.

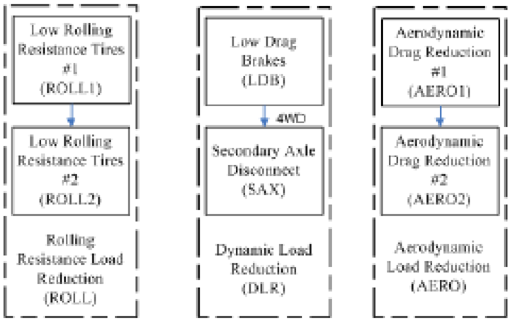

Figure 3-4 Rolling resistance, driveline resistance and aerodynamic resistance applicability paths **(30)**

Many weeks were necessary to understand all this issues and be ready to apply them to the model in this Thesis. As me, some other companies showed concerns about how to understand the data and how to use it for engineering purposes. Besides, many companies complained about some optimistic values of FC reduction and cost of the technologies (10). This is because this data was used by NHTSA and EPA to set up the future values of CO_2 and FE limits. Therefore optimistic values would forecast better technologies cost efficiency than actual which is detrimental for companies since the target would worsen.

3.2.2 The technology synergies

The synergies are an adjustment to better approach the results. It is based on adjustments for the cost of the technology and the CO_2 reduction of the technology.

The fact is that cost and the CO_2 emissions reductions of a technology may differ from the reference value depending on circumstances. Therefore, saying that the cost or the CO_2 reduction of a technology is always the same would be a quite rough approximation. To this, NHTSA have included in their models the synergies. And it has been applied as well in this work.
The synergy, as can be imagine thanks to its name, is an adjustment value that takes place when pairs of technologies occurring in a package are susceptible to an adjustment on its cost or CO_2 reduction. *i.e.*:

Adjustment needs to be applied when two different technologies are based in the same CO_2 reduction principle or when a technology shifts the engine working point and therefore it increases or reduces the CO_2 reduction achieved by others technologies. For example, Cylinder deactivation and higher number of gears are two technologies that work partially on the same principle, *i.e.* make the engine work in a higher efficiency point in the BSFC engine map. Therefore, the total CO_2 reduction is not the sum of the partial reductions. The Table 3-1 shows a numeric example and the error introduced by not accounting the synergy on the example:

Table 3-1 Error by not considering FC reduction synergy. Example DEACO vs 8SPD

Percentage of FC reduction					
Cylinder deactivation on OHV DEACO	**8-Speed Trans (Auto or DCT) 8SPD**	**Addition DEACO+8SPD**	**Synergy**	**Adjusted addition DEACO+8SPD -Synergy**	**Error if no adjustment**
5,86%	4,57%	10,43%	-0,70%	9,73%	7,1%

Cost synergy is an adjustment to be applied when two different technologies costs differ from the reference one (*i.e.* just adding both costs). An example may be two different technologies that share some vehicle parts. The cost of these parts should not be counted twice and so an adjustment has to be done.

Synergies are particularly common when technologies belong to different paths because otherwise, since most of the times there is an applicability sequence, the synergy is automatically accounted.

All the data is in the annexes. A detailed explanation of particular values of the synergies cannot be given in this work as there is no more information about that in the public sources. If the reader does not agree with some of the numbers, remember that it has to be understood as a whole and there is no sense in trying to understand a specific value without making an extensive analysis. Most probably, only the persons who created the data could understand properly some of the values.

3.2.3 Other hypotheses and assumptions

The cost of the technologies is independent from the volume of production. It is assumed that the production is large enough to be well approached with the values of cost given by NHTSA (32) (10). However, NHTSA does not explicitly tell the actual supposed volumes. Therefore as a consequence, the model assumes that every studied year (2018, 2020, 2022 and 2024), a new calculation is done without any relation to what the previous results are. This means that every year is assessed separately from any other year. Thus, the model may consider that the year 2020, mass reduction of 20% should be applied while on the year 2022, only 10% mass reduction should be applied to the reference model. Since the car cannot be redesigned every two years but rather every 5 years, the results have to be gathered and a trade-off have to be found according to the company policies. Nevertheless, it doesn't mean that results are wrong because they can be extrapolated for other cars of the fleet and anyway it is useful to see how compliant technology packages vary along the years depending on the regulations stringency, the reference car and the criteria used.

Cost is always assessed as direct cost plus indirect cost. Learning is considered along the years and is one of the reasons why costs lower as time passes. The cost is always measured in 2010 US dollars coherent with the data gathered.

3.3 What's the CO_2 emissions target of the model?

The target in this calculation is to achieve at least a neutral car in the fleet CO_2 emissions (EU) and CAFE (US) average value, which would make the Automobile manufacturer to comply with a value at least equal to the limit value of the regulation more stringent *i.e.* as if the vehicle was the only Automobile manufacturer's sold model. However, on the second study case ("fleet model"), a "real" fleet CO_2 calculation is done.

In order to clarify what just explained the following example is given:

Table 3-2 Accepted or rejected package decision example

Technology package (*i*)	**NEDC limit [g/km]**	**CAFE limit [mpg]**	**Vehicle's NEDC CO_2 value [g/km]**	**Vehicle's CAFE CO_2 value [mpg]**	**Accepted/rejected package**
1	90	40	92	43	Rejected. Non-compliant in EU.
2	90	42	89	45	Accepted. Always compliant
3	90	44	100	45	Rejected. Never compliant.

Only when a package is compliant according to both regulations is evaluated as possible best package. The CAFE limit and the NEDC limit are calculated according to the lookup tables year-footprint (CAFE) and year-mass (NEDC).

3.4 Reference model. Which car and engines have been studied?

The reference model is the car (body and engine) that has been selected to make the analysis. Therefore, is the car at which applicable packages are assessed in order to find the best packages according to the several criteria. The body considered is a Midsize[5] car that is marketed in both US and EU.

For reasons of simplicity, not the whole grid of engines has been considered in the calculations, but only two gasoline engines. The 1.4 NA MT and a 1.3T AT. However, for reasons of confidentiality neither the characteristics of the body nor the characteristics of the engines are exactly the actual ones.

3.5 Technologies description and in-path packages overview

In this chapter a description including some details regarding the model technologies' working principle, pros and cons, important values, synergies with other technologies is given and a general overview of their potential CO_2 reduction and its costs will be showed in a graphical and intuitive way.

All the technologies are showed below but some of them may be applicable to a given reference vehicle or not according to what said in the chapter 3.2.1. Technologies are gathered according to the engine system to which they belong (also called path): Engine, transmission, electrification, mass reduction, aerodynamic improvements, rolling resistance improvements, driveline improvements and other Off-cycle improvements.

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[5] Called like this for confidentially reasons

3.5.1 Engine path

3.5.1.1 Low-friction lubricants (LUB1)

Low viscosity and advanced low friction lubricants oils are nowadays available with improved performance and better lubrication. Low friction lubricants are basic method of reducing fuel consumption in engines. Advanced multi-viscosity engine oils are available today which yield improved performance in a wider temperature band and with better lubricating properties.

These advances are accomplished by changes to the oil base and through changes to lubricant additive packages (*e.g.,* friction modifiers and viscosity improvers). The use of 5W-30 motor oil is now widespread and auto manufacturers are introducing the use of lower viscosity oils, such as 5W-20 and 0W-20, to improve cold flow properties and reduce cold start friction (33). However, in some cases, changes to the crankshaft, connecting rod and main crankshaft bearing designs and/or materials along with the mechanical tolerances of engine components may be required. In all cases, durability testing would be required to ensure that durability is not compromised.

Shifting to lower viscosity and lower friction lubricants can also improve the management of valve train technologies such as cylinder deactivation or variable valve timing (34).

3.5.1.2 Reduction of engine friction losses (EFR1)

In addition to low friction lubricants, manufacturers can also reduce friction and improve fuel consumption by improving the design of engine components and subsystems. It can be achieved through low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, and other improvements in the design of engine components and subsystems that improve engine operation. Approximately 10 percent of the energy consumed by a vehicle is lost to friction, and just over half is due to frictional losses within the engine. Additionally, as computer-aided modelling software continues to improve, more opportunities for evolutionary friction reductions may become available. All reciprocating and rotating components in the engine are potential candidates for friction reduction (30).

It is forecast that additional to the improvements already explained a second level of improvement will be available from MY 2017: EFR2

3.5.1.3 Second level of low-friction lubricants and engine friction reduction (LUB2_EFR2)

As technologies advance between now and 2017-2025, developments are expected enabling lower viscosity and lower friction lubricants and more engine friction reduction technologies to be available (30).

3.5.1.4 Cylinder deactivation (DEACS, DEACD and DEACO)

Deactivates the intake and exhaust valves and prevents fuel injection of some cylinders during light-load operation. The engine runs temporarily as if it were a smaller engine, which substantially reduces pumping losses because throttle is more opened. Cylinder deactivation (DEAC) can improve engine efficiency by disabling or deactivating (usually) half of the cylinders when the load is less than half of the engine's total torque capability.

Cylinder deactivation is achieved by keeping specific cylinder valves closed and stopping fuel flow to the specified cylinder. As a result, the trapped air within the deactivated cylinders is simply compressed and expanded as an air spring, with reduced friction and heat losses.
This technology is never applied in this study since it requires a higher number of cylinders than four, which is the number of cylinders of the reference cars in study. In some years technology advances may lead companies to apply this technology even for a reduced number of cylinders but it is still not really known.

Noise and vibration issues reduce the operating range where cylinder deactivation is allowed, however manufacturers continue exploring vehicle changes that enable increasing the amount of time that cylinder deactivation might be suitable.

Cylinder deactivation has seen a recent resurgence thanks to better valvetrain designs and engine controls. Effectiveness improvements scale roughly with engine displacement-to-vehicle weight ratio: the higher displacement-to-weight vehicles, operating at lower relative loads for normal driving, have the potential to operate in part-cylinder mode more frequently.

The FC improvement depends upon the engine valvetrain configuration. For example, DOHC engines already equipped with DCP and DVVLD achieve little benefit, 0.5 percent for DEACD, from adding cylinder deactivation since the pumping work has already been minimized and internal Exhaust Gas Recirculation (EGR) rates are maximized. However, SOHC engines, which have CCP and DVVLS applied, achieve effectiveness ranging from 2.5 to 3 percent for DEACS. And finally, OHV engines, without VVT or VVL technologies, achieved effectiveness for DEACO ranging from 3.9 to 5.5 percent (30).

3.5.1.5 Variable valve timing (Coupled Cam Phasing on SOHC CCPS, Inlet Cam Phasing ICP and Dual Cam Phasing DCP)

Alters the timing or phase of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control residual gases. Variable valve timing (VVT) encompasses a family of valve-train designs CCPS, ICP, DCP…which lead to different features, performances and costs. Some valve train architectures allow a limited number of possibilities as SOHC which only allows CCPS.

VVT reduces pumping losses when the engine is lightly loaded by controlling valve timing closer to an optimum needed to sustain horsepower and torque. VVT can also improve volumetric efficiency at higher engine speeds and loads. Additionally, VVT can be used to alter (and optimize) the effective compression ratio where it is advantageous for certain engine operating modes (*e.g.*, in the Atkinson Cycle).

VVT has now become a widely adopted technology. Manufacturers are currently using many different types of variable valve timing, which have a variety of different names and methods which are based on a cam phaser to adjust the camshaft angular position relative to the crankshaft position, referred to as “camshaft phasing”. The majority of current cam phaser applications use hydraulically-actuated units, powered by engine oil pressure and managed by a solenoid that controls the oil pressure supplied to the phaser.

The three major types of VVT are, as already pointed out:

- Intake Cam Phasing (ICP): Is the simplest of the cam phasing technologies, can modify the timing of the inlet valves by phasing the intake camshaft while the exhaust valve timing remains fixed.
- Coupled Cam Phasing (CCP): Valvetrains with coupled (or coordinated) cam phasing can modify the timing of both the inlet valves and the exhaust valves an equal amount by phasing the camshaft of a single overhead cam (SOHC) engine or an overhead valve (OHV) engine. For SOHC engines, this requires the addition of a cam phaser on each bank of the engine. For OHV engines, which have only one camshaft to actuate both inlet and exhaust valves, CCP is the only VVT implementation option available and requires only one cam phaser.
- Dual Cam Phasing (DCP): The most flexible VVT design is dual (independent) cam phasing (DCP), where the intake and exhaust valve opening and closing events are controlled independently. This allows the option of controlling valve overlap, which can be used as an internal EGR strategy. At low engine loads, DCP creates a reduction in pumping losses, resulting in improved fuel consumption/reduced CO_2 emissions. Increased internal EGR also results in lower engine-out NO_X emissions. Fuel consumption and CO_2 emissions improvements enabled by DCP are dependent on the residual tolerance of the combustion system. Additional improvements are observed at idle, where low valve overlap could result in improved combustion stability, potentially reducing idle fuel consumption. DCP is only applicable to dual overhead cam (DOHC) engines. (30)

3.5.1.6 Variable valve lift (VVL)

Varying and controlling the amount of cylinder valve lift across and engine operating range provides a potential for further efficiency improvements. By optimizing the valve-lift profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. By moving the throttling losses further downstream of the throttle valve, the heat transfer losses that occur from the throttling process are directed into the fresh charge-air mixture just prior to compression, delaying the onset of knock-limited combustion processes. In addition, variable valve lift control can also be used to induce in-cylinder mixture motion, which improves fuel-air mixing and can result in improved thermodynamic efficiency. Furthermore, it can also potentially reduce overall valve train friction. At the same time, such systems may also incur increased parasitic losses associated with their actuation mechanisms.

A number of manufacturers have already implemented VVL into their fleets. There are two major classifications of variable valve lift, described in the following sections:

3.5.1.7 Discrete variable valve lift (Discrete Variable Valve Lift for SOHC DVVLS Discrete Variable Valve Lift for DOHC DVVLD and Variable Valve Actuation VVA)

Discrete variable valve lift (DVVL) systems allow the selection between two or three discrete cam profiles by means of a hydraulically-actuated mechanical system. These cam profiles consist of a low and a high-lift lobe, and may include an inert or blank lobe to incorporate cylinder deactivation (in the case of a 3-step DVVL system). DVVL is normally applied together with VVT control.

DVVL is also known as Cam Profile Switching (CPS). EPA have revised the effectiveness range of DVVL systems to 2.8 to 3.9 percent above that realized by VVT systems.

VVA is considered as the combination of CCP and DVVL only for OHV.

3.5.1.8 Continuous variable valve lift (CVVL)

Is an electromechanically controlled system in which cam period and phasing is changed as lift height is controlled. This yields a wide range of performance optimization and volumetric efficiency, including enabling the engine to be valve throttled.

BMW has considerable production experience with CVVL systems and has sold port-injected "Valvetronic" engines since 2001.

Variable valve lift gives a further reduction in pumping losses compared to that which can be obtained with cam phase control only, with CVVL providing greater effectiveness than DVVL, since it can be fully optimized for all engine speeds and loads, and is not limited to a two or three step compromise.

There may also be a small reduction in valvetrain friction when operating at low valve lift, resulting in improved low load fuel consumption for cam phase control with variable valve lift as compared to cam phase control only. Most of the fuel economy effectiveness is achieved with variable valve lift on the intake valves only. CVVL is only applicable to double overhead cam (DOHC) engines. (30)

3.5.1.9 Stoichiometric gasoline direct-injection technology (SGDI and SGDIO)

Injects fuel at high pressure directly into the combustion chamber to improve cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency.

Stoichiometric Gasoline Direct Injection (SGDI), or Spark Ignition Direct Injection (SIDI), requires changes to the injector design, an additional high pressure fuel pump, new fuel rails to handle the higher fuel pressures and changes to the cylinder head and piston crown design.

Direct injection of the fuel into the cylinder improves cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency without the onset of combustion knock.

Recent injector design advances, improved electronic engine management systems and the introduction of multiple injection events per cylinder firing cycle promote better mixing of the air and fuel, enhance combustion rates, increase residual exhaust gas tolerance and improve cold start emissions.

SGDI engines achieve higher power density and match well with other technologies, such as boosting and variable valvetrain designs. Several manufacturers are manufacturing vehicles with SGDI engines and many of them have announced plans to significantly increase the number of SGDI engines in their portfolios. NHTSA and EPA reviewed estimates from the Alliance of Automobile Manufactures, which projects 3 percent gains in fuel efficiency and a 7 percent improvement in torque.

The torque increase provides the opportunity to downsize the engine allowing an increase in efficiency of up to a 5.8 percent. Combined with other technologies (*i.e.*, boosting, downsizing, and in some cases, cooled EGR), SGDI can achieve greater reductions in fuel consumption and CO_2 emissions compared to engines of similar power output.

The NHTSA and EPA cost estimates for SGDI take into account the changes required to the engine hardware, engine electronic controls, ancillary and Noise Vibration and Harshness (NVH) mitigation systems. (30)

3.5.1.10 Turbocharging and downsizing (TRBDS1 and TRBDS2)

The specific power of a naturally aspirated engine is primarily limited by the rate at which the engine is able to draw air into the combustion chambers. Boosting increases the available airflow and specific power level, allowing a reduced engine size (and so weight) while maintaining performance. This reduces pumping losses at lighter loads in comparison to a larger engine.

Three levels of boosting are considered (18 bar brake mean effective pressure (BMEP), 24 bar BMEP and 27 bar BMEP) along with three levels of downsizing. 18 bar BMEP is applied with 33 percent downsizing, 24 bar BMEP is applied with 50 percent downsizing, and 27 bar BMEP is applied with 56 percent downsizing and EGR because it is considered that with such pressures, the temperature is so high that there is a need to use EGR to avoid excessive NO_x emissions.

To achieve the same level of torque when downsizing the displacement of an engine by 50 percent, approximately double the manifold absolute pressure (2 bar) is required. Accordingly, with 56 percent downsizing, the manifold absolute pressure range increases up to 2.3 bar. Ricardo states in their 2011 vehicle simulation project report that advanced engines in the 2020–2025 timeframe can be expected to have advanced boosting systems that increase the pressure of the intake charge up to 3 bar.

GDI is a key enabler for modern, highly downsized turbocharged engines, this difference will be overshadowed by the higher effectiveness for turbocharging and downsizing when they are combined into packages.

Specific power levels for a boosted engine often exceed 100 hp/L, compared to average naturally aspirated engine power densities of roughly 70 hp/L. As a result, engines can be downsized roughly 30 percent or higher while maintaining similar peak output levels.

In the last decade, improvements to turbocharger turbine and compressor design have improved their reliability and performance across the entire engine operating range. New variable geometry turbines and ball-bearing center cartridges allow faster turbocharger spool-up (virtually eliminating the once-common “turbo lag”) while maintaining high flow rates for increased boost at high engine speeds. Low speed torque output has been dramatically improved for modern turbocharged engines.

However, due to reduced torque values at low engine speed conditions the potential to downsize engines may be less on vehicles with low displacement to vehicle mass ratios in order to provide adequate acceleration from standstill, particularly up grades or at high altitudes.

Use of GDI systems with turbocharged engines also reduces the fuel octane requirements for knock limited combustion and allows the use of higher compression ratios, because of better charge cooling. Recently published data with advanced spray-guided injection systems and more aggressive engine downsizing targeted towards reduced fuel consumption and CO_2 emissions reductions indicate that the potential for reducing CO_2 emissions for turbocharged, downsized GDI engines may be as much as 15 to 30 percent relative to port-fuel-injected engines. These reported fuel economy benefits show a wide range depending on the SGDI technology employed. (30)

3.5.1.11 Exhaust-gas recirculation boost (CEGR1 and CEGR2)

Increases the exhaust-gas recirculation used in the combustion process to increase thermal efficiency and reduce pumping losses. This technology is only applied to 24 bar and 27 bar BMEP turbocharged engines with GDI in this analysis.

Vehicle simulation modelling of technology packages using the more highly boosted and downsized cooled EGR engines (up to 27-bar BMEP, and utilizing EGR rates of 20-25%) with dual-stage turbocharging has been completed as part of EPA's contract with Ricardo Engineering.

Cooled exhaust gas recirculation or boosted EGR is a combustion concept that involves utilizing EGR as a charge diluent for controlling combustion temperatures and cooling the EGR prior to its introduction to the combustion system.

Higher exhaust gas residual levels at part load conditions reduce pumping losses for increased fuel economy. The additional charge dilution enabled by cooled EGR reduces the incidence of knocking combustion and obviates the need for fuel enrichment at high engine power. This allows for higher boost pressure and/or compression ratio and further reduction in engine displacement and both pumping and friction losses while maintaining performance.

The EGR systems considered use a dual-loop system with both high and low pressure EGR loops and dual EGR coolers. The engines would also use single-stage, variable geometry turbocharging with higher intake boost pressure available across a broader range of engine operation than conventional turbocharged SI engines.

Such a system is estimated to be capable of an additional 3 to 5 percent effectiveness relative to a turbocharged, downsized GDI engine without cooled-EGR.

Further, the agencies believe that 24 bar BMEP engines are capable of maintaining NOx control without cooled EGR, so it can be choose 24 bar BMEP engines with and/or without cooled EGR. However, 27 bar BMEP engines are considered to require cooled EGR to maintain NOx emission control.

3.5.1.12 Diesel engines (ADSL)

They have several characteristics that give superior fuel efficiency, including reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at a higher compression ratio, with a very lean air/fuel mixture, than an equivalent-performance gasoline engine. As a result, turbocharged light-duty diesels typically achieve much higher torque levels at lower engine speeds than equivalent-displacement naturally-aspirated gasoline engines and greater fuel efficiency.

However diesel fuel also contains higher carbon content which leads to a more CO_2 emissions if the FC is equal than a gasoline car. Anyway, the higher efficiency of these engines more than outwheight the Carbon offset. This is usually called the diesel's "carbon penalty". So a manufacturer that invests in diesel technology to meet CAFE standards may have more trouble meeting the GHG standards. Remember that CAFE standard refer to FE and GHG refer to CO_2 emissions.

Diesel engines also have emissions characteristics that present challenges to meeting federal Tier 2 NOx emissions standards (USA) U.S. Tier 2 emissions fleet average requirement of bin 5 require roughly 45 to 65 percent more NOx reduction compared to the Euro VI standards. The fact is that Euro VI define different emissions limit for gasoline and diesel while Tier2 does not give such flexibilities even though the nature of the two combustions is different given rise to diverse emissions.

Despite considerable advances by manufacturers in developing Tier 2-compliant diesel engines, it remains somewhat of a systems-engineering challenge to maintain the full fuel consumption advantage of the diesel engine while meeting Tier 2 emissions regulations because some of the emissions reduction strategies can increase fuel consumption. A combination of combustion improvements (that reduce NOX emissions leaving the engine) and after treatment (capturing and reducing NO_X emissions via a NOx adsorption catalyst, or via selective catalytic reduction (SCR) using a reductant such as urea) that have left the engine before they leave the vehicle tailpipe) are being introduced on Tier 2 compliant light duty diesel vehicles today.

With respect to combustion improvements, several key advances in diesel engine combustion technology have made it possible to reduce emissions coming from the engine prior to aftertreatment, which reduces the need for aftertreatment. These technologies include improved fuel systems (higher injection pressure and multiple-injection capability), advanced controls and sensors to optimize combustion and emissions performance, higher EGR levels and EGR cooling to reduce NOx, and advanced turbocharging systems.

These systems are available today and they do not adversely impact fuel efficiency. However, additional improvements in these technologies will be needed to reduce engine emissions further, should future emissions standards become more stringent. Further development may also be needed to reduce the fuel efficiency penalty associated with EGR.

With respect to catalytic exhaust emission control systems, typical 3-way exhaust catalysts without NOx storage capability are not able to reduce NOx emissions from engines operated lean of stoichiometry (diesel or lean-burn gasoline). To reduce NOx, hydrocarbons, and particulate emissions, all diesels will require a catalyzed diesel particulate filter (CDPF) and sometimes a separate diesel oxidation catalyst (DOC), and either a lean NOx trap (LNT) or the use of a selective catalytic reduction system, typically base-metal zeolite urea-SCR.

The increased cost of diesel emissions control technologies relative to powertrains with stoichiometric gasoline engines that are approaching comparable efficiency may also make diesels less attractive to manufacturers as a technology solution for more stringent CAFE and GHG standards. These higher costs result from more costly components, more complex systems for emissions control, and other factors. The vehicle systems that are impacted include:

Fuel systems (higher pressures and more responsive injectors)

Controls and sensors to optimize combustion and emissions performance

Engine design (higher cylinder pressures require a more robust engine, but higher torque output means diesel engines can have reduced displacement)

Turbocharger(s)

Aftertreatment systems, which tend to be more costly for diesels

In conclusion, the model will place as low cost effective the diesel technology (high cost relatively to their FC savings) basically because US regulations are highly stringent (more than European) and therefore high electrification on gasoline engines will be chosen first to Diesel engines.

This technology considers that the engine is replaced, of course by a Diesel engine with equivalent performance. (30)

3.5.1.13 CNG and LPG engines

They are bi-fuel cars, which may work both with petrol and gas although they show a lower performance when working with CNG/LPG. They both are cleaner fuels that reduce CO_2 emissions specially CNG which seems to have the greater potential use in the future (especially in some countries). Fuel prices use to be also cheaper (for same energy content) but their cost is higher than a conventional petrol car and they weight more and have less space for luggage. Furthermore they offer the inconvenient that not always a fuel station with CNG/LPG filler can be found; especially in some countries where because of that the market of these vehicles is very low.

Since no reliable data on this issue has been found, rough values of cost and CO_2 reduction have been given by my tutor.

The calculation of the MPG value for CNG and LPG and the CO_2 reduction for CAFE and NEDC purposes respectively is explained in detail in the chapter 3.7.4.

LPG CO_2 emissions reduction value should have synergies when applied along with DI engines because: Regarding to CO_2 reduction, when talking about DI engines, some gasoline has to be injected along with LPG in some working conditions to not damage the injectors. However, manifold injection engines do not have this condition which increases their CO_2 reduction potential compared to that on DI engines. On the other hand, for what concern cost, it may differ among DI and manifold injection since different technologic approaches should be taken. However, since no reliable data on this issue was found, no synergies are considered.

Due to the fact that CNG has high knock resistance and low energy content, CNG-compatible engines achieve especially high CO_2 reduction when applied in high compression ratio engines with GDI. When using common port injection, the performance of the car is highly reduced but the cost is as well cheaper. Although these differences, which lead to rise on synergies, it has not be considered synergies for the same reason as the LPG technology (35) (36).

3.5.2 Transmission path

3.5.2.1 Manual 6-speed transmission (6MAN)

Manual transmissions are the most efficient transfer of energy of all transmission layouts, because it has the lowest internal gear losses, with a minimal hydraulic system, and the driver provides the energy to actuate the clutch. From a systems viewpoint, however, vehicles with manual transmissions have the drawback that the driver may not always select the optimum gear ratio for fuel economy. Nor the driving cycle gear shift time schedule is optimum for FE.

Nonetheless, increasing the number of available ratios in a manual transmission can improve fuel economy by allowing the driver to select a ratio that optimizes engine operation more often. Such improve is also feasible on the driving cycles with shift schedule. Typically, this is achieved through adding overdrive ratios to reduce engine speed at cruising velocities (which saves fuel through reduced engine pumping losses) and pushing the torque required of the engine towards the optimum level.

However, if the gear ratio steps are not properly designed, this may require the driver to change gears more often in city driving, resulting in customer dissatisfaction.

Additionally, if gear ratios are selected to achieve improved launch performance instead of to improve fuel economy, then no fuel saving effectiveness is realized.
6MAN technology offers an additional gear ratio, from five gears to six.

3.5.2.2 Improved automatic transmission controls (IATC)

Optimizes shift schedule to maximize fuel efficiency under wide ranging conditions, and minimizes losses associated with torque converter slip through lock-up or modulation.

Particularly Aggressive Shift Logic ASL an Early Torque Converter Lockup ETCL are the two technologies making up IATC.

Aggressive Shift Logic is an improved transmission’s controller that manages the operation of the transmission by scheduling the upshift or downshift, and, in automatic transmissions, locking or allowing the torque converter to slip based on a preprogrammed shift schedule. The shift schedule contains a number of lookup table functions, which define the shift points and torque converter lockup based on vehicle speed and throttle position, and other parameters such as temperature. Aggressive shift logic (ASL) can be employed in such a way as to maximize fuel efficiency by modifying the shift schedule to upshift earlier and inhibit downshifts under some conditions, which reduces engine pumping losses and engine friction.

A first level of ASL is linked to IATC while a second level of ASL is considered to be the “Shift Optimization” in the chapter 3.5.2.7. The first level of ASL is an early upshift strategy whereby the transmission shifts to the next higher gear “earlier” (or at lower RPM during a gradual acceleration) than would occur in a traditional automatic transmission. This early upshift reduces fuel consumption by allowing the engine to operate at a lower RPM and higher load, which typically moves the engine into a more efficient operating region.

Early Torque Converter Lockup is an improved torque converter. The torque converter is a fluid coupling located between the engine and transmission in vehicles with automatic transmissions and continuously-variable transmissions (CVT). This fluid coupling allows for slip so the engine can run while the vehicle is idling in gear (as at a stop light), provides for smoothness of the powertrain, and also provides for torque multiplication during acceleration, and especially launch. During light acceleration and cruising, the inherent slip in a torque converter causes increased fuel consumption, so modern automatic transmissions utilize a clutch in the torque converter to lock it and prevent this slippage. Fuel consumption can be further reduced by locking up the torque converter at lower vehicle speeds, provided there is sufficient power to propel the vehicle, and noise and vibration are not excessive. If the torque converter cannot be fully locked up for maximum efficiency, a partial lockup strategy can be employed to reduce slippage. Early torque converter lockup is applicable to all vehicle types with automatic transmissions. Some torque converters will require upgraded clutch materials to withstand additional loading and the slipping conditions during partial lock-up.

However, as with aggressive shift logic, this operation can result in a perceptible degradation in noise, vibration, and harshness (NVH). The degree to which NVH can be degraded before it becomes noticeable to the driver is strongly influenced by characteristics of the vehicle, and although it is somewhat subjective, it always places a limit on how much fuel consumption can be improved by transmission control changes, especially for higher segments (30).

3.5.2.3 Six- and seven-speed automatic transmissions (NAUTO)

The gear ratio spacing and transmission ratio are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions.

Additional ratios allow for further optimization of engine operation over a wider range of conditions, but this is subject to diminishing returns as the number of speeds increases. As additional planetary gear sets are added (which may be necessary in some cases to achieve the higher number of ratios), additional weight and friction are introduced.

Furthermore the additional shifting of such a transmission can be perceived as bothersome to some consumers, so manufacturers need to develop strategies for smooth shifts.

However a FC reduction has been stablished for this package, which considers the technological shift from 4-5 speeds automatic gearbox to 6-7 speeds automatic gearbox (30).

3.5.2.4 Dual clutch transmission (DCT)

They are similar to a manual transmission, but the vehicle controls shifting and launch functions. A dual-clutch automated shift manual transmission uses separate clutches for even-numbered and odd-numbered gears, so the next expected gear is pre-selected, which allows for faster, smoother shifting. When a shift is required, the controller disengages the oddgear clutch while simultaneously engaging the even-gear clutch, thus making a smooth shift. If, on the other hand, the driver slows down instead of continuing to accelerate, the transmission will have to change to second gear on the idling shaft to anticipate a downshift. This shift can be made quickly on the idling shaft since there is no torque being transferred on it.

Wet clutch AMTs offer a higher torque capacity that comes from the use of a hydraulic system that cools the clutches. Wet clutch systems are less efficient than the dry clutch systems due to the losses associated with hydraulic pumping. Additionally, wet AMTs have a higher cost due to the additional hydraulic hardware required.

Overall, DCTs likely offer the greatest potential for effectiveness improvements among the various transmission options presented in this report because they offer the inherently lower losses of a manual transmission with the efficiency and shift quality advantages of electronic controls.

The lower losses stem from the elimination of the conventional lock-up torque converter, and a greatly reduced need for high pressure hydraulic circuits to hold clutches or bands to maintain gear ratios (in automatic transmissions) or hold pulleys in position to maintain gear ratio (in Continuously Variable Transmissions).

However, the lack of a torque converter will affect how the vehicle launches from rest, so a DCT will most likely be paired with an engine that offers sufficient torque at low engine speeds to allow for adequate launch performance or provide lower launch gears to approximate the torque multiplication of the torque converter to provide equivalent performance (30).

3.5.2.5 Eight-speed automatic transmissions (8SPD)

The transmission gear ratios are optimized including more gears to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions.

