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Tool for the environmental assessment in the automotive context: analysis of the use stage for different typologies of LCA study

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Summary

The work is developed in the context of the automotive Life Cycle Assessment (LCA) and it is aimed to represent a valid support for practitioners in the design for environment of both conventional and innovative lightweight solutions. The final target of the research is to conceive a tool able to perform the LCA of the use stage in applications to Internal Combustion Engine (ICE) turbocharged vehicles within the following typologies of study:

- LCA of a specific vehicle component;
- comparative LCA between a reference and an innovative lightweight alternative.

The tool is constituted by a series of environmental models able to treat with the needs of the cited typologies of study and to achieve specific enhancements with respect to existing literature. The work is articulated into two main sections: simulation modelling and environmental modelling. Simulation modelling performs an in-depth calculation of weight-induced Fuel Consumption (FC) whose outcome is the Fuel Reduction Value (FRV) coefficient evaluated for a wide range of vehicle case studies. Environmental modelling refines a series of environmental models able to perform

- allocation of impacts to the component (LCA of a specific vehicle component)
- estimation of impact reduction achieved through light-weighting (comparative LCA)

basing on the FRVs obtained by simulations. The implementation of the FRVs within the environmental models represent the added value of the research and makes the tool flexible and tailorable for any generic case study.

The first part of the work defines the topic of the research, aiming to explain the relevance of the design for environment within the automotive LCA context. An introduction to the LCA methodology is provided and the importance of the use stage in the determination of the overall vehicle impact is highlighted. Chapter 2 is constituted by a State Of the Art (SOA) analysis regarding the considered typologies of LCA study; the review includes both findings from research and practices usually adopted in current LCA analyses. Literature data are collected and presented to support this section, from existing automotive LCAs to studies that deal with the determination of the mass-induced fuel consumption reduction. Current approaches are described in detail, analyzed, and critically commented, evidencing the main points of criticism they are subject to. In the light of critical analysis, the

enhancements with respect to existing literature are identified and translated into specific requirements the environmental tool has to fulfill.

Chapter 3 describes the stages needed in order to conceive the tool, evidencing the partition between simulation and environmental modelling. In the simulation modelling the modality for calculating the use stage FC and evaluating the Fuel Reduction Value (FRV) coefficient is established. FC is determined for different car mass-configurations and the FRV is obtained as the relationship between FC and mass; the FRV is evaluated for both the cases of Primary Mass Reduction (PMR) only and implementation of car re-design (Secondary Effects, SE). The section illustrates the main features of the use stage simulation model, the extension of the analysis in terms of both vehicle classes and driving cycles and the implementation of SEs. The environmental modelling defines structure and operation of the use stage environmental models; basic equations that quantify input/output flows between processes are defined evidencing the central role of the FRV coefficient.

Chapter 4 illustrates the implementation of the use stage simulation model within the AMESim environment, including equations, logic and parameters which govern its operation. The setting of model parameters is explained in detail with the support of figures and tables in SI appendix; this phase includes also data collection, analysis and treatment performed by the Candidate.

Chapter 5 reports the results of the research subdivided between simulation and environmental modelling: values of FC and FRV obtained by simulations for the various case studies (simulation modelling) and implementation of environmental models within the software GaBi6 (environmental modelling).

The results are critically discussed in chapter 6. At first the values of FRV are commented by evaluating the influence of vehicle class, driving cycle and SEs. After that the existence of any correlation between the FRV and the main vehicle technical features is investigated and a criterion for implementing the coefficient within the environmental models is identified. Finally the environmental models are commented placing particular emphasis on the possibility to set up the FRV basing on technical features of the specific case study. Such a possibility represents the added value of the research with respect to existing literature and makes the environmental models a flexible and tailorable tool for application to real case studies.

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Acronyms List

BMEP: Brake Mean Effective Pressure
DT: Diesel Turbocharged
ECE: Economic Commision for Europe duty cycle
EoL: End of Life
EU: European Commission
FC: Fuel Consumption
FRV: Fuel Reduction Value
FTP72: Federal Test Procedure 72
FU: Functional Unit
G&S: Goal and Scope
GHG: GreenHouse Gas emissions
GRPE: Working party on Pollution and Energy Group
GT: Gasoline Turbocharged
GWP: Global Warming Potential
ICE: Internal Combustion Engine
JC08: Japanese driving Cycle 08
LC: Life Cycle
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LCIn: Life Cycle Intrepretation
MPS: Mean Piston Speed
MVEG: Motor Vehicle Emissions Group
NEDC: New European Driving Cycle
PMR: Primary Mass reduction
PMR: Power-to-Mass Ratio
PU: Process Unit
SBR: Stroke-to-Bore Ratio
SE: Secondary Effects
S&S: Start and Stop system
TTW: Tank-To-Wheel
UNECE: United Nations Economic Commission for Europe
U.S. EPA: United States Environmental Protection Agency
WLTC: Worldwide harmonized Light Test Cycle
WLTP: Worldwide harmonized Light Test Procedure
WTT: Well-To-Tank

Preface

Transportation plays a lading role within our global society and the development trends indicate a substantial growth in this sector over the coming decades. Considering the European Union, the transportation industry is currently the second largest contributor to anthropogenic GreenHouse Gas (GHG) emissions; around 20% of these emissions are generated by road transports. In this context light-duty vehicles account for approximately 10% of total energy use and GHG emissions and according to the World Business Council for Sustainable Development, they could increase from roughly 700 million to 2 billion over the period 2000-2050. Against this background, the experts predict a dramatic increase in gasoline and diesel demand with implications on energy security, climate change and urban air quality.

From past studies it is known that about 85% of a passenger car’s Global Warming Potential (GWP) is caused by the use stage, whereas about one third of Internal Combustion Engine (ICE) vehicle’s total fuel consumption directly depends on its weight. Accordingly, lightweight design has been recognized as one of the key measures for reducing vehicle consumption, along with power train efficiency, aerodynamics and electrical power management. At the same time, it is undoubted that many lightweight materials such as aluminum, magnesium, or carbon fibers are comparatively energy-intensive to produce, and cause significantly higher CO_2 emissions prior to the use stage than, for instance, conventional steel concepts. This yields break-even kilometrages, i.e., the total driving distance required to compensate these emissions through reduced fuel consumption.

Life Cycle Assessment (LCA) can be described as an environmental accounting methodology which enables the quantification and evaluation of environmental effects, associated with a specific service, manufacturing process or product. In recent periods the LCA has been largely employed in the transportation sector and particularly in the automotive field for evaluating the environmental progress from one product generation to the next.

This work is developed in the context of the automotive LCA and it is aimed to represent a valid support for practitioners in the design for environment of both conventional and innovative lightweight solutions. The final target of the research is to conceive a tool able to perform the LCA of the use stage within specific automotive applications:

- LCA of a specific vehicle component;
- comparative LCA between a reference and an innovative lightweight alternative.

The tool is constituted by a series of environmental models able to treat with the needs of the cited typologies of study and to achieve specific enhancements with respect to existing literature. The work is based on an in-depth calculation of weight-induced fuel consumption whose outcome is the Fuel Reduction Value (FRV) coefficient evaluated for a wide range of vehicle case studies. The values of FRV are implemented within the environmental models making the tool flexible and tailorable for any generic case study.

1. Introduction

Our global society is strongly dependent on transportation and the development trends indicate a substantial growth in this sector over the coming decades (Hawkins at al., 2012). The transportation industry (including all transport modes, from air to surface traffic) is currently the second largest contributor to anthropogenic GreenHouse Gas (GHG) emissions within the European Union and around 20% of these emissions are generated by road transports, including both private/public and passenger/freight vehicles (Witik et al., 2011). More specifically light-duty vehicles account for approximately 10% of total energy use and GHG emissions (Solomon et al., 2007a,b) and according to a study commissioned by the World Business Council for Sustainable Development (2004), they could increase from roughly 700 million to 2 billion over the period 2000-2050. These patterns forecast a dramatic increase in gasoline and diesel demand with implications on energy security, climate change and urban air quality (Ford et al., 2011; Hawkins et al., 2012; IPCC, 2013; Moawad et al., 2013; O'Neill and Oppenheimer, 2002; Steffen et al., 1998; Susan, 2007; U.S. EPA; U.S. National Highway Traffic Safety Administration, 2012; U.S. EPA, 2013, 2014).

Against this background, many countries have put regulations in order to reduce fuel consumption and air emissions, including high taxes on fuels to promote energy conservation. Considering the European context, emission requirements for road vehicles have existed since the early 1970s; requirements have been repeatedly tightened over the years and the process is still ongoing. Today, vehicle emissions are controlled under two basic frameworks: the "Euro standards" and the regulation on carbon dioxide emissions.

The "Euro standards" regulate emissions of nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), and particle numbers (PN). The standards are designated "Euro" and followed by a number (i.e. Euro 1, Euro 2). Compliance is determined by running the vehicle in a standardized test cycle. New standards apply only to new vehicles; non-compliant cars cannot be sold in the European Union (EU). The first Euro standard, Euro 1 (European Union, 1991), entered into force in 1992-1993; since then, the standards have subsequently been updated several times with emissions limits progressively more severe. In December 2006 the EU established the currently applicable Euro standards (European Union, 2007). The present standard, the Euro 6, applies to the approval of new vehicles as of September 2014, and to the sale of all new vehicles as from September 2015.

The regulation on carbon dioxide emissions (CO_2) dates back to 2009, when the EU first introduced mandatory CO_2 standards for new passenger cars. The carbon dioxide directive differs from the Euro standard in that compliance is not required for a single vehicle but for the weighted performance of the entire fleet produced by a manufacturer in a year. In

2013, the European Parliament and the Council of the European Union established two regulations that will implement mandatory 2020 CO_2 emission targets for new passenger cars and light-commercial vehicles in the EU. The passenger car standards are 95 [g/km] of CO_2, phasing in for 95% of vehicles in 2020 with 100% compliance in 2021. The 95 [g/km] target for 2020 corresponds to about 3.8 liters per 100 kilometer of fuel consumption. The existing regulation has already led to noticeable results: the average CO_2 emission level of new cars decreased from about 160 [g/km] in 2006 to 132 [g/km] in 2012 (17% reduction) and the annual reduction rate is about twice what it was before introduction of mandatory emission targets. The required reduction between 2015 and 2020 is 27% for all manufacturers (ICCT, 2014).

1.1. Design for sustainability in automotive industry

Sustainability has become a critical issue for the automotive industry, motivating more significant reductions to the overall environmental impact of vehicles. This trend adds more pressure on the original equipment manufacturers, as nowadays cars have to meet also environmental targets additionally to the traditional ones (safety, performance and functionality). Sustainability ensures that the needs of both the business customer and society are met while preserving the ecosystem. From this definition the inherent complexity of the term “sustainability” directly derives, as it involves treating different issues within the product development process, such as social, ethic, environmental and economic. In order to ensure the automobile is an environmental sustainable asset, design for sustainability follows the design-for-X principles (Figure 1.1.).

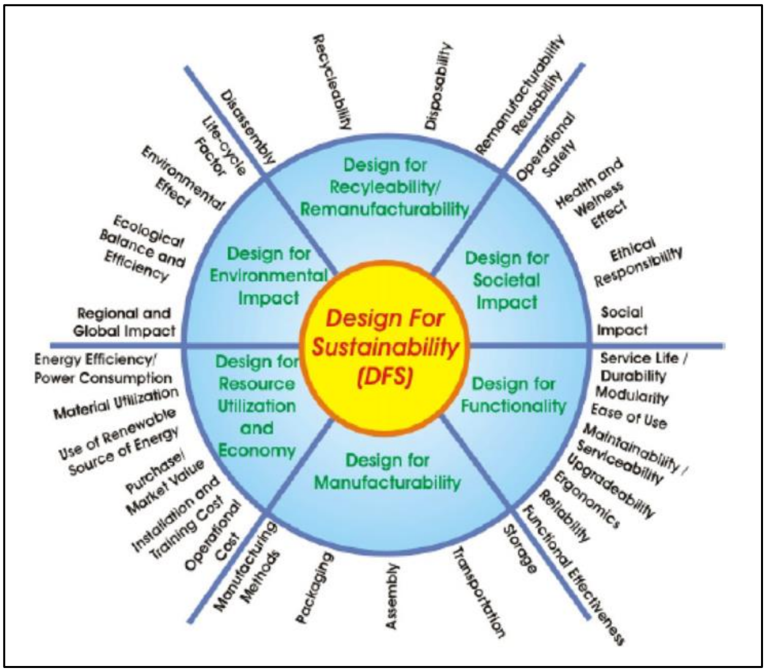


Figure 1.1. Major application fields of design for sustainability

The design-for-X covers several and distinct areas of interest: manufacturing, durability, energy efficiency and recyclability.

Design for manufacturing is targeted to reduce both time and cost of production. The guidelines of design for manufacturing include product adoption at the company level, the product family, the product structure and components. A derivative of design for manufacturing is the design for assembly, which focuses on assembly and fastening strategies; an example of implementation of design for assembly is the reduction of number parts and part variations.

Design for durability has the scope to increase the period of time or amount of usage during which the product functions without failure; designing product to last longer leads advantages in both resource consumption and waste generation.

Design for energy efficiency is aimed to reduce the amount of energy consumed by vehicle during use stage. Additionally to improving thermal efficiency of the engine, the use of lightweight materials represents an interesting and fruitful solution: as rolling resistance and acceleration forces are directly proportional to vehicle weight (Cheah and Heywood, 2011; Ungureanu et al., 2007), mass is the key factor in order to achieve significant reductions in energy consumption and air emissions. According to Mcauley (Mcauley, 2003), using plastics in light-weight vehicles save 30 times more energy over lifecycle than the energy required for fabrication. Lightweighting concentrates into three main areas: use of lightweight materials, use of stronger materials and design optimization. The first area envisages to reduce vehicle weight and improve fuel economy through the adoption of material characterized by low density. On the other hand the cost of these materials (such as aluminium, magnesium, carbon fiber reinforced polymers and sandwich materials) and the difficulty involved in their manufacturability represent the major obstacles to this solution. The second approach to lightweighting is based on the use of stronger materials (such as modified steel alloys and grades). This solution allows car designers reducing vehicle weight through thinner gauges. The last area is design optimization and it is based on optimized cross-sectional shapes of structures; this solution enables to achieve better loading performance without increasing weight.