3.5.2.6 High Efficiency Gearbox (automatic, DCT or manual) (HETRANS and HETRANSM)

Continuous improvement in seals, bearings and clutches, super finishing of gearbox parts, and development in the area of transmission lubrication, all aimed at reducing frictional and other parasitic load in the system for an automatic, DCT or manual type transmission
Note that the high efficiency gearbox technology is applicable to any type of transmission. (30)

3.5.2.7 Shift Optimization (SHFTOPT)

Tries to keep the engine operating near its most efficient point for a given power demand. The shift controller attempts to emulate a traditional continuously-variable transmission (CVT) by selecting the best gear ratio for fuel economy at a given required vehicle power level to take full advantage of high BMEP engines.

ASL-level 2 is a shift optimization strategy whereby the engine and/or transmission controller(s) continuously evaluate all possible gear options that would provide the necessary tractive power (while limiting the adverse effects on driveline NVH) and select the gear that lets the engine run in the most efficient operating zone. Ricardo acknowledged in its report that the ASL-level 2 (“shift optimization”) strategy currently causes significant implications for drivability and hence affects consumer acceptability. However, it is thought that such technology will be commonly used on the 2020-2025 timeframe with the assumption that manufacturers will develop a means of yielding the fuel economy benefit without adversely affecting driver acceptability. The agencies believe these drivability challenges could include shift busyness *i.e.* a high level of shifting compared to current vehicles as perceived by the customers. However the shifting time will be less and less long due to technological improvements which will result in a smother torque transitions and so overcoming such busyness. Thus improving customer perception/satisfaction. Nevertheless, the challenge becomes greater due to the introduction of gearbox with high number of gears (8SPD) which incur in a higher number of shifting events. At the same time, the associated closer gear spacing will generally result in smaller engine speed changes during shifting that may be less noticeable to the driver so it is in some amount improved. (30)

3.5.3 Rolling resistance path. Low-rolling-resistance tires (ROLL1 and ROLL2)

Low rolling resistance technologies have characteristics that reduce frictional losses associated with the energy dissipated in the deformation of the tires under load, thereby reducing the energy needed to move the vehicle. There are two levels of rolling resistance reduction considered in this analysis, ROLL1 and ROLL2, which assume 10 percent and 20 percent rolling resistance reduction, respectively. Other tire design characteristics (*e.g.,* materials, construction, and tread design) influence durability, traction (both wet and dry grip), vehicle handling, and ride comfort in addition to rolling resistance. A typical low rolling resistance tire's attributes could include: increased specified tire inflation pressure, material changes, and tire construction with less hysteresis, geometry changes (*e.g.,* reduced aspect ratios), and reduction in sidewall and tread deflection. These changes would generally be accompanied with additional changes to vehicle suspension tuning and/or suspension design. The agencies expect that tire manufacturers will be able to achieve widespread, production application of the 20 percent rolling resistance reduction level in time for MY 2017 and later. Since ROLL2 technology does not yet exist in the marketplace today, the agencies relied on ROLL1 history, costs, market implementation, and information provided by the 2010 NAS report (30).

3.5.4 Driveline improvements path

3.5.4.1 Low-drag brakes (LDB)

Reduce the sliding friction of disc brake pads on rotors when the brakes are not engaged because the brake pads are pulled away from the rotors either by mechanical or electric methods.

3.5.4.2 Front or secondary axle disconnect for four-wheel drive systems (SAX)

Provides a torque distribution disconnect between front and rear axles when torque is not required for the non-driving axle, which reduces associated parasitic energy losses. At the moment it seems that there is any manufacturer offering this technology. However, it is possible this technology could be introduced.

3.5.5 Aerodynamic improvements path. Aerodynamic drag reduction (AERO1 and AERO2)

Is achieved by changing vehicle shape or reducing frontal area, including skirts, air dams, underbody covers, and more aerodynamic side view mirrors.

The first level AERO1 includes such body features as air dams, tire spats, and perhaps one underbody panel. The second level AERO2 includes such body features as active grille shutters, rear visors, larger under body panels or low-profile roof racks.

These two levels of aerodynamic drag reduction considered in this analysis assume 10 percent and 20 percent drag reduction, respectively. (30)

Furthermore, active aerodynamics may introduce off-cycle credits for GHG compliance purposes.

3.5.6 Mass reduction path. MR1-5%, MR2-10%, MR3-15%, MR4-20%, MR1 CNG LPG-10%, MR1 CNG LPG-15% MR1 CNG LPG-20%, MR1E-10%, MR2E-15%, MRE3-20%

Mass reduction encompasses a variety of techniques to make vehicles lighter, ranging from improved design and better component integration to application of lighter and higher-strength materials. A lighter has lower FC and , all else equal, mass reduction can also lead to collateral fuel economy benefits due to downsized engines and/or ancillary systems (transmission, steering, brakes, suspension, etc.).

Automobile manufacturers can consider modular systems design, secondary mass effects, multi-material concepts, and new manufacturing processes to help optimize the design. There are several studies in the public domain that illustrate the potential for these approaches to achieve significant amounts of mass reduction although it is important to also recognize that the studies use some assumptions that do not account for some of the considerations that are important to manufacturers. One example is the need to share some components across platforms to manage cost and part complexity for assembly and service, which limits the ability to optimize the amount of mass reduction on every vehicle component. Care must also be taken in any study to assure that vehicle functionality and performance, such as stiffness, NVH, safety and vehicle dynamics, continue to meet manufacturer objectives and consumer demands. (37)

Note as well that manufacturers are not willing to reduce roominess (vehicle size) to reduce fuel consumption. First because this is a customer choice and so it will depend on the market. Second because vehicle size and emissions limits are paired in US standards and so no advantage can be found here general speaking. Furthermore, for some reasons most of the people in US think that big cars are safer than small cars, which is actually only true in few cases. On the other hand, emission limits and weight are paired in other regulations such as European so Manufacturers may not have incentive to reduce weight.

The term "glider" refers to a complete vehicle minus the powertrain. The non-powertrain systems normally account for 75 percent of vehicle weight.

For the model analysis only 10% and 20% mass reduction has been taken into account and they offer different cost and FC reduction for conventional cars, HEVs and FFVs. (38)

3.5.7 Electrification path

Hybrid Electric Vehicles HEVs are part of a continuum of vehicles using systems with differing levels of electric drive and electric energy storage. This range of vehicles includes relatively basic system without electric energy storage such as engine start/stop systems; HEV systems with varying degrees of electric storage and electric drive system capability including mild-hybrid electric vehicles (MHEV) with limited capability but lower cost; strong hybrid electric vehicles (SHEV) with full hybridization capability such as the P2 hybrid technology which the agencies evaluate as a compliance option; plug-in hybrid electric vehicles (PHEV) with differing degrees of all electric range and battery electric vehicles (EV) that rely entirely on electric drive and battery electric energy storage. Different HEV, PHEV and EV concepts utilize these mechanisms differently, so they are treated separately for the purposes of this analysis.

In many applications, particularly with PHEV and EV, the battery represents the most costly and system-limiting sub-component of the hybrid system. Currently, there are many battery chemistries being developed and refined for hybrid applications that are expected to enhance the performance and reduce the cost of future hybrid vehicles.

3.5.7.1 Electric power steering (EPS) and electro-hydraulic power steering (EHPS)

Is an electrically-assisted steering system that has advantages over traditional hydraulic power steering because it replaces a continuously operated hydraulic pump and only operates when needed, thereby reducing parasitic losses from the accessory drive.

EPS is an enabler for all vehicle hybridization technologies since it provides power steering when the engine is off.

3.5.7.2 Improved accessories (IACC1 and IACC2)

There are two levels of IACC applied in this analysis. The first level of IACC includes an electric water pump and cooling fans and a high efficiency alternator (70% efficiency); the second level of IACC includes some mild alternator regenerative braking as well as intelligent cooling in addition to what is included in the first level of IACC. This excludes other electrical accessories such as electric oil pumps and electrically driven air conditioner compressors.

The accessories on an engine, including the alternator, coolant and oil pumps are traditionally mechanically-driven. A reduction in CO_2 emissions and fuel consumption can be realized by driving them electrically, and only when needed.

Electric water pumps and electric fans can provide better control of engine cooling. For example, coolant flow from an electric water pump can be reduced and the radiator fan can be shut off during engine warm-up or cold ambient temperature conditions which will reduce warm-up time, reduce warm-up fuel enrichment (and so FC), and reduce parasitic losses.

Further benefit may be obtained when electrification is combined with an improved, higher efficiency engine alternator.

3.5.7.3 12-volt Stop-Start (MHEV)

Also known as idle-stop or 12V micro hybrid and commonly implemented as a 12-volt belt-driven integrated starter-generator, this is the most basic hybrid system that facilitates idle-stop capability. Along with other enablers (EPS, IACC), this system replaces a common alternator with an enhanced power starter-alternator, both belt driven, and a revised accessory drive system. When vehicle comes to a stop, the system will automatically shut down the internal combustion engine and restarts the engine when vehicle starts to move again. This is especially beneficial to reduce emission and fuel consumption when vehicle spends significant amount of time stopping in inner city driving or a traffic jam.

These systems typically incorporate an improved battery to prevent voltage-droop on restart.

3.5.7.4 Mild Hybrid/Integrated Starter Generator (ISG)

ISG provides idle-stop capability and launch assistance (which is not possible on micro hybrids) and uses a high voltage battery with increased energy capacity over typical automotive batteries.

Mild hybrid systems, also called Higher Voltage Stop-Start and Belt Mounted Integrated Starter Generator (BISG) systems are similar to a micro-hybrid system, offering idle-stop functionality, except that they utilize larger electric machine and a higher capacity battery, typically 42 volts or above, thus enabling a limited level of regenerative braking which is even smaller for a MHEV (Micro Hybrids).

However, because of the limited torque capacity of the belt-driven design, these systems have a smaller electric machine, and thus less capability than crank-integrated or stronger hybrid systems

The limited electrical requirements of these systems allow the use of lead-acid batteries or supercapacitors for energy storage, or the use of a small lithium-ion battery pack.

The FC reduction values and cost estimation results show that the mild hybrid system could be a cost effective technology. For the ISG technology it is considered a system using a 15 kW starter/generator and 0.25 kWh Li-ion battery pack, which is similar to General Motors' eAssist BISG, which is available in MY 2012 Buick LaCrosse, Buick Regal, and Chevrolet Malibu vehicles. The values of cost and FC reductions for small/midsize cars (as the reference car) assumes engine downsizing to maintain approximately equivalent performance.

3.5.7.5 Strong Hybrid (SHEV1-power split or 2 mode and SHEV2-p2 parallel or 2 mode)

A hybrid vehicle is a vehicle that combines two or more sources of propulsion energy, where one uses a consumable fuel (like gasoline), and one is rechargeable (during operation, or by another energy source). Hybrids in general and especially strong hybrids reduce fuel consumption through four major mechanisms:

- The internal combustion engine can be optimized (through downsizing, modifying the operating cycle, or other control techniques) to operate near its most efficient point most of the time. At the same time, power loss from engine downsizing can be mitigated by employing power assist from the secondary power source.
- Some of the energy normally lost as heat while braking can be captured and stored in the energy storage system for later use. In a greater amount than MHEV explained before.
- The engine is turned off when it is not needed, such as when the vehicle is coasting or when stopped. Hybrid vehicles utilize some combination of the three above mechanisms to reduce fuel consumption and CO_2 emissions.
- A fourth mechanism to reduce petroleum fuel consumption, available only to plug-in hybrids, is by substituting the petroleum fuel energy with energy from another source, such as the electric grid.

The effectiveness of fuel consumption and CO_2 reduction depends on the utilization of the above mechanisms and how aggressively they are pursued. One area where this variation is particularly prevalent is in the choice of engine size and its effect on balancing fuel economy and performance. Some manufacturers choose not to downsize the engine when applying hybrid technologies. In these cases, performance is vastly improved, while fuel efficiency improves significantly less than if the engine was downsized to maintain the same performance as the conventional version. If the engine is downsized, the battery can be quickly drained during a long hill climb with a heavy load, leaving only a downsized engine to carry the entire load. This is a negative point for engine downsizing in strong hybrids.

Although hybrid vehicles using other energy storage concepts (flywheel, hydraulic) have been developed, the automotive systems in production for passenger cars and light trucks are all hybrid electric vehicles (HEV) that use battery storage and electric drive systems. This appears likely to be the case for the foreseeable future.

The Figure 3-5 is showed in order to explain the concepts of intelligent hybrid concepts.

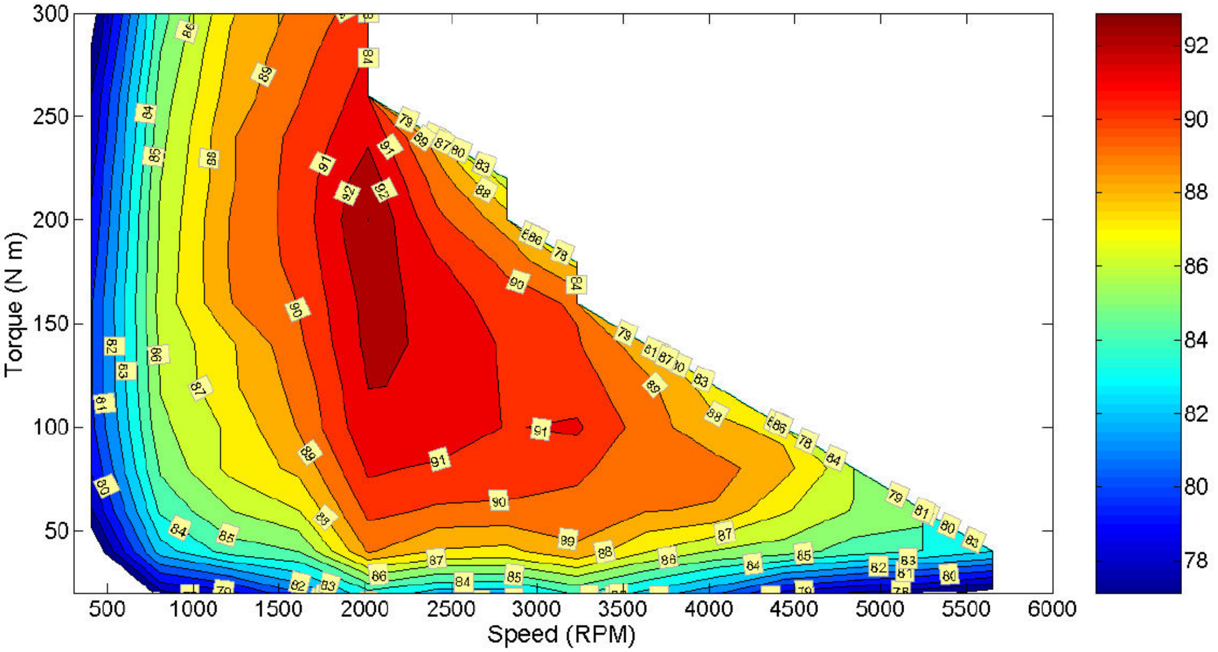

Figure 3-5 2007 Camry hybrid motor-inverter efficiency map **(39)**

Similarly to the BSFC map showed in the Figure 1-1 electric motor/generators also have their own efficiency map. The most efficient control techniques for HV are based in an optimum combination of the two power sources to work in the most efficient point of the efficiency maps. Either when delivering power or recovering power (in the case of the electric motor).

SHEV1 and SHEV2 are not fully described as it is not easy to forecast what will prevail in such a complex technology path, however NHTSA has given values on cost and FC assuming that SHEV1 corresponds to power split or 2 mode hybrids and SHEV2 corresponds to p2 parallel or 2 mode hybrid.

P2 hybrid

A P2 hybrid is hybrid technology that uses a transmission-integrated electric motor placed between the engine and a gearbox or CVT and coupled to the engine crankshaft via a clutch. The engine and the drive motor are mechanically independent of each other, allowing the engine or motor to power the vehicle separately or combined. Disengaging the engine clutch allows all-electric operation and more efficient brake-energy recovery. The P2 HEV system is similar to the Honda IMA HEV architecture with the exception of the added clutch, and larger batteries and motors. Examples of this include the Hyundai Sonata HEV and Infiniti M35h. The agencies believe that the P2 is an example of a "strong" hybrid technology that is typical of what will be prevalent in the timeframe of this analysis, replacing costlier power-split or 2-mode architectures while providing substantially similar efficiency improvement. At the present time, P2 hybrids are relatively new to the market and the agencies have not attempted to quantify any measurable performance differential between these technologies.

The agencies are aware of some articles in trade journals, newspapers and other reviews that some first generation P2 hybrid vehicles with automatic transmissions have trade-offs in NVH and drivability – though these reviews do not cover all of the P2 systems available today, and a number of reviews are very positive with respect to NVH and drivability.

Power-split Hybrid (PSHEV)

Is a hybrid electric drive system that replaces the traditional transmission with a single planetary gearset and two motor/generators. The smaller motor/generator uses the engine to either charge the battery or supply additional power to the drive motor. The second, more powerful motor/generator is permanently connected to the vehicle’s final drive and always turns with the wheels. The planetary gear splits engine power between the first motor/generator and the drive motor to either charge the battery or supply power to the wheels.

2-Mode Hybrid (2MHEV)

Is a hybrid electric drive system that uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors that control the ratio of engine speed to vehicle speed, while clutches allow the motors to be bypassed. This improves both the transmission torque capacity for heavy-duty applications and reduces fuel consumption at highway speeds relative to other types of hybrid electric drive systems. It is believed that industry is expected to trend toward more cost effective hybrid configurations.

3.5.7.6 Plug-in hybrid electric vehicle (PHEV2)

Are hybrid electric vehicles with the means to charge their battery packs from an outside source of electricity (such as the electric grid), as well as a gasoline engine. These vehicles have larger battery packs than non-plug-in hybrid electric vehicles with more energy storage and a greater capability to be discharged. They also use a control system that allows the battery pack to be substantially depleted under electric-only or blended mechanical/electric operation, allowing for reduced fuel use during “charge depleting” operation. Only PHEV2 has been applied in this study. It corresponds to a 30mi range.

3.5.7.7 Electric vehicle (EV1)

Are vehicles with all-electric drive and with vehicle systems powered by energy-optimized batteries charged from grid electricity and regenerative breaking. EV1 range is 75 mile.

3.5.8 Other Off-cycle/Eco-innovative technologies

As already explained in the chapters 2.3.4.4 and 2.4.2.2, there are some technologies that do contribute to a CO_2 reduction in real world but do not account (in part or as a whole) during neither NEDC procedure nor the two cycle test procedure for GHG and CAFE. Instead, they can account for a given number of g/mi or g/km as Off-cycle credits if the so called reduction is demonstrated. In the case of GHG regulations there is a pre-approved list, which is shown below. This leads to an easier and less costly earning of credits because no very complicated test procedures are needed to demonstrate such reductions. However, there is no pre-approved list in NEDC regulations which may make manufacturers to refuse to use eco-innovations for the high cost of the demonstrating procedures. The list of available Off-cycle and eco-innovative technologies is different for GHG and NEDC regulations. While still not set up for CAFE regulations.

Table 3-3 Off-cycle credits for US GHG program **(10)**

Name	Simplified name	Applicable according to NEDC	Applicable according to US GHG	Maximum potential credits according to US GHG [g/mi]
A/C High efficiency – Level 1	AC1	No	Yes	1
A/C Very high efficiency – Level 2	AC2	No	Yes	1,5
Glass or Glazing	G	No	Yes	2,9
Passive Cabin Ventilation	PCV	No	Yes	1,7
Active Transmission Warm-Up	ATW-EU	Yes	Yes	1,5
Active Engine	AEW-EU	Yes	Yes	1,5

Warm-up				
Active Seat Ventilation	ASV	No	Yes	1
Solar Reflective Paint	SRP	No	Yes	0,4
Active Cabin Ventilation	ACV	No	Yes	2,1
High Efficiency Exterior Lights* (at 100 watt savings)	HEEL-EU	Yes	Yes	1
Solar Panels	SP-EU	Yes	Yes	3,3
Waste Heat Recovery (at 100W)	WHR-EU	Yes	Yes	0,7
Aero Drag Reduction, Level 2	$AERO_2$	No	Yes	0,6
12V Micro-Hybrid (Stop-Start)	MHEV	No	Yes	2,5

Note that AERO2 and MHEV account for extra reduction because they are as well On-cycle technologies. Note as well the lack of data referring to NEDC off-cycle credits usually called as Eco-innovations.

The cost effectiveness of these technologies is quite bad compared to the previous On-Cycle technologies but the most cost effective will be widely applied in some fleets. This is the case of High efficiency AC and 12V Micro hybrids. Since much of the technologies only account in the case of GHG regulations, it seems that only in America it will have an important impact.

The credits given in the last column are maximum values in general. In some cases they can be increased proportionally to their actual level of savings. As in the case of solar panels, which is scalable. In any case, manufacturers that want to acquire a higher value of off-cycle credits have to make specific conformity procedures and no pre-approved values are available.

For two main reasons off-cycle technologies are not taken into account in the model of this Thesis but instead just explained in a qualitative way:

- The conversion equations made by regressions used to convert emissions from CAFE procedures to NEDC procedures cannot be applicable to GHG values with a good level of approximation since regressions are made without Off-cycle techs. See chapter 3.7.4.
- Lack of reliable data: Neither FE reduction is defined according to NHTSA nor costs. The data relating the cost of these off-cycle technologies was not taken from official sources but they are rough values given by my tutor.

However, it is interesting to mention how off-cycles technologies help to reduce GHG emissions.

A/C system

There are two mechanisms by which A/C systems contribute to the emissions of greenhouse gases:

The first is through direct leakage of the refrigerant into the air. The hydrofluorocarbon (HFC) refrigerant compound currently used in all recent model year vehicles is R-134a (also known as 1,1,1,2-Tetrafluoroethane, or HFC-134a). Based on the higher global warming potential of HFCs, a small leakage of the refrigerant has a greater global warming impact than a similar amount of emissions of some other mobile source GHGs. R-134a has a global warming potential (GWP) of 1,43. This means that 1 gram of R-134a has the equivalent global warming potential of 1,43 grams of CO_2 (which has a GWP of 1).

In order for the A/C system to take advantage of the refrigerant's thermodynamic properties and to exchange heat properly, the system must be kept at high pressures even when not in operation. Typical static pressures can range from 50-80 psi depending on the temperature, and during operation, these pressures can get to several hundred psi. At these pressures leakage can occur through a variety of mechanisms. The refrigerant can leak slowly through seals, gaskets, and even small failures in the containment of the refrigerant. Through normal use, the rate of leakage may also increase due to wear on the system components. Leakage may also increase more quickly through rapid component deterioration such as during vehicle accidents, maintenance or end-of-life vehicle scrappage (especially when refrigerant capture and recycling programs are less efficient). Small amounts of leakage can also occur continuously even in extremely “leak-tight” systems by permeating through hose membranes and seals. This last mechanism is not dissimilar to fuel permeation through porous fuel lines (and seals).

Manufacturers may be able to reduce these leakage emissions through the implementation of technologies/designs such as leak-tight, non-porous, durable components. The global warming impact of leakage emissions also can be addressed by using alternative refrigerants, such as HFO-1234yf, R-744 (CO_2), HFC-152a (R-152a), or other refrigerants under development with lower global warming potentials than R -134a.

Refrigerant emissions can also occur during maintenance and at the end of the vehicle’s life (as well as emissions during the initial charging of the system with refrigerant), and these emissions are already addressed by the CAA Title VI stratospheric ozone program.

The second mechanism by which vehicle A/C systems contribute to GHG emissions is through the consumption of additional fuel required to provide power to the A/C system and from carrying around the weight of the A/C system hardware year-round. These indirect emissions result from the additional fuel which is required to provide power to the A/C system (and the additional fuel is converted into CO_2 by the engine during combustion). These increased emissions due to A/C operation can be reduced by increasing the overall efficiency of the vehicle’s A/C system. (31) (40)

Waste Heat Recovery

Combustion engines expel a great amount of head through the exhaust pipe and the cooling system. This system gathers part of the “lost” energy to normally, recharge the batteries. This effect is not well captured in the 2-cycle test procedure, it is underestimated. For this reason, an off-cycle credit is added to the GHG calculation. This is the difference between 5-cycle procedure and 2-cycle procedure results. Note that CAFE regulations use only the 2-cycle procedure. Adding, only in the case of not well represented technologies, the difference among 5-cycle and 2-cycle test.

WHR technologies are usually based in a Rankine Cycle. A typical Rankine Cycle is a thermodynamic cycle that uses a fluid and works thanks to four reversible processes. In transportation, Rankine cycle systems vaporize a pressurized fluid, thanks to a steam generator located in the exhaust pipe. As a result of the heating by exhaust gases, the fluid is turned into steam/vapor. The pressure will then drive the expander of the Rankine engine, which could be a turbine as well as a volumetric expander. This expander can be either directly tied to the crankshaft of the thermal engine or linked to an alternator to generate electricity that will recharge the battery (most commonly option) (31).

High Efficiency Exterior Lights

The current EPA test procedures are performed with vehicle lights (notably, headlights including daytime running lamps (DRLs)) turned off. Because of this, improvement to the efficiency of a vehicle's headlights is not captured in the existing test procedures and is appropriately addressed through the off-cycle crediting scheme. Similarly to the WHR, the number of credits is equivalent to the CO_2 reduction obtained in the 5-cycle test procedure (31).

Solar Panels

How it helps to reduce CO_2 emission is quite obvious. Solar panels can recharge batteries but they are not actuation neither during the 2-cycle nor 5-cycle test procedures. Only HEVs, PHEVs and EVs are eligible for this credit (31).

Aero Drag Reduction, Level 2

The aerodynamic efficiency of a vehicle is usually captured in a coast down test that is used to determine the dynamometer parameters used during both the two-cycle and five-cycle tests. Some active aerodynamic technologies are activated only at certain speeds to improve aerodynamic efficiency while preserving other vehicle attributes or functions. The coast down method may be at a speed or conditions in which such element is not activated and so coast down coefficients and two and five cycles test procedures results remain the same as if such technology wasn't in use.

Two examples of active aerodynamic technologies are active grill shutters and active
ride height control (31).

12V Micro-Hybrid (Stop-Start)

Engine idle start-stop technologies enable a vehicle to turn off the engine when the vehicle comes to a rest, and then quickly restart the engine when the driver applies pressure to the accelerator pedal. The benefit of this system is that it largely eliminates fuel consumption at idle. The EPA FTP (city) test does contain short periods of idle, but not as much idle as is often encountered in real world driving. Therefore, some off-cycle credits are added.

MOVES estimate that 13.5% of all driving (in terms of vehicle hours operating) nationwide is at idle, and compared to a 9% idle rate for the combined (two-cycle) test, idle-off could theoretically approach an extra 50% of the existing benefit seen on the FTP/HWFE test (31).

Active Transmission Warm-Up

Active Transmission warm-up uses waste heat from a vehicle's exhaust system to warm the transmission oil to operating temperature quickly using a heat exchanger in the exhaust system. This heat exchanger loop must have a means of being selectable, so that the transmission fluid is not overheated under hot operating conditions. In cold temperatures, the exhaust heat warms the transmission fluid much more quickly than if the vehicle relies on passive heating alone. Other methods of heating the fluid can be implemented using electric heat for example, but these are not included in this analysis because of the additional energy consumption that would likely eliminate most of the benefit. This technology could also be used for other driveline fluids such as axle and differential lubricant on rear-wheel-drive vehicles or even engine oil, but only transmission fluid warming is considered here.

Since 2-cycle test are made at "high" temperature, the potential GHG reduction accounted in the procedure is very low, However EPA assumes 2,5% GHG reduction at -7 degrees Celsius of ambient temperature while only 1% at 10 degrees Celsius (31).

Active Engine Warm-up

Similar to active transmission warm-up, active engine warm-up uses waste heat from a vehicle's exhaust system to warm targeted parts of the engine, reducing friction and cold start enrichment requirements, and thereby increasing fuel economy. EPA assumed that similar to active transmission warm-up, a similar magnitude benefit would also be applicable for active engine warm-up. As a result, credit values for active engine warm-up are identical to those for active transmission warm-up, and are additive if a manufacturer can demonstrate the presence of both technologies (independent to one another, *i.e.*, separate heating pathways) on a similar vehicle (31).

Passive and active Cabin Ventilation

Given that today's vehicles are fairly well sealed (from an air leakage standpoint), the solar energy that enters the cabin area through conductive and convective heat transfer is effectively trapped within the cabin. During soak periods, this heat gain builds, increasing the temperature of the cabin air as well as that of all components inside the cabin (*i.e.* the thermal mass). By venting this heated cabin air to the outside of the vehicle and allowing fresh air to enter, the heat gain inside the vehicle during soak periods can be reduced.

The NREL study demonstrated that active cabin ventilation technology, where electric fans are used to pull heated air from the cabin, a temperature reduction of 6.9 °C can be realized. For passive ventilation technologies, such as opening of windows and/or sunroofs are and use of floor vents to supply fresh air to the cabin (which enhances convective airflow), a cabin air temperature reduction of 5.7 °C can be realized. This way, reducing the use of A/C when the driver enters into the car (31).

Active Seat Ventilation

The NREL study investigated the effect that ventilating the seating surface has on the cooling demand for a vehicle. By utilizing a fan to actively remove heated, humid air that is typically trapped between the passenger and the seating surface, passenger comfort can be improved, and NREL's Thermal Comfort Model predicted that A/C system cooling load could be reduced, and a 7.5% reduction in A/C-related emissions can be realized. While seat ventilation technology does not lower the cabin air temperature, it indirectly affects the load placed on the A/C system through the occupants selecting a reduced cooling demand due to their perception of improved comfort (31).

Solar Reflective Paint

As the vehicle's body surface is heated by solar energy when parked, heat is transferred to the cabin through conduction and convection. Paint or coatings which increase the amount of infrared solar energy that is reflected from the vehicle surface can reduce cabin temperature during these solar soak periods. This way, reducing the use of A/C when the driver enters into the car.

While the amount of heat entering the cabin through the body surface is less than that which enters through the glazing, its effect on cabin air heat gain is measureable (31).

Glass or Glazing

When a vehicle is parked in the sun, more than half of the thermal energy that enters the passenger compartment is solar energy transmitted through, and absorbed by, the vehicle's glazing (or glass). The solar energy is both transmitted through the glazing and directly absorbed by interior components, which are then heated, and absorbed by the glazing, which then heats the air in the passenger compartment through convection and interior components through re-radiation.

By reducing the amount of solar energy that is transmitted through the glazing, interior cabin temperatures can be reduced, which results in a reduction in the amount of energy needed to cool the cabin and maintain passenger comfort. Glazing technologies exist today which can reduce the amount of solar heat gain in cabin by reflecting or absorbing some of the infrared solar energy. This way, reducing the use of A/C when the driver enters into the car (31).

3.5.9 On-path packages

The spreadsheets in the annexes give a rather vague idea of the technologies that can be part of a package and its features in terms of cost and CO_2 reduction. For this reason several plots have been created to illustrate the possible combinations of technologies in a given path in a much more intuitive way.

Although synergies do exist, the plots do not show possible synergies among technologies neither in the same path nor between different paths (different plots), obviously. This is evaluated in an exhaustive way in the model. Even though since the values of the synergies are relatively low, the reader can consider the plots as quite accurate and thus can make fast calculations of supposed multiple-path packages (whole vehicle package of technologies). Note that the cost effectiveness which is the ratio between cost and CO_2 reduction is plotted. All the costs are expressed in 2010 dollars and the costs shown are expected for the MY 2018.

By supposing a reference car with no low CO_2 technologies applied, all the possible packages in each path have been evaluated. Note that the architecture of this reference car has not been defined in this chapter and so a great number of possibilities will be showed since architectures as SOHC, SOHC, MT, AT and so on is considered.

3.5.9.1 Engine path

This is the biggest path, with a huge number of possible packages of technologies. Only those correspondents to SOHC and DOHC with Small Displacement SD engines will be showed. They include the possibility to replace the engine for an Advanced Diesel Small Displacement ADSL or converting it to a GPL or even CNG engine.

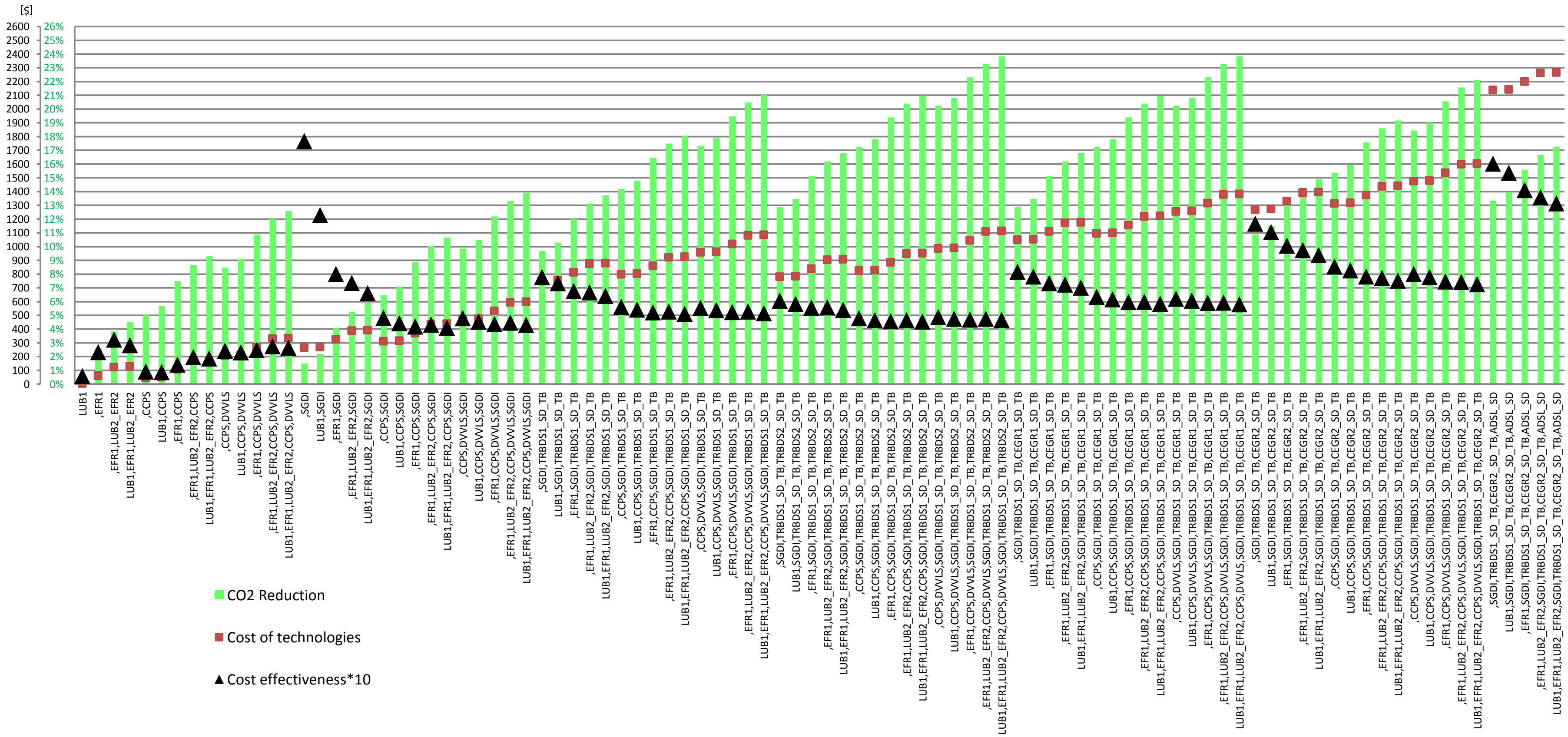

Figure 3-6 Engine technologies packages for SOHC SD and MY 2018. 2010 Dollars.

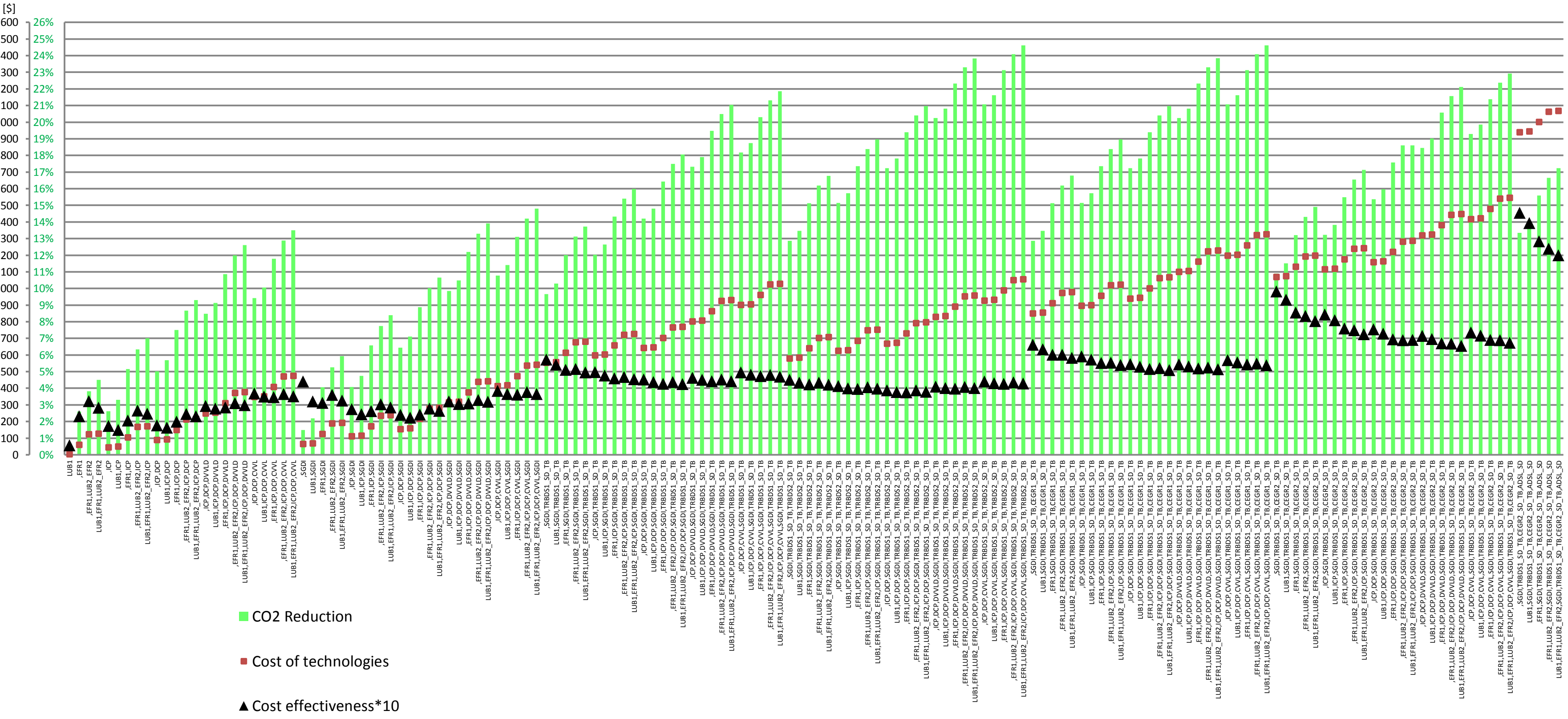

Figure 3-7 Engine technologies packages for DOHC SD and MY 2018. 2010 Dollars.

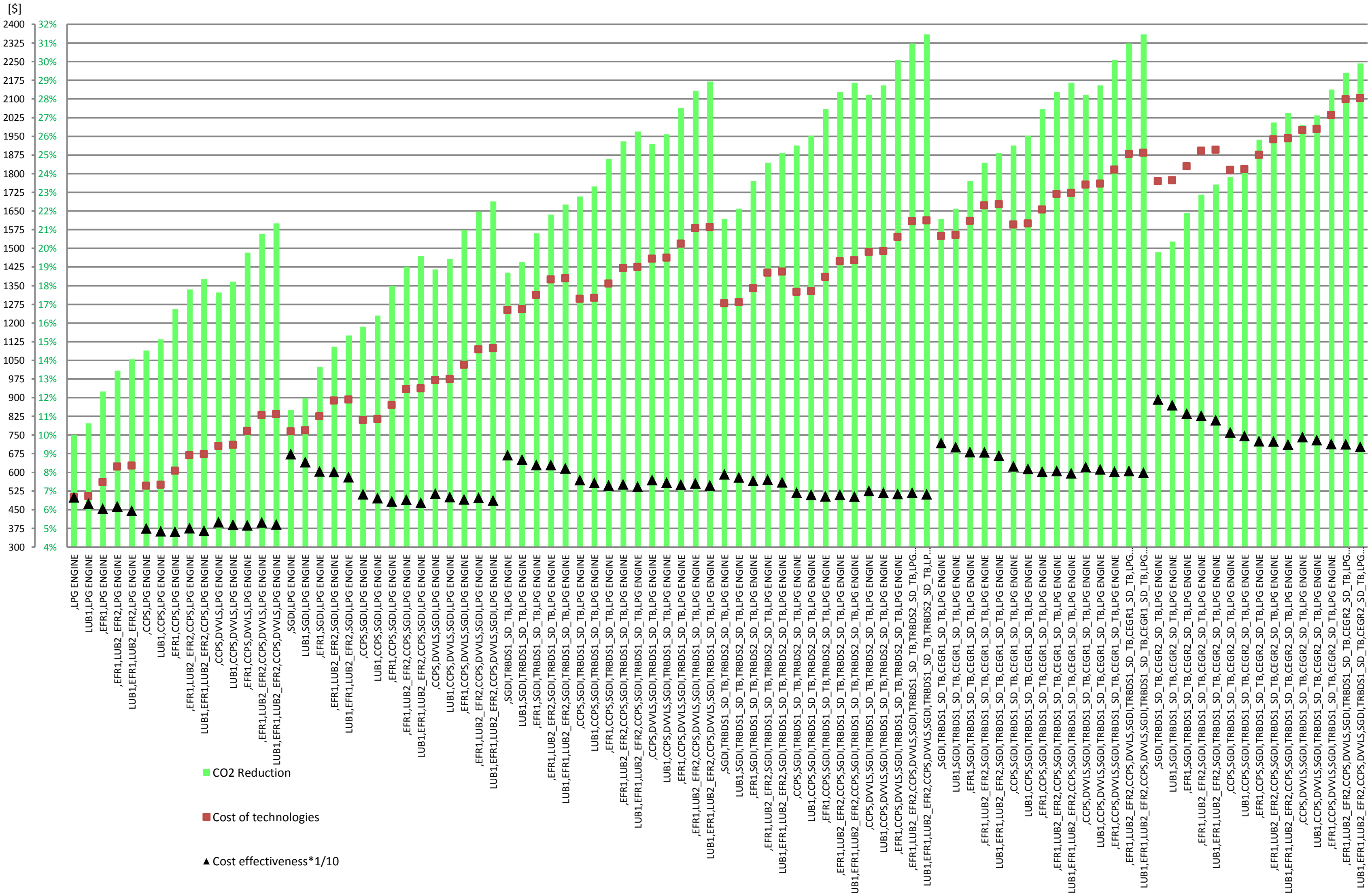

Figure 3-8 Engine technologies packages for SOHC SD LPG and MY 2018. 2010 Dollars.

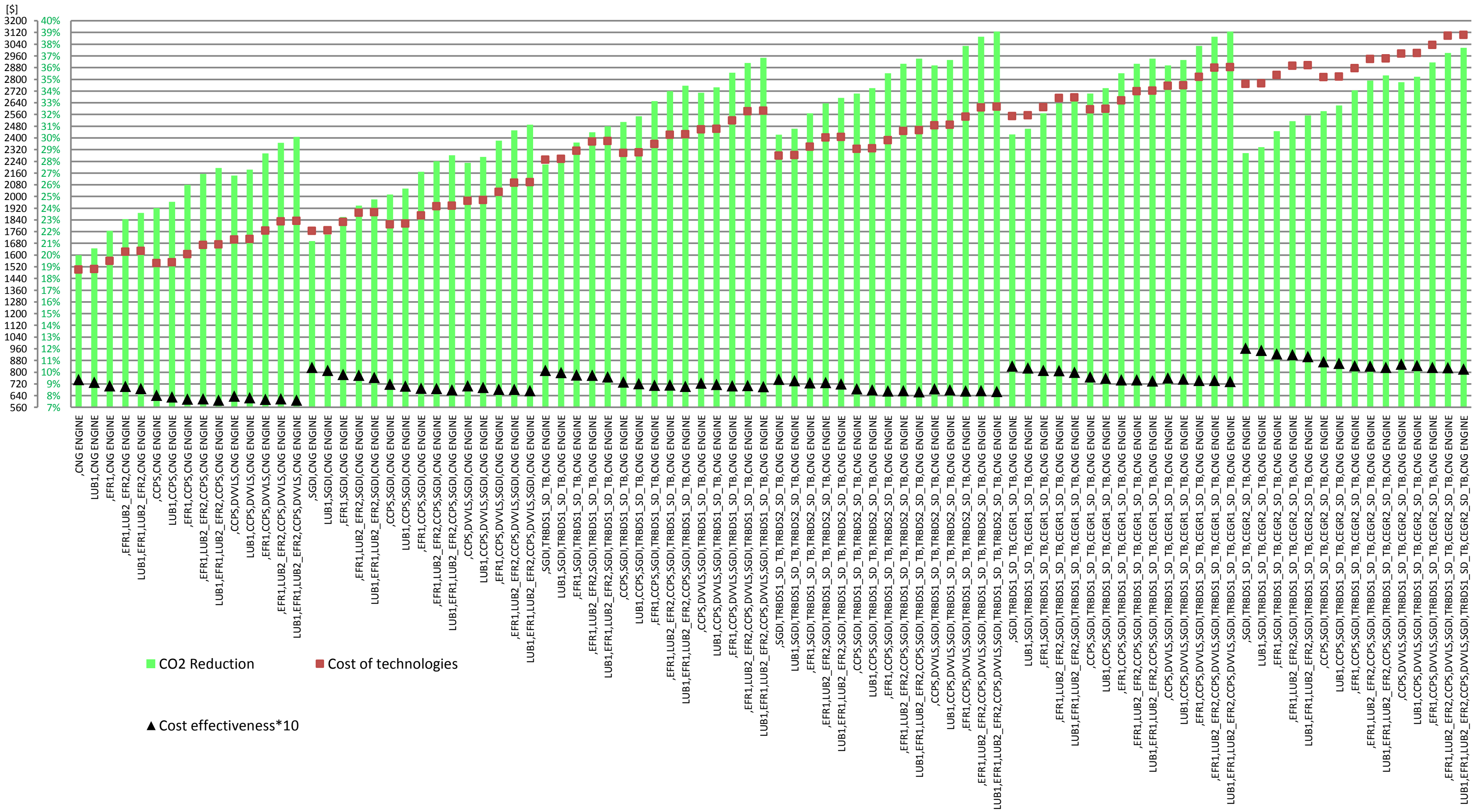

Figure 3-9 Engine technologies packages for SOHC SD CNG and MY 2018. 2010 Dollars.

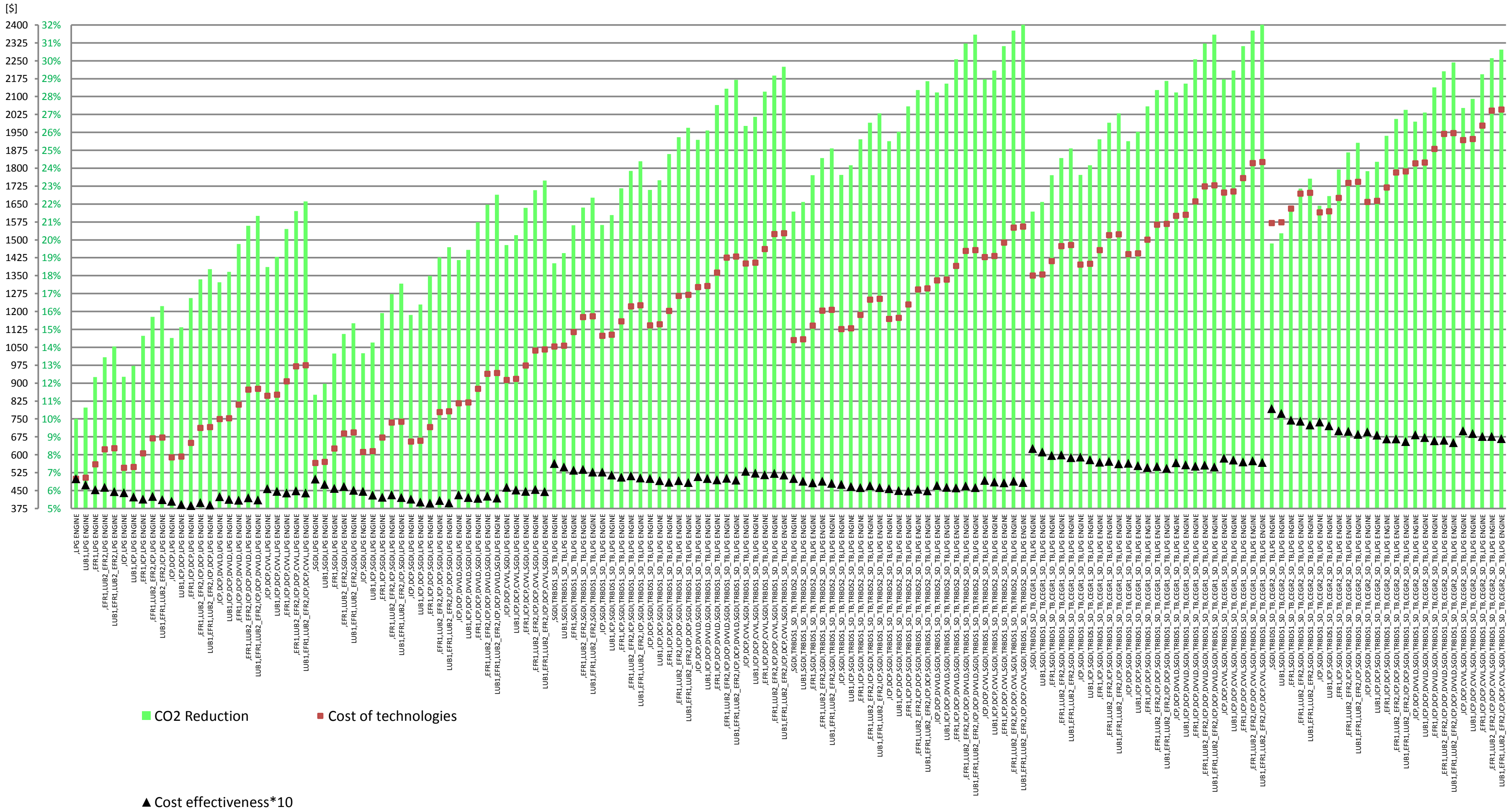

Figure 3-10 Engine technologies packages for DOHC SD LPG and MY 2018. 2010 Dollars.

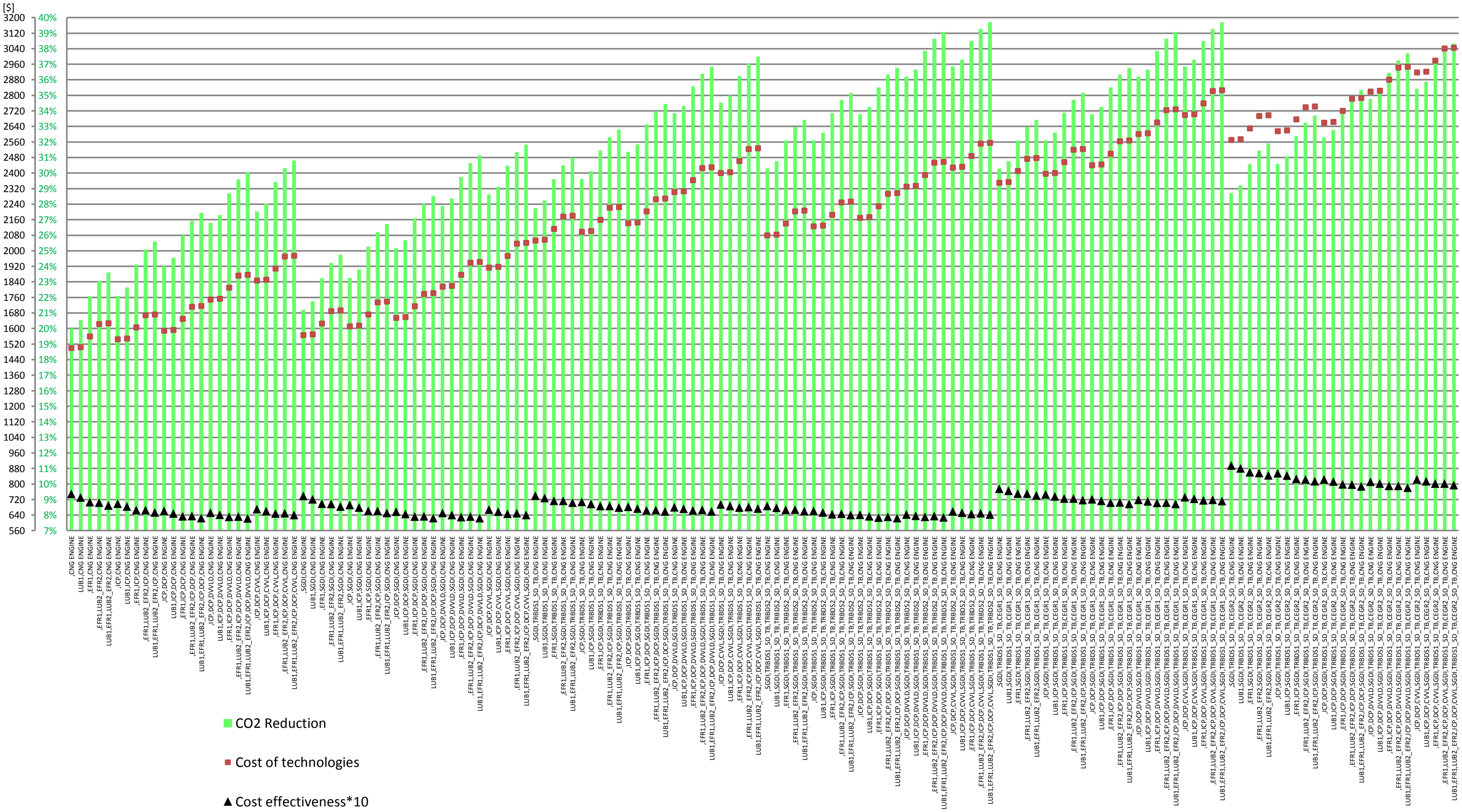

Figure 3-11 Engine technologies packages for DOHC SD CNG and MY 2018. 2010 Dollars.

3.5.9.2 Mass reduction path

The mass reduction technologies are actually differentiated by three engine architectures. Thus unlike levels of CO_2 reduction and costs are achieved for an equal value of mass reduction:

The acronyms MR1-5%…MR4_20% are used for conventional cars and they correspond to a 5 to 20% Mass reduction.

The acronyms MR1CNG LPG-10%…MR3_CNG LPG20% are used for CNG/LPG cars which because of their additional mass with relation to the reference vehicle, they have an additional cost (as the HEV) for a given percentage of mass reduction. A value of 5% of additional mass has been considered for this kind of cars.

The acronyms MR1E-10%…MR3E_20% are used for HEV which have not only a differentiated cost but a different value of CO_2 reduction for an equal level of mass reduction.

The Figure 3-12 shows the data relating to mass reduction technologies.

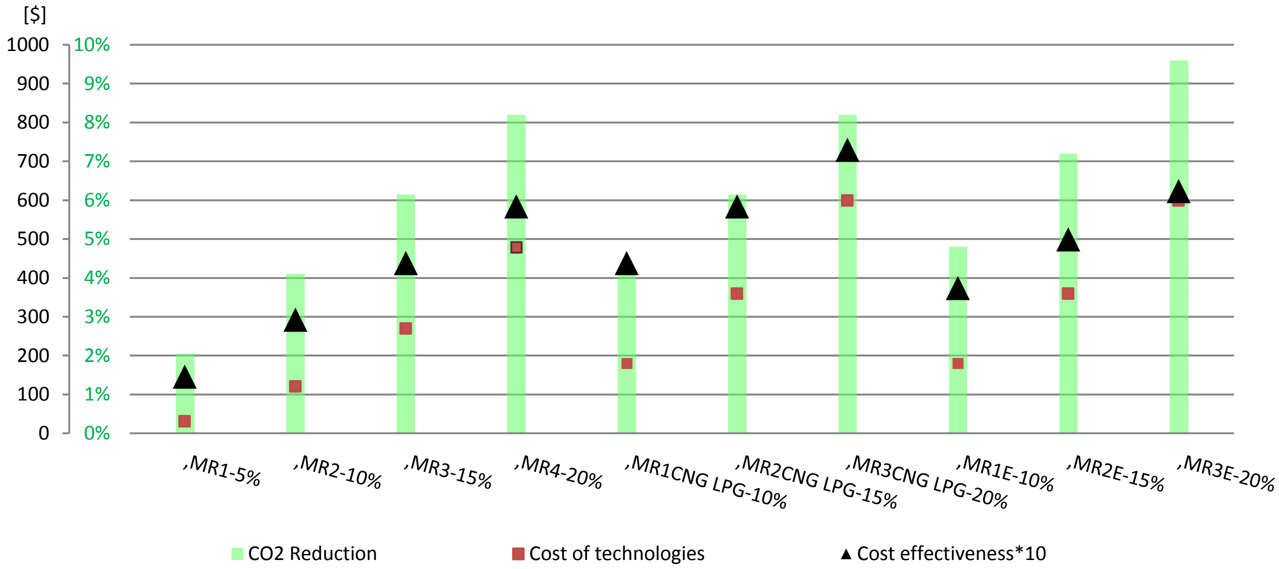

Figure 3-12 Mass reduction path. The data was taken from **(30)** **(38)**. MY 2018. 2010 Dollars.

Note that the cost rises in a nonlinear way with the percentage of mass reduction. It is actually exponential which peaks for higher mass reduction levels.

Thus, in terms of FC reduction, conventional engines and engines converted to CNG or LPG behave the same for a given mass reduction (remember that the mass reduction is calculated from the reference vehicle which is a conventional car) for this reason, as the weight of a converted-to-CNG/LPG car is greater than a conventional vehicle, the cost of a given percentage of mass reduction is lower for a conventional car.

The same explanation is done for HEV in terms of cost: The cost of the mass reduction technologies in HEV is bigger than a conventional due to the fact that an HEV has usually a higher mass than a conventional car and so, for a given percentage of mass reduction from the reference car, the cost is higher. Actually, it has been considered that HEV, CNG and LPG cars have a 5% higher mass than a conventional car and so, a 10% weight reduction from the reference car is like a 15%, which is more costly.

The differences between CO_2 emissions reduction in HEV with respect to the rest of the vehicles are due to the fact that the drive train behaves completely different way. The use of electric motors and the regenerative braking make up these differences. It has been calculated that when powertrain is not resized (case of this Thesis), the FC reduction is greater than in a conventional car. On the other hand, if the Powetrain is resized, the FC reduction is a bit lower in HEV than others. Note that in HEV lower mass implies lower potential of regenerative braking due to lower kinetic energy. This is one of the reasons why, in some cases, HEV mass reduction technologies are not so widely applied.

3.5.9.3 Electrification path

Prior to comment the concepts of the plot, the meaning of the horizontal axis (correspondent to technology package) should be explained here because especially in the Figure 3-13 some confusion may arise. As explained in the chapter 3.2 the model adds technologies in an incremental way, although not obvious, the best way to make the assessment. This means that for example IACC2 cannot be included if IACC1 and EPS is not included and so on, as shown in the Figure 3-13. The last name is the one that actually prevails so the horizontal axis could be understood as: EV1 or as EPS, IACC1, IACC2, MHEV, ISG, SHEV1, SHEV2, PHEV2 and EV1 prevailing the last name. Some costs are divided in two components NB and B, coherent with the cost of the technology without batteries and the cost of the batteries, because batteries represent a huge cost. However, here the two costs (NB and B) are added.

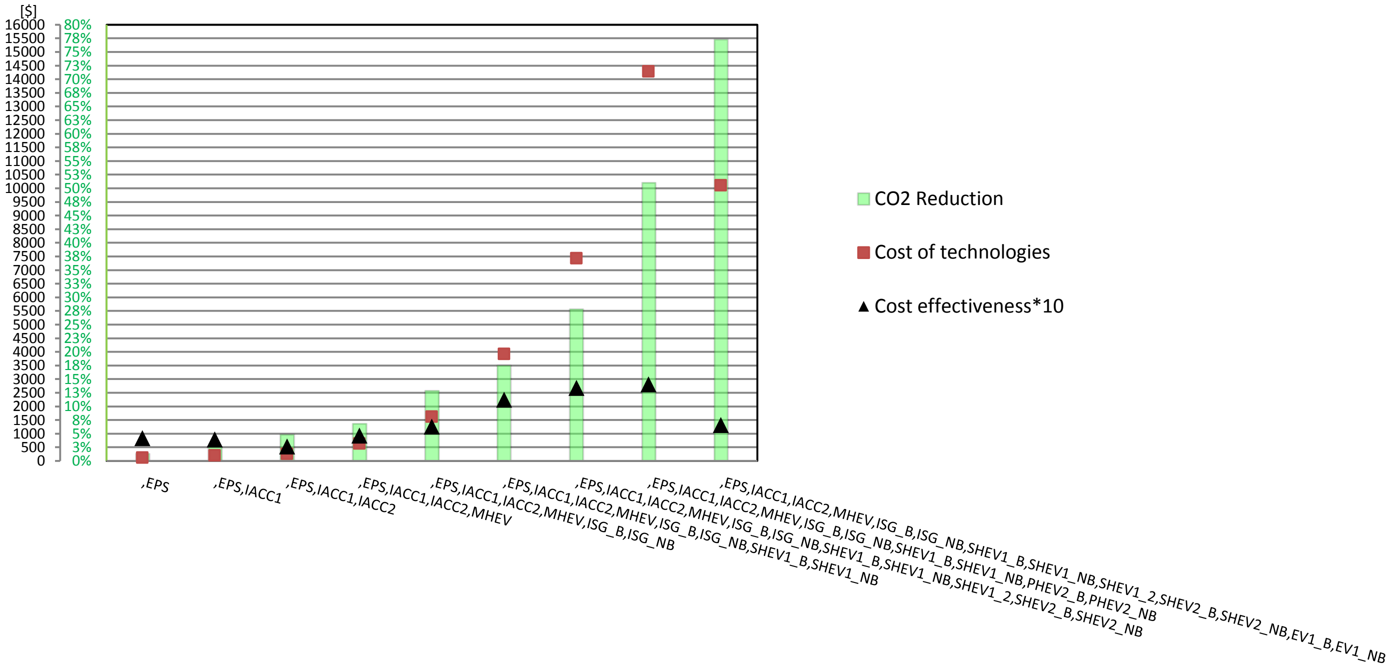

Figure 3-13 Electrification/hybridization path. MY 2018. 2010 Dollars.

In the electrification path the greatest values of CO_2 reduction are reached as well as the most costly technologies. The strong electrification packages (SHEV, PHEV and EV) get the highest values of cost effectiveness but since there are no other technologies capable of reaching such high CO_2 reductions, they will become more and more present in modern cars as the only way to meet the regulations although its high cost, as seen in the outputs of the model.

Note that there is an inflection point between Micro-Mild hybrids (Represented by IACC2, MHEV, ISG) and the Strong hybrids (represented by SHEV, PHEV and EV) which is caused by the high cost of the powerful batteries that these vehicles need in order to feed their motors. Therefore Micro and Mild hybrids which use re-sized Pb batteries or small Li-ion batteries will be a common choice among manufacturers. This statement is, however, highly dependent on the new achievements in terms of battery technologies in which many battery manufacturers are focused on and Automobile manufacturer's are aware of.

It is useful to notice the lower cost and cost effectiveness of the EV with regard to PHEV thanks to the savings for not including a thermal engine. The draw-back is of course the range, in this case of 75 mi.

3.5.9.4 Low rolling resistance path

The first level of rolling resistance reduction (ROLL1) is widely applied for its low cost and cost effectiveness. ROLL2 is still under development but the cost and CO_2 reduction have been approximated by the agencies and seems to be potentially applicable for its great CO_2 reduction and its costs relating other technologies with similar values of CO_2 reduction. They are showed in the Figure 4-13.