Design for recyclability envisages that end-of-life materials are processed out of one form and remade into a new product. The use of recycled materials not only minimizes the consumption of virgin raw materials, energy and water, but also has a leading role in reducing waste, air/water pollution and energy consumption. Another remarkable advantage represented by lowering the need of virgin materials is the saving in money thanks to the avoidance of further extraction processes. Design for recyclability includes design for disassembly and design for remanufacturing. These different areas are strictly connected. On one hand design for disassembly makes that a product is disassembled at minimum cost and effort and this ensures not only a fast disassembly process but also recovering a larger proportion of system components; on the other hand design for remanufacturing is targeted to return the vehicle assemblies and components to acceptable performance level in order to be reused. A common guideline of design for recyclability is avoiding mixing of materials in assemblies and minimizing the number of parts made of different materials; such expedients facilitate the process of disassembling, sorting and collecting the materials, enhancing vehicle recyclability. An example of this regarding the plastics is provided by Mcauley (2003): a move toward parts consolidation into one polymer family some-time called “mono-material construction”, can lead to improved recyclability as well as reduced parts count and vehicle weight. From a practical point of view, recycling can be realized at different levels. The highest one is the “closed loop recycling”, in which vehicle components are remanufactured into the same kind of product, without any addition of virgin raw materials. Closed loop recycling is the ideal target for every application, as 100% material recycling is unrealistic; on the other hand the lowest level of recycling is the landfilling of all materials used in the vehicle. Usually materials are remanufactured into a lower grade substance, or combined with first-use material. Another EoL recovery process is reuse. Reuse envisages that the disassembled components are employed in new vehicles without any reprocessing; surely it represents the most eco-friendly solution for materials end-of-life. Because of the annual waste flux due to end-of-life for passenger vehicles is considerable, (Ferrao and Amaral (2006) states that in the European Union alone it is estimated to be around 8–9 million tons), the material fluxes associated with vehicles disposal have become increasingly important. For this reason recently the EU established new environmental policies and in 2000 the European Parliament approved the Directive 2000/53/EC which deals with End-of-Life of Vehicles (ELV) (Ferrao and Amaral, 2006). The directive has subsequently been updated several times: current regulation envisages that vehicles put on the market cannot contain lead, mercury, cadmium or hexavalent chromium and the recoverability rate must be at least 95% on a mass basis.

In the light of principles of design-for-X, the new trend in vehicle design aims not only to improve fuel efficiency, but also to enhance driving performance while lowering air emissions at the same time. At this regard several methodologies for material selection have been developed for incorporating the environmental concerns. Such methodologies can be classified basing on multiple criteria:

- Design approach. The methodologies can emphasize the ease of manufacturability, rather than environmental sustainability or economic aspect;
- Portion of vehicle LC. There are methods that set up the design phase taking into account only a single LC stage while others attempt to consider the entire life-time;
- Quantitative/qualitative approaches. Some approaches provide a set of guidelines based on qualitative selection methodologies while others rate the materials using quantitative indicators.

From previous considerations it directly derives that materials selection is not led by an unique factor but is rather made up of a mixing of technical, economic and environmental issues.

In conclusion, it can be stated that significant challenges still lie ahead for the automotive industry and its design as well as the use of advanced materials in order to attain sustainability goals. Yet, considering that the earth contains limited resources enclosed in a single life-sustaining atmosphere, society must drive the industry toward sustainable product design in a long-term basis.

1.2. Life Cycle Assessment in automotive industry

Life Cycle Assessment (LCA) (Chanaron, 2007; Finnveden et al., 2009; Mayyas et al., 2012a, WorldAutoSteel, 2012) can be described as an environmental accounting methodology which enables the quantification and evaluation of environmental effects, associated with a specific service, manufacturing process or product. It has established itself as the predominant tool for

- assessing the environmental effects of services, processes or products
- assisting with the optimization of environmental performance of a product
- comparing products to determine the most environmentally favourable ones.

The environmental effects quantified by LCA are expressed as potential impacts: climate change, ozone depletion, tropospheric ozone creation, eutrophication, acidification, toxicological stress on human health and ecosystems, depletion of resources and land use are the impact categories most frequently adopted (Rebitzer et al., 2004). The LCA follows a “from cradle-to-grave” approach which begins with the gathering of raw materials from the earth and ends at the point when all materials are returned to the earth. In this perspective all stages of product Life Cycle (LC) are evaluated from the perspective they are interdependent, meaning that one operation leads to the next. Such an approach enables to estimate the cumulative environmental impacts resulting from the entire LC, including impacts not considered in more traditional analyses. So that a more accurate picture of the true environmental trade-offs in product and process selection is achievable and the LCA becomes an essential tool for decision-makers in order to identify the product or process with the least impact to the environment.

1.2.1. LCA methodology

A typical product LC is deemed to be made up of four main stages: raw materials acquisition, production, use, and End-of-Life (EoL). Figure 1.2. illustrates the typical LC stages and input/output measured; a description of them is reported below.

- Raw materials acquisition. The LC of a product begins with the removal of raw materials and energy sources from the earth; transportation of these materials from the point of acquisition to the point of processing is also included;

- Production. The production stage consists of three steps: materials manufacture (activities that convert raw materials into a form that can be used to fabricate a finished product), product fabrication (activities that take the manufactured material and process it into a product that is ready to be filled or packaged), and filling/packaging/distribution of the manufactured product;

- Use/Reuse/Maintenance. All the activities associated with useful life-time are included in this stage. Actual use, reuse, and maintenance are considered; all energy demands and environmental wastes from both product storage and consumption are taken into account;

- End-of-Life. The EoL stage includes the energy requirements and environmental wastes associated with recovery, recycling and disposition of the product.

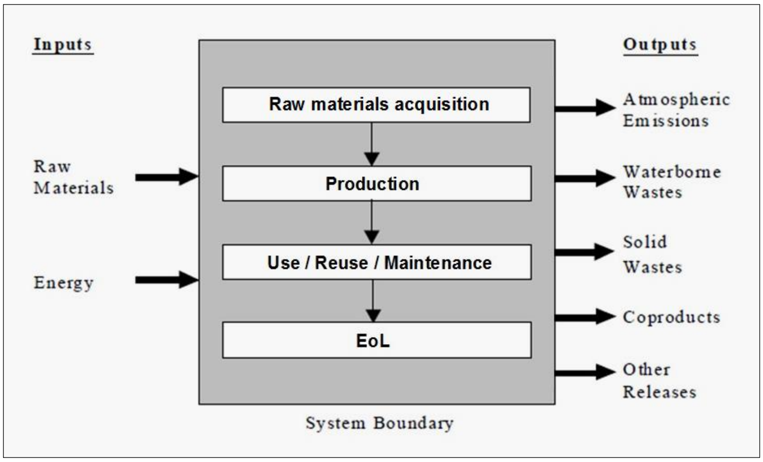


Figure 1.2. Main stages of product LC

The LCA methodology is supported by a set of standards from the ISO (Finkbiener, 2006; ISO 14040, 2006; ISO 14044, 2006) and according to them it follows four phases: Goal and Scope definition (G&S), Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Life Cycle Interpretation (LCIn). Figure 1.3. shows the LCA framework evidencing the interaction between phases according to UNI EN ISO 14040:2006 and UNI EN ISO 14044: 2006 (ISO 14040/14044, 2006).

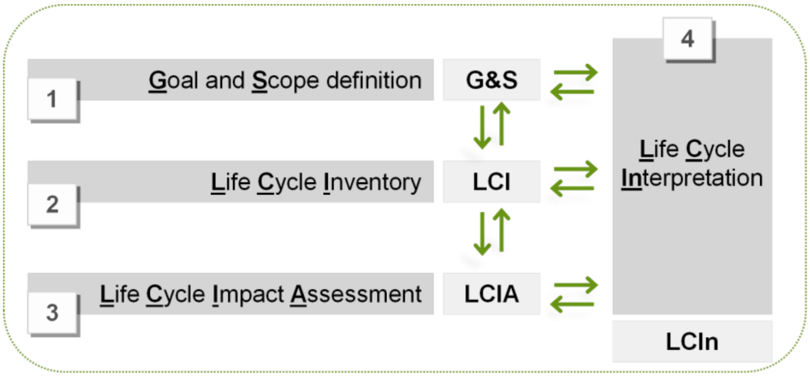


Figure 1.3. LCA framework and interaction between phases of the study

Below a brief description of the phases of a LCA study is reported.

Goal and Scope definition (G&S). G&S is the first phase of a LCA; it influences the conduction of the entire study and has impact on the relevance of final results. G&S defines the purpose and method of including LC environmental impacts into the decision-making process, how accurate the results must be and how the results should be interpreted and displayed in order to be meaningful and usable. Two essential elements for the development of the entire study are defined in the G&S: system boundaries and functional unit.

System boundaries define the product system; they comprehend all process units that describe the key elements of physical systems and define across which boundaries the exchange of elementary flows with nature takes place (Hiederer, 2011). Within the system, a distinction between “Foreground system” and “Background system” is made: “Foreground” indicates the main object of the analysis while “Background” represents all the activities required to realize the Foreground processes. Ideally, the product system should be modelled in such a manner that inputs and outputs at its boundaries are elementary flows.

Functional Unit (FU) describes the primary function(s) fulfilled by the product system and it indicates how much of this function is to be considered in the intended LCA study. FU enables that different systems are treated as functionally equivalent and reference flows are determined for each one of them; so that FU is used as a basis for selecting one or more alternative (product) systems that might provide the same function(s).

Life Cycle Inventory (LCI). LCI collects and processes all data required in order to analyze the system described in the G&S. These are the exchanges with the ecosphere that are triggered during product LC: quantities of energy and raw materials, atmospheric emissions, waterborne emissions, solid wastes, and other releases attributed to product LC are quantified and allocated to the defined FU. LCI is composed by two main steps: data collection and modelling.

Data collection collects and organizes all relevant data regarding product LC with the aim to depict the average behaviour of the system, including, additionally to normal operation and nominal functioning, also abnormal operation. The level of detail and accuracy by which data collection is performed influences the significance and truthfulness of the entire study. The final output of a LCI is a list of the amounts of consumed energy and materials and pollutants released to the environment; the results can be segregated by LC stage, media (air, water, and land), specific process, or any combination thereof.

Modelling determines and quantifies all elementary flows that characterize the environmental profile of the product.

Both data collection and modelling are strongly influenced by G&S. The findings of LCI become the input for the subsequent LCIA phase and also provide the feedback to G&S as initial scope settings often need adjustments. In literature a series of LCI databases exists; they hold data on energy and materials supply, chemicals, metals, resource extraction, transport and waste management. One of such databases is Ecoinvent (Frischnecht et al., 2004; Ecoinvent Centre, 2009) which is currently regarded as the world’s leading database with around 4000 datasets accompanied by supporting documentation. The LCI databases may be linked to LCA specific softwares such as Simapro (PRè Consultants) that enable the user to build complex product systems. Data which is not available in these databases may be acquired from reliable industrial sources, experimentation or literature sources.

Life Cycle Impact Assessment (LCIA). The LCIA phase consists in the evaluation of potential human health and environmental impacts starting from the contributions of emissions, waste and resources determined in the inventory analysis. A LCIA attempts to establish a linkage between the product or process and its potential environmental impacts; all the elementary flows that have been collected in the LCI are translated into an ensemble of environmental impact indicators. The results of LCIA should be seen as environmentally relevant impact potential indicators, rather than predictions of actual environmental effects and represent the basis for the last phase of the LCA study, the interpretation. LCIA is composed of mandatory and optional steps. ISO 14040 describes classification and characterization as obligatory elements.

Classification assigns the elements of the LCI data to relevant impact categories such as climate change, toxicological stress land use etc; for instance methane (CH_4) and carbon dioxide (CO_2) are both assigned to the global warming category.

Characterization determines the contribution of each classified elementary flow to the proper impact categories by multiplying it with the relative characterization factors. To do an example, within the global warming category results are given in kg of CO_2 equivalents (eqv) and therefore 1 kg of CO_2 quantified in the LCI would be indicated by 1 kg of CO_2 eqv in the climate change impact category. CH_4 on the other hand contributes 25 times more to climate change than CO_2; therefore the characterization factor would be 25 and 1 kg of CH_4 from the LCI would be communicated as 25 kg of CO_2 equivalents in this category. Usually classification and characterization are performed based on complete sets of LCIA methods developed by LCA experts. To date a number of LCIA methods already exist (Acero et al., 2014; Dreyer et al. 2003) such as Eco-indicator 99 (Goedkoop and Spriesma, 2000), CML 2 (CML, 2001), and Impact 2002+ (Jolliet et al., 2003); the appropriate method is chosen with respect to the outputs defined in the G&S. Depending on association with specific environmental aspects, LCIA results are shared in various indicators which refer to different impact categories: Climate change, (Stratospheric) Ozone depletion, Human toxicity, Respiratory inorganics, Ionizing radiation, (Ground-level) Photochemical ozone formation, Acidification (land and water), Eutrophication (land and water), Eco-toxicity, Land use, Resource depletion (metals, minerals, fossil, nuclear and renewable energy sources, water). The impact categories can then be further processed into three areas of protection:

- Human health;
- Natural environment;
- Natural resources.

Typically, impact categories are also called “midpoints”, while the three areas of protection are referred to as “endpoints”. The type and number of impact categories taken into account in a study vary depending on the G&S. Figure 1.4. shows a summary of the LCIA framework within the International reference Life Cycle Data system (ILCD) (Hiederer 2011).

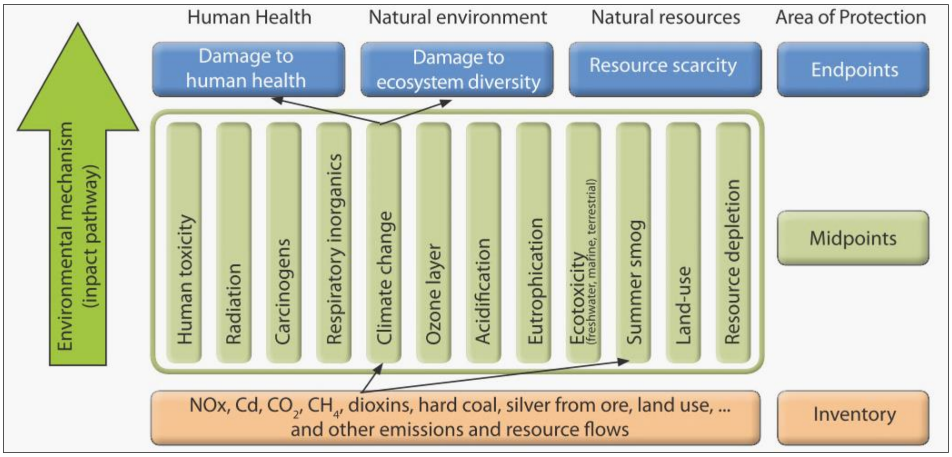


Figure 1.4. Summary of the LCIA framework within the ILCD (source: Hiederer, 2011)

The LCIA optional steps are normalization and weighting.