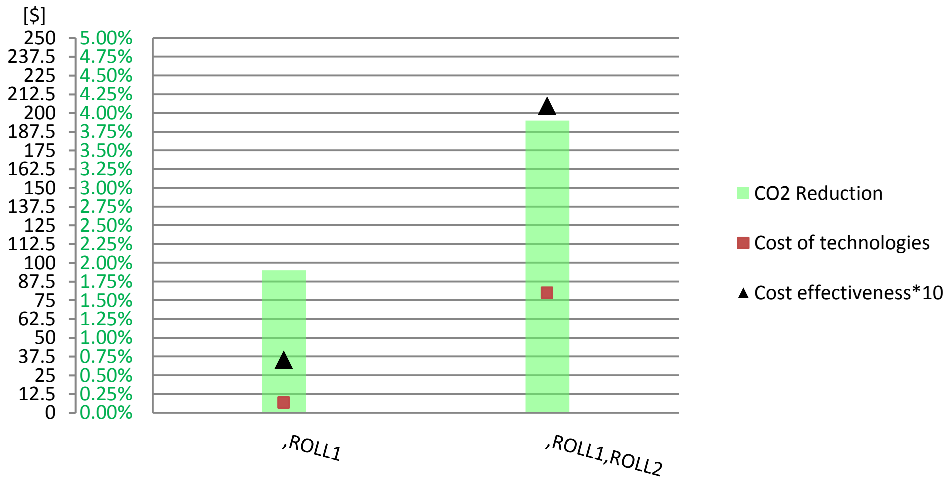

Figure 3-14 Low rolling resistance path. MY 2018. 2010 Dollars.

3.5.9.5 Low driveline drag path

They are quite costly technologies and do not introduce high values of CO_2 reduction which makes them not very attractive for any automobile manufacturers.

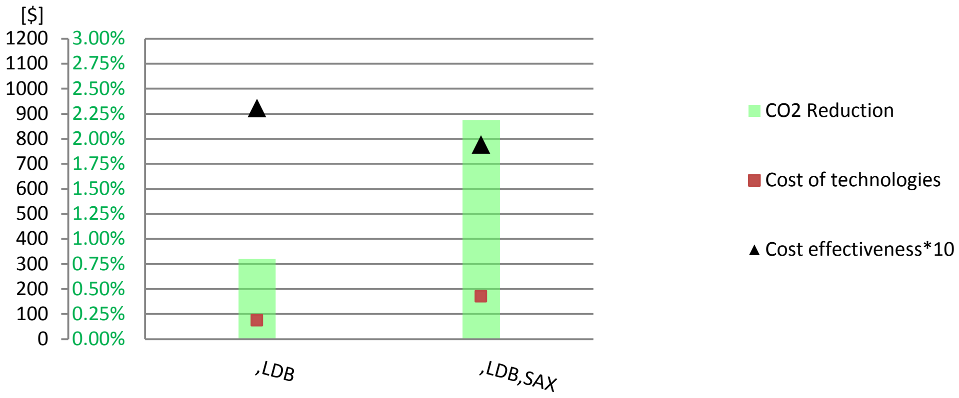

Figure 3-15 Low driveline drag path MY 2018. 2010 Dollars.

3.5.9.6 Aerodynamic improvements path

The first level of aerodynamic improvements (AERO1) is already used widely in the market because of its cost effectiveness and great CO_2 reduction potential, as shown in the Figure 3-16. It can be achieved with quite a simple shape shift and the addition of some covers and deflectors. AERO2 is quite expensive because it includes full undercover and active grille shutters but since it has great CO_2 reduction it seems that it will become a common choice in the future, especially in US where Off-cycle credits may be gained.

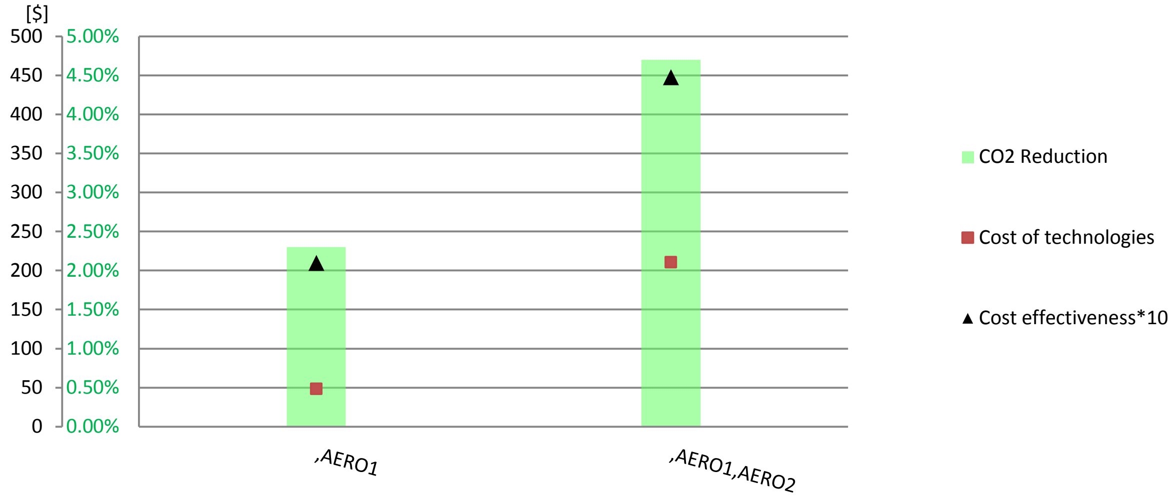

Figure 3-16 Aerodynamic improvements path. MY 2018. 2010 Dollars.

3.5.9.7 Transmission technologies path

This path, along with engine and electrification paths have the major rule for CO_2 reduction since it can achieve up to 19% CO_2 reduction. Differentiation between MT and AT has to be done because of two reasons. First, they are two differentiated architectures and so there is no assessment of the cost to pass from one to another but rather, the cost of maintaining the architecture and add technological improvements. Secondly, the commercialization of MT or AT vehicles is unfortunately, the market's choice (the customer's choice). The last statement makes automobile manufacturers to have limited potential CO_2 reduction strategies on this AT path.

The reference car is a 4/5 gears MT or AT to which the plotted technologies in the Figure 4-16 can be added. No comparison between MT technologies and AT technologies can be made because they are relative to their own reference car. To be able to compare between them, costs of the reference technologies should be taken into account.

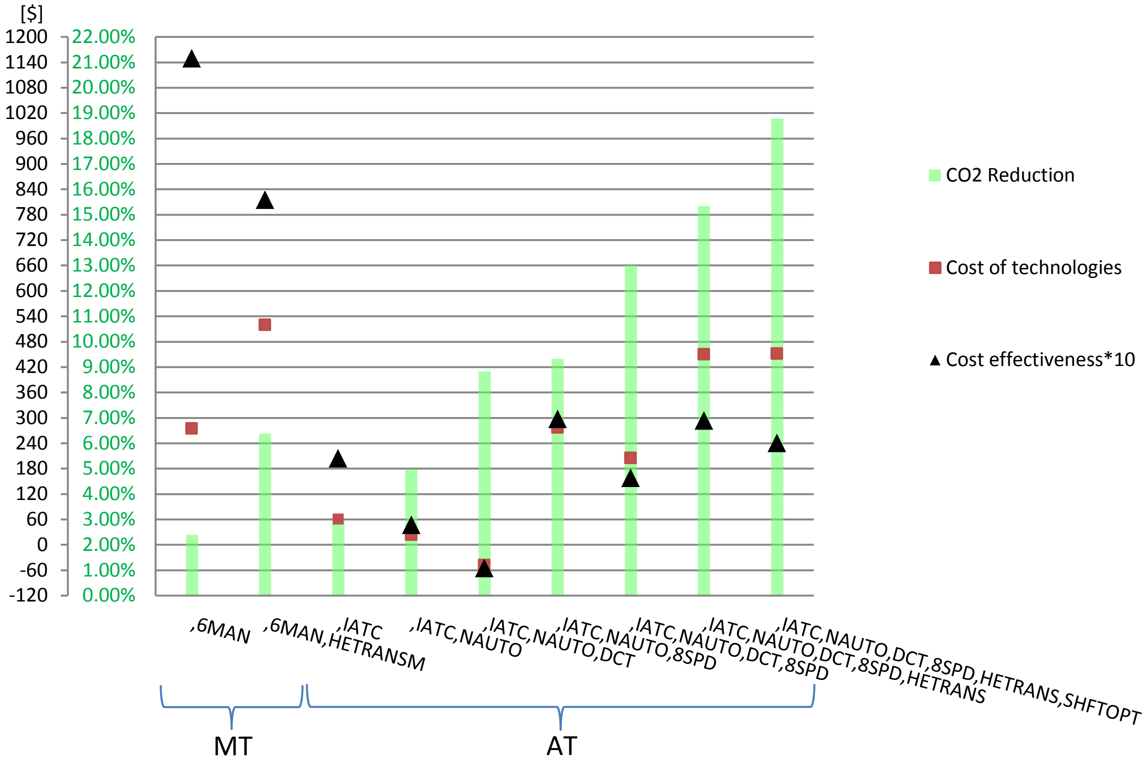

Figure 3-17 Transmission technologies path. MY 2018. 2010 Dollars.

Note that agencies forecast that MT technologies cost effectiveness improves quite a lot by adding HETRANSM to a six gears MT.

For what concerns AT: by looking the cost effectiveness in the Figure 3-17, there are two packages that seem to be good choices.

IATC, NAUTO, DCT has the minimum incremental cost (actually it is negative) which means that this will be the base package that AT engines will use for its low cost and high CO_2 reduction.

For further reduction the addition of more gears 8SPD is a very competitive choice.

3.5.9.8 Other off-cycle technologies

In this case no combinations of the technologies are depicted in the Figure 3-18 because they can be combined in whatever way. All of them may be used as off-cycle credits according to EPA GHG regulations but only the acronyms followed by "–EU" are technologies susceptible to eco-innovative credits according to NEDC regulations. As said before in the chapter 3.5.8, they have been taken out of the model analysis.

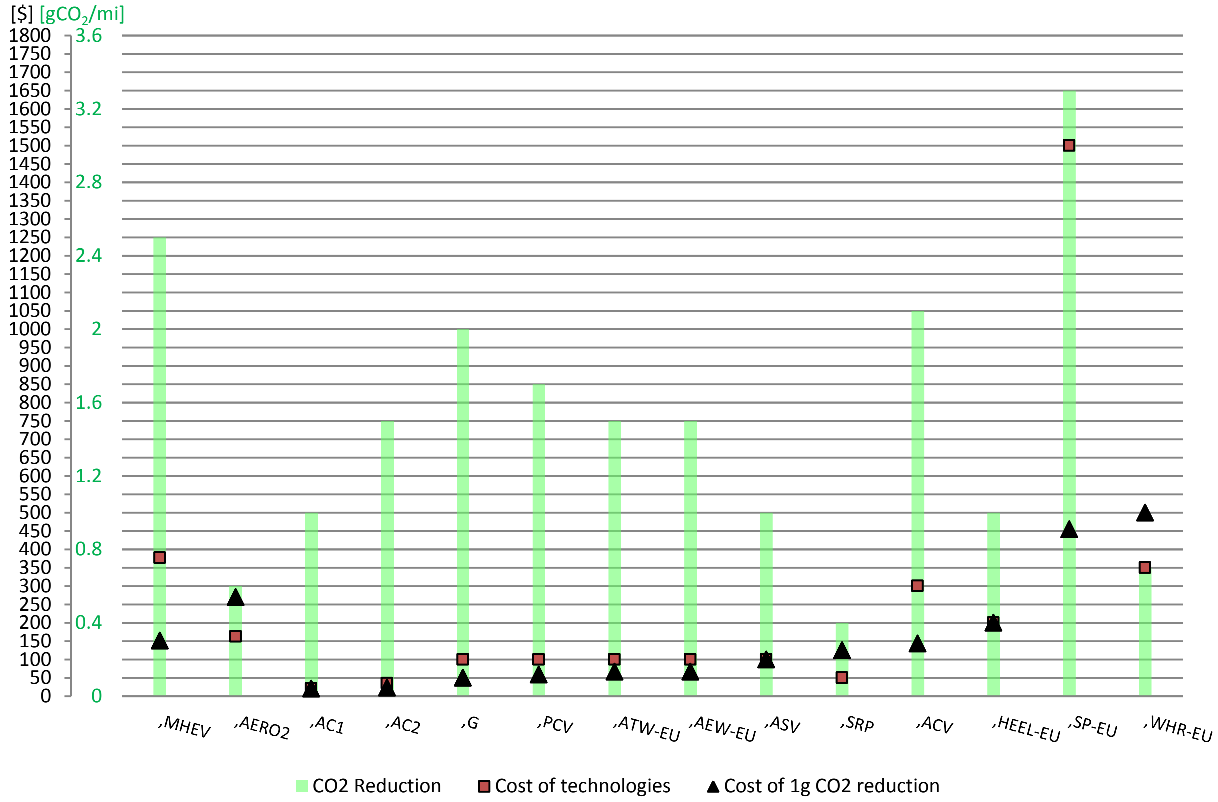

Figure 3-18 Off-cycle technologies for EPA GHG calculation.

Data relating the costs of these technologies have been taken from non-official sources so non committed conclusions can be made from this. Nevertheless It can be said that AC1 (high efficiency AC system) is been more and more common because of its ratio between cost and CO_2 reduction. It corresponds to 1g/mi reduction (if formal justification is valid) which is in rough numbers about 0,5% CO_2 reduction and a cost of about 20$.

3.6 Model inputs

As will be showed, there are not many inputs because the major amount of model parameters are intrinsic in the algorithm and therefore, it automatically adapts to the reference model studied. In other words, only the data that has to be introduced by the user is given here. However the user can change all the parameters in the model but the more susceptible-to-change ones are the following ones.

As two engines have been studied, there are two differentiated model inputs data. However, some of the values remain the same as the reference body is the same. Most of the input data is not the actual data since no "confidential" information should be published.

3.6.1 Vehicle reference mass

It is used to find the CO_2 target according to NEDC regulations. It is the curb weight. The Reference mass may vary among the different motorizations but in this case it has been assumed that:

$$RefMass[kg] = 1395$$

3.6.2 Vehicle footprint

It defines the CAFE MPG target through the created lookup table. It is defined as the average track width TW times the wheelbase WB.

$$\boldsymbol{Footprint[ft^2] = Average\ TW \cdot WB = \frac{59{,}4in+59{,}1in}{2} \cdot 102{,}8in \cdot 0.083^2\, {ft^2}/{in^2} = 42{,}3} \qquad \text{Equation 3-1}$$

3.6.3 Already applied technologies

This is a list of technologies that are considered as already applied to the reference models and therefore considered as not applicable (but belonging) to the package. Expressed as $BaseTechs_k$.

Table 3-4 Low FC technologies already applied to the reference car. $\boldsymbol{BaseTechs_k}$**.**

Midsize car 1.4NA MT Engine (DOHV)	**Midsize car 1.3T AT Engine (SOHV)**
ICP (engine)	EFR1 (engine)
DCP (engine)	CCPS (engine)
CVVL (engine)	DVVLS(engine)
	SGDI (engine)
	Turbo 24BMEP & Down + EGS (engine)
	IACT (transmission)
	NAUTO (transmission)
	DCT (transmission)
	AERO1 (aerodynamic)

3.6.4 Technology applicability matrix

This input is highly related to the previous one because it has to be created upon the already applied technologies and the vehicle's architecture. It is a matrix filled with 1 and 0 corresponding to the variable x_{izk} which is a Boolean that takes value of 1 when technology $\mathrm{SN_z}$ is applyaple in the package i of the reference car k and 0 otherwise. To see how should be implemented, see the example in the Table 4-5.

Table 3-5. Example of technology applicability matrix.

Model technology name	**SN_1**	**SN_2**	**SN_3**	**SN_4**	**Packages**
Simplified name of technology	**TechA**	**TechB**	**TechC**	**TechD**	
Incremental to	**Reference car**	**TechA**	**Reference car**	**TechA & Tech C**	
Package 1 (i=1)	1				TechA
Package 2 (i=2)	1	1			TechA+TechB
Package 3 (i=3)			1		TechC
Package 4 (i=4)	1		1		TechA+TechC
Package 5 (i=5)	1	1	1		TechA+TechB+TechC
Package 6 (i=6)	1		1	1	TechA+TechC+TechD
Package 7 (i=7)	1	1	1	1	TechA+TechB +TechC+TechD

In the example, there are four technologies and 7 possible packages. Not $2^4=16$ as if any conditions were given. The row “incremental to” refers to the conditions for the applicability of a technology. So for example, TechB cannot be applied if TechA is not in the package.

If the reference car does already apply some of the technologies or its architecture does not allow the application of some technologies then the matrix shifts. Let’s imagine that TechC cannot be applied for some of the previous reasons. Then the matrix become as shown in the Table 3-6:

Table 3-6 Example of technology applicability matrix when technologies are already applied in the reference car.

Model technology name	**SN_1**	**SN_2**	**SN_3**	**SN_4**	**Packages**
Simplified name of technology	**TechA**	**TechB**	**TechC**	**TechD**	
Incremental to	**Reference car**	**TechA**	**Reference car**	**TechA & Tech C**	
Package 1 (i=1)	1				TechA
Package 2 (i=2)	1	1			TechA+TechB

Yes, this is a quite common exercise that can be solved with some mathematical tools as Matlab® in a more or less complex way. Unfortunately only Microsoft Excel ® licenses were available and so a manual process was used. However, although it may seem a slow and tiring process, it is not because most of the times just copy-paste and addition of columns of ones is needed to complete the matrix. In some 10 minutes can be solved. Besides, it allows the user to create whatever combination of technologies easily and see automatically the results.

3.6.5 Vehicle reference cost

This is used in the calculation of the highest profits package in the sections 3.7.19 and 3.7.18. A value of 15000$ has been used as a reference for the reference model with a 1.3T AT engine and 14000$ for the reference model with 1.4 NA MT engine.

$$RefCost_1[\$] = \$14000$$

$$RefCost_2[\$] = \$15000$$

3.6.6 Type of drive train

Used in order to choose among one of the two lookup tables (passenger cars or light duty trucks) for the CAFE MPG target.

RWD and FWD use passenger cars table while AWD uses light duty trucks table. Only the name has to be introduced into the appropriate cell. Furthermore, when car architecture is AWD, low FC emissions technology SAX (Secondary Axle disconnection) can be used.

3.6.7 Reference CO_2 emissions, FE or FC

They the reference value related to the reference vehicle model to which the percentage of FC reduction due to technologies is applied. It is worth to give some explanation of this issue to not create confusion to the reader. However, further information and calculations are shown in the chapter 3.7.4.

In this study case there are four possible ways to express the reference CO_2 emissions, FC or FE. It is depicted in the Figure 3-19:

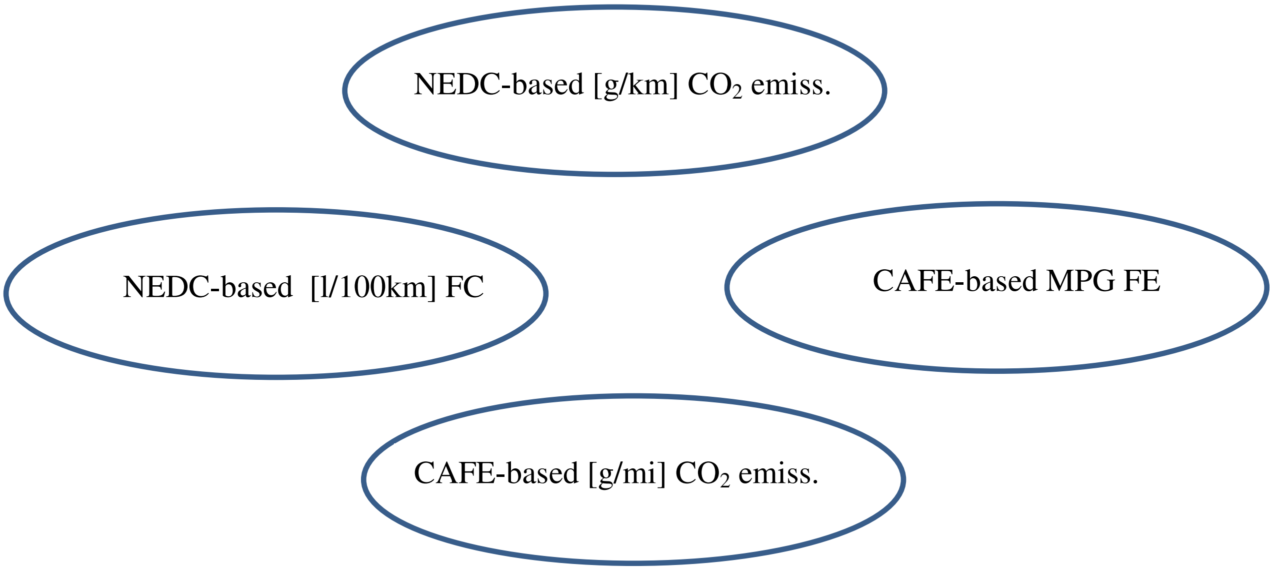

Figure 3-19 Four main ways of measuring CO_2 emissions/FC/FE

Bear in mind that the relation among NEDC-based and CAFE-based units is not a simple unit conversion because the test procedures are different, as has been discussed along the work.

It makes a lot of sense to assume that the reference value will be given in NEDC-based due to the fact that "brand[6]" models are basically marketed (and so homologated) in Europe. Therefore the CAFE-based value is not known in principle.

The reference CO_2 emissions values are 125g/km (NEDC-based) for 1.3T model and 150g/km (NEDC-based) for the 1.4NA model.

$$NEDC\_RefEmissions_1 = 150g/km$$
$$NEDC\_RefEmissions_{\mathbf{2}} = 125g/km$$

However, because the percentages of FC reduction are given as CAFE-based the model has to: Convert reference from NEDC-based to CAFE-based, then calculate the new CAFE-based MPG after technologies are applied (this is the actual value that will be compared to the CAFE target) and finally calculate from the new CAFE-based MPG, the new NEDC-based (This is the actual value that will be compared to the NEDC target).
This process is depicted in the Figure 3-20 and is explained in detail in the chapter 3.7.4.

3.6.8 Market sales coefficients

The user can play with the percentage of sales in a specific country over the total sales of a particular model. The package which offers the best global margin may switch depending on this. The current value for the two reference models assessed is the same and it is: 20% of the total sales are in USA and the remainder 80% in Europe.

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[6] It is assumed that most of the product portfolio is basically commercialized in Europe

3.6.9 Other parameters

Of course the user may be interested in playing with other model parameters. Probably the most interesting ones are: Cost of the technologies, FC reduction of the technologies, price of the fuels, price vs performance, car price vs FC and the extra costs of exporting to USA.

3.7 Created mathematical model

In this chapter, a detailed description of how the outputs have been obtained will be given. To understand the following equations it is important to remind that the index i defines the package, the index *j* defines the year, the index *z* defines the technology and the index *k* the reference car.

3.7.1 Technology package G_PACK$_{ik}$:

Given a reference car with a reference engine, a vector with i different packages may be calculated. G_PACK_{ik} gives a vector in which any cell *i* shows a different technology package.

$$\boldsymbol{G\_PACK_{ik} = x_{i1k}SN_z \& \ldots \& x_{iz_{max}}SN_z} \qquad \text{Equation 3-2}$$

Where:

& symbolizes the union of strings in one word/cell.

SN_z is the simplified name of the technology *z*.

x_{izk} is a Boolean that takes value of 1 when technology SN_z is applicable in the package *i* and reference model *k*. This variable will be used from now in other formulas.

3.7.2 CAFE FC reduction without synergies C_FCR$_{ik}$

Gives the percentages of FC reduction according to CAFE regulations of a technology package *i* without taking into account synergies between technologies in the package. For any of the reference car models *k*.

$$\boldsymbol{C\_FCR_{ik} = 1 - \prod_{1}^{z_{max}} x_{izk} \cdot (1 - R_z)} \qquad \text{Equation 3-3}$$

Where:

R_z Is the CO_2 reduction due to the application of a single technology *z* without taking into account synergies among different technologies in the package *i*.

3.7.3 CAFE FC reduction variation due to synergies C_FCS$_{ik}$:

Since its calculation includes functions it can be expressed in terms of functions for a better comprehension.

$$\boldsymbol{C\_FCS_{ik} = Find(G\_PACK_{ik}, BaseTechs_k, SYNCO2)} \qquad \text{Equation 3-4}$$

Where:

$SYNCO2$ is a table with pairs of technologies and its FC reduction variation with reference to the C_CO2R_{ik}. See the spreadsheets in the annexes.

$Find$ is a function which returns the total CO_2 emissions variation due to synergies between technologies in the package G_PACK_{ik} for any package i and reference car model *k*.

$BaseTechs_k$ is a cell which contains all the technologies already applied to the reference car (see Table 3-4) that may be sensible to synergies with technologies in the package *i*. In this way, the G_PACK_{ik} vector is complemented by $BaseTechs_k$ so that all synergies can be assessed, even those technologies that are out of the packages because they are already applied to the reference car. For example, Discrete Variable Valve Lift DVVL has been considered as already applied in the reference car and so it does not appear in G_PACK_{ik} vector but it does appear in $BaseTechs_k$so the synergies with other applicable technologies are assessed.

3.7.4 CAFE MPG resultant C_MPG_{ik} and NEDC resultant CO_2 emissions N_CO_{2ik}

This is the most critical point of the model, where the final values of FE and CO_2 emissions will be calculated in order to assess CAFE and NEDC compliance. It is not an obvious calculation because many factors are in play here. As an example, MPG for CAFE calculation is quite differently calculated depending on the kind of fuel. Another example is EV which account as well-to-wheel in CAFE regulations and tank-to-wheel in NEDC regulations and therefore as >0g/mi on the first case and 0g/km on the second case. Furthermore, since all data on FC reduction is CAFE-based, special conversion coefficients have to be used to find NEDC-based CO_2 emissions values. In order to understand how this problem has been faced, the Figure 3-20 is showed and some explanation is given. Furthermore, in the following chapters it is studied deeply.

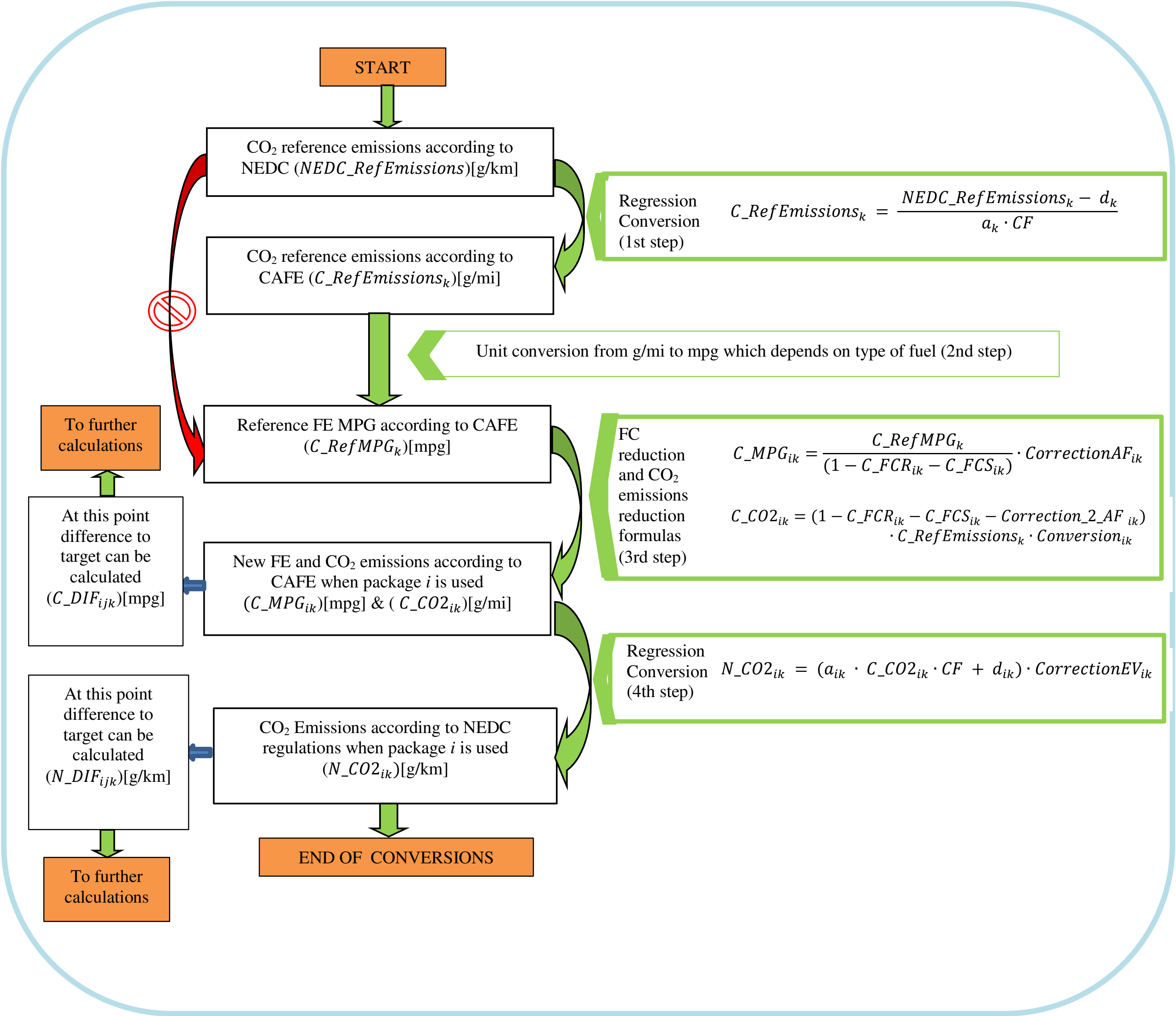


Figure 3-20 CAFE-NEDC: FC, FE and CO_2 emissions conversion process

From the starting point, the reference vehicles CO_2 emissions according to NEDC procedure is known as already explained in detail in the chapter 3.6.7. From this point, an explanation step to step is done:

- First and second step: Since the model FC reduction values are CAFE-based and the reference emissions known are NEDC-based, a conversion from $NEDC\_RefEmissions_k$ to C_RefMPG_k is needed. To this concern the regressions equations are used (1st step) and a simple units conversion from g/mi to mpg (2nd step) is performed.
- Third step: Both CAFE-based MPG C_MPG_{ik} and CO_2 emissions of the reference car when packages of technologies are applied are calculated. No simple unit conversion is between these two terms because AFV as LPG and CNG MPG are calculated in a special way. $CorrectionAF_{ik}$ is a coefficient that deals with it. At this point the resultant MPG can be compared to the target/limit MPG according to CAFE regulations.
- Forth step: From the CAFE-based CO_2 emissions C_CO2_{ik} the NEDC-based CO_2 emissions $N_CO2_{ik}$are calculated. This is by using the regression equations and a correction coefficient for EV. Which gives 0g/km emissions for NEDC regulations (tank-to-wheel) and >0g/mi (and therefore not infinite MPG) for CAFE regulations (well-to wheel). The regression equations are supposed to give a mid-degree of approximation for any other conventional and hybrid car.

3.7.4.1 CAFE MPG resultant C_MPG_{ik}

So, if the reference CO_2 emission is given according to NEDC regulations, it has to be transferred to CAFE with the following equation:

$$\boldsymbol{C\_RefEmissions_k} = \frac{\boldsymbol{NEDC\_RefEmissions_k - d_k}}{\boldsymbol{a_k \cdot CF}} \qquad \text{Equation 3-5}$$

Where:

$NEDC\_RefEmissions_i$:Is the NEDC reference CO_2 emissions [g/km]

$C\_RefEmissions\ _k$:Is the CAFE reference CO_2 emissions [g/mi]

CF:Is the conversion factor from [g/mi] to [g/km] which is 0,62137

And the regression parameters of d_k and a_k can be found on the Table 3-7 particularly: “Gasoline all data” regression parameters are chosen for the 1.4 NA Engine reference car model and “Gasoline AT6 PRE BASELINE” regression parameters are chosen for the GSET4 engine reference car model. A detailed explanation of this choice can be found in the section 3.7.4.3.

From the Equation 3-5, the FE achieved by any of the technology packages applicable to a given reference car is assessed with Equation 3-6:

$$\boldsymbol{C\_MPG_{ik} = \frac{C\_RefMPG_k}{(1 - C\_FCR_{ik} - C\_FCS_{ik})} \cdot CorrectionAF_{ik}} \qquad \text{Equation 3-6}$$

Where C_RefMPG_k has to be calculated from $C\_RefEmissions_k$ as a conversion and since both reference cars are fueled with gasoline the conversion is:

$$\boldsymbol{C\_RefMPG_{1,2} = \frac{2400.8 * 3{,}785}{C\_RefEmissions_{1,2}}} \qquad \text{Equation 3-7}$$

And the conversion factor can be found in the chapter 2.2.