Normalization normalizes the LCIA results through multiplication by factors that represent the overall inventory of a reference (e.g. a whole country or an average citizen); normalized dimensionless LCIA results are obtained.

Weighting evaluates the significance of the normalized LCIA results through multiplication by a set of weighting factors. The weighting factors reflect the different relevance that different impact categories (midpoint level related weighting) or areas of protection (endpoint level related weighting) have. The final output is represented by normalized and weighted LCIA results that can be summed up to a single-value impact indicator.

Life Cycle Interpretation (LCIn). In the LCIn phase the outcomes of the study are appraised in order to answer the questions posed in the G&S. Results are collectively considered and analyzed in the light of accuracy, completeness and precision of the LCI data collection; additionally the sensitivity of significant issues with regard to their influence on the overall results is evaluated. The final target of LCIn is double: on one hand improving the LCI model in order to meet the needs derived from the G&S and on the other hand deriving robust conclusions and recommendations once the final results are available. As the LCA must be constantly measured against its initial goals and scope and refined during its duration, the LCIn has continuous interactions with the other phases of the study (Figure 1.3.).

1.2.2. LCA of ICE vehicles

The LCA methodology has been largely employed in the transportation sector and particularly in the automotive field for the following purposes:

- Estimating the environmental profile of current vehicles and automotive components;
- Evaluating the environmental progress from one product generation to the next.

As said in paragraph 1.2., the LCA analysis evaluates the environmental impacts involved by all stages that compose LC of the investigated system. Similarly to other products, the main LC stages of a car are production, use and EoL (Figure 1.5.).

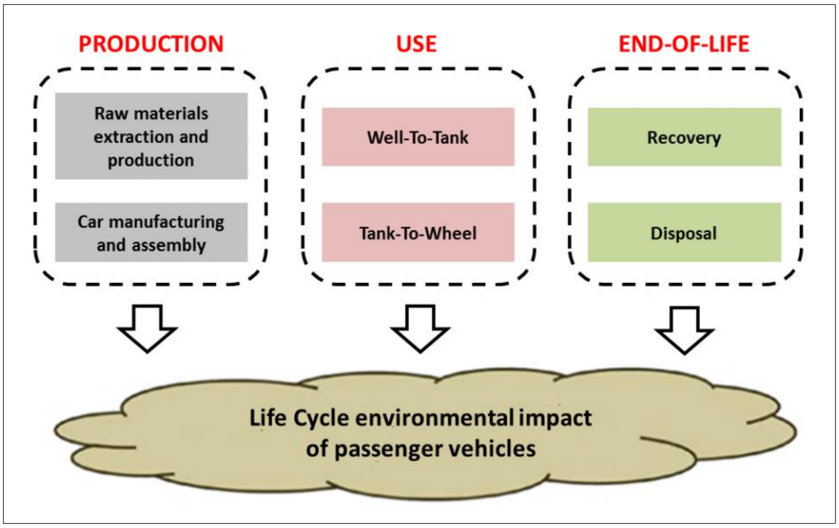


Figure 1.5. LC stages that determine the overall Life Cycle environmental impact of an automobile

The main LC stages of a car can be divided into Process Units (PUs) which in turn include the single processes. Below a brief description of PUs and processes is reported for each one of car LC stages:

1. ***Production***. Production is the first stage of car LC and it includes all manufacturing and assembly processes of vehicle components. It involves the following PUs and processes:

    - PU *Raw materials extraction and production*. Production of electricity, heat, steam and fuel for raw materials extraction and production of car components and spare parts;
    - PU *Car manufacturing and assembling*. Production of electricity, heat, steam and fuel for manufacturing and assembly activities.

2. ***Use.*** Use is the most complicated stage of car LC as it comprises both fuel cycle and vehicle operation. It includes the following PUs and processes:

    - PU *Well-To-Tank (WTT)*. Fuel transformation processes upstream to fuel consumption: fuel production from recovery or production of the feedstock, its transportation, conversion of the feedstock to the final fuel and subsequent storage, distribution, and delivery to the vehicle fuel tank;
    - PU *Tank-To-Wheel (TTW)*. Fuel consumption for car driving: energy required to drive the vehicle, exhaust and evaporative emissions from the vehicle over its life-time.

3. ***End-of-Life***. EoL is the final stage of car LC and it includes all activities of recovery and disposal at the end of vehicle lifetime. It involves the following PUs and processes:

   - PU *Recovery*. Transportation of the vehicle to dismantling facilities, disassembly, shredding, materials recovery, energy recovery;
   - PU *Disposal*. Landfilling of waste materials and shredder residue.

Figure 1.6. illustrates the subdivision of the main LC stages of a car into PUs and single processes.

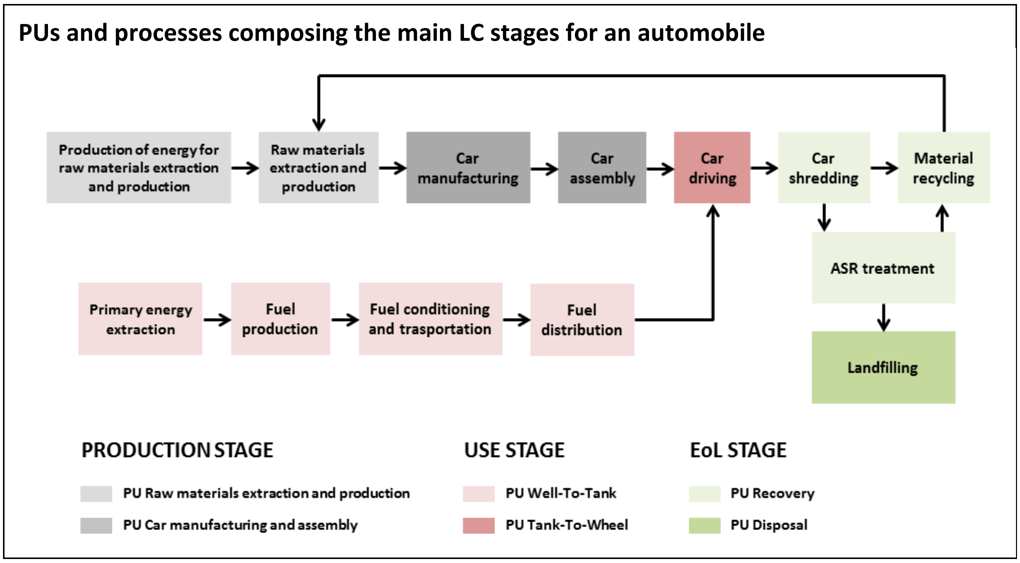


Figure 1.6. PUs and processes composing the main LC stages for an automobile

In literature three main typologies of automotive LCA study exist: LCA of an entire vehicle, LCA of a specific vehicle component and comparative LCA between two or more alternatives.

- **LCA of an entire car.** The focus of the study is to quantify the environmental impact involved by LC of the whole vehicle. Many examples of LCA of entire cars exist in literature, both scientific papers and technical reports. The extension of the analysis, the accuracy of primary data and the level of detail by which vehicle LC is investigated depend on the typology of analysis. Some researches perform simplified LCA in order to compare the environmental profile of different competitive powertrain technologies for the automotive sector (Boureima et al. 2009; Casadei and Broda 2008; Delorme et al., 2010; Kobayashi et al. 1998; Messagie et al. (2014); Nemry et al., 2008; Nicolay et al., 2000; Pagerit et al., 2006; Redelbach et al., 2012; Spielmann and Althaus, 2006; Suzuki and Takahashi, 2005; Suzuki et al., 2005; Ugaya and Walter, 2004; Weiss et al., 2000; Wolehcker et al., 2007). As the target is to capture the features of entire technologies, these studies are based on average data coming from aggregated databases. Other works focus on specific car models and their aim is the quantification of vehicle LC impact as accurately as possible; therefore the accuracy of data collection is higher and the information come directly from production sites and real operators (Chanaron, 2009; Finkbeiner et al., 2006; Kaniut et al., 1997; Kobayashi, 1997; Kobayashi et al., 1998; Koffler, 2007; Saur et al., 1997; Schmidt et al., 2004; Schweimer and Schukert, 1996; Spielmann and Althaus 2006). In this context recently great attention was paid by car manufacturers to the development of methods to assess the environmental impacts of their products; these are environmental declarations based on LCAs performed in accordance with the ISO 14040 standards (ISO 14040, 2006). An example is represented by the Environmental Product Declaration, a method developed by the cooperation between the Swedish Environmental Institute and the Volvo car Corporation (Graedel and Allenby, 1994). The purpose of an EPD is enabling customers to evaluate the environmental impact of different vehicles (European Union, 2011). The EPD system covers all stages of vehicle LC, from raw materials extraction to EoL, and provides information on the environmental impact of each; to date published certificates and commendations exist for a large variety of vehicles (Daimler-Mercedes-Benz Cars, 2006, 2011, 2012; Volkswagen AG, 2008, 2010a, 2010b, 2010c, 2010d, 2010e, Warsen and Gnauck, 2011);

- **LCA of a specific vehicle component.** The focus of the study is to quantify the environmental impact involved by component LC. In this case the existing studies are very heterogeneous depending on the component object of the analysis: there are works that treat with heavy structural parts such as Body-in-White (Franze, 1995; Grujicic et al., 2008; Kojima et al., 2003; Mayyas et al., 2012b) and studies that focus on components which represent exiguous percentage of total vehicle weight (Ehrenberger, 2013; Das, 2005; Puri et al. 2009; Ribeiro et al. 2007; Saur et al., 2000; Subic and Schiavone 2006);
- **Comparative LCA.** Innovative engineering for automobiles is steadily gaining in importance as a viable technological avenue in order to accomplish the continuously rising environmental demands and ever-tougher emissions standards. Most particularly lightweight design has been unanimously recognized as one of the key measures for improving the environmental profile of a car through a reduction of fuel usage (Alonso et al., 2012; Gaines and Cuenca, 2004; Helms and Lambrecht, 2004, 2006; Koffler, 2007; Moon et al., 2006; Overly et al., 2002; Rodhe-Brandenburger and Obernolte, 2002, 2008; Schäper and Leitermann, 1996; Saur et al., 1997b; Schäper, 1997a; Stodolsky et al. 1995; Tolouei et al. (2009)). As shown in paragraph 1.1., the adoption of lightweight materials allows to lower the use stage impact by a reduction of energy consumption (Kelly et al., 2015; Kim et al., 2010; Kim et Wallington, 2013b; Mayyas et al., 2013; Raugei et al., 2015) but, on the other hand, it involves negative consequences in the production and EoL stages (Atherton, 2007; Berzi et al., 2013; Cheah, 2010; Ciacci et al., 2010; Funazaki et al. 2003; Geyer, 2008; Grujicic et al., 2009; Kim et al., 2004; Levizzari et al.; 2001; McMillan et al., 2012; Rajendran et al., 2012; Schmit et al., 2004). Indeed many lightweight materials such as aluminium, magnesium or carbon fibre are energy-intensive to produce and involve higher CO_2 emissions prior to the use stage if compared, for instance, with conventional steel (Das, 2011; Du JD et

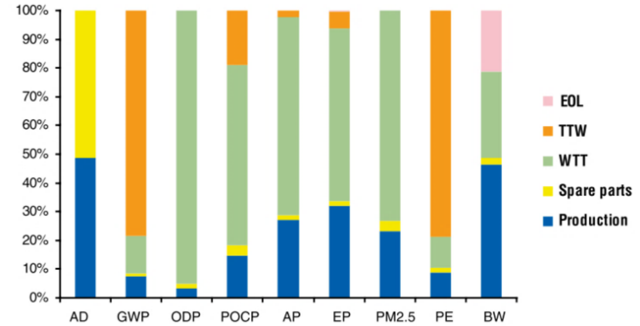
al., 2010; Khanna and Bakshi, 2009; Modaresi et al., 2014; Shaw and Coates, 2009; Sivertsen et al., 2003; Tharrumarajah and Koltun, 2010). Additionally, carbon fibre and composite materials are more difficult to be recycled at EoL than metals. The opposite effect that light-weighting has on production/EoL and use stages requires a balance of benefits and disadvantages over the entire LC of the automotive system. This yields break-even kilometrages, i.e., the total driving distance required to compensate the production stage emissions through reduced FC during operation. In this context the comparative LCA is aimed to establish the effective environmental convenience of innovative lightweight materials, technologies and solutions in the replacement of traditional ones. This is a typology of study that have had great diffusion in recent periods and the literature provides several case studies. The existing LCAs perform assessments of various lightweight solutions: replacement of traditional materials by weight-efficient ones (Alves et al., 2010; De Medina, 2006; Duflou et al., 2009; Geyer, 2007, 2008; Joshi et al. (2004); Koffler, 2013; Zah et al., (2006)), optimization and novel use of manufacturing technologies and processes (Luz et al., 2010; Ribeiro et al. 2007; Vinodh and Jayakrishna, 2011; Weiss et al., 2000; Witik et al. 2011), redesign and optimization of vehicle components/assemblies (Baroth et al., 2012; Dhingra and Das, 2014; Dubreuil et al., 2010; Edwards et al., 2014; Hamakada et al., 2007; Koffler and Zahller 2012; Li, N. 2004; Mayyas et al., 2012b; Reppe et al., 1998; Saur et al., 1995; Schmidt et al., 2004).