$CorrectionAF_{ik}$ is the correction coefficient for AFV such as LPG and CNG. Therefore when the package includes these conversions, a correction for MPG calculation has to be done according to CAFE regulations. Particularly reminding what explained in the chapter 2.3.4.2 (*i.e.* supposing UF=1…):

For LPG packages Equation 3-8 prevails

$$\boldsymbol{CorrectionAF_{LPGk} = \frac{0{,}95}{1{,}35 \cdot 0{,}15} = 4,3} \qquad \text{Equation 3-8}$$

Where 1,35 stands for the increased FC due to LPG’s lower energetic content relating to gasoline. So it is converted to GGE (Gasoline Gallon Equivalent), following the regulations.

The 0,15 divisor is basically an incentive multiplier which increases the final MPG.The 0,95 multiplier is coherent with a 5% reduction in fuel efficiency due to not optimal operation in LPG and Gasoline mode.

For CNG packages Equation 3-9 prevails:

$$\boldsymbol{CorrectionAF_{CNGk} = \frac{0{,}95}{0{,}15} = 5{,}3} \qquad \text{Equation 3-9}$$

CNG regulation says that the methodology determines a gasoline equivalent MPG based on the energy content of the gaseous fuel consumed. So the 0,95 multiplier takes into account it by supposing that the actual efficiency will be 5% lower.
The 0,15 divisor is basically an incentive multiplier which increases the final MPG.

3.7.4.2 CAFE resultant CO2 emissions C_CO2ik

Which is the actual value of the CO_2 emissions for the given vehicle and package.

$$\boldsymbol{C\_CO2_{ik} = (1 - C\_FCR_{ik} - C\_FCS_{ik} - Correction\_2\_AF_{\ ik}) \cdot RefEmissions_k \cdot Conversion_i} \qquad \text{Equation 3-10}$$

Where:
$RefEmissions_k$ has been calculated in the Equation 3-5.
$Conversion_i$ is the coefficient which allows to estimate the CO_2 emissions increase due to use of a fuel with higher carbon content which worsens the CO_2 emissions. This is, Diesel engines have greater emissions than gasoline engines if the FC or FE is the same. So, if the package i is diesel then:

$$\boldsymbol{Conversion_i = \frac{2667.6}{2400.8}} \qquad \text{Equation 3-11}$$

Otherwise its value is 1.

It is reminded that the sense of this is because the model works with FC reduction percentages so fuel considerations are important when passing to CO_2 emissions.

For LPG and CNG engines, a correction has to be done since C_FCR_{ik}, C_FCS_{ik} do not introduce CO_2 emissions reduction due to the use of cleaner fuels. Therefore, when conversion to CNG engine is considered:

$$\boldsymbol{Correction\_2\_AF}\ _{\boldsymbol{i_{CNG}k}} = \mathbf{20\%} \qquad \text{Equation 3-12}$$

When conversion to LPG engine is considered:

$$\boldsymbol{Correction\_2\_AF}\ _{\boldsymbol{i_{LPG}k}} = \mathbf{10\%} \qquad \text{Equation 3-13}$$

3.7.4.3 NEDC Resultant CO_2 emissions N_CO2_i

CAFE procedures and NEDC procedures are different and so, they give different values of CO_2 emissions. Since the data gathered to build the model refers only to CAFE regulations, the CO_2 emissions according to NEDC procedures are, in principle, unknown.

Some studies have been performed along the past years in order find a relation between both procedures which is useful to forecast the results of NEDC knowing CAFE and vice versa. This kind of study is particularly useful to forecast whether a fleet of vehicles only sold in EU (or USA) will meet the regulations in USA (or EU) or not without the need of performing both test procedures, which is expensive. Of course this is just some useful information for a study case, in which the cost of an extra test cycle may be avoided. However these relations will never be applicable as a conformity procedure.

An agency called International Council of Clean Transportation ICCT has been working for many years on this issue and it has developed some approaches to this concern (24). They have developed two studies in the years 2007 and 2014 in which CO_2 results were simulated over the test cycles for a variety of vehicle and technology packages using a sophisticated vehicle emission model developed by Ricardo Engineering, the DVT, which has been introduced in the chapter 1.4.2. Current vehicle architectures and advanced innovative technologies focusing on the 2020/2025 horizon were covered and so, the results are supposed to fit in this Thesis. Different types of regression analyses were applied in the 2014 study to the modelled CO_2 emission data in order to reduce the error of the regression. The idea is that a regression is done for some likely-to-occur packet of technologies. In such a way, regressions with lower Standard Error (StdErr) were found by ICCT (24). The likely-to-occur packages were: Gasoline – pre-baseline; Gasoline – baseline; Gasoline – advanced ICE; Gasoline – hybrid; Gasoline - advanced ICE and hybrid; Diesel – pre-baseline; Diesel – baseline and advanced ICE; Gasoline all-data; Diesel all-data.

Gasoline all-data and diesel all-data have been used when the reference car does not correspond to neither of the likely-to-occur packets. For example, in the case of the MT the vehicle, it has been considered better to use all data regressions for gasoline since there are no packets including MT. The same for the LPG and CNG packages in the MT reference car, where just "gasoline all-data" has been used.

Regression type:

$$\boldsymbol{N\_CO2_{ik} = a_{ik} \cdot C\_C02_{ik} \cdot CF + d_{ik}} \qquad \text{Equation 3-14}$$

Where:

N_CO2_{ik} :Is the NEDC CO_2 emissions [g/km]

C_C02_{ik} :Is the CAFE CO_2 emissions [g/mi]

CF: Is the conversion factor from [g/mi] to [g/km] which is 0,62137

Diverse vehicle architecture/packages will acquire different regression coefficients. The Table 4-7 describes it.

Table 3-7 Regression type used depending on vehicle architecture **(24)**

Regression type	a_{ik}	d_{ik} [gCO$_2$/km]	**StErr[gCO$_2$/km]**	**Vehicle architecture**
Gasoline Advanced ICE & DCT	1,0033	-1,476	1,16	EGR and DCT, IACC1
Gasoline AT6 Pre-baseline	1,1722	-8,003	4,75	AT, Lack of Start-stop, no energy recovery, low efficiency alternator
Gasoline all data	1,1325	-13,739	4,47	Any
Diesel baseline & advanced ICE	1,0094	0,785	1,49	AT, Advanced diesel, IACC1
Advanced ICE & Hybrid	0,9834	1,162	1,64	Strong hybrid
Diesel all data	1,2209	-21,218	7,02	Any

As can be seen, different standard error is given for each type of regression. The most accurate regressions are those in which packages have been considered. For example, in the case of Gasoline Advanced ICE & DCT, it can be stated that with 95% of certainty the value of N_CO2_{ik} is the actual value $\pm 1{,}16 g/km$ which is a variation of around 1,5%.

The algorithm automatically uses the coefficients that best fit the packages.
When analysing the 1.3T AT engine with strong electrification, the coefficients in the regression type “Advanced ICE and Hybrid” are used. However, if there is no strong electrification in the package but there is DCT and a first level of electrification, the regression type “Gasoline Advanced ICE & DCT” is used. Finally, in any other case the regression type “Gasoline AT6 Pre-baseline” is used unless conversion to diesel is done. In this last case “Diesel baseline & advanced ICE” regression type is used when electrification level 1 is applied and “diesel all data” is used in any other case. When considering conversion to CNG or LPG, they are simply considered as gasoline engines and the “gasoline all data” regression is used.

When analysing the 1.4NA MT engine, only “gasoline all data” type regression has been considered unless conversion to diesel is considered, in which “diesel all data” type regression has been used. This is because of the lack of regression packages with MT. As can be seen, in this case there is a much higher standard error in the calculation of N_CO2_{ik}.

3.7.5 CAFE CO_2 emissions reduction $C\_CO_2R_{ik}$

From the reference CO_2 emissions and the CO_2 emission of specific applied packages, the specific CO_2 reduction according to CAFE can be calculated as:

$$\boldsymbol{C\_CO2R_{ik}} = \frac{\boldsymbol{C\_RefEmissions_k - C\_CO2_{ik}}}{\boldsymbol{C\_RefEmissions_k}} \qquad \text{Equation 3-15}$$

3.7.6 CAFE MPG target C_MPGT_j

According to CAFE regulations, the FE limit depends on the vehicle class, the year and the footprint of the vehicle; the last one remains the same as the reference car body size does not change.

The vehicle class may change from passenger car to light truck when a vehicle meets definition in the Collection Code of Federal Regulations (annual edition) 49 CFR 523.2 – Definitions see annexes. To this it is important to highlight that an AWD vehicle may be considered a light truck if compliant with few more specifications. That’s why it has been considered of interest to add in the model the possibility to evaluate a light truck. In USA many people owns pick-ups, off-road vehicles and minivans which are considered as light trucks (although used for passenger transport) and so, with less stringent regulation limits concerning FE than a PC.

When the input AWD is written in the given model input cell, the MPG limit changes and becomes softer, easier to meet. Again, it depends on the footprint and the MY considered.

The algorithm simply looks for the MPG limit correspondent to the closest footprint which is equal or smaller than the reference one. This is done for each of the years in study.

This is modelled using the functions if(), Index() and compare() combined:

Compare(): Finds the position of the footprint in the table.
Index(): Gives the value of the CO_2 limit on the position given by the former function.
If(): Used to look at the passenger car table or light truck table.

3.7.7 CAFE Difference to target C_DIF_{ij}

This is the difference between the target MPG and the vehicle FE according to CAFE procedures when the several technology packages are applied. As already said the target is the limit according to CAFE.
Calculated as:

$$C\_DIF_{ijk} = C\_MPGT_{ik} - C\_MPG_{ik} \qquad \text{Equation 3-16}$$

3.7.8 Actual vehicle mass AM_{ik}

One of the low FC technologies that may be applied is the mass reduction which directly affects the CO_2 limits according to NEDC Procedures. As already said in the chapter 3.5.6, mass reduction is the only technology that affects the performance of the car by changing the mass of the car while maintaining the characteristics of the engine. Therefore, the actual mass of the car has been used either for: Calculation of the actual NEDC CO_2 emissions limit or calculation of the "most profitable package" due to the fact that the price of the car rises when performance is higher.

For simplicity reasons only 0%, 10% and 20% of mass reduction has been considered. The cost and the CO_2 emissions reduction varies depending on the vehicle architecture of the package analysed.

3.7.9 NEDC CO_2 emissions limit $N\_CO_2T_{ijk}$

According to NEDC regulations, the CO_2 target/limit depends on the vehicle class, the year and the reference weight of the vehicle which of course varies when applying weight reduction technologies.

An urban vehicle, differently from CAFE regulations, can only be a passenger car and so only one lockup table is used in this case.

The algorithm simply looks for the CO_2 limit correspondent to the closest which is equal or smaller than the reference one. This is done for any of the years in study.

This is modeled using the functions Index() and compare() combined:

Compare(): Finds the position of the weight in the table.

Index(): Gives the value of the CO_2 limit on the position given by the former function.

3.7.10 NEDC Difference to target N_DIF_{ijk}

This is the difference between the vehicle CO_2 emissions according to NEDC procedures when the several technology packages are applied and the target CO_2 emissions. As already said the target is the limit according to NEDC. Calculated as:

$$\boldsymbol{N\_DIF_{ijk} = N\_CO2_{ik} - N\_CO2T_{ijk}} \qquad \text{Equation 3-17}$$

3.7.11 Globally-Compliant packages GC_PACK_{ijk}

Globally compliant packages are those packages that make the vehicle to be compliant with both legislations and therefore, the ones that meet both inequalities:

$$\boldsymbol{N\_DIF_{ijk} \leq 0} \qquad \text{Equation 3-18}$$

$$\boldsymbol{C\_DIF_{ijk} \leq 0} \qquad \text{Equation 3-19}$$

The model writes the matrix with the packages using the following simple logic:
If the package *i* meets both requirements the cell *i* of the matrix GC_PACK_{ijk} takes the value of the cell *i* from the vector already explained $G\_PACK_{ik.}$ Otherwise the cell remains as void. This is done for any of the years *j* 2018 to 2024 and the two reference cars.
From this point, all packages considered in the following steps of the analysis are those that are complaints with both regulations.

3.7.12 Globally compliant incremental cost of technology package without considering synergies GC_ICWOS_{ijk}

It is the cost of the packages without taking into account the synergies that may vary the cost of a given technology when applied at the same time with a complementary technology. The model writes a matrix with the total incremental cost using the functions *sumif* and *if* and the following logic: If the package *i* is compliant, the cell takes the value of the sum of costs in the package *i.* Otherwise, the cell takes a value extremely high. The function that sums the costs of the technologies that are applied in a given package is *sumif* which of course, just adds the cost of the technology *z* when these have been included in the package *i*.
It can be expressed like this:

```
for j=2018 to 2024
for i=1 to $i_{max}$
If ($N\_DIF_{ijk} \leq 0$ and $C\_DIF_{ijk} \leq 0$ )
        $GC\_ICWOS_{ijk}$ = SumIF($x_{izk}$>0,$Cost_z$)
Else if $GC\_ICWOS_{ijk}$ = 99999999
end for
end for
```

3.7.13 Globally compliant incremental cost of technology package due to synergies GC_ICS_{ik}

The same concept explained in the chapter 3.7.3 but this time it refers to cost synergies. The calculation includes functions therefore it can be expressed in terms of functions for a better comprehension.

$$\boldsymbol{GC\_ICS_{ik} = Find(G\_PACK_{ik}, BaseTechs_{k}, SYNCOST)}$$ Equation 3-20

Where:

$SYNCOST$ is a table with pairs of technologies and its cost variation with reference to the GC_ICWOS_{ijk}. See the spreadsheets in the annexes.

3.7.14 Globally compliant incremental cost of technology package GC_IC_{ijk}

It is the total incremental cost of any possible compliant package *i*, taking into account the synergies among technologies. Calculated as:

$$\boldsymbol{GC\_IC_{ijk} = GC\_ICS_{ijk} + GG\_ICWO_{ijk}}$$ Equation 3-21

3.7.15 Globally compliant cost effectiveness (CAFE Based) GC_CE_{ijk}

It is defined as the ratio between the cost and the CO_2 reduction of a given package *i* in a year *j*. It is an interesting coefficient because when minimized, it tells us which package reaches the best values of cost and CO_2 reduction.

In order to calculate the cost effectiveness, CAFE- based CO_2 reduction values has been used and not FC reduction values. This is basically because FC reduction values are far to be obvious and similar to those of NEDC regulations (remember, the 0,15 divisor for FE calculations in CAFE regulations. See chapter 2.3.4).

Besides, although CAFE regulations limit FC, it has to be mind that the best indicator of GHG is CO_2 and so, European regulations and EPA GHG regulations are based on that.

$$GG\_CE_{ijk} = \frac{GC\_IC_{ijk}}{C\_CO2R_{ik}}$$ Equation 3-22

3.7.16 Most cost effective globally compliant package and its characteristics

Minimum cost effectiveness GC_MCE$_{jk}$

It is the value of the most cost effective globally compliant package for any of the years *j* in study.

$$GC\_MCE_{jk} = \min(GG\_CE_{ijk}) = GC\_CE_{i_{minCE}jk}$$ Equation 3-23

Most cost effective package GC_MCE_P$_{jk}$

It is the list of technologies of the most cost effective compliant package. Calculated using the functions *index()* and *compare()* where the former function gives the list of technologies corresponding to the index found by the function *compare()*which finds the index of the package corresponding to the minimum cost effectiveness GC_MCE_j.

$$GC\_MCE\_P_{jk} = GC\_PACK_{i_{minCE}jk}$$ Equation 3-24

Most cost effective compliant package incremental cost of technology package GC_MCE_IC$_{jk}$

It is the cost of the most cost effective compliant package cost. Found using the same functions as the previous calculation.

$$GC\_MCE\_IC_{jk} = GC\_IC_{i_{minCE}jk}$$ Equation 3-25

Most cost effective compliant package CO_2 emissions reduction (CAFE Based) GC_MCE_CO_2R_{jk}

It is the CO_2emissions reduction of the most cost effective compliant package only according to CAFE regulations. Found using the same functions as the previous calculation.

$$\boldsymbol{GC\_MCE\_CO2R_{jk} = C\_CO2R_{i_{minCE}jk}} \qquad \text{Equation 3-26}$$

3.7.17 Minimum incremental cost of globally compliant technology package

Cheapest globally compliant package cost GC_C_{jk}

It is the cost of the cheapest package that is globally compliant. Calculated as:

$$\boldsymbol{GC\_C_{jk} = \min(GC\_IC_{ijk}) = GC\_IC_{i_{minC}jk}} \qquad \text{Equation 3-27}$$

Cheapest globally compliant Package $GC\_C\_P_{jk}$

It is the list of technologies of the cheapest compliant package. Calculated using the functions *index()* and *compare()* where the former function gives the list of technologies corresponding to the index found by the function *compare()*which finds the index of the package corresponding to the minimum cost GC_C_j

$$\boldsymbol{GC\_C\_P_{jk} = GC\_PACK_{i_{minC}jk}} \qquad \text{Equation 3-28}$$

Cheapest globally compliant package cost effectiveness GC_CCE_{jk}

It is the cost effectiveness of cheapest compliant package. Found using the same functions as the previous calculation.

$$\boldsymbol{GC\_CCE_{jk} = GC\_CE_{i_{minC}jk}} \qquad \text{Equation 3-29}$$

Cheapest globally compliant package CO_2 emissions Reduction (CAFE Based) $GC\_CCO_2R_{jk}$

It is the CO_2 emissions reduction of the cheapest compliant package only according to CAFE regulations. Found using the same functions as the previous calculation.

$$GC\_CCO2R_{jk} = C\_CO2R_{i_{minC}jk}$$ Equation 3-30

3.7.18 EU Market Most profitable package

Most profitable package is a concept that has been "created" in this Thesis to assess which package gives the most profitablefor the automobile manufacturer in terms of the gap between price and cost.

$$Profit\ Margin = price\ of\ the\ car - cost\ of\ the\ car \propto CMC$$ Equation 3-31

In order to link the properties of the different packages to the price and the cost, three coefficients have been created and a combination of these is the final coefficient (Compounded Margin Coefficient CMC). The so called CMC is the final indicator of the margin linked to a package. The bigger is the coefficient, the higher is the margin for the company.

In order to be closer to the real world, two CMC coefficients have been created for the two main markets considered in this work, Europe and USA. This stands for the fact that those markets are completely different. One of the main differences is the low price of fuel in USA which makes buyers to not be willing to pay as much as Europeans for a lowest fuel consumption car.
Of course this is just a rough calculation. The real margin is highly susceptible to the characteristics of the market in each country/region/state and even the automobile manufacturers do not really know what are the packages to achieve the best margin and its link to the price of the car. In other words, many Thesis could be done trying to find a solution to this problem. In the frame of this work, it has been considered that only the following three coefficients have to do with the margin and a detailed explanation of them is showed as follows:

- Margin performance Coefficient: It is based on the fact that buyers are willing to pay more for cars with greater performance.

- Margin FC coefficient: It is based on the fact that buyers are willing to pay more for either cars with lower FC or cars which fuel is cheaper relatively to other fuels, like GPL compared to gasoline.
- Margin Cost coefficient: It assesses the fact that the cost of the car increases more or less depending on the package applied and if it has to be exported or not. Affecting in this way, the margin.

Margin performance Coefficient EU_MPC$_{ijk}$

To this concern the performance of the car and its relation with the price of the car has to be defined. A definition of performance widely used is the ratio between power and mass of the car. As already said, the performance of the car is maintained the same when applying all technologies but the mass reduction technology, which by changing the mass and maintaining the engine size varies the performance. From this assumption, it can be stated the following:

$$\boldsymbol{Performance_{ijk} = \frac{Power_k}{Mass_{ik}} \propto \frac{1}{1 - Mass\ reduccion_{ik}}} \qquad \text{Equation 3-32}$$

In this way, easily it can be said that if vehicle mass is maintained the same, $Performance_{ijk} = 1$ because it is the same as the reference car, if vehicle mass is reduced by 20% then the $Performance_{ijk} = 1{,}25$ and finally, if vehicle mass is reduced by 10% then $Performance_{ijk} = 1{,}11$.

Note that the Performance not only depends on the applied package *i* but also in the year *j*. This is because when packages are not compliant for a given year, the cells take the value of -99999. In this way, not globally compliant packages are kept out of the analysis.

Finally, from the info given by my tutor about the relation between price and performance "$Price\ sesitivity\ to\ performance$", the performance margin coefficient can be calculated.

$$\boldsymbol{Price\ sesitivity\ to\ performance = \frac{43\$}{0{,}01 hp/kg}} \qquad \text{Equation 3-33}$$

And taking the reference price of 18000$ for both reference cars, the performance margin coefficient is:

$$\text{If } \boldsymbol{Performance_{ijk} = 1,25 \ \rightarrow EU\_MPC_{ijk}} = \frac{\mathbf{18000+0,25\cdot {}^{43}/_{0,01}}}{\mathbf{18000}} = \mathbf{1,06} \qquad \text{Equation 3-34}$$

$$\text{If } \boldsymbol{Performance_{ijk} = 1,11 \rightarrow EU\_MPC_{ijk}} = \frac{\mathbf{18000+0,11\cdot {}^{43}/_{0,01}}}{\mathbf{18000}} = \mathbf{1,03} \qquad \text{Equation 3-35}$$

Margin FC coefficient EU_MFCC$_{ik}$

As already said there are basically two reasons why potential customers may pay more to purchase a car. Cars with lower FC or Cars which fuel is cheaper relatively to other fuels, like GPL compared to gasoline are susceptible to a higher price (as well as higher cost of course, which has already been calculated on GC_IC_{ij}). To deal with this, it has been considered very important to divide the market at least in two regions: Europe and USA. Obviously a detailed study of this issue would require a study for each of the countries/states or even smaller zones but it is out of the scope of this Thesis.

The coefficient is directly a number that multiplied by the reference car price, gives the approximated price of the car with the specific package. It has been defined as:

$$\boldsymbol{EU\_MFCC_{ik} = 1 + EU\_PSFC \cdot \frac{1}{EU\_FPC_{ik}} \cdot (C\_FCS_{ik} + C\_FCR_{ik})} \qquad \text{Equation 3-36}$$

Where:

EU_PSFC is the Price Sensitivity to FC reduction coefficient in Europe.

EU_FPC_{ik} is the Fuel Price Coefficient in Europe.

$C\_FCS_{ik} + C\_FCR_{ik}$ Has been defined before as the FC reduction of the package i (CAFE based)

It has been found a forecast which estimates the rise in the price of both gasoline and Diesel vehicles due to the FC reduction in the 2015 to 2020 period. It says that EU_PSFC equals to 0,35 in both types of cars while no specific data was found for HEV, LPG and CNG cars and so 0,35 is used as well for these cars. Probably it is still a good estimation. Therefore it has been supposed that EU_PSFC times the FC reduction is the car price increase.

Although the data found do not cover exactly the time period in study (2018 to 2024), It will be used as an estimation.

The EU_FPC_{ik} is a bit tricky concept that has been considered interesting to introduce. It has been thought that the EU_PSFC coefficient may be susceptible to variations due to differences in the price of the fuels. For example, the price of a gasoline package that shows the same FC reduction than a GPL package should be lower because GPL fuel price is lower than Petrol. Therefore, the horizontal axis of the plot is considered as equivalent to a reduction in the price of filling the tank. To face this issue, EU_FPC_{ik} has been created. And the following table shows how.

Table 3-8$\boldsymbol{EU_FPC_{ik}}$ assessment

		Conversion factors				
	Emissions [gCO_2/km]	**[gCO_2/l] or [gCO_2/kg] (for CNG)**	**Average Price in EU [€/l] or [€/kg] (for CNG)**	**Cost of 100km run [€/100km]**	**Fuel Price Coefficient**	**Adjusted Fuel Price Coefficient in Europe $\boldsymbol{EU\_FPC_i}$**
Gasoline	100	2330,0	1,16	4,98	1,00	1,00
Diesel	100	2640,0	1,10	4,17	0,84	0,84
LPG	100	1528,0	0,62	4,06	0,82	0,86
CNG	100	2669,0	1,04	3,90	0,78	0,82

The table above shows different fuels and its prices when CO_2 emissions are the same for all of them. Notice the variations in the cost of running 100km.

The Fuel Price Coefficient column shows the relative price of the fuel relative to the price of the gasoline. The final value, which is given in the last column, is the former adjusted. The adjustment is based on the fact that it has been considered appropriate to multiply by 1,05 the Fuel Price Coefficient of those fuels that cannot be found in all the fuel stations and so they are less convenient. Of course they are CNG and LPG. Finally, the model automatically uses the coefficient that corresponds to the fuel of the package i.

Note how in Europe, in average, any other fuel different from gasoline, shows price advantages at same level of CO2 emissions. The cheapest one is CNG followed by Diesel and finally LPG.

Margin Cost coeff. EU_MCC_{ijk}

It assesses the fact that the cost of the car increases more or less depending on the package applied and if it has to be exported or not. The $EU\_ExtraCost$ which takes into account the expenses due to exportation procedures (shipping, documentation…) has been considered 0 in Europe and in the case USA its value is 400$.

$$\boldsymbol{EU\_MCC_{ijk} = \frac{EU\_ExtraCost + RefCost_k + GC\_IC_{ijk}}{RefCost_k}} \qquad \text{Equation 3-37}$$

Compounded margin coeff. EU_CMC_{ijk}

As already said this is the final margin coefficient for Europe

$$\boldsymbol{EU\_CMC_{ijk} = EU\_MPC_{ijk} + EU\_MFCC_{ik} - EU\_MCC_{ijk}} \qquad \text{Equation 3-38}$$

MAX Margin EU_MCMC_{jk}

It is the maximum value of the EU_CMC_{ij} for any of the years.

$$\boldsymbol{EU\_MCMC_{jk} = Max(EU\_CMC_{ijk}) = EU\_CMC_{i_{maxMEU}jk}} \qquad \text{Equation 3-39}$$

Package EU_MCM_P_{jk}

It is the list of technologies of the compliant package of maximum margin in Europe. Calculated using the functions *index()* and *compare()* where the former function gives the list of technologies corresponding to the index found by the function *compare()* which finds the index of the package corresponding to the maximum margin EU_MCMC_{jk}

$$EU\_MCM\_P_{jk} = GC\_PACK_{i_{maxMEU}jk} \quad \text{Equation 3-40}$$

CO_2 emissions Reduction (CAFE Based) EU_MCM_CO_2R_{jk}

It is the CO_2emissions reduction of the best EU margin package only according to CAFE regulations. Found using the same functions as the previous calculation.

$$EU\_MCM\_CO2R_{jk} = C\_CO2R_{i_{maxMEU}j} + C\_CO2S_{i_{maxMEU}j} \quad \text{Equation 3-41}$$

Incremental cost of technology package EU_MCMC_IC_{jk}

It is the cost of the technology package with highest EU margin. Found using the same functions as the previous calculation.

$$EU\_MCMC\_IC_{jk} = GC\_IC_{i_{maxMEU}jk} \quad \text{Equation 3-42}$$

Cost effectiveness EU_MCMC_CE_{jk}

It is the ratio between cost and CO_2 emissions reduction of most profitable compliant package. Found using the same functions as the previous calculation.

$$EU\_MCMC\_CE_{jk} = GC\_CE_{i_{maxMEU}jk} \quad \text{Equation 3-43}$$

3.7.19 USA Market most profitable package

The introduction of this concept and the entire explanation has been shown in the chapter 3.7.18. Consequently, only the differences will be exposed here.

Margin performance Coefficient USA_MPC$_{ijk}$

The coefficient“$Price\ sesitivity\ to\ performance$” has been considered the same in EU and US therefore rely on chapter 3.7.18 for further information.

Margin FC coefficient USA_MFCC$_{ik}$

$$\boldsymbol{USA\_MFCC_{ik} = 1 + USA\_PSFC_k \cdot \frac{1}{USA\_FPC_{ik}} \cdot (C\_FCS_{ik} + C\_FCR_{ik})} \qquad \text{Equation 3-44}$$

Where:

USA_PSFC_k is the Price Sensitivity to FC coefficient in USA

USA_FPC_{ik} is the Fuel Price Coefficient in USA

$C\_CO2S_{ik} + C\_CO2R_{ik}$ Has been defined before as the CO_2 emissions reduction of the package i (CAFE based)

From, the Annual Energy Outlook (41), it has been found a forecast that states that in US gasoline cars, from MY2010 to MY2025 will experience a improvement in FC of around 51% and an increase in price of a 10% while diesel cars will improve its FC in around 22% and the price will maintain roughly the same. Thanks to this data, USA_PSFC_k has been made as an estimation of the price increase related due FC improvements. Therefore It has been supposed that USA_PSFC_k times the FC reduction is the car price increase. In USA, differently from what happens in Europe, the price sensitivity to FC coefficient (USA_PSFC_k) for Diesel cars and petrol cars has a totally different value. While for Diesel vehicles USA_PSFC_k is 0 which means that potential customers won’t pay more for a lower FC car, for petrol cars the slope is 0,19. Although the value of USA_PSFC_k for Diesel cars in USA (cero) may seem strange, it can be justified by the fact that Diesel market in USA is a niche market which behaves totally different than petrol market. For CNG and LPG vehicles the same value as for gasoline engines has been supposed.

Remember that the value of EU_PSFC is 0,35. The smaller value of the petrol coefficient in USA compared to EU stands most probably because of the much lower price of the petrol in USA which is around 3 times cheaper.

For what concernsUSA_FPC_{ik}, the Table 3-9 has been made to be able to compare fuel pricing in USA and Europe. The prices were taken from (42) as an average price in US in 2014.Other data from (6).

Table 3-9 Fuel price conversion form US units to European units **(42)** **(6)**.

	From \$/gall and \$/GGE to €/l and €/kg				
	\$/gall	**\$/GGE**	**\$/kg**	**€/l**	**€/kg**
Gasoline	3,51			0,75	
Diesel	3,89			0,83	
LPG	3,15			0,67	
CNG		2,14	0,84		0,68

1 USA gallon to l	3,7854
1 \$ to €	0,8079
1 GGE to kg of CNG	2,56

Furthermore, the USA_FPC_{ik} is given in the last column of the Table 3-9.

Table 3-10 $\boldsymbol{USA\_FPC_{ik}}$ assessment

		Conversion factors				
	Emissions [gCO_2/km]	**[gCO_2/l] or [gCO_2/kg] (for CNG)**	**Average Price in EU [€/l] or [€/kg] (for CNG)**	**Cost of 100km run [€/100km]**	**Fuel Price Coefficient**	**Adjusted Fuel Price Coefficient in USA $\boldsymbol{USA\_FPC_i}$**
Gasoline	100	2400,8	0,75	3,12	1,00	1,00
Diesel	100	2667,6	0,83	3,11	1,00	1,00
LPG	100	1528,0	0,67	4,39	1,41	1,48
CNG	100	2669,0	0,68	2,53	0,77	0,81

Note how at same level of CO2 emissions, gasoline and diesel are the same price and LPG is quite expensive while CNG is cheaper, in average.

Margin Cost coefficient USA_MCC$_i$

$$\boldsymbol{USA\_MCC_{ijk}} = \frac{\boldsymbol{USA\_ExtraCost + RefCost_k + GC\_IC_{ijk}}}{\boldsymbol{RefCost_k}}$$ Equation 3-45

Notice that $USA\_ExtraCost$ is 400$ due to expenses for procedures as shipping and documentation for importing vehicles in USA.

The outputs mentioned bellow show the same definition the EU case explained in the chapter 3.7.18.

Compounded margin coefficient USA_CMC$_{ijk}$
MAX Margin USA_MCMC$_{jk}$
Package USA_MCM_P$_{jk}$
CO_2 emissions Reduction (CAFE Based) USA_MCM_CO_2R_{jk}
Incremental cost of technology package USA_MCMC_IC$_{jk}$
Cost effectiveness USA_MCMC_CE$_{jk}$

3.7.20 Best global margin package

On the previous chapters the packages which offer bests margins for EU and USA have been calculated. Therefore, two different solutions can be found for each year. However, one of the targets of this Thesis was to find a global solution instead of regional solutions. The following coefficient faces this issue.