2. The use stage in the LCA of ICE vehicles

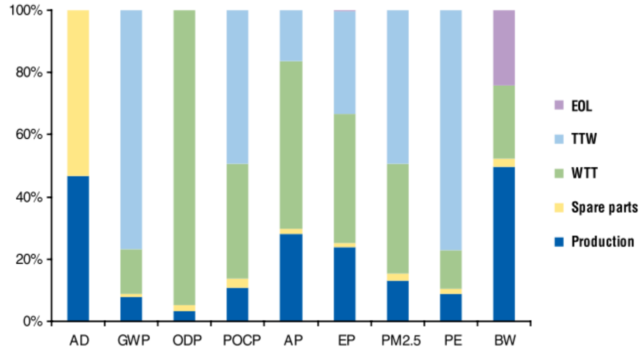
2.1. The use stage in the automotive LCA

For an ICE car the use stage is responsible of a relevant quota of total LC impact (Chlopek and Lasocki, 2013; Delogu, 2009; WorldAutoSteel, 2012); this is due on one hand to the exhaust gas emissions during operation and on the other hand to the fuel production processes. Obviously the relevance of the use stage depends on impact category; for instance with respect to Global Warming Potential (GWP), about 85% of total LC impact is caused by use (Koffler, 2007; Rodhe-Brandenburger and Obernolte, 2008; Stichling and Hasenberg, 2011). The remarkable influence of use stage emerges from LCAs conducted on both complete cars (Schmidt et al., 2004, Volkswagen AG, 2008, 2010a, 2010b, 2010c, 2010d, 2010e, Warsen and Gnauck, 2011) and specific vehicle components (Delogu et al., 2015; Puri et al., 2009; Ribeiro et al., 2007; Subic and Schiavone, 2006). Below some examples of such studies are reported.

Nemry et al. (2008) perform a comparative from cradle to grave LCA of two generic car models (one petrol and one diesel) to provide a comprehensive analysis of technical improvement options that could be achieved to lower the environmental impact. The results, expressed on a percentage basis for a broad set of LCIA categories, are reported in Figure 2.1.



a) Petrol car



b) Diesel car

Figure 2.1. LCIA results of petrol and diesel car obtained by Nemry et al., 2008

The evidences show that for both petrol and diesel vehicle the use stage quota (TTW and WTT) largely results the biggest contribution for the majority of impact categories. The outcomes of Nemry et al. (2008) are qualitatively confirmed by the profile that emerges from the Environmental Certificate of the Mercedes-Benz M-Class (Daimler AG-Mercedes-Benz Cars, 2011): use (Fuel production and Operation) is the most relevant LC stage for all LCIA categories with the only exception of AP (Figure 2.2.).

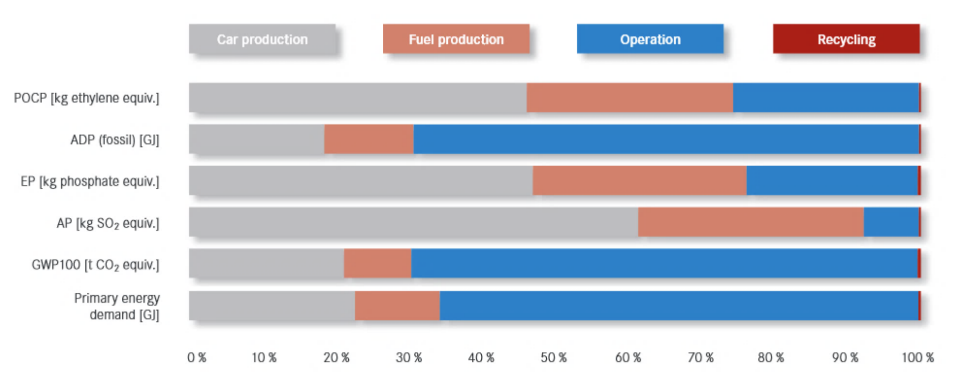
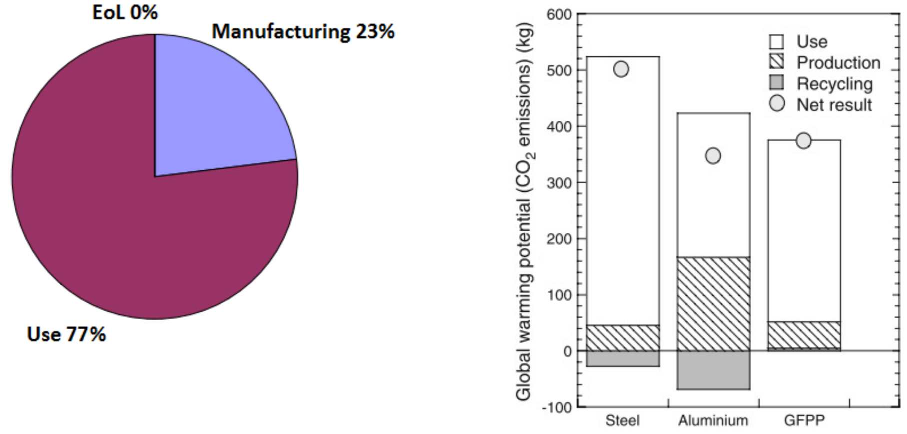


Figure 2.2. LCIA results for the Mercedes-Benz M-Class (source: Daimler AG, Mercedes-Benz Cars, 2011)

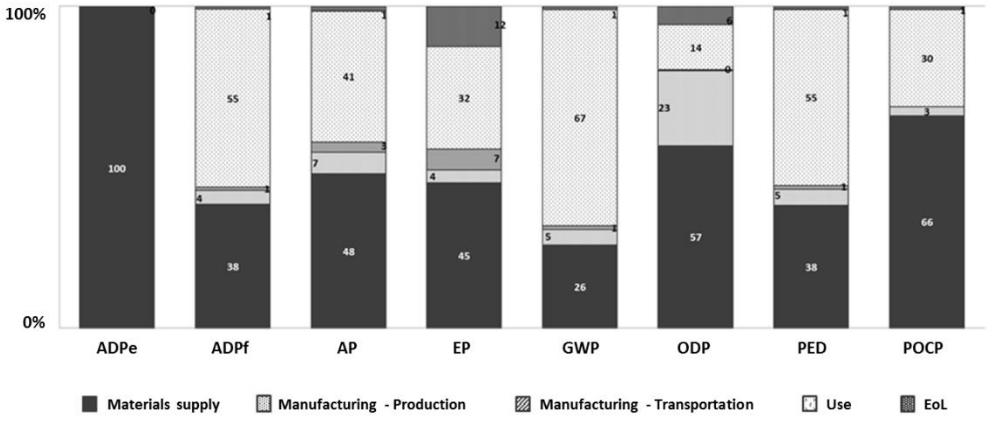
The predominance of the use stage with respect to production and EoL is confirmed also by LCAs conducted on specific vehicle components. In this respect the following studies are considered:

- Subic and Schiavone (2006). The work deals with the LCA of a car seat assembly in order to identify the hot-spots of component LC; the chosen LCIA method is the Ecoindicator 99. The contribution analysis by LC stage of impact shows that almost 80% of total is attributed to the use stage (Figure 2.3.a);
- Puri et al. (2009). The LCA of an Australian automotive component, namely an exterior door skin, is performed in order to identify the most environmentally acceptable material alternative for the component. At this scope three materials are considered: steel, aluminium and glass-fibre polypropylene composite. Results for Global Warming Potential (GWP) in Figure 2.3.b highlights that use is the most influential stage for all the alternatives;
- Delogu et al. (2015). The adoption of two alternative thermoplastic materials for the construction of a MagnetiMarelli air intake manifold are assessed: polyamide reinforced with 30% of glass fibre and polypropylene reinforced with 35% of glass fibre. For the LCIA the mid-score method CML2001 is chosen. Figure 2.3.c reports the contribution analysis by LC stage of potential environmental impacts for the polypropylene alternative: the higher impacts definitely refer to materials supply and use stages as they amount to more than 90% for six of the eight impact categories.

Contribution analysis by LC stage of impact



a) Subic and Schiavone (2006) **b) Puri et al. (2009)**



c) Del Pero et al. (2015)

Figure 2.3. Contribution analysis by LC stage of impact: a) Subic and Schiavone (2006); b) Puri et al. (2009); c) Del Pero et al. (2015)

As shown in Figures 1.5. and 1.6., for an automotive LCA the use stage impact is due to

- fuel production chain (WTT)
- exhaust gas emissions during operation (TTW)

and therefore it directly depends on the amount of fuel consumed over vehicle LC. Consequently the relationship between use stage impact and FC represents a key factor in order to accurately determine the overall LC impact of the system. Such a relationship is treated by different approaches depending on the typology of study:

1. LCA of an entire vehicle
   The focus is the quantification of the impact involved by use stage of the entire car. At this scope it is needed to determine as accurately as possible the amount of fuel that car consumes during its lifetime. This latter is calculated through the per-kilometre FC basing on use stage total mileage.

2. LCA of a specific vehicle component
   The focus is to quantify the quota of overall car use stage impact that is attributable to the specific component. At this scope the allocation of operation FC to the component study is needed. The main issue is the quantification, based on mass, of the significance of the single component with respect to the entire vehicle.

3. Comparative LCA between a reference and an innovative lightweight alternative
   The focus of the use stage is to determine the reduction of use stage impact achievable through mass reduction. At this scope the quantification of FC reduction induced by mass decrease is needed.

2.2. Use stage impact and fuel consumption: State Of Art analysis

Paragraph 2.1. states that use stage impact

- has a preponderant role within the economy of the overall study
- directly depends on the quantity of fuel consumed during operation.

In the light of this, below it is reported a review of existing approaches adopted in order to treat with the use stage within the main typologies of automotive study. As the focus of the use stage varies depending on the specific analysis and the approaches are different, the treatise is developed separately per each typology. Both findings from research and practices usually employed in current LCA applications are included.

2.2.1. LCA of an entire vehicle

The quantification of use stage impact requires an affordable value of vehicle per-kilometre FC. For the calculation of FC as well as exhaust gas emissions, both scientific papers (Boureima et al. 2009; Del Pero et al. 2015; Messagie et al. 2014; Nemry et al., 2008) and environmental certificates/commendations (Daimler-Mercedes-Benz Cars, 2006, 2011, 2012; Volkswagen AG, 2008, 2010a, 2010b, 2010c, 2010d, 2010e) refer to standardized driving cycles prescribed by law-makers: New European Driving Cycle (NEDC) for Europe, US City and Highway Driving Cycle for United States (Schweimer and Levin, 1999) and Japanese driving Cycle 08 (JC08) for Japan.

2.2.2. LCA of a specific vehicle component

The determination of component use stage impact requires an appropriate method for the allocation of component’s consumption. In the context of Phase 2 of the EUropean Council for Automotive R&D (EUCAR) LCA project, Lynne Ridge (1997) gives an overview of the commonly used approaches for allocation of the hypothetical fuel and energy consumption to a specific component. Two fundamentally different methods are identified: Incremental and Proportional. For both methods the target is to determine the quota of FC ascribable to the specific component starting from the knowledge of

- mass and FC of the vehicle
- mass of the specific component.

The **Incremental method** is based upon the assumption that component FC compared to vehicle FC is equal to the ratio between component and vehicle mass multiplied by a constant *c*:

$$\frac{FC_{comp}}{FC_{veh}} = \frac{m_{comp}}{m_{veh}}\, c \qquad \text{Eq. 2.1.}$$

Where:
FC_{comp} = Fuel Consumption attributed to the specific component [l/100km];
FC_{veh} = Fuel Consumption of the entire vehicle [l/100km]
m_{comp} = mass of the specific component [kg];
m_{veh} = mass of the entire vehicle [kg];
c = proportionality constant [null].

The Incremental method takes into account only the influence on consumption of mass by the proportionality constant which has to be defined a priori. As the proportionality between consumption and mass is represented by the non-dimensional ratio *c*, the sum of contributions coming from all vehicle components is not equivalent to the consumption of the entire car. Hence such a method should be used under the condition that the component is less than or equal to 20% of the mass of entire vehicle. Since the Incremental method is mass-oriented, the second condition which has to be verified is that the considered component has no other effect on vehicle efficiency. For the proportionality constant *c*, the value 0.6 suggested by Lynne Ridge (1997) is widely adopted by existing LCAs that use the Incremental method (Bonino, 2014; Ribeiro et al., 2007; Riccomagno, 2014; Subic and Schiavone, 2006).

The **Proportional method** is based upon the assumption that the ratio between component and vehicle FC is equal to the ratio between component and vehicle mass.

$$\frac{FC_{comp}}{FC_{veh}} = \frac{m_{comp}}{m_{veh}} \qquad \text{Eq. 2.2.}$$

Where:
FC_{comp} = Fuel Consumption of the specific component [l/100km]
FC_{veh} = Fuel Consumption of the entire vehicle [l/100km]
m_{comp} = mass of the specific component [kg];
m_{veh} = mass of the entire vehicle [kg].

Unlike the Incremental, the Proportional method takes into account all the aspects of motion resistance considering, additionally to the mass-dependent quota, also the share of FC independent of weight. Therefore it is appropriate for allocation of component’s consumption when one at least of the following conditions is verified:

- the component/sub-assembly is greater than 20% of the mass of the entire vehicle;
- the component/sub-assembly has effect on vehicle efficiency.

It has to be noted that Incremental and Proportional methods give discordant results if applied to the same case study. The difference depends on the value of the proportionality constant c which characterizes the Incremental method. As in existing LCA applications the value of the proportionality constant is minor than 1 (the value 0.6 is widely adopted), the Incremental method attributes minor significance to the use stage energy consumption with respect to the Proportional one. This is due to the fact that in the Proportional method the mean shares of driving resistance for entire vehicle are allocated to each component, regardless the level of such individual resistance factors. At this regard, Eberle and Franze (1998) report the production/use energy consumption for a steel midsize-car body-in-white calculated by both methods: opposite to a constant value of 141000 [MJ] obtained by the Proportional, the energy consumption determined by the Incremental method varies from 50000 [MJ] to 151000 [MJ], respectively for $c = 0.3$ and $c = 1.05$ (Figure 2.4.).

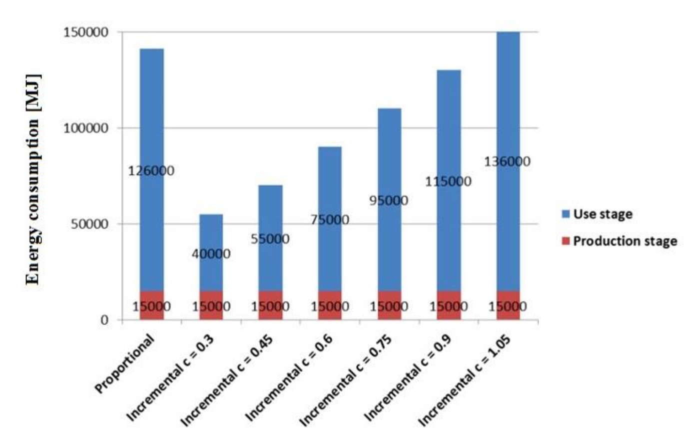


Figure 2.4. Production/Use energy consumption determined by the Proportional and Incremental methods for different values of c (source: Eberle and Franze, 1998)

The Incremental and Proportional methods can be adopted also in comparative LCA between a reference and innovative lightweight alternative (Eberle and Franze, 2000). In this case both methods are based on the following equation:

$$\frac{\Delta FC}{\Delta m} = \frac{FC_{ref\ veh}}{m_{ref\ veh}} * c \qquad \text{Eq. 2.3.}$$

Where:
ΔFC = variation of vehicle Fuel Consumption between the car equipped with the reference and the innovative lightweight component(s) [l/100km];
Δm = variation of vehicle mass between the car equipped with the reference and the innovative lightweight component [kg];
$FC_{ref\ veh}$ = Fuel Consumption of the reference vehicle [l/100km];

$m_{ref\,veh}$ = mass of the reference vehicle [kg];
c = proportionality constant [null].

The term *ΔFC/Δm*, defined as the Fuel Reduction Value (FRV), quantifies the fuel saving obtained by a certain reduction of vehicle mass and it is expressed in [l/100km*100kg]. From equation 2.3. it directly derives that the FRV is automatically defined once the proportionality constant is fixed and both the mass and FC of reference vehicle are known.

With respect to calculation of FC of the lightweight component, the Incremental and Proportional methods diversify. Equation 2.3. can be expressed as:

$$\frac{FC_{ref\,comp} - FC_{light\,comp}}{m_{ref\,comp} - m_{light\,comp}} = \frac{FC_{ref\,veh}}{m_{ref\,veh}} * c \qquad \text{Eq. 2.4.}$$

Where:
$FC_{ref\,comp}$ - $FC_{light\,comp}$ = ΔFC [l/100km];
$m_{ref\,comp}$ - $m_{light\,comp}$ = Δm [kg];
$FC_{ref\,comp}$ = Fuel Consumption attributed to the reference component(s) [l/100km];
$FC_{light\,comp}$ = Fuel Consumption attributed to the innovative lightweight component(s) [l/100km];
$m_{ref\,comp}$ = mass of the reference component(s) [kg];
$m_{light\,comp}$ = mass of the innovative lightweight component(s) [kg].

By substituting into Equation 2.4. the expression of $FC_{ref\,comp}$ taken from Equation 2.1., the consumption attributed to the lightweight component according to the **Incremental method** is obtained as

$$FC_{light\,comp} = \frac{FC_{ref\,veh}}{m_{ref\,veh}} * c * m_{light\,comp} \qquad \text{Eq. 2.5.}$$

In terms of *FRV*, the consumption of the lightweight component becomes:

$$FC_{light\,com} = FRV * m_{light\,com} \qquad \text{Eq. 2.6.}$$

It has to be noted that in the Incremental method the FRV represents the proportionality constant between FC and mass of the lightweight component and therefore it should be given a share in consumption depending exclusively on the level of FRV. Similarly, by substituting into Eq. 2.4., the expression of $c_{ref\,comp}$ taken from Equation 2.2., the consumption attributed to the lightweight component according to the **Proportional method** is obtained as

$$FC_{light\,comp} = \frac{FC_{ref\,veh}}{m_{ref\,veh}} * c * m_{light\,comp} + \frac{FC_{ref\,veh}}{m_{ref\,veh}} * (1-c) * m_{ref\,comp} \qquad \text{Eq. 2.7.}$$

and in terms of *FRV* it becomes

$$FC_{light\,comp} = FC_{ref\,comp} - \Delta m * FRV \qquad \text{Eq. 2.8.}$$

From comparison of Eq. 2.8. and Eq. 2.7., the difference between the two methods is represented by the addend

$$\frac{FC_{ref\ veh}}{m_{ref\ veh}} * (1 - c) * m_{ref\ comp} \qquad \text{Eq. 2.9.}$$

This fraction, only dependent on the reference vehicle, is constant for all the examined alternative components and represents the influencing parameters on FC apart from the mass. Therefore, when the Proportional method is applied in order to analyze the weak points of various alternative options for a component, it should be given preference to energy-saving during operation with respect to production stage. On the other hand the Incremental method allocates only the mass-related FC to the individual component; in this case the relevance of the use stage appears lower and the analysis of the weak points could tend to focus on the production stage rather than on the light-weight technology. At this regard Figure 2.5. reports the energy consumption of three options (steel, aluminum and BMC) for a tailgate using both the Proportional and Incremental method (Lynne Ridge, 1997). Figure 2.5. refers to the same application of Figure 2.4. and shows the contribution analysis by LC stage (use/production) of energy consumption (Lynne Ridge, 1997).

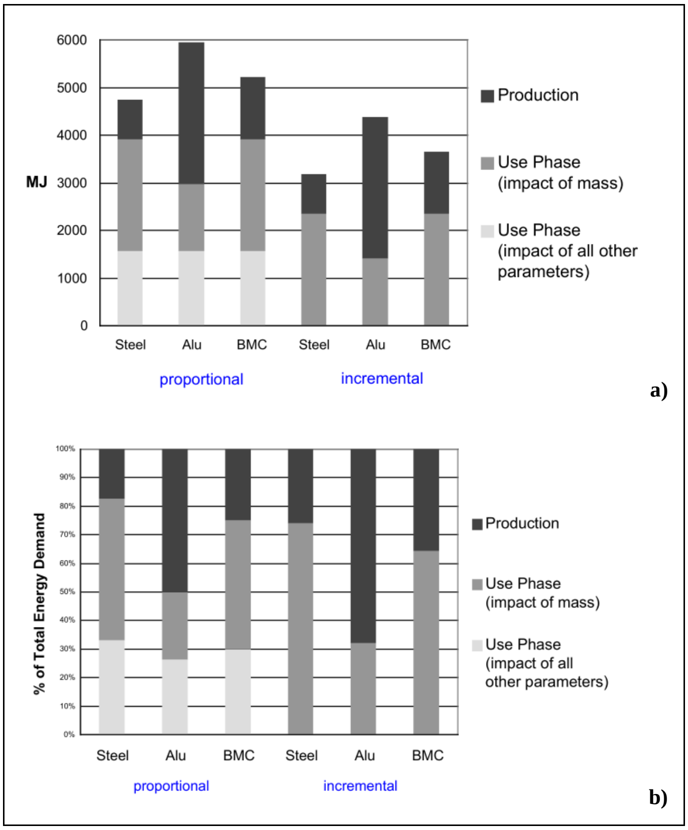


Figure 2.5. Analysis of three different options (steel, Aluminum and BMC) for a tailgate using both the Proportional and Incremental method (c = 0.6) (source: Lynne Ridge, 1997). **a)** Energy consumption by LC stage (use/production) **b)** Contribution analysis by LC stage (use/production) of the energy consumption

Another interesting example is reported in Figure 2.6. (Eberle and Franze, 1998). The energy consumption by LC stage (production/use) of a typical midsize car body-in-white is determined for both the reference component (made of steel) and the innovative lightweight one (made of aluminum). The authors show the discordant results obtained by Incremental and Proportional methods at varying of FRV from 0.2 to 0.7 [l/100km*100kg]: the Proportional method gives greater significance to the use stage as opposed to the production stage, particularly for low FRVs.

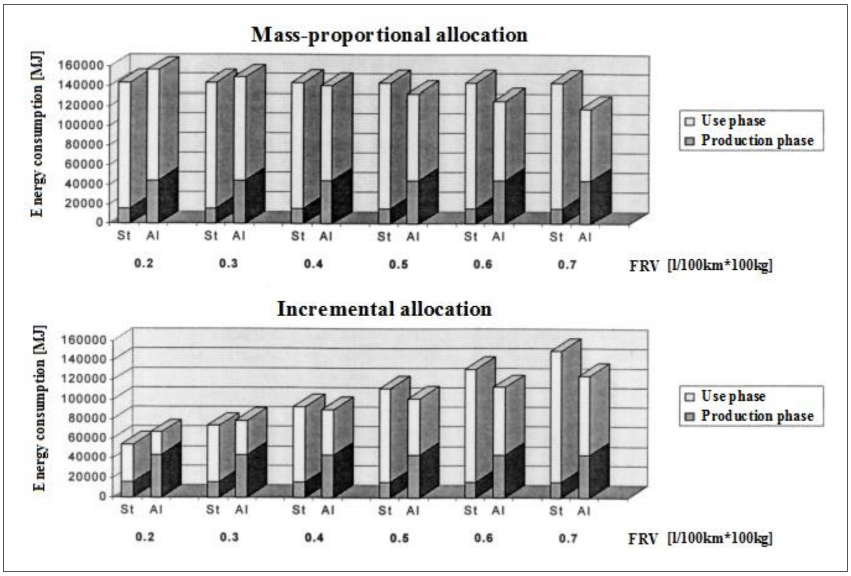


Figure 2.6. Energy consumption by LC stage (production/use) of a typical midsize car body-in-white reported both for the reference component and the innovative lightweight one (m_{steel} = 300kg; $m_{aluminium}$ = 180kg; $m_{ref\ veh}$ = 1500kg; $C_{ref\ veh}$ = 10l/100km$_{NEDC}$) (source: Eberle and Franze, 1998)

To overcome the problem of the discordant results achieved by the implementation of the two methods, Eberle and Franze (1998) propose to consider the use stage FC subdivided into two contributions, the mass-dynamic factor and the mass-static factor. The mass dynamic factor represents the quota of FC dependent on mass and therefore reducible by a weight reduction; the mass-static factor represents the quota of consumption that derives from the driving resistance shares as a mean figure of the entire vehicle and it is independent of mass. Figure 2.7. refers to the same application of Figure 2.6.; the energy consumption by LC stage (production/use) using the Proportional, Incremental and Proportional-Subdivided methods are reported.

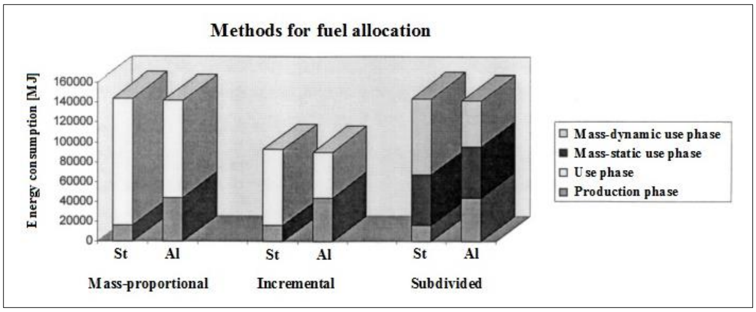


Figure 2.7. Energy consumption by LC stage (production/use) for Proportional, Incremental and Proportional-Subdivided methods (FRV = 0.4 l/100km*100kg) (source: Eberle and Franze, 1998)

Some examples of LCA applications that adopt the Incremental and Proportional methods are Bonino (2014), Pegoretti et al. (2014), Ribeiro et al. (2007), Riccomagno (2014), Subic and Schiavone (2006).

2.2.3. Comparative LCA between a reference and an innovative lightweight alternative

The determination of use stage impact reduction achievable through light-weighting requires an affordable method for the quantification of FC saving during operation. In existing literature the most widespread method is the FRV-based approach (Delogu et al., 2015; SABIC, 2013) and it is based on the following relation (Koffler and Rodhe Branderburger, 2010):

$$\Delta FC = \Delta m * FRV * 0.01 = (m_{ref\ comp} - m_{light\ comp}) * FRV * 0.01 \qquad \text{Eq. 2.10.}$$

Where:
$\Delta FC = FC_{ref\ comp} - FC_{light\ comp}$
$\Delta m = m_{ref\ comp} - m_{light\ comp}$
$FC_{ref\ comp}$ = Fuel Consumption of the reference component [l/100km];
$FC_{light\ comp}$ = Fuel Consumption of the lightweight component [l/100km];
$m_{ref\ comp}$ = mass of the reference component [kg];
$m_{light\ comp}$ = mass of the lightweight component [kg];
FRV = Fuel Reduction Value [l/100km*100kg].

The previous equation is valid in case the aim is to determine the consumption reduction due to a lightweight solution applied only to a specific component. In case more than one component is interested by lightweighting re-design, the relation has to be modified in such a way that it includes all the components:

$$\Delta FC = \sum (m_{ref\ comp,i} - m_{light\ comp,i}) * FRV * 0.01 = \sum \Delta m_i * FRV * 0.01 \qquad \text{Eq. 2.11.}$$

Where:
$m_{ref\ comp,\ i}$ = mass of reference component i [kg];
$m_{light\ comp,\ i}$ = mass of innovative lightweight component i [kg].

The FRV has a determinant role in order to establish the convenience of any lightweight automotive solution. To give an example of this, Figure 2.8. reports the influence of the FRV in order to determine the energy payback of various aluminum alternatives for the rear axle of the 1998 BMW 730i (Eberle, 2000) in comparison with the reference component made of steel.