Global Margin coefficient GM_GMC$_{ij}$

Calculated as:

$$\boldsymbol{GM\_GMC_{ijk} = EU\_CMC_{ijk} \cdot EU\_Mkt\_Share_k + USA\_CMC_{ijk} \cdot USA\_Mkt\_Share_k}$$ Equation 3-46

Where:

$EU\_Mkt\_Share_k$ is the fraction of vehicles that are supposed to be sold in Europe over the total sold vehicles. It has been supposed a value of 80%.
$USA\_Mkt\_Share_k$ is the fraction of vehicles that are supposed to be sold in USA over the total sold vehicles.

Furthermore, The outputs mentioned bellow show the same definition the EU case explained in the chapter 3.10.
Compounded margin coefficient USA_CMC_{ijk}
MAX Global Margin GM_MGM_{ik}
Package $GM\_MGM\_P_{jk}$
CO_2 emissions Reduction (CAFE Based) $GM\_MGM\_CO_2R_{jk}$
Incremental cost of technology package $GM\_MGM\_IC_{jk}$
Cost effectiveness $GM\_MGM\_CE_{jk}$

3.8 Model outputs and results

3.8.1 Model outputs

The model outputs explained in detail in the chapters 3.7 are summarized in the following table and afterwards, the results are given.

Table 3-11 Outputs summary

Model technology Name	Output referring to	Name	units (If case). [-] when dimensionless	Indexing	Comments and definitions
G_PACK_{ik}	Global	Technology package		i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the technologies for the corresponding package and reference car model.
C_FCR_{ik}	CAFE	FC Reduction	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the value of the percentage of FC reduction for the corresponding package and reference car model without taking into account synergies
C_FCS_{ik}		FC variation due to synergies	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the value of the percentage of FC variation due to synergies for the corresponding package and reference car model
C_MPG_{ik}		Resultant MPG	mpg	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the value of the FE for the corresponding car reference model and package
C_CO_{2ik}		Resultant CO_2 emissions	g/mi	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the value of the CO_2 emissions for the corresponding car reference model and package

$C\_CO_2R_{ik}$		CAFE CO_2 Reduction	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the CO_2 reduction according to CAFE regulations. Calculated from the $C\_RefEmissions_k$ defined in the inputs chapter and the C_CO_{2ik}
C_MPGT_{jk}		FE target(limit)	mpg	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Contains the FE limit according to CAFE regulations, the car footprint and the type of car (PC or Light duty truck) for the year 2018 to 2024
C_DIF_{ijk}		Difference to target	g/mi	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the value of the difference between the target FE and the real package FE for any package , reference model and year 2018 to 2024
N_CO_{2ik}	NEDC	Resultant CO_2 emissions	g/km	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the value of the CO_2 emissions for the corresponding reference car model and package
AM_{ik}		Actual vehicle mass	kg	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the actual reference mass of the car because mass reduction technologies may be applied in a given package of a given reference model.
$N\_CO_2L_{ijk}$		CO_2 emissions limit	g/km	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Contains the CO_2 emission limit according to NEDC regulations. Thus, according to the car actual reference mass for the years 2018 to 2024 and reference car model.
N_DIF_{ijk}		Difference to target	g/km	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the value of the difference between NCO_{2i} and NCO_2L_{ij} For any of the considered years 2018 to 2024 and reference car models.
GC_PACK_{ijk}	Global-Compliant packages	Packages		i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the technologies for the corresponding package. For any of the considered years 2018 to 2024 and reference car models.
GC_ICWOS_{ijk}		Incremental cost of technology package wo synergyes	$	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the incremental cost of the corresponding package without taking into account the synergies between them. This is done for every considered year 2018 to 2024 and reference car models.

GC_ICS$_{ik}$		Incremental cost of technology package due to synergies		$	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	Every cell contains the variation of the cost of the corresponding package due to the synergies between its technologies for any reference car model.
GC_IC$_{ijk}$		Incremental cost of technology package		$	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the total incremental cost of the corresponding package. This is done for every considered year 2018 to 2024 and reference car models.
GC_CE$_{ijk}$		Cost efectivenes (CAFE Based)		$	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the value of the cost effectiveness of the corresponding package. This is done for every considered year 2018 to 2024 and reference car models.
GC_MCE$_{jk}$		Most cost effective package	Minimum cost effectivenes	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the minimum value of the cost effectiveness and so, optimum of the cost effectiveness for any of the considered years and reference car models.
GC_MCE_P$_{jk}$			Package		j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the technologies that the most cost effective package has depending on the year 2018 to 2024 and reference car models.
			Incremental cost of technology package	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the incremental cost that the most cost effective package has depending on the year 2018 to 2024 and reference car models.
GC_MCE_CO$_2$R$_{jk}$			CO$_2$ Reduction (CAFE Based)	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the value of the CO$_2$ emissions reduction that the most cost effective package has depending on the year 2018 to 2024 and reference car models.
GC_C$_{jk}$		Cheapest package	Minimum incremental cost of technology package	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the minimum value of the cost and so, the incremental cost of the cheapest package for any of the considered years 2018 to 2024 and reference car models.

$GC\_C\_P_{jk}$			Package		j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the technologies that the cheapest package has depending on the year 2018 to 2024 and reference car models.
GC_CCE_{jk}			Cost effectiveness	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the cost effectiveness that the cheapest package has depending on the year 2018 to 2024 and reference car models.
$GC\_CCO_2R_{jk}$			CO_2 emi. Reduction (CAFE Based)	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the value of the CO_2 emissions reduction that the cheapest package has depending on the year 2018 to 2024 and reference car models.
EU_MPC_{ijk}	EU Market	Most profitable package	Margin perf. Coef.	-	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	This coefficient is proportional to the performance related to every package. For any of the considered years 2018 to 2024 and reference car models.
EU_MFCC_{ik}			Margin FC coef.	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	This coefficient is proportional to the fuel economy and depends upon the fuel used. Calculated for every package and reference car models.
EU_MCC_{ikk}			Margin Cost coef.	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	This coefficient is proportional to the cost increment of the packages and has a cost markup for cars exported to USA and reference car models.
EU_CMC_{ijk}			Compounded margin coef.	-	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	This is the compounded coeficient which gives the idea of the monetary margin that the Automobile manufacturer may achieve depending on the chosen package. For any of the considered years 2018 to 2024 and reference car models.
EU_MCMC_{jk}			MAX Margin	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.

$EU\_MCM\_P_{jk}$			Package		j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
$EU\_MCM\_CO_2R_{jk}$			CO_2 emi. Reduction (CAFE Based)	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the value of the CO_2 emissions reduction of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
$EU\_MCMC\_IC_{jk}$			Incremental cost of technology package	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the incremental cost of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
$EU\_MCMC\_CE_{jk}$			Cost effectiveness	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the cost effectiveness of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
USA_MPC_{ijk}	USA Market		Margin perf. Coef.	-	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	This coefficient is proportional to the performance related to every package.For any of the considered years 2018 to 2024 and reference car models.
USA_MFCC_{ik}			Margin FC coef.	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	This coefficient is proportional to the fuel economy and depens upon the fuel used. Calculated for every package and reference car models.
USA_MCC_{ik}			Margin Cost coef.	-	i=[1…Num_of_packages] k=[1…Num_of_RefMod]	This coefficient is proportional to the cost increment of the packages and has a cost markup for cars exported to USA and reference car models.
USA_CMC_{ijk}			Compounded margin coef	-	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	This is the compounded coefficient which gives the idea of the monetary margin that the Automobile manufacturer may achieve depending on the package. For any of the considered years 2018 to 2024 and reference car models.

USA_MCMC$_{jk}$			MAX Margin	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
USA_MCM_P$_{jk}$			Package		j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
USA_MCM_CO$_2$R$_{jk}$			CO$_2$ emi. Reduction (CAFE Based)	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the value of the CO$_2$ emissions reduction of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
USA_MCMC_IC$_{jk}$			Incremental cost of technology package	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the incremental cost of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
USA_MCMC_CE$_{jk}$			Cost effectiveness	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the cost effectiveness of the package which gives the maximum value of the compounded margin coef. For any of the considered years 2018 to 2024 and reference car models.
GM_MGC$_{ijk}$	Global Market	Best global margin package	Margin Global coef.	-	i=[1…Num_of_packages] j=[1…Num_of_Years] k=[1…Num_of_RefMod]	This is the compounded coefficient which gives the idea of the monetary margin that the Automobile manufacturer may achieve depending on the package given a % of sells in USA and EU. For any of the considered years 2018 to 2024 and reference car models.
GM_MGM$_{jk}$			MAX Global Margin	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains the maximum value of the compounded global margin coef. For any of the considered years 2018 to 2024 and reference car models.

$GM\_MGM\_P_{jk}$			Package		j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the names of the package which gives the maximum value of the compounded global margin coef. For any of the considered years 2018 to 2024 and reference car models.
$GM\_MGM\_CO_2R_{jk}$			CO_2 emi. Reduction (CAFE Based)	-	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the value of the CO_2 emissions reduction of the package which gives the maximum value of the compounded global margin coeff. For any of the considered years 2018 to 2024 and reference car models.
$GM\_MGM\_IC_{jk}$			Incremental cost of technology package	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the incremental cost of the package which gives the maximum value of the compounded global margin coef. For any of the considered years 2018 to 2024 and reference car models.
$GM\_MGM\_CE_{jk}$			Cost effectiveness	$	j=[1…Num_of_Years] k=[1…Num_of_RefMod]	Every cell contains a list of the cost effectiveness of the package which gives the maximum value of the compounded global margin coef. For any of the considered years 2018 to 2024 and reference car models.

It is useful to note that there are two differentiated output data, signalized by the white and grey background colours in the table. Grey colour gives the final results:

- Globally compliant packages and its features
- Most cost effective compliant package and its features
- Cheapest compliant package and its features
- Most profitable package for EU
- Most profitable package for USA
- Best global margin package

While the part of the table with white background is internal base calculations which data is used to find the results in grey background colour.

3.8.2 Results – Reference car Midsize 1.4 NA MT

Table 3-12 Most cost effective compliant packages for Midsize 1.4 NA MT

Most cost effective package - Midsize 1.4 N.A Manual trans.					
Year	**Special conversions considered**	**Cost effectivenes [\$/%CO$_2$Red.CAFE]**	**Package technologies**	**Incremental cost [\$]**	**FC Red. CAFE bas. [%]**
2018	To CNG and LPG Vehicle with mild electrification	41	LUB1,EFR1,LUB2_EFR2,LPG ENGINE,ROLL1,ROLL2	707	17,4%
	To diesel and MHEV ISG	35	LUB1,EFR1,LUB2_EFR2,EPS,IACC1,IACC2,ROLL1,MR2-10%	502	14,5%
2020	To CNG and LPG Vehicle with mild electrification	64	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$,MR1CNG LPG-10%	2498	39,3%
	To diesel and MHEV ISG	77	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR2-10%	2714	35,1%
2022	To CNG and LPG Vehicle with mild electrification	61	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$	2252	36,7%
	To diesel and MHEV ISG	75	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR2-10%	2623	35,1%
2024	To CNG and LPG Vehicle with mild electrification	61	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$	2252	36,7%
	To diesel and MHEV ISG	73	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR2-10%	2548	35,1%

Table 3-13Cheapest compliant packages for Midsize 1.4 NA MT

Cheapest package - Midsize 1.4 N.A Manual trans.					
Year	**Special conversions considered**	**Incremental cost [$]**	**Package technologies**	**CO$_2$ Red. CAFE bas. [%]**	**Cost effectivenes [$/%CO$_2$Red.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	703	,EFR1,LUB2_EFR2,LPG ENGINE,ROLL1,ROLL2	16,8%	42
	To diesel and MHEV ISG	383	LUB1,EFR1,LUB2_EFR2,EPS,IACC1,IACC2,ROLL1	10,8%	35
2020	To CNG and LPG Vehicle with mild electrification	2315	,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$	36,3%	64
	To diesel and MHEV ISG	2595	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2	32,4%	80
2022	To CNG and LPG Vehicle with mild electrification	2248	,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$	36,3%	62
	To diesel and MHEV ISG	2503	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2	32,4%	77
2024	To CNG and LPG Vehicle with mild electrification	2197	,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$	36,3%	61
	To diesel and MHEV ISG	2428	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2	32,4%	75

Table 3-14 Best profit margin package EU for Midsize 1.4 NA MT

Most profitable package UE - 500L 1.4 N.A Manual trans						
Year	**Special conversions considered**	**MAX Margin EU**	**Best EU margin package**	**CO2 Red. CAFE bas. [%]**	**Cost of technology package [$]**	**Cost effectivenes [$/%CO2Red.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	104,1%	LUB1,EFR1,LUB2_EFR2,LPG ENGINE,ROLL1,ROLL2,MR3CNG LPG-20%	24,2%	1306	54
	To diesel and MHEV ISG	107,7%	LUB1,EFR1,LUB2_EFR2,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	19,8%	934	47
2020	To CNG and LPG Vehicle with mild electrification	100,6%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO2,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	99,8%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR4-20%	37,8%	3073	81
2022	To CNG and LPG Vehicle with mild electrification	101,0%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO2,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	100,4%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR4-20%	37,8%	3073	81
2024	To CNG and LPG Vehicle with mild electrification	101,3%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO2,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	100,9%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR4-20%	37,8%	3073	81

Table 3-15 Best profit margin packages USA for Midsize 1.4 NA MT

Most profitable package USA - Midsize 1.4 N.A Manual trans						
Year	**Special conversions considered**	**MAX Margin USA**	**Best USA margin package**	**CO_2 Red. CAFE bas. [%]**	**Cost of technology package [$]**	**Cost effectivenes [$/%$CO_2$Red.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	97,4%	LUB1,EFR1,LUB2_EFR2,LPG ENGINE,ROLL1,ROLL2,MR3CNG LPG-20%	24,2%	1306	54
	To diesel and MHEV ISG	96,8%	LUB1,EFR1,LUB2_EFR2,EPS,IACC1,IACC2,ROLL1	10,8%	383	35
2020	To CNG and LPG Vehicle with mild electrification	89,0%	,EFR1,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,CNG ENGINE,ROLL1,ROLL2,AERO$_2$,MR3CNG LPG-20%	41,6%	3052	73
	To diesel and MHEV ISG	87,3%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2	32,4%	2595	80
2022	To CNG and LPG Vehicle with mild electrification	89,4%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	87,3%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2	32,4%	2595	80
2024	To CNG and LPG Vehicle with mild electrification	91,8%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO$_2$,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	87,3%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2	32,4%	2595	80

Table 3-16 Best global margin packages for Midsize 1.4 NA MT

Best global margin - 500L 1.4 N.A Manual trans						
Year	**Special conversions considered**	**MAX Global Margin**	**Best global margin package**	**CO2 Red. CAFE bas. [%]**	**Cost of technology package [$]**	**Cost effectivenes [$/%FCRed.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	102,8%	LUB1,EFR1,LUB2_EFR2,LPG ENGINE,ROLL1,ROLL2,MR3CNG LPG-20%	24,2%	1306	54
	To diesel and MHEV ISG	105,1%	LUB1,EFR1,LUB2_EFR2,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	19,8%	934	47
2020	To CNG and LPG Vehicle with mild electrification	98,2%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO2,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	96,6%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR4-20%	37,8%	3073	81
2022	To CNG and LPG Vehicle with mild electrification	98,7%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO2,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	104,2%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR4-20%	37,8%	3073	81
2024	To CNG and LPG Vehicle with mild electrification	99,4%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,LPG ENGINE,HETRANSM,EPS,IACC1,IACC2,MHEV,ROLL1,ROLL2,AERO2,MR3CNG LPG-20%	41,9%	2917	70
	To diesel and MHEV ISG	97,7%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,MR4-20%	37,8%	3073	81

3.8.3 Results – Reference car Midsize 1.3T AT

Table 3-17 Most cost effective compliant packages for Midsize 1.3T AT

Most cost effective package - Midsize 1.3T Automatic Transmission					
Year	**Special conversions considered**	**Cost effectivenes [$/% CO_2Red.CAFE]**	**Package technologies**	**Incremental cost [$]**	**CO_2 Red. CAFE bas. [%]**
2018	To CNG and LPG Vehicle with mild electrification	43	LUB1,LPG ENGINE,ROLL1,ROLL2	574	13,4%
	To diesel and HEV	4	,ROLL1	7	1,9%
2020	To CNG and LPG Vehicle with mild electrification	48	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2	1022	21,3%
	To diesel and HEV	59	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR2-10%	1387	23,4%
2022	To CNG and LPG Vehicle with mild electrification	47	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2	992	21,3%
	To diesel and HEV	57	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR2-10%	1335	23,4%
2024	To CNG and LPG Vehicle with mild electrification	46	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2	976	21,3%
	To diesel and HEV	55	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR2-10%	1299	23,4%

Table 3-18 Cheapest compliant packages for Midsize 1.3T AT

Cheapest package - Midsize 1.3T Automatic Transmission					
Year	**Special conversions considered**	**Incremental cost [$]**	**Package technologies**	**CO_2 Red. CAFE bas. [%]**	**Cost effectivenes [$/%$CO_2$Red.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	490	,LPG ENGINE	10,0%	49
	To diesel and HEV	7	,ROLL1	1,9%	4
2020	To CNG and LPG Vehicle with mild electrification	944	LUB1,LPG ENGINE,8SPD,ROLL1,ROLL2,$AERO_2$	18,8%	50
	To diesel and HEV	1267	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2	20,2%	63
2022	To CNG and LPG Vehicle with mild electrification	922	LUB1,LPG ENGINE,8SPD,ROLL1,ROLL2,$AERO_2$	18,8%	49
	To diesel and HEV	1216	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2	20,2%	60
2024	To CNG and LPG Vehicle with mild electrification	908	LUB1,LPG ENGINE,8SPD,ROLL1,ROLL2,$AERO_2$	18,8%	48
	To diesel and HEV	1179	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2	20,2%	58

Table 3-19 Best profit margin package EU for Midsize 1.3T AT

Most profitable package UE - Midsize 1.3T Automatic Transmission						
Year	**Special conversions considered**	**MAX Margin EU**	**Best EU margin package**	**CO$_2$ Red. CAFE bas. [%]**	**Cost of technology package [$]**	**Cost effectivenes [$/%CO$_2$Red.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	116,45%	LUB1,LPG ENGINE,ROLL1,ROLL2,MR3CNG LPG-20%	20,5%	1172	57
	To diesel and HEV	107,60%	LUB1,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR4-20%	22,0%	1063	48
2020	To CNG and LPG Vehicle with mild electrification	103,37%	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR3CNG LPG-20%	27,6%	1672	61
	To diesel and HEV	104,71%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,7%	1746	65
2022	To CNG and LPG Vehicle with mild electrification	103,56%	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR3CNG LPG-20%	27,6%	1672	61
	To diesel and HEV	105,06%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,7%	1746	65
2024	To CNG and LPG Vehicle with mild electrification	103,67%	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR3CNG LPG-20%	27,6%	1672	61
	To diesel and HEV	105,30%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,7%	1746	65

Table 3-20 Best profit margin packages USA for Midsize 1.3T AT

Most profitable package USA - Midsize 1.3T Automatic Transmission						
Year	**Special conversions considered**	**MAX USA Margin**	**Best USA margin package**	**CO_2 Red. CAFE bas. [%]**	**Cost of technology package [$]**	**Cost effectivenes [$/%$CO_2$Red.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	98,1%	LUB1,LPG ENGINE,ROLL1,MR3CNG LPG-20%	18,82 %	1099	58
	To diesel and HEV	97,8%	LUB1,ROLL1	2,59 %	11	4
2020	To CNG and LPG Vehicle with mild electrification	96,0%	LUB1,LPG ENGINE,8SPD,ROLL1,ROLL2,AERO$_2$,MR3CNG LPG-20%	25,31 %	1588	63
	To diesel and HEV	97,8%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT, EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,72 %	1746	65
2022	To CNG and LPG Vehicle with mild electrification	96,2%	LUB1,LPG ENGINE,8SPD,ROLL1,ROLL2,AERO$_2$,MR3CNG LPG-20%	25,31 %	1588	63
	To diesel and HEV	93,1%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT, EPS,IACC1,IACC2,ROLL1,ROLL2	20,17 %	1267	63
2024	To CNG and LPG Vehicle with mild electrification	96,3%	LUB1,LPG ENGINE,8SPD,ROLL1,ROLL2,AERO$_2$,MR3CNG LPG-20%	25,31 %	1588	63
	To diesel and HEV	93,3%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT, EPS,IACC1,IACC2,ROLL1,ROLL2	20,17 %	1267	63

Table 3-21 Best global margin packages for Midsize 1.3T AT

Best global margin - Midsize 1.3T Automatic Transmission						
Year	**Special conversions considered**	**MAX Global Margin**	**Best global margin package**	**CO_2 Red. CAFE bas. [%]**	**Cost of technology package [$]**	**Cost effectivenes [$/%FCRed.CAFE]**
2018	To CNG and LPG Vehicle with mild electrification	112,7%	LUB1,LPG ENGINE,ROLL1,ROLL2,MR3CNG LPG-20%	20,46%	1172	57
	To diesel and HEV	105,3%	LUB1,ROLL1,ROLL2,MR4-20%	12,40%	563	45
2020	To CNG and LPG Vehicle with mild electrification	101,8%	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR3CNG LPG-20%	27,56%	1672	61
	To diesel and HEV	103,3%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,72%	1746	65
2022	To CNG and LPG Vehicle with mild electrification	102,0%	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR3CNG LPG-20%	27,56%	1672	61
	To diesel and HEV	102,3%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,72%	1746	65
2024	To CNG and LPG Vehicle with mild electrification	102,2%	LUB1,LPG ENGINE,8SPD,HETRANS,SHFTOPT,ROLL1,ROLL2,MR3CNG LPG-20%	27,56%	1672	61
	To diesel and HEV	102,5%	LUB1,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR4-20%	26,72%	1746	65

4. Model calculation for a fleet of vehicles

4.1 Introduction

This model is complementary to the first model (chapter 3). While the first model was focused on finding the bests packages of low FC technologies according to several criteria, the second model gives as an outcome how should be implemented an automobile manufacturer fleet to get the higher margin in a particular year (2020). This is, by choosing the technology packages that best fits the final company target: highest total profit margin.

Since for the purpose of this work (academic and public purpose) it is useless to consider the whole real fleet, it will be considered that the "whole fleet" is just four models and the input data will be taken from the outputs of the previous model.

The previous model has generated thousands of technology packages and has defined package's features, such as difference CO_2 emissions to the limit or the profit margin coefficient. The idea is to pick up some of the most convenient packages (compliant or non-compliant packages) and suppose a number of sales of each model. Convenient packages are those which feature high cost effectiveness and high profit margin coefficients.

The CAFE and NEDC regulations apply for the whole fleet and therefore the packages can be compliant or not with any of the two regulations NEDC and CAFE. Depending on the fleet average MPG or CO_2 emissions value, automobile manufacturer may be fined by any of the governments, which may be as well an option if the value of the fine is low enough compared to the increase in cost to comply with the stringent regulations.

Once more, the main purpose of this model is to figure out which is the best choice of the 20 possible packages in order to commercialize just 4 packages and obtain the highest margin. Therefore, 625 possible combinations are assessed. In order to face this problem, basically a four loop algorithm has been built in Visual Basic.

4.2 Hypothesis

The first algorithm “the package model” has given outputs regarding only to the reference model but in this chapter the algorithm works on the whole fleet.

However, some of the data from the first algorithm has been gathered to use as input for the second algorithm. To this concern, it is useful to point out the following concept regarding the cost variation of the technologies due to production volume variation: The cost of technologies has been considered constant no matter what is the production volume. That is why the same car body (the reference “midsize” model) may use different mass reduction levels or different aerodynamic improvements to each of the four models instead of sharing a maximum number of components.

To the concern of this calculation, the four models are representing a whole fleet and therefore, even though they are apparently the same body, they should be treated as different bodies assembled in different production lines. A direct consequence of this as just said is that the four car models may have distinctive mass reduction levels or aerodynamic improvements, which makes no sense in the same car model/body because it would increase the costs too much. Nevertheless, thanks to that, the outputs from the first mathematical model can be collected for use in the second algorithm.

4.3 Model inputs

Considered as model input data and parameters susceptible to change (the user may be interesting in playing with them). The main inputs are the sales of the model in US and EU; the reference profit margin of the model and the features of the considered packages coming from the outputs of the first mathematic model (*i.e.* profit margin coefficient, MPG gap to the limit and CO_2 emissions gap to the limit)

The tables below summarizes what just defined and gives more detail about the four models that have to be commercialized in the year 2020.

Table 4-1 Fleet definition MY2020

Name	**Body**	**Reference Engine**	**Hybrid**	**Energy source**	**# possible packages**	**Reference power**	**Sales EU**	**Sales USA**	**Reference profit margin [$]**
Diesel	Midsize	G 1.4NA	NO	Diesel	5	95	50000	5000	3000
Petrol1	Midsize	G 1.4NA	NO	Petrol	5	95	50000	30000	2000
Petrol2	Midsize	1.3T AT	NO	Petrol	5	120	50000	30000	2500
PHEV	Midsize	1.3T AT	YES Plug-in	Petrol + Electricity	5	120	2000	1000	3000

Table 4-2 Diesel considered packages and their features

Car Reff. Model	Package features for j=2 (2020)		Package #				
	Name	**Model name**	**1**	**2**	**3**	**4**	**5**
Diesel k=1	**Margin Coefficient USA [-]**	USA_CMC_{ijk}	0,81	0,81	0,70	0,76	0,74
	Margin Coefficient EU [-]	EU_CMC_{ijk}	0,95	0,95	0,89	0,89	0,93
	FE gap to the limit CAFE [mpg]	C_DIF_{ijk}	-11,79	-13,11	-24,04	-27,35	-33,41
	CO_2 emissions gap to the limit NEDC [gCO_2/km]	N_DIF_{ijk}	20,99	18,20	-1,02	-5,73	-9,03
	Package technologies	G_PACK_{ik}	LUB1,SGDI,TRBDS1_SD_TB,CEGR2_SD_TB,ADSL_SD,EPS,IACC1,LDB,MR2-10%	,EFR1,SGDI,TRBDS1_SD_TB,CEGR2_SD_TB,ADSL_SD,EPS,IACC1,LDB,MR2-10%	LUB1,SGDI,TRBDS1_SD_TB,CEGR2_SD_TB,ADSL_SD,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,AERO$_2$,MR2-10%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,CEGR2_SD_TB,ADSL_SD,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,AERO$_2$, MR2-10%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,CEGR2_SD_TB,ADSL_SD,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,LDB,MR4-20%

Table 4-3 Petrol1 (95hp) considered packages and their features

Car Reff. Model	**Package features for j=2 (2020)**		**Package #**				
	Name	**Model name**	**1**	**2**	**3**	**4**	**5**
Petrol 1 k=2	**Margin Coefficient USA [-]**	USA_CMC_{ikj}	0,98	0,98	0,97	0,94	0,84
	Margin Coefficient EU [-]	EU_CMC_{ijk}	1,01	1,05	1,05	1,04	0,99
	FE gap to the limit CAFE [mpg]	C_DIF_{ijk}	-1,70	-3,81	-5,26	-13,46	-26,74
	CO_2 emissions gap to the limit NEDC [gCO_2/km]	$N\_DIF_{ij}k$	39,56	37,65	33,88	15,88	-0,54
	Package technologies	G_PACK_{ik}	,EFR1,ROLL1,ROLL2	,EFR1,ROLL1,ROLL2,MR2-10%	LUB1,EFR1,LUB2_EFR2,ROLL1,ROLL2,LDB,MR2-10%	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,ROLL1,MR2-10%	,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,LDB,MR4-20%

Table 4-4 Petrol2 (120hp) considered packages and their features

Car Reff. Model	**Package features for j=2 (2020)**		**Package #**				
	Name	**Model name**	**1**	**2**	**3**	**4**	**5**
Petrol 2 k=3	**Margin Coefficient USA [-]**	USA_CMC_{ijk}	0,99	0,98	0,95	0,95	0,92
	Margin Coefficient EU [-]	EU_CMC_{ijk}	1,05	1,05	1,01	1,01	0,98
	FE gap to the limit CAFE [mpg]	C_DIF_{ijk}	-12,86	-15,09	-11,89	-15,78	-14,96
	CO_2 emissions gap to the limit NEDC [gCO_2/km]	N_DIF_{ijk}	11,06	7,31	8,79	-1,80	-4,67
	Package technologies	G_PACK_{ik}	LUB1,LUB2_EFR2,8SPD,HETRANS,SHFTOPT,EPS,ROLL1,ROLL2,MR2-10%	LUB1,LUB2_EFR2,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR2-10%	LUB1,8SPD,HETRANS,SHFTOPT,EPS,IACC1,ROLL1,ROLL2,AERO$_2$	,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,AERO$_2$,MR2-10%	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,AERO$_2$

Table 4-5 PHEV considered packages and their features

Car Reff. Model	**Package features for j=2 (2020)**		**Package #**				
	Name	**Model name**	**1**	**2**	**3**	**4**	**5**
PHEV k=4	Margin Coefficient USA [-]	USA_CMC_{ijk}	0,354215243	0,359038939	0,361463436	0,344957836	0,373478035
	Margin Coefficient EU [-]	EU_CMC_{ijk}	0,354215243	0,359038939	0,361463436	0,344957836	0,373478035
	FE gap to the limit CAFE [mpg]	C_DIF_{ijk}	-65,62013189	-69,77253294	-75,30755578	-82,65004295	-94,68189081
	CO_2 emissions gap to the limit NEDC [gCO_2/km]	N_DIF_{ijk}	-43,7552914	-45,46385165	-47,56191208	-50,07008565	-49,62476517
	Package technologies	G_PACK_{ik}	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,SHEV1_B,SHEV1_NB,SHEV2_B,SHEV2_NB,PHEV2_B,PHEV2_NB	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,SHEV1_B,SHEV1_NB,SHEV2_B,SHEV2_NB,PHEV2_B,PHEV2_NB,ROLL1	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,SHEV1_B,SHEV1_NB,SHEV2_B,SHEV2_NB,PHEV2_B,PHEV2_NB,ROLL1,ROLL2	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,SHEV1_B,SHEV1_NB,SHEV1_2,SHEV2_B,SHEV2_NB,PHEV2_B,PHEV2_NB,LDB	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,SHEV1_B,SHEV1_NB,SHEV1_2,SHEV2_B,SHEV2_NB,PHEV2_B,PHEV2_NB,ROLL1,LDB,MR1E-10%

4.4 Model algorithm

Here a detailed explanation of the created code and its parameters is given. The whole Visual Basic code can be found in the annexes.

For the resolution of this problem, there are two basic calculations. The fleet CO_2 emissions gap to the limit and the total profit margin.

4.4.1 Fleet CO_2 emissions gap to the limit

According to CAFE and NEDC regulations, the fulfilment of the legislations depends upon the harmonic average MPG/CO_2 of the fleet. Thus, the fleet gap to the limit can be calculated as:

$$\boldsymbol{Fleet\_MPG\_USA\_GapToLimit}[\boldsymbol{mpg}] = \boldsymbol{CAFE\_AverageFleetFE} - \boldsymbol{CAFE\_FleetLimitFE} = \frac{\sum_{k=1}^{4} \boldsymbol{USA\_SalesVol}_k \cdot \boldsymbol{C\_DIF}_{ijk}}{\sum_{k=1}^{4} \boldsymbol{USA\_SalesVol}_k} \qquad \text{Equation 4-1}$$

$$\boldsymbol{Fleet\_CO2\_EU\_GapToLimit}[\frac{\boldsymbol{g}}{\boldsymbol{km}}] = \boldsymbol{EU\_AverageFleetCO2} - \boldsymbol{EU\_FleetLimitCO2} = \frac{\sum_{k=1}^{4} \boldsymbol{EU\_SalesVol}_k \cdot \boldsymbol{IM}_{\boldsymbol{NEDC}_k} \cdot \boldsymbol{N\_DIF}_{ijk}}{\sum_{k=1}^{4} \boldsymbol{EU\_SalesVol}_k} \qquad \text{Equation 4-2}$$

Where:

IM_{NEDC_k} is the incentive multiplier according to NEDC regulations created in order to incentive companies to increase the production of clean vehicles. In calculating the average specific emissions of CO_2 , each new passenger car with specific emissions of CO_2 of less than 50 g CO_2 /km shall be counted as IM_{NEDC_k} =2 for passenger cars in 2020.