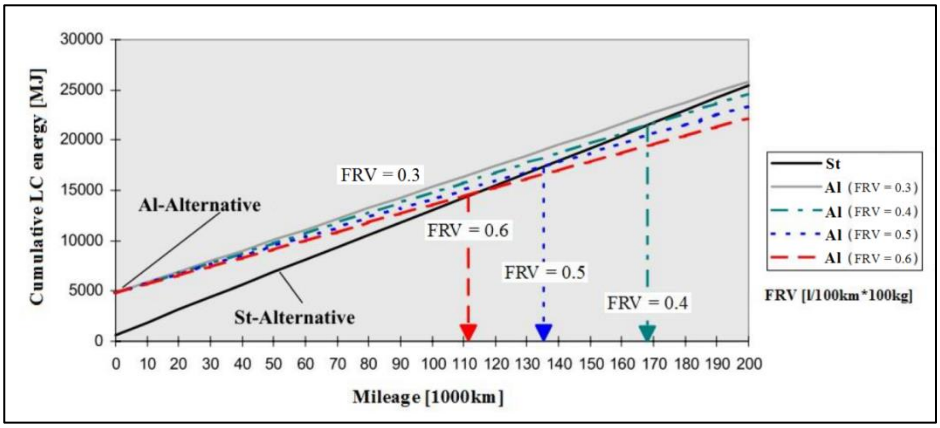


Figure 2.8. Influence of *FRV* on the energy payback of an aluminum alternative for the rear axle of the 1998 BMW 730i in comparison with the reference component made of steel (source: Eberle and Franze, 1998)

The diagram shows that if FRV is lower than 0.4 [l/100km*100kg], the energy expenditure for production is not amortized within the average mileage of 200.000 km and therefore the reference component made of steel results to be cheaper; on the other hand if a value higher than 0.4 is assumed, the energy payback mileage is consistent with the LC mileages of current vehicles (for FRV = 0.6 the energy payback amounts to 110.000 km).

For the FRV coefficient, literature regarding current LCA practices supplies a range of 0.02 and 1.00 [l/100km*100kg] (Table 2.1. reports the FRVs used by some comparative analyses in literature).

References	Vehicle class	Includes secondary effects?	FC reduction due to 100kg mass saving [l/100km*100kg]	Percent decrease of FC due to 10% mass reduction [%]
An and Santini, 2004	C (gasoline NA)	Yes	–	8.0
	SUV (gasoline NA)	Yes	–	7.9
Birat et al., 2004	Generic (gasoline NA)	No	0.26	–
Cheah, 2007	Generic (gasoline NA)	Yes	–	1.9 – 8.2
Das, 2000	Generic (gasoline NA)	No	–	5.0
Du et al., 2010	Not specified	No	0.48	–
Delogu et al., 2015	C (gasoline NA)	No	0.15	–
Dubreuil et al., 2010	Generic (gasoline NA)	Yes	0.46	–
Helms et al., 2004	Not specified	Yes	0.15 – 1.00	–
Keoleain et al., 1998	Generic (gasoline NA)	No	0.23	–
Keoleian and Kar, 2003	Not specified	No	0.20	–
Keoleian and Sullivan, 2012	Not specified	Yes	0.37	–
Kiefer et al., 1998	Generic (gasoline NA)	No	0.23	–
		Yes	0.36	–
National Research Council, U.S., 2002	C (gasoline NA)	Not specified	–	8.0
Ribeiro et al., 2008	Not specified	Not specified	0.6	–
Ridge, 1997	Generic (gasoline NA)	No	0.02 – 0.50	–
		Yes	0.19 – 0.60	–
	Generic (turbodiesel)	No	0.10 – 0.35	–
		Yes	0.26 – 0.37	–
Saur et al., 1997	Not specified	No	0.39	–
Schmidt et al., 2004	Generic (gasoline NA)	Not specified	0.38	–
Shen et al., 1999	Not specified	No	0.23	–
Stichling, 2009	Not specified	Not specified	0.3 – 0.6	–
Stichling and Hasenberg, 2011	Generic (gasoline NA)	No	0.15	–
		Yes	0.35	–
	Generic (turbodiesel)	No	0.12	–
		Yes	0.28	–
Stodolsky et al., 1995	Generic (gasoline NA)	Yes	0.43	–
Sullivan and Hu, 1995	Generic (gasoline NA)	No	0.27	–
		Yes	0.40	–
Tharumarajah and Koltun, 2007	Generic (gasoline NA)	No	0.39	–
Thiel and Jenssen, 2000	Generic (gasoline NA)	No	0.35	–
Wotzel et al., 1999	C (gasoline NA)	No	0.3 – 0.5	–

Table 2.1. Values of FRV adopted by some comparative LCAs in literature

The reference values for the FRV adopted by current LCAs are from other studies which investigate the relationship between FC and mass. In the following pages a review of such a typology of researches is reported; special consideration and detail are dedicated to the works that have been developed within the LCA context.

Some authors consider the reduction of FC as a function of vehicle mass by applying regression curves to data of different vehicles (Figure 2.9.) (Rechs et al., (1995) and Schäper (1997b) use a linear correlation while Aichinger (1995) opts for an exponential curve) and determine the FRV as the slope of consumption in function of mass. Assuming a linear consumption function, the FRV is independent of the observed mass; on the other hand, with an exponential function the consumption is dependent on the mass level and for heavy vehicles higher consumption reductions are given than for the smaller ones. Both the types of correlations seem to be inappropriate to derive a reasonable value for the FRV since they do not take into account the numerous factors that characterize a vehicle (such as engine concept, gear ratios, aerodynamics, tires, performance, etc) and therefore strongly vary from one application to another.

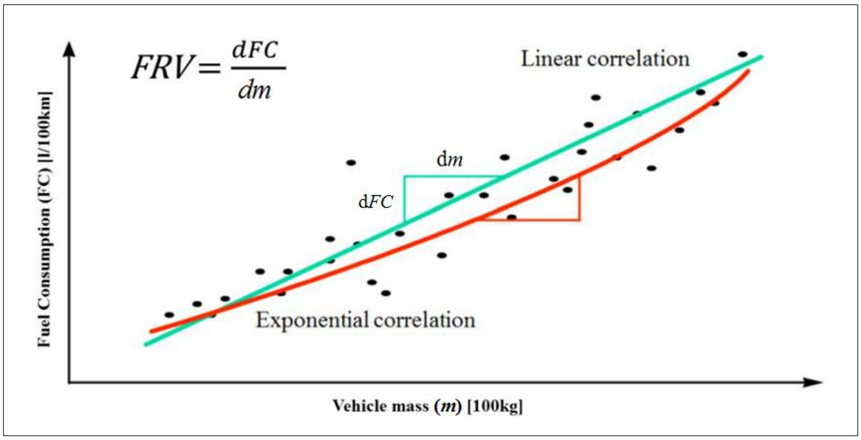


Figure 2.9. Application of regression curves to fuel consumption in function of mass for different vehicles (source: Eberle, 2000)

Eberle and Franze (1998), Koffler (2010), Kim and Wallington (2013) and Kim et al. (2015) are the only studies that

- deal with the calculation of weight-induced fuel saving in lightweight LCA of ICE vehicles;
- perform calculation investigating the theoretical background and underlying physical correlations;
- point out some notable particularities that need to be taken into account when conducting a comparative study.

For this reason a detailed description of calculations, simulation and outcomes of both the cited researches is reported in the following pages.

Based on physical considerations, Eberle and Franze (1998) derives an analytical approach to calculate FC and FRV for the entire BMW's 1998 model range. Since the complexity of calculation, the simulation program FALKE is employed. As reference for the profile of gear ratio and vehicle speed, the NEDC is used; furthermore, two other driving cycles (“Consumption optimized” and “Sporting”) are used in order to perform sensitivity analysis based on cycle.

Below the analysis performed by Eberle and Franze is described taking into account the only model BMW 528i. The determination of the absolute FC is based on calculation of the power required to drive the wheels (calculated by multiplying driving resistance with vehicle speed) and the specific FC of the engine (determined by the consumption map through engine speed and torque):

$$FC = \frac{b_e * P_{req}}{\rho_{fuel} * v * \eta_{DT}} * 100 \qquad \text{Eq. 2.14.}$$

Where:
FC = Fuel Consumption [l/100km];
b_e = specific FC [g/kWh];
P_{req} = Power required to drive the wheels [kW];
ρ_{fuel} = density of the fuel [g/l];
v = velocity of the vehicle [km/h];
η_{DT} = efficiency of Drive Train [null].

In the first step of the research, Eberle and Franze calculate FC for different values of car mass within the range -350 - +350 [kg] with respect to the actual model mass. Car mass values are identified by applying increments of 50 [kg] from the minimum to the maximum of the range. As representative of car performance, the 0-100 [km/h] acceleration as well as the 80-120 [km/h] elasticity in 5th gear are determined for each value of mass. Finally the FRV is calculated as the slope of the regression line of consumption in function of mass. Figure 2.10. reports FC and performance as function of vehicle weight for the BMW 528i.

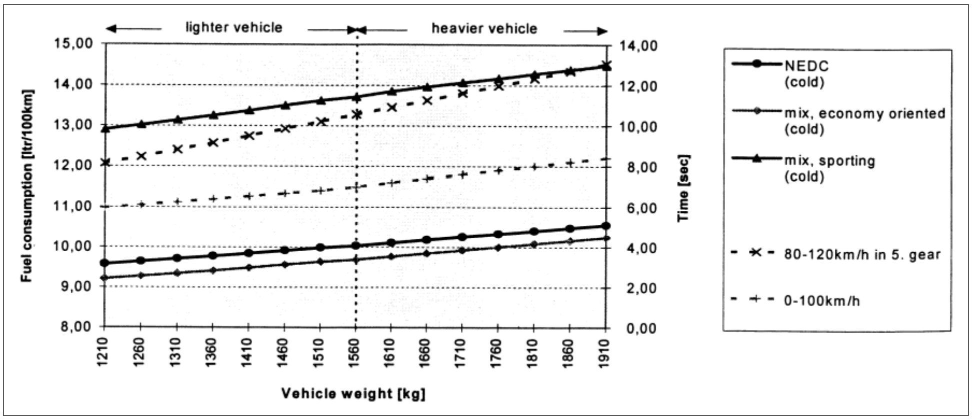


Figure 2.10. FC and performance as a function of vehicle weight for the 1998 BMW 528i (source: Eberle and Franze, 1998)

The results of the first step of the research show that:

- both FC and driving performance, with the exception of “acceleration 0-100 [km/h]” are proportional to vehicle mass, the reduction in FC thus not depending on vehicle’s weight level;

- FRV ranges from 0.134 (NEDC) through 0.141 (“Consumption optimized” driving cycle) all the way to 0.235 [l/100km * 100kg] (“Sporting” driving cycle). The reduction in absolute FC and the increase in performance due to mass reduction occur since the operating point of the engine moves towards lower loads with more surplus torque available for acceleration. The consumption saving due to a reduction of vehicle mass is identified as “primary mass-saving effect”.

In the second step of the research, Eberle and Franze investigate the dependence of FC on the rear axle transmission ratio through variations by 2%, covering a total range from -20% to +20% with respect to the original ratio. Figure 2.11. reports FC and performance as a function of the rear axle transmission ratio for the BMW 528i.

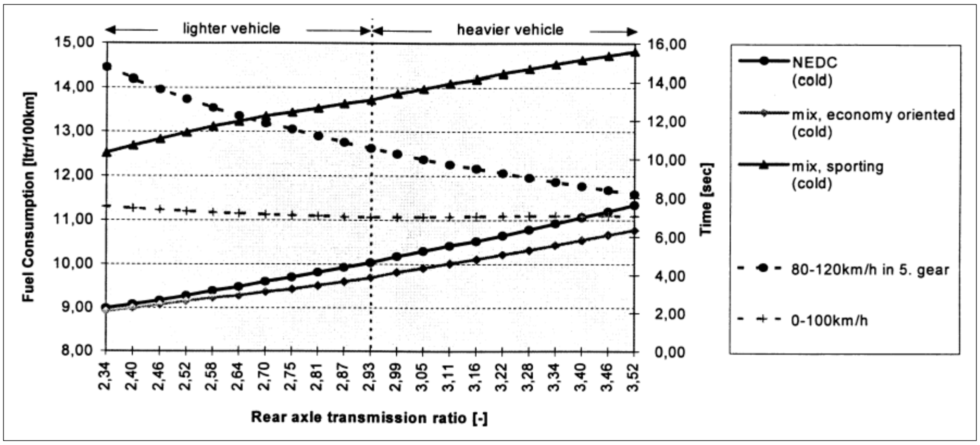


Figure 2.11. FC and performance as a function of rear axle transmission ratio for the 1998 BMW 528i (source: Eberle and Franze, 1998)

The results of the second step of the research show that:

- the performance deteriorates over-proportionally with the rear axle ratio becoming longer, while FC shows a linear dependency between the transmission ratio and the level of FC;
- using as reference the rear axle ratio extended by 10%, the FRV ranges from 0.378 (“Consumption optimized” driving cycle), through 0.526 (NEDC) all the way to 0.594 [l/100km * 100kg] (“Sporting” driving cycle). The reduction in absolute FC and the deterioration in performance due to a reduction of rear axle ratio occur since the operating point of the engine moves towards higher loads with lower engine speed.

Since lowering the mass and lengthening the rear axle ratio lead to an opposite effect on car performance, in the last step of the research Eberle and Franze combine these two consumption-reducing effects in order to maintain the same performance. In this way a lighter vehicle with similar performance to the original one and adjusted rear axle ratio allows to achieve a further reduction of consumption over and above the primary mass-saving effect. As performance criterion Eberle chooses the elasticity when accelerating from

80 to 120 [km/h] in 5th gear. This criterion was selected because passing other vehicles at high speed is a situation often encountered in everyday and represents a risk which has to be minimized. Furthermore, choosing elasticity in 5th gear represents a minimum criteria because elasticity from 80 to 120 [km/h] in the lower gears are also improved by this way. The adjustment of rear axle ratio is identified as "secondary effect" since it is originated by the primary mass reduction. The combination of these two consumption-reducing expedients involves the following effects:

- the driving resistance forces are shifted towards a lower level (reduction of vehicle weight);
- the operating point of the engine moves towards higher forces and lower engine speed thus maintaining the same performance level (elongation of final drive ratio).

FC and performance as a function of the rear axle ratio are reported in Figure 2.12. for the BMW 528i.