4.4.2 The total profit margin

The profit margin depends upon the input data showed in the chapter 6.4.1 and some other parameters as the fines that governments may impose to the Automobile manufacturers if they are not compliant with the CO_2 average corporate limit.

According to the chapter 3, fines are stablished in MY 2020 as:

EU: 95€ for each gCO_2/km multiplied by the total volume of the cars produced on the year. This is 118,14$ for each gCO_2/km (1$=0,804€).

$$\boldsymbol{Fine\_EU}[\frac{\$}{\frac{g}{mi}}] = \mathbf{118,14} \qquad \text{Equation 4-3}$$

USA: \$5,5 for each tenth of a mpg that a manufacturer's average fuel economy falls short of the standard for a given model year multiplied by the total volume of vehicles.

$$\boldsymbol{Fine\_USA}[\frac{\$}{\mathbf{0,1}\boldsymbol{mpg}}] = \mathbf{5,5} \qquad \text{Equation 4-4}$$

So the Profit margin is defined as:

$$Total\ margin = Margin\ USA + Margin\ EU =$$
$$\sum_{k=1}^{4} \boldsymbol{USA\_SalesVol_k} \cdot \boldsymbol{USA\_RefProfitMargin} \cdot \boldsymbol{USA\_CMC_{ij}} + \boldsymbol{Fine\_USA} \cdot$$
$$\sum_{k=1}^{4} \boldsymbol{USA\_SalesVol_k} + \sum_{k=1}^{4} \boldsymbol{EU\_SalesVol_k} \cdot \boldsymbol{EU\_RefProfitMargin} \cdot \boldsymbol{EU\_CMC_{ij}} + \boldsymbol{Fine\_EU} \cdot$$
$$\boldsymbol{EU\_SalesVol_{k_{ol}}}$$

Equation 4-5

Note that k_{ol} index indicates that only the volume of vehicles over the CO_2 emissions limit are considered.

Two criteria have been used to maximize the function above:

First, as if the automobile manufacturer is not willing to pay any fine. This may not be the best choice in terms of profits as defined above but anyway some companies may be interested in this option. It is true that in terms of marketing (Company image) It may be better to avoid being fined than the increment in margin.

Second, as if the automobile manufacturer pay fines. The company may be willing to pay fines if this is the way to obtain the maximum profit.

And therefore the targets are:

$$\textbf{Target function}_{Criteria1,Criteria2} = \mathbf{max}(\boldsymbol{Total\ margin}_{Criteria1,Criteia2}) \qquad \text{Equation 4-6}$$

4.5 Model outputs and results

The table which gives the best package number/# (see Table 4-2, Table 4-3 ,Table 4-4 and Table 4-5) for any of the *k* reference car models that belong to the fleet according to the two defined criteria.

Table 4-6 Fleet model resultant packages.

	Automobile manufacturer pay fines		**Automobile manufacturer is not willing to pay fines**	
Car Model	#	**Package technologies**	#	**Package technologies**
Diesel	5	LUB1,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,CEGR2_SD_TB,ADSL_SD,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,LDB,MR4-20%	5	“”
Petrol 1	5	,EFR1,LUB2_EFR2,SGDI,TRBDS1_SD_TB,TRBDS2_SD_TB,HETRANSM,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,ROLL1,ROLL2,LDB,MR4-20%	5	“”
Petrol 2	1	LUB1,LUB2_EFR2,8SPD,HETRANS,SHFTOPT,EPS,ROLL1,ROLL2,MR2-10%	2	LUB1,LUB2_EFR2,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,ROLL1,ROLL2,MR2-10%
PHEV	5	LUB1,LUB2_EFR2,CEGR2_SD_TB,8SPD,HETRANS,SHFTOPT,EPS,IACC1,IACC2,MHEV,ISG_B,ISG_NB,SHEV1_B,SHEV1_NB,SHEV1_2,SHEV2_B,SHEV2_NB,PHEV2_B,PHEV2_NB,ROLL1,LDB,MR1E-10%	5	“”

The Table 4-7 gives the profit margin in dollars for the two different criteria. It is showed how the profit margin is higher if the company avoids paying fines for non-compliance, even if the cost of the technologies is higher.

Table 4-7 Profit margin for the selected fleets according to the two criteria

	Automobile manufacturer pay fines	**Automobile manufacturer is not willing to pay fines**
Profit margin [$]	472.324.827,5	480.974.124,3

The Table 4-8 shows the CO_2 emissions and MPG difference to the limit according to the two regulations and the two criteria.

Table 4-8 Fleet gap to the limit according to the two criteria

Automobile manufacturer pay fines		**Automobile manufacturer is not willing to pay fines**	
USA gap to the limit [mpg]	**EU gap to the limit [g/km]**	**USA gap to the limit [mpg]**	**EU gap to the limit [g/km]**
-21,97	0,50	-22,98	-0,75

Notice that the compliant fleet overcomes by 23MPG the CAFE regulation and by 0,75g/km EU regulation. Therefore credit banking can be used as a strategy to comply with more stringent future CAFÉ limits. Equally, pooling may be used on EU regulation and Automobile manufacturer can get an important income from this.

5. Conclusions

Greenhouse gases emissions regulations are established worldwide and are set quite differently in the most relevant regions *i.e.* North America, Europe, China, India, Brazil… and it is expected to remain this way. Every regulation evolves and many parameters and procedures as driving cycles, measuring methods and compliance flexibilities are adjusted or completely shifted. **This regulation framework is a threat but at the same time an opportunity** that can be exploited being able to meet the target in a sustainable way, *i.e.* finding the best trade of between fuel economy, cost and customer value.

To answer this challenge the **Thesis aimed to combine the technical information with the economic issues to support the identification of the most profitable** product configuration to deal with the European and North American regulation on CO_2 emission and fuel economy. These two Regions have been selected due to their relevance for the automotive market and because the technical challenge that they imply.

A **test case on two reference midsize cars sold both in Europe and in US** has been fully developed both at version level, *i.e.* single powertrain and at model level, *i.e.* all powertrains (gasoline, diesel, CNG, automatic transmission, manual transmission…) and related take rates have been considered.
To achieve this objective a tool has been developed and it uses as an input:

- The reference **vehicle characteristics and viable technologies**
- The **cost and fuel consumption reduction related to each technology** or technology package
- The **differential price based on the willingness to pay considering the benefit in terms of cost of ownership (lower fuel consumption) and of the performance**. The differences between European and North American market have been also included.

Furthermore, among the important parameters of the model there are: the **conversion equations** and **correction terms** which are fundamental to develop the model. Such parameters deal with the differences among the regulations such as the unlike driving cycles and flexibilities. Furthermore, US and EU **fuel economy and emissions limits have been introduced even considering the possibility that the vehicle is a light duty truck thus easing the target.** Moreover specific modelling issues as the **synergies** which account for shifts on reference cost and FC reduction estimations has been faced and solved.

The approach developed within the Thesis deals with US CAFE and EU regulations during the period years 2018 to 2024 and it integrates engineering issues with a business perspective. The approach is split in two parts called “package model” and “fleet model” which give differentiated outputs:

- The “**package model**” is focused on the reference models and gives as an output the best package of technologies according to several criteria which include: **Cheapest** compliant package; most **cost effective** compliant package; **most profitable profit** compliant package **for EU market**; most profitable profit compliant package **for US market** and the most profitable profit compliant package **for a global market**.

  While the cheapest and most cost effective packages do not depend on customer value, most profitable packages do take into account customer value.
- The “**fleet model**” has as a target to deal with the entire fleet. The EU and US regulations establish actual limits on the entire automobile **manufacturer’s fleet so this is the final indicator of manufacturer’s compliance.** The output is an optimized fleet in terms of revenue taking into account customer value and regulations flexibilities. The input data is the output results from the first model.

The model runs have been made and the **results have appeared to be logic and correct**. Nevertheless, because of being a quite general approach, the calculations have some assumptions and therefore it is **difficult to fully rely on the outputs** without giving further explanation about the whole issue. For this reason, **information and discussions have been given on the entire argument**. Most of this information is in the first two chapters of the Thesis and it includes: definitions and comparison on worldwide regulations; a hint to vehicle dynamics and GHG simulation software; a real case study comparison among vehicle models marketed in EU and US.

Concerning the results of the “package model”, it is difficult to go deeper and try to generalise because the outputs depend in a lot of parameters however, we can notice **some patterns**:

- **Mass reduction technologies become a good option mainly when customer value is assessed** because although mass reduction technologies lower the CO2 limit on EU regulations, such technologies not only lessen the FC but also improve the performance and so, the price.
- There is indeed a **difference among most cost effective compliant packages and the cheapest compliant packages** coherent with its definition. Furthermore automobile

manufacturers have to worry more about achieving highly cost effective packages than cheapest packages because what is important is to achieve the best CO_2 results by paying the less and use the remaining credits to counteract other vehicle's emissions by averaging the whole fleet.

- Usually, the packages who best fit the global margin taking into account both US and EU markets are the same as the ones which achieve the highest profits in EU. This is coherent with the fact that sales volume in EU is much bigger than sales volume in US.
- It can be noticed **a high step** on the applied technologies from MY2018 to MY2020, consistent with the huge CO_2 limit shift from 130g/km to 95g/km in European regulations.
- **Low friction lubricants and rolling resistance reduction** seem to be technologies that have to be applied almost systematically to whatever vehicle, since they appear in almost every scenario.
- Since the cost of the technologies vary along the years, the cost of the packages shift and it may even happen that the composition of the best-packages differs because some technologies have become more cost effective, but this cannot be said at first glance, as the variation of the emissions limits also plays a role.
- **Diesel and CNG engine technologies do not seem to be a good choice** in any case which is coherent with its high cost estimates. Instead, LPG engines or gasoline with high hybridization seem better choices. Anyway such result is not obvious since apparently CNG fuel is much cheaper than LPG in America, which should result in greater customer value. The low value of the "price sensitivity to fuel consumption USA_PSFC_k" has much probably something to do with this.

On the "fleet model", the greater conclusion has been that it is **worthless to choose the way of non-compliance because fines are too high** and counteract the effect of less costly non-compliant fleet.

The use of the conversion regression equations from ICCT has been essential. Thanks to the conversion equations, it has been possible to evaluate the effect of the different cycles and the effects of specific technologies whose effects may change depending on the test driving cycle. This means that, **although the data on fuel consumption reduction was US CAFE driving cycles based, it has been possible to assess compliance in the NEDC using best fit equations** depending on the technologies belonging to each package. The utility of the conversion regression equations have been verified assessing real cases. It is here where the difficulty to perform benchmarking due to the use of flexibilities and the shortage of data on public sources has been understood. Furthermore, **concerns about the usability of such conversion equations for assessment on small vehicles have arisen**.

The technologies' fuel consumption reduction and cost estimates published by NHTSA and used in this Thesis seem to be very accurate since they give specific values based on vehicle architectures (midsize, compact, large…), engine size (Small, medium and large displacement) and number of cylinders. **Either way, some doubts about the accuracy of the data gathered from NHTSA arise when trying to extrapolate the values of cost an fuel consumption from US to EU regulations**. As an example, Diesel engines are probably more expensive and less efficient in US, where the regulations concerning hazardous gases (Tier 2…) are more severe for Diesel engines than European ones (Euro 5…). Furthermore, the fact that NHTSA do not specify the volumes of production on which their cost estimates are based raises some concerns. Moreover, sometimes it is not completely clear which are the technological features making up the technologies, especially for very new and complex developments as Strong Hybrids.

Although the data on FC reduction has been gathered from NHTSA, **simulations have been performed using the free version of Data Visualization Tool DVT and the huge potential of this tool has been assessed**: it is useful to assess performance metrics, test cycle emissions and FE for a given vehicle architecture in which many vehicle parameters can be modified and ranged. However no data on Cost is given and so its utility is very limited in this paper.

The fact that US CAFE estimates well-to-wheel emissions and NEDC assesses tank-to-wheel emissions has also brought some complications because electric cars are considered as 0g/km on European regulations while not on US CAFE.

The limit curve, its shape and the attribute on which they are based (Curb mass/footprint) is very differently approached among the regulations. Some regulations measure FE/FC, as china or US CAFE which may benefit the use of dirtier fuels (as diesel) as long as FC is lower. Other regulations measure CO2 emissions as US GHG or EU and finally there is Brazil, where cleaner fuels are widely used and the limit is based on energy consumption meaning that Brazil standards care about the efficiency of the combustion rather than emissions. On the other hand, differently from the rest of the regulations, **US uses footprint as attribute based limit which make a challenge the comparison among regulations since footprint/weight ratio is something specific of a vehicle**, and not easily generalizable. **Consequently, cars with low footprint/weight ratio (SUVs, off-road…) are prone to be limited by US regulations rather than EU regulations**. Moreover, **mass reduction technologies are more convenient in US**, than in other markets where a reduction on mass involve more stringent limits due to curb mass based limits.

Furthermore, the shapes of the limit curves are not always linear. **US regulations stablish a S shape curve which is detrimental for very large cars but favors very small vehicles, similarly to EU new limit slope which favors brands who produce smaller, lighter cars**. Equally, China limits are based on bins classes, favoring or being detrimental to cars that are at the limit of the step among consecutive bin classes, similarly to what happens for the inertia class in the bench dynamometer during type approval TA driving cycles. Then, automobile manufacturers can target cars with a curb weight in the bin's limit.

Furthermore, some regulations as China phase-in the limits and allow c**redit banking or carrying forward**. On the other hand, **European regulations do not allow such provisions but pools are accepted** and therefore automobile manufacturers may decide to share a fleet and buy or sell compliance credits. Some regulations implement new limits once every few years without phasing in, making huge steps (as Brazil or European regulations), while in US new limits are specified for every year but other kind of flexibilities are available. For this reason, even if in general CAFE regulation is more relaxed than EU regulation, notice that the year before the new limit take effect (*i.e.* 2019,2024), CAFE is quite probably more stringent. When comparing US and EU regulations stringencies, it should be bear in mind the effects of **loopholes from where manufacturers take profit**, especially in Europe. The large use of test procedure flexibilities or loopholes has contributed to and eases on reach emissions targets. However, the new **WLTC will remove some of the flexibilities and will involve a shift on FC strategies** because of its new nature and it will become a challenge for manufacturers.

Emissions policies are way beyond to be a simple limit in emissions and regional economic/political decisions play an important role, giving rise to even a more complex and heterogeneous standards aimed to fit the region's conditions and interests. In parallel, automobile manufacturers have to choose the best strategies in the path of regulation's compliance and most important: maximum business revenue. A clear example of government economy polices related to regulations is **Brazil, where the regulation clearly defines reduction on taxes for those manufacturers investing in the national automotive industry while producing more efficient vehicles**. Consequently, Automobile manufacturers may choose to create facilities in Brazil because of GHG Brazil regulations.

Incentives and eases to support specific type of technologies as HEVs, FFVs are implemented in some regulations as CAFE or China, for specific periods, while less extended in other regulations as EU. Therefore, **automobile manufacturers can decide to earn a lot of compliance credits in these periods where incentives are given and use them afterwards, when regulations become more stringent**, to avoid the use of costly technologies.

Eco-innovations and off-cycle credits is becoming a common way to earn credits for compliance, **however regulations do not share the same potentially qualifying technologies**, which may make automobile manufacturers to not consider them as a good option. Moreover they may not be cost effective, especially in EU. Besides the regulations stablish limits on the number of credits that can be gained.

Emissions limits are set for singular cars, for a whole fleet or both as in China regulations. Such provision is a problem for automobile manufacturers who aim to sell some low fuel economy vehicles as cars with high power or big displacement engines. Nevertheless, any other regulations do average emissions making possible to counteract the sales of low fuel economy FE vehicles.

Automobile manufacturers have to face secondary effects of the low GHG emissions technologies, as for example the increase on NHV coming from early torque converter lockup, cylinder deactivation or highly turbocharged engines. Equally, some **issues on drivability and comfort** may come from an increment on shifting evens (shift busyness) especially for MT or the lack of torque during launch in highly downsized engines. Similarly, DCT systems, which apparently show very good results on FC reduction, seem to not be indicated in highly downsized engines, for **reduced launch performance** due to the lack of conventional torque converter. Furthermore, some technologies may have some **counter-productive effects** as high compression ratios, turbocharged engines or lean operation, which **produce more pollutants**. In order to counteract this, expensive control techniques have to be used. As technologies improve and these issues are solved, further reductions on emissions will be achieved.

Bibliography

1. *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of theIntegovernmental Panel on Climate Change* . IPCC. s.l. : Watson, R.T. and the Core Writing Team (eds.), 2001. http://www.ipcc.ch/ipccreports/tar/vol4/english/002.htm.
2. **Robert EDWARDS (JRC), Heinz HASS (EUCAR),Jean-François LARIVÉ (CONCAWE), Laura LONZA (JRC),Heiko MAAS (EUCAR), David Rickeard (CONCAWE).** *Well-to-wheel analysis of future automotive fuels and powertrains in the european context.* Joint Research Center, the European Comission . s.l. : Simon Godwin (EUCAR), Heather Hamje (CONCAWE), Alois Krasenbrink (JRC), Robin Nelson (CONCAWE), Kenneth D. Rose (CONCAWE), 2014. http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw_report_v4a_march_2014_final_333_rev_140408.pdf. ISSN 1831-9424.
3. http://ecomodder.com/.
4. **Stefano d'Ambrosio, Antonio Mittica, Daniel Misul.** *Class notes from Combustion Enigines and Applications to Vehicle.* Dipartimento Energia (DENERG), Politecnico di Torino.
5. **Sun, John.** *Car Battery Efficiencies.* 2010. Submitted as coursework for Physics 240, Stanford University, Fall 2010.
6. **EPA.** *Unit conversions, emissions factors and other reference data.* 2004. http://www.epa.gov/cpd/pdf/brochure.pdf.
7. **John J.Kasab, Velliyur Subbarao.** *USER GUIDE FOR DATA VISUALIZATION TOOL.* 2012. http://www.theicct.org/sites/default/files/Ricardo_Data_Visualization_Tool_UserGuide_v09-May-2012.pdf.
8. **Gerrit Kadijk, Maarten Verbeek, Richard Smokers, Jordy Spreen, Artur Patuleia, Martijn van Ras, John Norris, Angela Johnson, Simon O'Brien, Simon Wrigley, Julien Pagnac, Martin Seban, Dick Buttigieg.** *Supporting Analysis on Test Cycle and Technology Deployment for Reviews of Light Duty Vehicle CO2 Regulations.* TNO, AEA, Ricardo, IHS Global Insight. 2012. http://ec.europa.eu/clima/policies/transport/vehicles/cars/docs/report_2012_en.pdf.
9. **EDGAR, Olivier, J.G.J., Van Aardenne, J.A., Dentener, F., Ganzeveld, L. and J.A.H.W.** *Recent trends in global greenhouse gas emissions: regional trends and spatial distribution of key sources.* Rotterdam : EDGAR, 2005. http://www.mnp.nl/edgar/model/v32ft2000edgar/docv32ft2000/. ISBN 90 5966 043 9.
10. *2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule.* Department of Transportation,, National Highway Traffic Safety Administration NHTSA and Enviromental Protection Agency EPA. 2012. Federal Register. EPA and NHTSA have established dockets for this action under Docket ID No. EPA–HQ–OAR–2010–0799 and NHTSA 2010–0131, respectively. All documents in the docket are listed in the http://www.regulations.gov.
11. *REGULATION (EC) No 443/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles.*
12. http://www.engineeringtoolbox.com/.
13. *Fuel Economy Testing and Labeling.* Office of Transportation and Air Quality, Enviromental Protection Agency EPA. 2014. http://epa.gov/fueleconomy/documents/420f14015.pdf.
14. **EPA.** *MPG: Label Values vs. Corporate Average Fuel Economy (CAFE) Values.* 2014. EPA-420-B-14-015.
15. *amending Annex I to Regulation (EC) No 443/2009 of the European Parliament and of the Council in order to take into account the evolution of the mass of new passenger cars registered in 2011, 2012*

and 2013. The European Comission. Brussels : s.n., 2014. http://ec.europa.eu/transparency/regdoc/rep/3/2014/EN/3-2014-7892-EN-F1-1.Pdf.
16. *FCA internal resources.*
17. **Peter Mock, Jörg Kühlwein, Uwe Tietge, Vicente Franco, Anup Bandivadekar, John German.** *The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU.* ICCT. 2014.
18. *Technical Guidelinesfor the preparation of applications for theapproval of innovative technologies pursuant to Regulation (EC) No 443/2009 of the European Parliament and of the Council.* Institute for Energy and Transport, Unit F.8 Sustainable Transport, The Joint Research Centre. 2013. http://ec.europa.eu/clima/policies/transport/vehicles/cars/docs/guidelines_en.pdf.
19. *Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements.* Regulation No. 83. E/ECE/TRANS/505/Rev.1/Add.82/Rev.4.
20. *China Phase 4 passenger car fuel consumption standard proposal.* International Council on Clean Transportation. 2014. http://www.theicct.org/china-phase-4-passenger-car-fuel-consumption-standard-proposal.
21. *Brazil's Inovar-Auto incentive program.* The International Council on Clean Transportation ICCT. 2013. http://www.theicct.org/brazils-inovar-auto-incentive-program.
22. **Jr., Henry Joseph.** *Flex Fuel Vehicles in Brazil.* ANFAVEA, Energy & Environment Affairs Commission. Brasilia : s.n., 2013.
23. **Sergio Barros, Agricultural Specialist.** *Brazil Biofuels Annual Report .* Agricultural Trade Office, Sao Paulo. 2014. http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_7-25-2014.pdf.
24. **Jorg Kuhlwein, John German, Anup Bandivardekar.** *Development of test cycle conversion factors among worldwide light-duty vehicle CO2 emission standards.* ICCT. 2014. http://www.theicct.org/sites/default/files/publications/ICCT_LDV-test-cycle-conversion-factors_sept2014.pdf.
25. **ICCT, International Council of Clean Transportation.** *EU CO2 emissions standards for passenger cars and light-comercial vehicles.* 2014. http://www.theicct.org/sites/default/files/publications/ICCTupdate_EU-95gram_jan2014.pdf.
26. **EPA.** *FE trends.* http://www.epa.gov/otaq/fetrends.htm.
27. http://www.fleetnews.co.uk/.
28. http://www.fueleconomy.gov/feg/findacar.shtml.
29. http://www.fueleconomy.gov/.
30. *Corporate Average Fuel Economy for MY 2017-MY 2025 Passenger Cars and Light Trucks.* Office of Regulatori Analysis and Evaluation, National Center for Statistics and Analysis, US Department Of Transportation, National Highway Traffic Safety Administration NHTSA. 2012. www.nhtsa.gov/staticfiles/rulemaking/.../FRIA_2017-2025.pdf.
31. *Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards.* Office of International Policy, Fuel Economy and Consumer programs ; National Vehicle and Fuel Emissions Laboratory, U.S. Department of Transportation NHTSA; U.S. Enviromental Protection Agency EPA. 2012. www.epa.gov/otaq/climate/documents/420r12901.pdf. EPA-420-R-12-901.
32. *2017 – 2025 Corporate Average Fuel Economy Compliance and Effects Modeling System Documentation.* National Highway Traffic Safety Adeministration NHTSA. 2011. www.nhtsa.gov/.../CAFE_Model_Documentation_2011.12.03.pdf.

33. **George Fenske, Layo Ajayi, Robert Erck, and Nicholaos Demas.** *Lubricants - Pathway to Improving Fuel Efficiency of Legacy Fleet Vehicles.* Argonne National Laboratory. 2011. http://energy.gov/sites/prod/files/2014/03/f8/deer11_fenske.pdf.
34. Lubrizol. http://www.pceo.com/articles/cylinder-deactivation-and-cam-phasing.
35. Gasitaly. http://www.gasitaly.com/f5direct.
36. *Prins vs. BRC.* Time for gas! International LPG CNG & LNG Magazine. http://www.czasnagaz.com.pl/downloads/pdf/61/cng_61_p12.pdf.
37. **Dan Meszler, John German, Peter Mock, Anup Bandivadekar.** *Summary of mass reduction impacts on EU cost curves.* ICCT. 2013.
38. **S. Pagerit, P. Sharer, A. Rousseau.** *Fuel Economy Sensitivity to Vehicle Mass for Advanced Vehicle Powertrains.* Argonne National Laboratory. 2006. http://papers.sae.org/2006-01-0665/.
39. **Oak Ridge National Laboratory. Mitch Olszewski, Program Manager.** *Evaluation of the 2007 toyota camry hybrid synergy drive system.* U.S. Department of Energy . 2008. Reports produced after January 1, 1996, are generally available free via the U.S. Department of Energy (DOE) Information Bridge:http://www.osti.gov/bridge.
40. **Compresors, Delphy.** Delphy compresors. http://www.delphi.com/.
41. *Annual Energy Outlook 2014.* U.S. Energy Information Administration, Office of Integrated and International Energy Analysis, U.S. Department of Energy. Washington, DC 20585 : s.n., 2014. http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf.
42. **Alternative Fuels Data Center, US Department of Energy.** http://www.afdc.energy.gov/.
43. *Regulated emissions of a Euro 5 passenger car measured over different driving cycles.* Institute for Enviroment and Sustainability. http://www.unece.org/fileadmin/DAM/trans/doc/2010/wp29grpe/WLTP-DHC-04-03e.pdf.
44. *REGULATION (EU) No 333/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 March 2014.* Official Journal of the European Union.
45. *Uniform provisions concerning the approval of passenger cars powered by an internal combustion engine only, or poweredby a hybrid electric power train with regard to themeasurement of the emission of carbon dioxide and fuelconsumption and/or...* 2013. Regulation No. 101; E/ECE/TRANS/505/Rev.2/Add.100/Rev.3.
46. *Computer Simulation of Light-DutyVehicle Technologies for GreenhouseGas Emission Reduction in the2020-2025 Timeframe.* Ricardo, Inc. 2011. http://www.epa.gov/otaq/climate/documents/420r11020.pdf.
47. **Greene, Dr. David L.** *POLICIES TO INCREASE PASSENGER CAR AND LIGHT TRUCK FUEL ECONOMY.* 2007.
48. **ICCT.** *Inertia Classes Proposal WLTP-DTP-LabProcICE-007.* 2011. http://www.theicct.org/sites/default/files/publications/WLTP_inertia_workingpaper_2011.pdf.

Annexes

Fleet model code

```
Sub COMBINAR()
Cells(3, 18).ClearContents
Cells(3, 19).ClearContents
Cells(3, 20).ClearContents
Cells(3, 21).ClearContents
Cells(3, 22).ClearContents
Cells(6, 18).ClearContents
Cells(6, 19).ClearContents
Cells(6, 20).ClearContents
Cells(6, 21).ClearContents
Cells(6, 22).ClearContents
Cells(9, 18).ClearContents
Cells(9, 19).ClearContents
Cells(9, 20).ClearContents
Cells(9, 21).ClearContents
FIN_B = Range("B1", Range("B" & Rows.Count).End(xlUp)).Rows.Count
FIN_F = Range("F1", Range("F" & Rows.Count).End(xlUp)).Rows.Count
FIN_J = Range("J1", Range("J" & Rows.Count).End(xlUp)).Rows.Count
FIN_N = Range("N1", Range("N" & Rows.Count).End(xlUp)).Rows.Count

VolumeDiesel_USA = Cells(3, 24)
VolumePetrol1_USA = Cells(3, 25)
VolumePetrol2_USA = Cells(3, 26)
VolumePHEV_USA = Cells(3, 27)
TotalVol_USA = VolumeDiesel_USA + VolumePetrol1_USA + VolumePetrol2_USA + VolumePHEV_USA
VolumeDiesel_EU = Cells(3, 28)
VolumePetrol1_EU = Cells(3, 29)
VolumePetrol2_EU = Cells(3, 30)
VolumePHEV_EU = Cells(6, 31)
TotalVol_EU = VolumeDiesel_EU + VolumePetrol1_EU + VolumePetrol2_EU + VolumePHEV_EU
PHEVMultiplier_USA = Cells(3, 32)
Minus50gMultiplier_EU = Cells(3, 32)
FineUSA = Cells(3, 35)
FineEU = Cells(3, 36) / Cells(3, 37)
Volume_diesel_fined_EU = 0
Volume_Petrol1_fined_EU = 0
Volume_Petrol2_fined_EU = 0
Volume_PHEV_fined_EU = 0
Volume_fined_EU = 0



Margin_to_actual_margin_Diesel = Cells(4, 24)
Margin_to_actual_margin_Petrol1 = Cells(4, 25)
Margin_to_actual_margin_Petrol2 = Cells(4, 26)
```

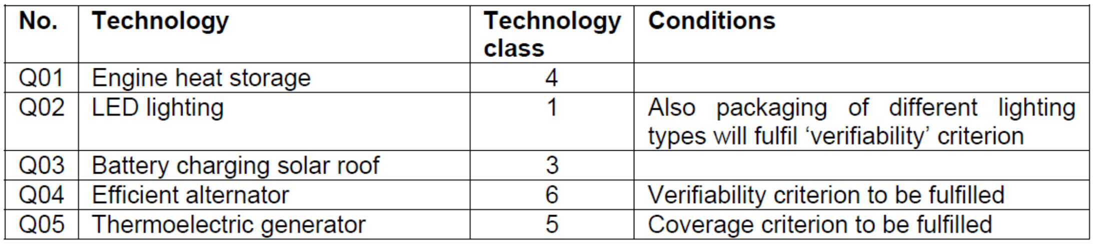
```
Margin_to_actual_margin_PHEV = Cells(4, 27)


MarginMax = 0
MarginMax2 = 0

For X = 3 To FIN_B
  For Y = 3 To FIN_F
   For Z = 3 To FIN_J
    For K = 3 To FIN_N

        Average_fleet_minus_target_fleet_co2_USA = (VolumeDiesel_USA * Cells(X, 4) + VolumePetrol1_USA * Cells(Y, 8) + VolumePetrol2_USA * Cells(Z, 12) + VolumePHEV_USA * PHEVMultiplier_USA * Cells(K, 16)) / TotalVol_USA
        Average_fleet_minus_target_fleet_co2_EU = (VolumeDiesel_EU * Cells(X, 5) + VolumePetrol1_EU * Cells(Y, 9) + VolumePetrol2_EU * Cells(Z, 13) + VolumePHEV_EU * Cells(K, 17)) * Minus50gMultiplier_EU / TotalVol_EU
        Margin_USA = VolumeDiesel_USA * Cells(X, 2) * Margin_to_actual_margin_Diesel + VolumePetrol1_USA * Cells(Y, 6) * Margin_to_actual_margin_Petrol1 + VolumePetrol2_USA * Cells(Z, 10) * Margin_to_actual_margin_Petrol2 + VolumePHEV_USA * Cells(K, 14) * Margin_to_actual_margin_PHEV
        Margin_EU = VolumeDiesel_EU * Cells(X, 3) * Margin_to_actual_margin_Diesel + VolumePetrol1_EU * Cells(Y, 7) * Margin_to_actual_margin_Petrol1 + VolumePetrol2_EU * Cells(Z, 11) * Margin_to_actual_margin_Petrol2 + VolumePHEV_EU * Cells(K, 15) * Margin_to_actual_margin_PHEV
        If (Average_fleet_minus_target_fleet_co2_USA < 0 And Average_fleet_minus_target_fleet_co2_EU < 0) Then
            If MarginMax < Margin_USA + Margin_EU Then
            MarginMax = Margin_USA + Margin_EU
            Cells(3, 18) = MarginMax
            Cells(3, 19) = X - 2
            Cells(3, 20) = Y - 2
            Cells(3, 21) = Z - 2
            Cells(3, 22) = K - 2
            Cells(9, 20) = Average_fleet_minus_target_fleet_co2_USA
            Cells(9, 21) = Average_fleet_minus_target_fleet_co2_EU
            End If

        Else
            If Cells(X, 5) > 0 Then
            Volume_diesel_fined_EU = VolumeDiesel_EU
            End If
            If Cells(X, 9) > 0 Then
            Volume_Petrol1_fined_EU = VolumePetrol1_EU
            End If
            If Cells(X, 13) > 0 Then
            Volume_Petrol2_fined_EU = VolumePetrol2_EU
            End If
            If Cells(X, 17) > 0 Then
            Volume_PHEV_fined_EU = VolumePHEV_EU
            End If
            Volume_fined_EU = Volume_diesel_fined_EU + Volume_Petrol1_fined_EU + Volume_Petrol2_fined_EU + Volume_PHEV_fined_EU
```

```
            If MarginMax2 < -Average_fleet_minus_target_fleet_co2_USA * FineUSA * TotalVol_USA - Average_fleet_minus_target_fleet_co2_EU * FineEU * Volume_fined_EU + Margin_USA + Margin_EU Then
            MarginMax2 = -Average_fleet_minus_target_fleet_co2_USA * FineUSA * TotalVol_USA - Average_fleet_minus_target_fleet_co2_EU * FineEU * Volume_fined_EU + Margin_USA + Margin_EU
            Cells(6, 18) = MarginMax2
            Cells(6, 19) = X - 2
            Cells(6, 20) = Y - 2
            Cells(6, 21) = Z - 2
            Cells(6, 22) = K - 2
            Cells(9, 18) = Average_fleet_minus_target_fleet_co2_USA
            Cells(9, 19) = Average_fleet_minus_target_fleet_co2_EU
            End If


        End If



      Next K
    Next Z
  Next Y
Next X
End Sub
```