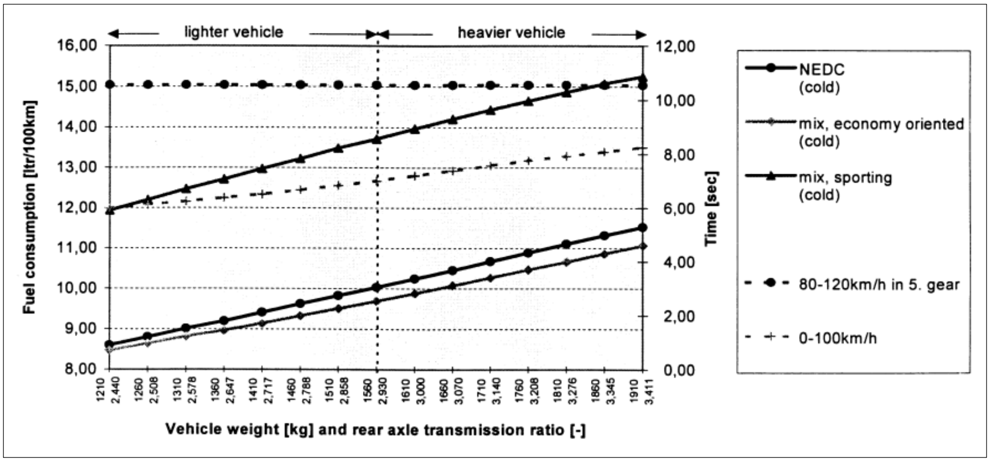
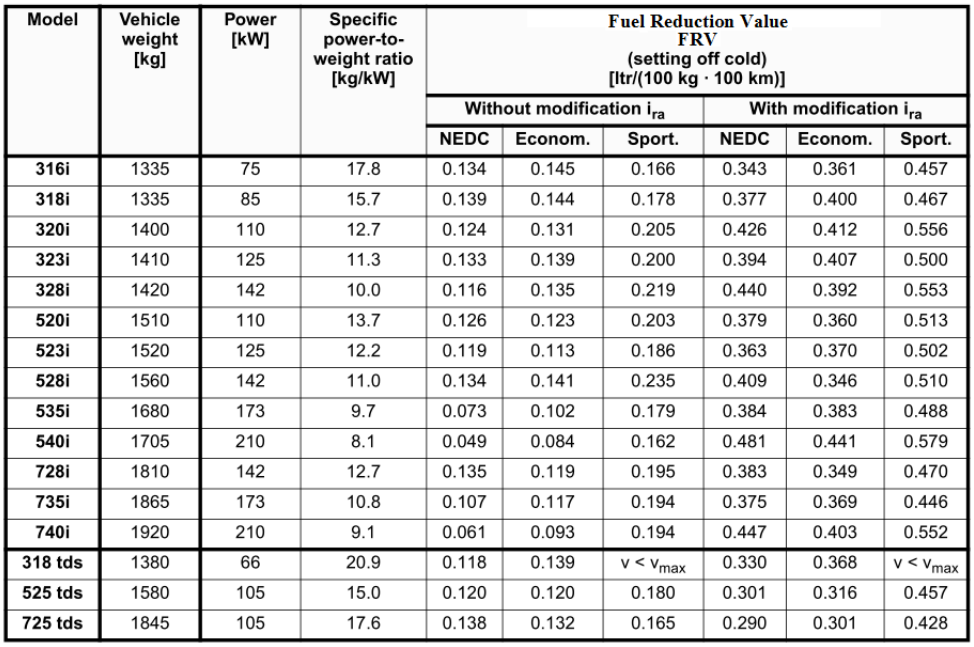


Figure 2.12. FC and performance as a function of vehicle weight and with modification of rear axle transmission ratio to elasticity 80-120 km/h in 5th gear for the 1998 BMW 528i (source: Eberle and Franze, 1998)

The results of the final step of the research show that while the selected performance criterion remains unchanged, the FRV ranges from 0.346 ("Consumption optimized" driving cycle), through 0.409 (NEDC) all the way to 0.510 [l/100km * 100kg] ("Sporting" driving cycle).

Table 2.2. reports the FRV for all the examined cars within the BMW's 1998 model range with respect to both primary mass reduction and secondary effects.



Model	Vehicle weight [kg]	Power [kW]	Specific power-to-weight ratio [kg/kW]	Fuel Reduction Value FRV (setting off cold) [ltr/(100 kg · 100 km)]					
				Without modification i_{ra}			With modification i_{ra}		
				NEDC	Econom.	Sport.	NEDC	Econom.	Sport.
316i	1335	75	17.8	0.134	0.145	0.166	0.343	0.361	0.457
318i	1335	85	15.7	0.139	0.144	0.178	0.377	0.400	0.467
320i	1400	110	12.7	0.124	0.131	0.205	0.426	0.412	0.556
323i	1410	125	11.3	0.133	0.139	0.200	0.394	0.407	0.500
328i	1420	142	10.0	0.116	0.135	0.219	0.440	0.392	0.553
520i	1510	110	13.7	0.126	0.123	0.203	0.379	0.360	0.513
523i	1520	125	12.2	0.119	0.113	0.186	0.363	0.370	0.502
528i	1560	142	11.0	0.134	0.141	0.235	0.409	0.346	0.510
535i	1680	173	9.7	0.073	0.102	0.179	0.384	0.383	0.488
540i	1705	210	8.1	0.049	0.084	0.162	0.481	0.441	0.579
728i	1810	142	12.7	0.135	0.119	0.195	0.383	0.349	0.470
735i	1865	173	10.8	0.107	0.117	0.194	0.375	0.369	0.446
740i	1920	210	9.1	0.061	0.093	0.194	0.447	0.403	0.552
318 tds	1380	66	20.9	0.118	0.139	$v < v_{max}$	0.330	0.368	$v < v_{max}$
525 tds	1580	105	15.0	0.120	0.120	0.180	0.301	0.316	0.457
725 tds	1845	105	17.6	0.138	0.132	0.165	0.290	0.301	0.428

Table 2.2. FRV for BMW cars in the 1998 model year (source: Eberle and Franze, 1998)

From the analysis of the overall set for the FRV, Eberle and Franze derive the final outcomes of the research:

- in case of primary mass saving the FRV ranges from 0.07 to 0.14 and from 0.12 to 0.14 [l/100km * 100kg] respectively for gasoline and diesel vehicles (NEDC). In case of secondary effects the FRV ranges from 0.34 to 0.48 and from 0.29 to 0.33 [l/100km * 100kg] respectively for gasoline and diesel vehicles (NEDC). For the “Consumption optimized” driving cycle, the FRV is generally slightly lower while for the “Sporting” driving cycle it is notably higher;
- a linear relationship between mass and FC can be identified so that saving in consumption is not dependent on the absolute car weight;
- no dependency of reduced FC on absolute vehicle weight, its power or specific power-to-weight ratio can be established for both gasoline and diesel vehicles.

Koffler and Rodhe-Branderburger (2010) calculate the FRV for both Primary Mass Reduction (PMR) only and implementation of Secondary Effects (SE). The calculation is performed for both gasoline and diesel vehicles over four driving cycles: NEDC, constant velocity, NEDC with two-fold increased dynamics and extreme highway dynamics. Below the followed approach is presented with respect to the reference driving cycle, the NEDC. For the calculation of FRV in case of primary mass reduction, the approach is purely analytical. At first the energy needed to move 100 kg on a distance of 100 km in the NEDC is determined as the sum of energy contributions necessary to overcome the mass-dependent resistances (rolling resistance, W_{R_NEDC} and acceleration resistance, W_{a_NEDC}). The energy needed to overcome the acceleration resistance is stored as kinetic energy and is therefore partially recuperated during deceleration to overcome the rolling and aerodynamic resistance: since about 15% of the NEDC total distance is constituted by deceleration phase, only 85% of the energy needed to overcome the rolling resistance is considered in the total sum. The resulting energy (W_{sum_NEDC}) is obtained by following equations:

$$W_{sum\_NEDC} = W_{R\_NEDC} * 0.85 + W_{a\_NEDC} \quad \text{Eq. 2.13.}$$

$$W_{R\_NEDC} = m * g * f_R * C_{WR\_NEDC} \quad \text{Eq. 2.14.}$$

$$W_{a\_NEDC} = m * C_{Wa\_NEDC} \quad \text{Eq. 2.15.}$$

Where:
m = 100 [kg];
g = acceleration of gravity (9.81 [m/s^2]);
f_R = Rolling resistance coefficient (0.01 [null]);
C_{WR_NEDC} = Rolling characteristic value for NEDC (11013 [m]);
C_{Wa} = acceleration characteristic value for NEDC (1227 [m^2/s^2]);
W_{R_NEDC} = energy needed to overcome the Rolling resistance in the NEDC [J];
W_{a_NEDC} = energy needed to overcome the acceleration resistance in the NEDC [J];
W_{sum_NEDC} = energy needed to overcome the mass-dependent resistances in the NEDC [J].

W_{sum_NEDC} results to be 1.95 [MJ]. Once the mass-induced energy demand is known, it is converted to energy taken from the fuel by the engine. Since the degree of efficiency of an ICE heavily depends on its point of operation in terms of speed and load, Koffler adopts a simplified procedure to identify a value of engine efficiency, the Willans line method. The Willans lines display the direct correlation between the energy intake and the output for a certain engine speed. Figure 2.13. reports the Willans lines of a 1.4 l gasoline engine. For low output and low engine speed, which are typical of the NEDC, the Willans lines run almost parallel, representing a nearly constant differential efficiency. As the differential efficiency of engines with the same working process is very similar (Rodhe-Branderburger 1996), Koffler adopts the differential efficiency as efficiency of the ICE. The values of FRV obtained in case of SE are displayed in Figure 2.14. for both gasoline and diesel vehicles.

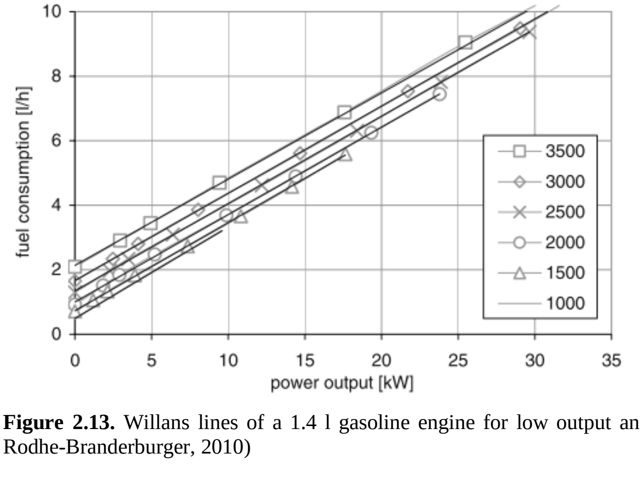


Figure 2.13. Willans lines of a 1.4 l gasoline engine for low output and low engine speed (source: Koffler and Rodhe-Branderburger, 2010)

For the calculation of FRV in case of mass reduction with implementation of secondary effects, Koffler makes use of a mathematical model implemented in a simulation program which takes into account vehicle driving resistances, engine efficiency, transmission ratios, and efficiency of gear/final transmission. The work necessary to overcome the driving resistances is calculated with the constant differential efficiency deduced from the Willans lines while the idle consumption is read at 0 kW at the ordinate of the diagram. The simulations are carried out for several vehicles belonging to the B class (both gasoline and diesel) in the only NEDC and two different types of secondary effects are implemented:

- adaptation of the gear ratio by a redesigned transmission so that elasticity 80-120 km/h in the top gear remains unaltered;
- adaptation of the displacement so that acceleration 0-100 [km/h] remains unaltered.

Similarly to Eberle and Franze (1998), FC is calculated for different values of car mass and the FRV is determined as the slope of the regression line of consumption in function of mass. The values of FRV obtained in case of secondary effects are displayed in Figure 2.14. for both gasoline and diesel vehicles. It can be noted that:

- according to Eberle and Franze (1998), the FRV in case of secondary effects is definitely higher with respect to the case of primary mass reduction only;
- the FRV in case of secondary effects is calculated through a simulation of car resistances, engine and transmission, thus referring to a specific vehicle; as simulations are performed for different car models in terms of size, weight, engine displacement and transmission ratios, only one area can be defined (Figures 2.14.). For this reason Koffler concludes that for a more precise statement simulations based on technical features (engine full characteristic and gear ratios) of the specific car have to be performed.

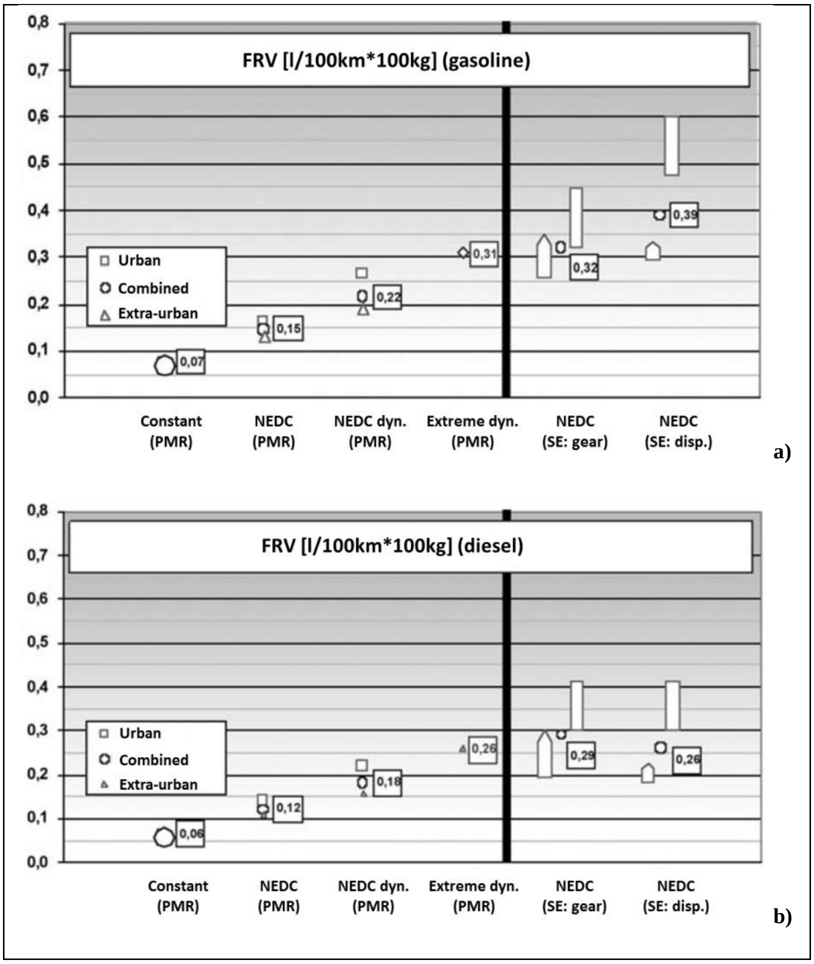


Figure 2.14. Complete set of FRVs obtained by Koffler for gasoline and diesel cars (source: Koffler and Rodhe-Branderburger, 2010)

Kim and Wallington (2013a) propose a physics-based model for estimating mass-induced FC of a vehicle for both PMR only and implementation of SEs. In case of SE, powertrain parameters *gear ratio* and *engine displacement* are adjusted to match the reduced vehicle weight for performance equivalence with baseline vehicle. In the model the chosen performance indicator is the product between the gear ratio N/V (N = average engine speed in rps; V = average vehicle speed in m/s) and the normalized engine displacement D/M (D = engine displacement in l; M = vehicle mass in kg). For both PMR and SE two distinct indexes for the mass-induced FC are defined: Fuel Reduction Value (*FRV*) and Mass Induced Fuel consumption (*MIF*).