Eco-innovations

European regulations as US regulations do offer the possibility to earn off-cycle credits for ease compliance. European potentially and non-potentially qualifying eco-innovations examples are given bellow:

Potentially qualifying Technologies:



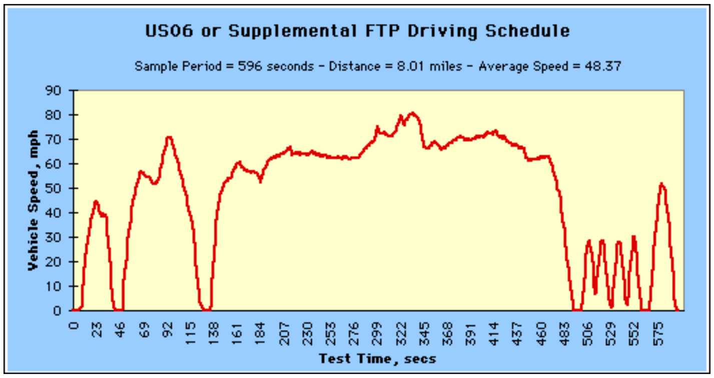
No.	Technology	Technology class	Conditions
Q01	Engine heat storage	4	
Q02	LED lighting	1	Also packaging of different lighting types will fulfil ‘verifiability’ criterion
Q03	Battery charging solar roof	3	
Q04	Efficient alternator	6	Verifiability criterion to be fulfilled
Q05	Thermoelectric generator	5	Coverage criterion to be fulfilled

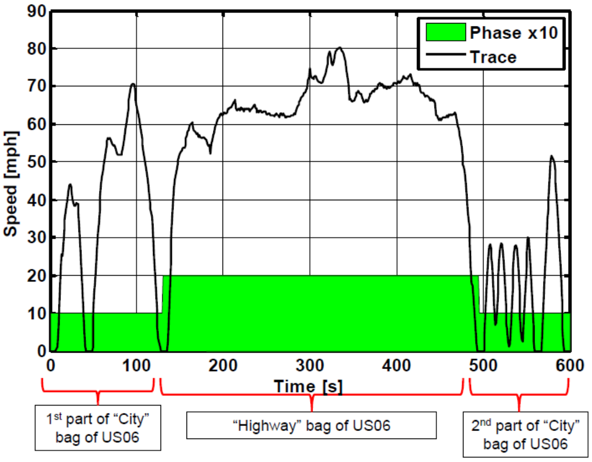
Potentially non qualifying technologies:

No.	Technology	Technology class	Reasons for non-qualification
N01	Recuperation	6	2.2 - 'Innovativeness' criterion not fulfilled
N02	Efficient seat heating	1	2.3 - 'Necessity' criterion not fulfilled
N03	Efficient HiFi system	1	2.3 - 'Necessity' criterion not fulfilled
N04	Efficient PTC cabin heater	1	2.3 - 'Necessity' criterion not fulfilled
N05	Efficient cabin lighting	1	2.4 - 'Verifiability criterion not fulfilled
N06	Efficient wiper motor	1	2.4 - 'Verifiability criterion not fulfilled
N07	Start/Stop system	7	2.5 - 'Coverage' criterion not fulfilled
N08	Electronic valve gear	2	2.5 - 'Coverage' criterion not fulfilled
N09	Flywheel	4	2.5 - 'Coverage' criterion not fulfilled
N10	Eco-driving mode	7	2.6 - 'Accountability' criterion not fulfilled
N11	Gear shift indicator	7	2.1 - 'Integrated approach measure' + 2.6 - 'Accountability' criterion not fulfilled
N12	Efficient air-conditioning system	2	2.1 - 'Integrated approach measure' + 2.3 - 'Necessity' criterion not fulfilled
N13	Tyre pressure monitor	2	2.1 - 'Integrated approach measure' + 2.6 - 'Accountability' criterion not fulfilled
N14	Low rolling resistance tyres	2	2.1 - 'Integrated approach measure' + 2.5 - 'Coverage' criterion not fulfilled
N15	Daytime running lights (DRL)	1	2.5 - 'Coverage' criterion not fulfilled
N16	Brake lights	1	2.5 - 'Coverage' criterion not fulfilled

US06 Test cycle

The full test consists of preconditioning the engine to a hot stabilized condition and an engine idle period of 1 to 2 minutes, after which the vehicle is accelerated into the US06 cycle.



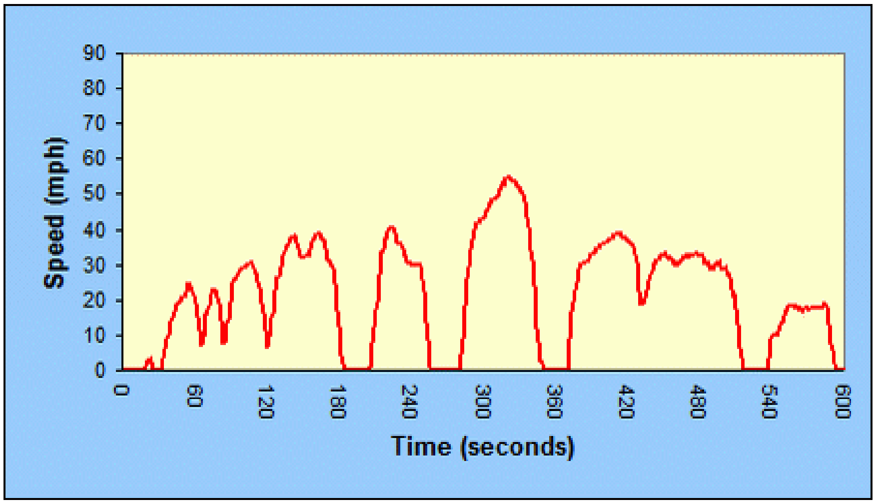


SC03 Test cycle

The test procedure is designed to determine gaseous exhaust emissions from light-duty vehicles and light-duty trucks with the air conditioner operating while during an urban trip at ambient conditions of 95 ºF (35 ºC), 100 grains of water/pound of dry air (40 % R.H.), and a solar heat load intensity of 850 W/m2.

The full test consists of vehicle preconditioning, an engine key-off 10 minute soak, an engine start, and operation over the SC03 cycle.

The radiant energy or solar heat load for this test is defined by the EPA based upon the global reference spectral irradiance standard, global AM 1.5. For this procedure, the radiant energy must be uniform within +/-15% over a 0.5 meter grid averaged at the centerline of the vehicle and at the base of the windshield and rear window.



Spreadsheets

Technology A	Technology B	FC Synergy	Technology A	Technology B	Cost synergy [$]
DEACD	CVVL	-0,40%	DEACD	CVVL	-27,9
TRBDS1_SD	CVVL	-0,72%	TRBDS1_SD	DVVLD	-10,4
TRBDS1_MD	CVVL	-0,21%	TRBDS1_MD	DVVLD	-137,5
TRBDS1_LD	CVVL	-0,21%	TRBDS1_LD	DVVLD	-151,1
TRBDS1_SD	VVA	4,79%	TRBDS1_SD	CVVL	-10,4
DCP	SHFTOPT	-0,60%	TRBDS1_MD	CVVL	-137,5
DCP	IACC1	-0,20%	TRBDS1_LD	CVVL	-151,1
DCP	IACC2	-0,40%	TRBDS1_SD	VVA	-420,1
CCPS	SHFTOPT	-0,60%	TRBDS1_MD	VVA	562,8
CCPS	IACC1	-0,20%	TRBDS1_LD	VVA	524,0
CCPS	IACC2	-0,40%	SHEV1	TRBDS1_SD	-420,1
DVVLS	IATC	-0,40%	SHEV1	TRBDS1_MD	29,3
DVVLS	MHEV	-0,50%	SHEV1	TRBDS1_LD	-523,5
DVVLS	IACC2	-0,80%	SHEV1	MHEV	-325,4
DVVLS	8SPD	-0,70%	SHEV2	TRBDS1_SD	-420,1
DVVLD	IATC	-0,40%	SHEV2	TRBDS1_MD	29,3
DVVLD	MHEV	-0,50%	SHEV2	TRBDS1_LD	-523,5
DVVLD	IACC2	-0,80%	SHEV2	MHEV	-325,4

DVVLD	8SPD	-0,70%
CVVL	IATC	-0,40%
CVVL	MHEV	-0,50%
CVVL	IACC2	-0,80%
CVVL	8SPD	-0,70%
DEACD	IATC	-0,40%
DEACO	MHEV	-0,50%
DEACO	IACC2	-0,80%
DEACO	8SPD	-0,70%
VVA	IATC	-0,40%
VVA	SHFTOPT	-0,60%
VVA	IACC1	-0,20%
VVA	IACC2	-0,40%
TRBDS1_SD	IATC	-0,50%
TRBDS1_MD	IATC	-0,50%
TRBDS1_LD	IATC	-0,50%
TRBDS1_SD	SHFTOPT	-0,20%
TRBDS1_MD	SHFTOPT	-0,20%
TRBDS1_LD	SHFTOPT	-0,20%
TRBDS2_SD	NAUTO	-0,50%
TRBDS2_MD	NAUTO	-0,50%
TRBDS2_LD	NAUTO	-0,50%
TRBDS2_SD	EPS	-0,20%
TRBDS2_MD	EPS	-0,20%
TRBDS2_LD	EPS	-0,20%
TRBDS2_SD	IACC2	-0,10%
TRBDS2_MD	IACC2	-0,10%
TRBDS2_LD	IACC2	-0,10%
CEGR1_SD	IACC2	-0,20%
CEGR1_MD	IACC2	-0,20%
CEGR1_LD	IACC2	-0,20%
CEGR2_SD	NAUTO	-0,60%
CEGR2_MD	NAUTO	-0,60%
CEGR2_LD	NAUTO	-0,60%
DCT	MHEV	-0,30%
SHFTOPT	MHEV	-0,30%
ROLL1	AERO1	0,20%
ROLL2	AERO$_2$	0,10%
MR4	AERO$_2$	0,40%
ADSL_SD	IATC	1,00%
ADSL_MD	IATC	1,00%
ADSL_LD	IATC	1,00%
NAUTO	SAX	-0,40%
SHEV1	AERO$_2$	1,00%
SHEV1	ROLL1	0,70%
SHEV1_2	AERO$_2$	0,20%

SHEV1_2	TRBDS2_SD	-19,9
SHEV1_2	TRBDS2_MD	-247,6
SHEV1_2	TRBDS2_LD	-417,4
SHEV1_2	CEGR1_SD	-285,2
SHEV1_2	CEGR1_MD	-285,2
SHEV1_2	CEGR1_LD	-285,2
SHEV1_2	CEGR2_SD	-495,2
SHEV1_2	CEGR2_MD	-495,2
SHEV1_2	CEGR2_LD	296,7
SHEV2	TRBDS2_SD	-19,9
SHEV2	TRBDS2_MD	-247,6
SHEV2	TRBDS2_LD	-417,4
SHEV2	CEGR1_SD	-285,2
SHEV2	CEGR1_MD	-285,2
SHEV2	CEGR1_LD	-285,2
SHEV2	CEGR2_SD	-495,2
SHEV2	CEGR2_MD	-495,2
SHEV2	CEGR2_LD	296,7

SHEV1_2	ROLL2	0,30%
SHEV2	$AERO_2$	1,20%
SHEV2	ROLL2	1,00%
SHEV2	MR2	-0,40%
SHEV2	MR3	-0,20%
SHEV2	MR4	-0,30%
PHEV1	$AERO_2$	0,10%
PHEV1	ROLL2	0,40%
IATC	CCPS	-1,40%
IATC	ICP	-1,40%
IATC	DEACO	-1,40%
8SPD	CCPS	-1,90%
8SPD	ICP	-1,90%
8SPD	DEACO	-1,90%
HETRANS	CCPS	0,50%
HETRANS	ICP	0,50%
HETRANS	DEACO	0,50%
IATC	TRBDS1_SD	1,40%
IATC	TRBDS1_MD	1,40%
IATC	TRBDS1_LD	1,40%
8SPD	TRBDS1_SD	1,90%
8SPD	TRBDS1_MD	1,90%
8SPD	TRBDS1_LD	1,90%
HETRANS	TRBDS1_SD	-0,50%
HETRANS	TRBDS1_MD	-0,50%
HETRANS	TRBDS1_LD	-0,50%

Technology type (Path)		Engine											
Technology		Low Friction Lubricants - Level 1	Engine Friction Reduction - Level 1- for 4 cyl	Low Friction Lubricants and Engine Friction Reduction - Level 2- for 4 cyl	Variable Valve Timing (VVT) - Coupled Cam Phasing (CCP) on SOHC	Discrete Variable Valve Lift (DVVL) on SOHC - for 4 cyl	Cylinder Deactivation on SOHC	Variable Valve Timing (VVT) - Intake Cam Phasing (ICP)	Variable Valve Timing (VVT) - Dual Cam Phasing (DCP)	Discrete Variable Valve Lift (DVVL) on DOHC- for 4 cyl	Continuously Variable Valve Lift (CVVL) - per 4 cyl	Cylinder Deactivation on DOHC	Stoichiometric Gasoline Direct Injection (GDI) - for 4 cyl
Technology Abbr.		LUB1	EFR1	LUB2_EFR2	CCPS	DVVLS	DEACS	ICP	DCP	DVVLD	CVVL	DEACD	SGDI
Incremental to		base engine	base engine	EFR1	base engine	CCPS	DVVLS	base engine	ICP	DCP	DCP	DVVLD or CVVL	base engine
Source		2012-2016 FR	2012-2016 FR	2017+ NPRM	2012-2016 FR	2012-2016 FR	2012-2016 FR	2012-2016 FR	2012-2016 FR	2012-2016 FR	2012-2016 FR	2012-2016 FR	FEV
FC Reduction Incremental [%]		0,70%	2,60%	1,26%	5,03%	3,64%	0,69%	2,62%	2,47%	3,64%	4,63%	0,69%	1,50%
Technology cost incremental [$] or [$]/lb. for mass red.	**2018**	4,02	60,50	62,84	45,59	160,65	32,00	45,59	43,60	160,65	258,62	32,00	264,56
	2020	3,86	58,09	62,84	42,25	144,21	28,61	42,25	39,14	144,21	232,15	28,61	236,56
	2022	3,86	58,09	62,84	40,86	139,75	27,75	40,86	37,93	139,75	224,97	27,75	229,40
	2024	3,86	58,09	62,84	39,53	135,47	26,92	39,53	36,77	135,47	218,08	26,92	222,52

Technology type (Path)		Engine									
Technology		Cylinder Deactivation on OHV	Variable Valve Actuation - CCP and DVVL on OHV	Turbocharging and Downsizing - Level 1 (18 bar BMEP) - Small Displacement	Turbocharging and Downsizing - Level 2 (24 bar BMEP) - Small Displacement	Cooled Exhaust Gas Recirculation (EGR) - Level 1 (24 bar BMEP) - Small Displacement - Turbo	Cooled Exhaust Gas Recirculation (EGR) - Level 2 (27 bar BMEP) - Small Displacement - Turbo	Advanced Diesel - Small Displacement	Advanced Diesel - Medium Displacement	CNG Engine - Level 1	LPG
Technology Abbr.		DEACO	VVA	TRBDS1_SD_TB	TRBDS2_SD_TB	CEGR1_SD_TB	CEGR2_SD_TB	ADSL_SD	ADSL_MD	CNG ENGINE	LPG ENGINE
Incremental to		base engine	DEACO	SGDI (SOHC Path)	TRBDS1_SD	TRBDS1_SD	TRBDS1_SD	CEGR2_SD	CEGR2_MD	Base engine	Base engine
Source		2012-2016 FR	2012-2016 FR	FEV	FEV	FEV	FEV	EPA	EPA	Tutor	Tutor
FC Reduction Incremental [%]		5,86%	3,45%	8,29%	3,54%	3,54%	1,36%	2,75%	2,75%	20,00%	10,00%
Technology cost incremental [$] or [$]/lb. for mass red.	**2018**	204,67	51,16	487,26	27,16	297,79	517,13	869,94	839,75	1500,00	500,00
	2020	183,72	45,92	425,91	18,85	289,28	502,36	928,84	942,49	1500,00	500,00
	2022	178,04	44,50	414,33	20,95	281,11	488,16	893,59	913,51	1500,00	500,00
	2024	172,58	43,14	403,20	22,97	273,26	474,53	859,74	885,69	1500,00	500,00

Technology type (Path)		Transmission							
Technology		6-Speed Manual/Improved Internals	High Efficiency Gearbox (Manual)	Improved Auto. Trans. Controls/Externals	6-Speed Trans with Improved Internals (Auto)	6-speed DCT	8-Speed Trans (Auto or DCT)	High Efficiency Gearbox w/ dry sump (Auto or DCT)	Shift Optimizer
Technology Abbr.		6MAN	HETRANSM	IATC	NAUTO	DCT	8SPD	HETRANS	SHFTOPT
Incremental to		base manual trans	6MAN	base auto trans	IATC	NAUTO	NAUTO or DCT	8SPD	HETRANS
Source		2012-2016 FR	2012-2016 FR	2012-2016 FR	FEV	FEV	FEV	EPA	EPA
FC Reduction Incremental [%]		2,39%	4,08%	3,00%	2,04%	4,06%	4,57%	2,68%	4,08%
Technology cost incremental[$]	**2018**	274,69	244,74	61,24	-37,99	-71,97	253,63	244,74	1,63
	2020	254,53	233,02	56,75	-38,93	-81,61	226,79	233,02	1,55
	2022	246,19	222,00	54,89	-36,92	-76,81	219,92	222,00	1,48
	2024	238,17	215,05	53,10	-35,00	-72,19	213,32	215,05	1,43

Technology type (Path)		Electric							
Technology		Electric Power Steering	Improved Accessories - Level 1	Improved Accessories - Level 2	12V Micro-Hybrid (Stop-Start)	Integrated Starter Generator - Battery	Integrated Starter Generator - Non-Battery	Strong Hybrid (Powersplit or 2-Mode) - Level 1 - Battery	Strong Hybrid (Powersplit or 2-Mode) - Level 1 - Non-Battery
Technology Abbr.		EPS	IACC1	IACC2	MHEV	ISG_B	ISG_NB	SHEV1_B	SHEV1_NB
Incremental to		base vehicle	EPS	IACC1	IACC2	MHEV	MHEV	TRBDS1, 8SPD, ISG	TRBDS1, 8SPD, ISG
Source		2012-2016 FR	2012-2016 FR	EPA	2012-2016 FR	2017 + FR	2017 + FR	2017+ NPRM	2017+ NPRM
FC Reduction Incremental [%]		1,30%	1,22%	2,36%	2,10%	6,50%		5,30%	
CO2 Credits Reduction Incremental[g/mi]					2,5				
Technology cost incremental [$] or [$]/lb. for mass red.	**2018**	107,65	87,55	53,30	376,82	230,20	757,91	396,76	1904,85
	2020	99,75	81,13	51,60	333,02	255,93	677,71	380,95	1514,72
	2022	96,48	78,47	49,97	317,68	246,74	657,18	366,07	1471,98
	2024	93,34	75,91	48,41	303,25	238,25	637,47	352,08	1430,93

Technology type (Path)		Electric						
Technology		Conversion from SHEV1 to SHEV2	Strong Hybrid (P2 Parallel or 2-Mode) - Level 2 - Battery	Strong Hybrid (P2 Parallel or 2-Mode) - Level 2 - Non-Battery	Plug-in Hybrid - 30 mi range - Battery	Plug-in Hybrid - 30 mi range - Non-Battery	Electric Vehicle (Early Adopter) - 75 mile range - Battery	Electric Vehicle (Early Adopter) - 75 mile range - Non-Battery
Technology Abbr.		SHEV1_2	SHEV2_B	SHEV2_NB	PHEV2_B	PHEV2_NB	EV1_B	EV1_NB
Incremental to		SHEV1	CEGR2, SHFTOPT, ISG	CEGR2, SHFTOPT, ISG	SHEV2_B	SHEV2_NB	PHEV2	PHEV2
Source		2017+ NPRM	2017+ NPRM	2017+ NPRM	2017+ NPRM	2017+ NPRM	2017+ NPRM	2017+ NPRM
FC Reduction Incremental [%]		12,46%	0,11%		40,65%		68,54%	
CO2 Credits Reduction Incremental[g/mi]								
Technology cost incremental [$] or [$]/lb. for mass red.	**2018**	1204,58	396,76	1904,85	7760,56	2601,20	5742,36	-3061,38
	2020	1159,51	380,95	1514,72	6536,68	2141,75	4930,80	-2209,61
	2022	1126,52	366,07	1471,98	6583,64	2079,94	4930,80	-2157,93
	2024	1098,49	352,08	1430,93	6627,82	2020,58	4930,80	-2084,08

Technology type (Path)		Rolling Resistance Tires		Driveline resistance		Aerodynamic improvement	
Technology		Low Rolling Resistance Tires - Level 1	Low Rolling Resistance Tires - Level 2	Low Drag Brakes	Secondary Axle Disconnect	Aero Drag Reduction, Level 1	Aero Drag Reduction, Level 2
Technology Abbr.		ROLL1	ROLL2	LDB	SAX	AERO1	$AERO_2$
Incremental to		base tire	ROLL1	base vehicle	LDB	base vehicle	AERO1
Source		2012-2016 FR	2017+ NPRM	2012-2016 FR	2012-2016 FR	2012-2016 FR	2010 TAR
FC Reduction Incremental [%]		1,90%	2,04%	0,80%	1,40%	2,30%	2,46%
CO_2 Credits Reduction Incremental[g/mi]							0,6
Technology cost incremental [$/lb]	**2018**	6,71	73,16	73,77	96,09	48,13	162,00
	2020	6,44	60,39	70,84	89,04	44,60	157,25
	2022	6,44	48,95	70,84	86,12	43,13	152,70
	2024	6,44	46,60	70,84	83,32	41,73	148,32

Technology type (Path)	Other off-cycle credits/ECO Innovations. In orange EU. All the other applicable for USA.											
Technology	A/C Efficiency credits - Level 1	A/C Efficiency credits - Level 2	Glass or Glazing (UP TO 2,9)	Passive Cabin Ventilation	Active Transmission Warm-Up	Active Engine Warm-up	Active Seat Ventilation	Solar Reflective Paint	Active Cabin Ventilation	High Efficiency Exterior Lights* (at 100 watt savings)	Solar Panels (based on a 75 watt solar panel)	Waste Heat Recovery (at 100W)
Technology Abbr.	AC1	AC2	G	PCV	ATW-EU	AEW-EU	ASV	SRP	ACV	HEEL-EU	SP-EU	WHR-EU
Incremental to	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle	base vehicle
Source	Tutor											
FC Credits Reduction Incremental[g/mi]	1	1,5	2	1,7	1,5	1,5	1	0,4	2,1	1	3,3	0,7
Technology cost incremental[$]	20,00	35,00	100,00	100,00	100,00	100,00	100,00	50,00	300,00	200,00	1500,00	350,00

Technology type (Path)		Mass reduction									
Technology		Mass Reduction - Level 1 - 5%	Mass Reduction - Level 2 - 10%	Mass Reduction - Level 3 - 15%	Mass Reduction - Level 4 - 20%	Mass Reduction - Level 1 - CNG LPG - 10%	Mass Reduction - Level 2 - CNG LPG - 15%	Mass Reduction - Level 3 - CNG LPG - 20%	Mass Reduction - Level 1 - HEV - 10%	Mass Reduction - Level 2 - HEV - 15%	Mass Reduction - Level 3 - HEV - 20%
Technology Abbr.		MR1-5%	MR2-10%	MR3-15%	MR4-20%	MR1CNG LPG-10%	MR2CNG LPG-15%	MR3CNG LPG-20%	MR1E-10%	MR2E-15%	MR3E-20%
Incremental to		base vehicle	base vehicle	base vehicle	base vehicle	CNG LPG vehicle	CNG LPG vehicle	CNG LPG vehicle	HEV vehicle	HEV vehicle	HEV vehicle
Source		mass vs fc:S. Pagerit, P. Sharer, A. Rousseau paper - Mass vs cost: NHTSA									
FC Reduction Incremental [%]		2,05%	4,10%	6,15%	8,20%	4,10%	6,15%	8,20%	4,80%	7,20%	9,60%
Technology cost incremental[$]	**2018**	0,22	0,44	0,65	0,87	0,65	0,87	1,09	0,65	0,87	1,09
	2020	0,22	0,44	0,65	0,87	0,65	0,87	1,09	0,65	0,87	1,09
	2022	0,22	0,44	0,65	0,87	0,65	0,87	1,09	0,65	0,87	1,09
	2024	0,22	0,44	0,65	0,87	0,65	0,87	1,09	0,65	0,87	1,09

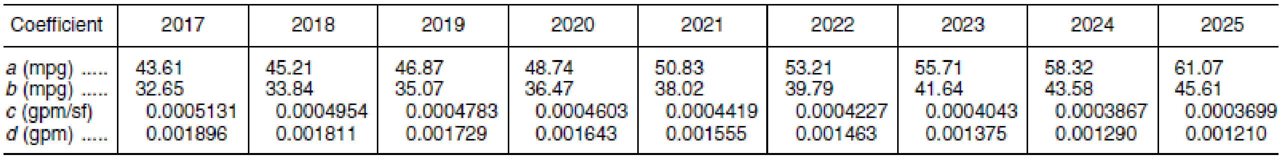
Light duty truck LDT definition

Any motor vehicle rated at 8,500 pounds GVWR or less which has a vehicle curb weight of 6,000 pounds or less and which has a basic vehicle frontal area of 45 square feet or less, which is:

1. Designed primarily for purposes of transportation of property or is a derivation of such a vehicle, or
2. Designed primarily for transportation of persons and has a capacity of more than 12 persons, or
3. Available with special features enabling off-street or off-highway operation and use (40 CFR 86.1803-01).

CAFE Target curve PC

$$TARGET = \frac{1}{MIN\left[MAX\left(c \times FOOTPRINT + d, \frac{1}{a}\right), \frac{1}{b}\right]}$$



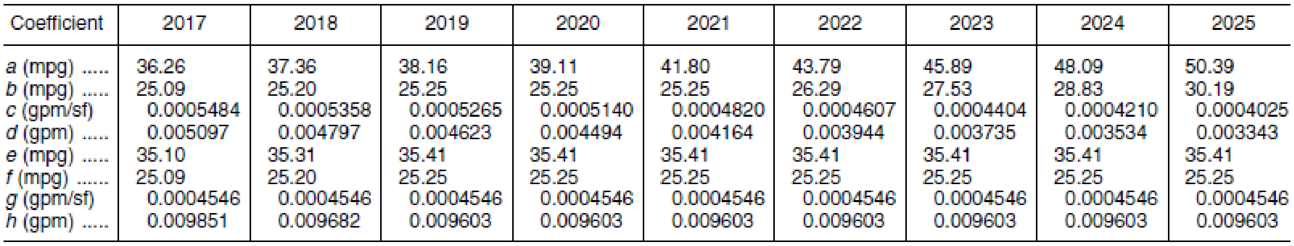
Coefficient	2017	2018	2019	2020	2021	2022	2023	2024	2025
a (mpg)	43.61	45.21	46.87	48.74	50.83	53.21	55.71	58.32	61.07
b (mpg)	32.65	33.84	35.07	36.47	38.02	39.79	41.64	43.58	45.61
c (gpm/sf)	0.0005131	0.0004954	0.0004783	0.0004603	0.0004419	0.0004227	0.0004043	0.0003867	0.0003699
d (gpm)	0.001896	0.001811	0.001729	0.001643	0.001555	0.001463	0.001375	0.001290	0.001210

Footprint [sqft]	MY 2018	MY 2020	MY 2022	MY 2024
35	45,21	48,74	53,21	58,32
36	45,21	48,74	53,21	58,32
37	45,21	48,74	53,21	58,32
38	45,21	48,74	53,21	58,32
39	45,21	48,74	53,21	58,32
40	45,21	48,74	53,21	58,32
41	45,20	48,74	53,21	58,32
42	44,21	47,67	52,11	57,04
43	43,27	46,65	50,99	55,81
44	42,36	45,67	49,91	54,63
45	41,49	44,73	48,88	53,50
46	40,65	43,83	47,89	52,42
47	39,85	42,96	46,94	51,37
48	39,08	42,13	46,03	50,37
49	38,34	41,33	45,15	49,41
50	37,62	40,55	44,30	48,48

51	36,93	39,81	43,49	47,59
52	36,27	39,10	42,70	46,73
53	35,63	38,40	41,95	45,90
54	35,01	37,74	41,22	45,10
55	34,41	37,09	40,51	44,33
56	33,84	36,47	39,83	43,58
57	33,84	36,47	39,79	43,58
58	33,84	36,47	39,79	43,58
59	33,84	36,47	39,79	43,58
60	33,84	36,47	39,79	43,58
61	33,84	36,47	39,79	43,58
62	33,84	36,47	39,79	43,58
63	33,84	36,47	39,79	43,58
64	33,84	36,47	39,79	43,58
65	33,84	36,47	39,79	43,58

CAFE Target curve LDT

$$TARGET = MAX\left(\frac{1}{MIN\left[MAX\left(c \times FOOTPRINT + d, \frac{1}{a}\right), \frac{1}{b}\right]}, \frac{1}{MIN\left[MAX\left(g \times FOOTPRINT + h, \frac{1}{e}\right), \frac{1}{f}\right]}\right)$$



Coefficient	2017	2018	2019	2020	2021	2022	2023	2024	2025
a (mpg)	36.26	37.36	38.16	39.11	41.80	43.79	45.89	48.09	50.39
b (mpg)	25.09	25.20	25.25	25.25	25.25	26.29	27.53	28.83	30.19
c (gpm/sf)	0.0005484	0.0005358	0.0005265	0.0005140	0.0004820	0.0004607	0.0004404	0.0004210	0.0004025
d (gpm)	0.005097	0.004797	0.004623	0.004494	0.004164	0.003944	0.003735	0.003534	0.003343
e (mpg)	35.10	35.31	35.41	35.41	35.41	35.41	35.41	35.41	35.41
f (mpg)	25.09	25.20	25.25	25.25	25.25	25.25	25.25	25.25	25.25
g (gpm/sf)	0.0004546	0.0004546	0.0004546	0.0004546	0.0004546	0.0004546	0.0004546	0.0004546	0.0004546
h (gpm)	0.009851	0.009682	0.009603	0.009603	0.009603	0.009603	0.009603	0.009603	0.009603

Footprint [sqft]	**MY 2018**	**MY 2020**	**MY 2022**	**MY 2024**
44	35,25	36,89	41,30	45,34
45	34,59	36,20	40,53	44,49
46	33,96	35,54	39,78	43,67
47	33,36	34,90	39,07	42,88
48	32,77	34,29	38,38	42,12
49	32,20	33,69	37,71	41,39
50	31,66	33,12	37,07	40,68
51	31,13	32,56	36,44	39,99
52	30,62	32,03	35,84	39,33

53	30,13	31,51	35,26	38,69
54	29,65	31,01	34,70	38,07
55	29,18	30,52	34,15	37,47
56	28,73	30,05	33,62	36,89
57	28,30	29,59	33,11	36,32
58	27,88	29,15	32,61	35,78
59	27,47	28,72	32,13	35,24
60	27,07	28,30	31,66	34,73
61	26,73	27,90	31,20	34,23
62	26,41	27,50	30,76	33,74
63	26,09	27,12	30,33	33,27
64	25,79	26,75	29,91	32,81
65	25,49	26,38	29,51	32,36
66	25,20	26,03	29,11	31,93
67	25,20	25,69	28,73	31,50
68	25,20	25,35	28,35	31,09
69	25,20	25,25	27,99	30,69