Primary Mass Reduction only. The FRV in case of PMR only (*FRV*) is defined as:

$$FRV = \frac{F_W}{M} * 100 \qquad \text{Eq. 2.16.}$$

Considering that

$$F_w = M * \frac{(1+\varepsilon)I_1 + (1-\varphi)C_R g\, I_2}{10000\, H_f \eta_i \eta_t\, mileage_{DC}} \qquad \text{Eq. 2.17.}$$

the *FRV* is obtained through the following relation:

$$FRV = \frac{(1+\varepsilon)I_1 + (1-\varphi)C_R g\, I_2}{100\, H_f \eta_i \eta_t\, mileage_{DC}} \qquad \text{Eq. 2.18.}$$

Where:
FRV = Fuel Reduction Value [l/100km*100kg];
F_w = Fuel consumption due to mass-induced loads [l/100km];
M = vehicle Mass [kg];
ε = rotational mass factor [null];
φ = fraction of idling time [null];
g = gravitational acceleration [m/s^2];
C_R = Rolling resistance Coefficient [null];
$I_1 = \int av\, dt$ [m^2/s^2];
$I_2 = \int v\, dt$ [m];
a = vehicle acceleration [m/s^2];
v = vehicle speed [m/s];
H_f = lower Heating value of fuel [MJ/l];
η_i = indicated engine efficiency [null];
η_t = transmission efficiency [null];
$mileage_{DC}$ = total mileage of Driving Cycle [km].

The MIF in case of PMR (*MIF*) is defined as:

$$MIF = 100\frac{F_w}{M}\left(\frac{F_w + F_x + F_f + F_l}{F_w + F_x}\right) = 100\frac{F_w}{M * \eta_m} \qquad \text{Eq. 2.19.}$$

Where:
MIF = Mass Induced Fuel consumption in case of PMR only [l/100km*100kg];
F_w = Fuel consumption due to mass-induced loads [l/100km];
F_f = Fuel consumption due to mechanical losses in the engine [l/100km];
F_l = Fuel consumption due to mechanical losses outside the engine [l/100km];
η_m = gross vehicle mechanical efficiency in case of PMR [null].

From Equations 2.17. and 2.19. it directly derives that *MIF* is obtained through the following relation:

$$MIF = \frac{FRV}{\eta_m} \qquad \text{Eq. 2.20.}$$

Secondary Effects. The FRV in case of SE (FRV^+) is defined as:

$$FRV^{+} = 100\frac{F_w + F_f^{+}}{M} \qquad \text{Eq. 2.21.}$$

Where:
FRV^{+} = Fuel Reduction Value in case of SE [l/100km*100kg].
F_f^{+} = Fuel consumption due to mechanical losses in the engine in case of SE [l/100km].

From Equation 2.21. and considering that

$$F_f^{+} = M * \frac{I_2 f_{mep}}{20000\, H_f \eta_i\, mileage_{DC}}\left(\frac{D}{M}\right)\left(\frac{N}{V}\right) \qquad \text{Eq. 2.22.}$$

FRV^{+} is obtained through the following relation:

$$FRV^{+} = \frac{(1+\varepsilon)I_1 + (1-\varphi)C_R g I_2}{100\, H_f \eta_i \eta_t\, mileage_{DC}} + \frac{I_2 f_{mep}}{200\, H_f \eta_i\, mileage_{DC}}\left(\frac{D}{M}\right)\left(\frac{N}{V}\right) \qquad \text{Eq. 2.23.}$$

Where:
f_{mep} = friction mean effective pressure [kPa].

The MIF in case of SE (MIF^{+}) is defined as:

$$MIF^{+} = 100\frac{F_w}{M}\left(\frac{F_w + F_x + F_f^{+} + F_l}{F_w + F_x}\right) = 100\frac{F_w}{M * \eta_m^{+}} \qquad \text{Eq. 2.24.}$$

Where:
MIF^{+} = Mass Induced Fuel consumption in case of SEs[l/100km*100kg];
F_f^{+}= Fuel consumption due to mechanical losses in the engine in case of SEs [l/100km];
η_m^{+} = gross vehicle mechanical efficiency in case of SEs [null].

From Equation 2.16. it directly derives that MIF^{+} is calculated through the following relation:

$$MIF^{+} = \frac{FRV}{\eta_m^{+}} \qquad \text{Eq. 2.25.}$$

As the difference between η_m and η_m^{+} is small, Kim and Wallington assume that $MIF = MIF.^{+}$ Figure 2.15. gives the breakdown of FC estimated by both the FRV and MIF methods for an example of 200 kg weight reduction for a specific vehicle model. For a 200 kg reduction scenario, FRV and FRV^{+} are 0.19 and 0.31 [l/100 km 100 kg] respectively, while MIF is 0.28 [l/100 km 100 kg].

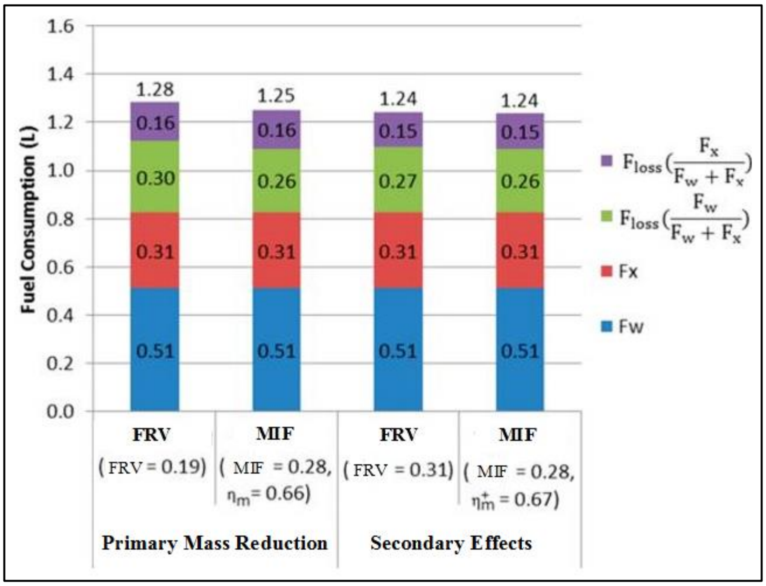


Figure 2.15. FC breakdown for a 200 kg weight reduction based on parameters of a specific vehicle model (source: Kim and Wallington, 2013)

In the second part of the research the authors determine *FRV* and *MIF* for 2013 model year ICE vehicles using the U.S. EPA’s fuel economy certification data. *FRV* is estimated based on vehicle load parameters available in the U.S. EPA certification data measured by the Federal Test Procedure (FTP); η_m is determined in function of vehicle mass based on fuel economy and load parameters. Data from an homogeneous cohort of cars with automatic transmissions and gasoline naturally aspirated engines are assumed; overall the mass-induced FC is evaluated for a total of 106 test records. Figure 2.16. reports *FRV* and *MIF* for the test records plotted against vehicle parameters.

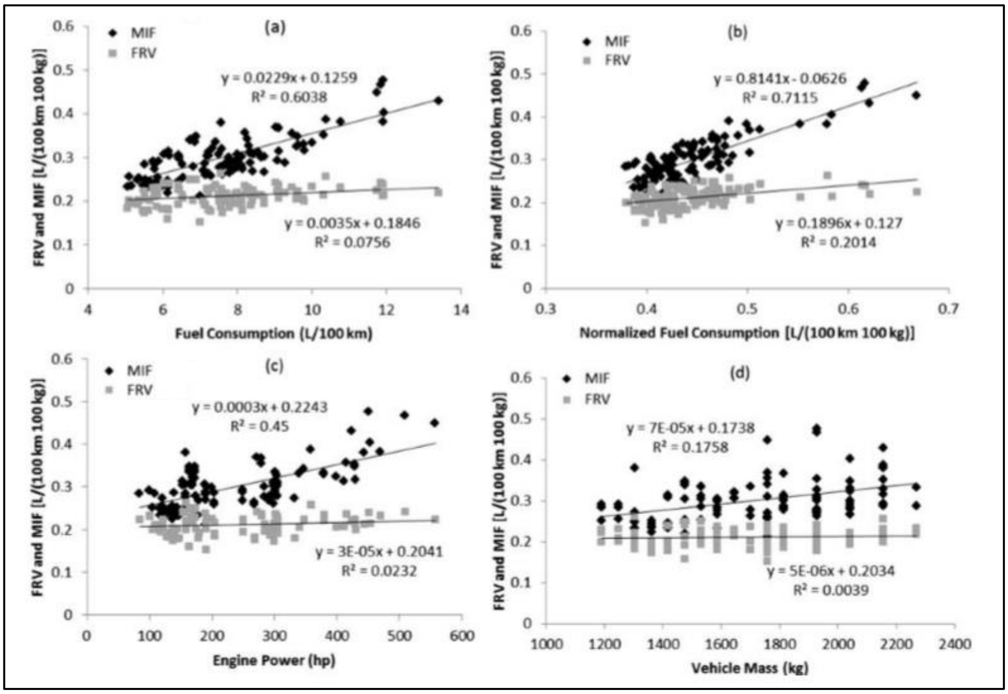


Figure 2.16. *FRV* and *MIF* estimated from the 2013 model year EPA fuel economy testa data for 106 vehicles (source: Kim and Wallington, 2013)

The paper arrives to the following conlusions:

- for both the FRV and MIF methods the mass-induced FC of a component for the baseline scenario is clearly defined. The FRV is typically measured in two versions: with and without powertrain adjustment. The former FRV is larger than the latter because it entails powertrain resizing for performance equivalency. Therefore, the baseline mass-induced FC is greater when the lightweighting scenario entails SEs than when the scenario does not assume them. On the other hand, in the MIF method $MIF = MIF^{+}$ for the baseline case since $\eta_m = \eta_m^{+}$. Thus the baseline mass-induced FC remains the same regardless of SEs;
- in the case of PMR only, the FRV method significantly (20−50%) underestimates the mass-induced FC with respect to the MIF method because it ignores the mechanical energy losses induced by mass (Figure 2.15.);
- in the application of the FRV and MIF methods to the EPA fuel economy test, results show that *FRV* and *MIF* lie respectively in the range 0.15-0.26 and 0.21-0.48 [l/100km*100kg]. *FRV* is unrelated or insignificantly related to the FC while *MIF* has a strong linear correlation. A unit mass reduction applied to a less efficient vehicle saves more fuel than the same mass reduction applied to a more efficient vehicle (Figure 2.16., a and b). A moderate correlation between the normalized fuel economy and the *FRV* is detected (Figure 2.16.b.). Engine power and thus displacement is closely related to *MIF* as fuel economy is usually a function of maximum power (Figure 2.16.c.); vehicle mass does not have a strong correlation with *MIF*.

Kim et al. (2015) is a work builded up on Kim and Wallington (2013a) that shows how the indexes *FRV* and *MIF* can be used in order to determine the use phase FC in LCAs of vehicle lightweighting. At this scope the FRV and MIF methods are adopted in order to quantify the use phase FC of a lightweight vehicle component (FC_{light}). The FRV method provides FC_{light} solely for the case of PMR only and it is based on the following relation:

$$FC_{light} = FRV * m_{ref} * d - FRV * \Delta m * d \qquad \text{Eq. 2.26.}$$

Where
FC_{light} = use phase FC of the lightweight vehicle component [l];
FRV = Fuel Reduction Value in case of PMR [l/100km*100kg];
m_{ref} = mass of the reference component [100kg];
d = use stage mileage [100km];
Δm = mass reduction due to lightweighting [100kg].

The MIF method provides FC_{light} for both the cases of PMR only and SE and it is based on the following relation:

$$FC_{light} = MIF * m_{ref} * d - FRV * \Delta m \quad \text{(PMR only)} \qquad \text{Eq. 2.27.}$$

$$FC_{light} = MIF * m_{ref} * d - FRV^{+} * \Delta m \quad \text{(SE)} \qquad \text{Eq. 2.28.}$$

Where
MIF = Mass Induced Fuel consumption [l/100km*100kg];
FRV^{+} = Fuel Reduction Value in case of SE [l/100km*100kg];

In the second part of the research the authors apply the FRV and MIF methods in order to determine the effect on LC GHG emissions of a grille opening reinforcement involved by substitution of conventional material (steel) with lightweight one (magnesium). Figure 2.17. reports the GHG emissions calculated by both methods.

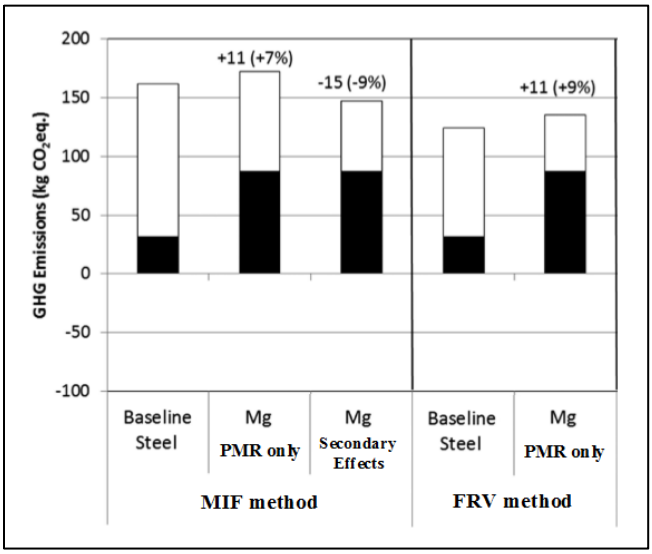


Figure 2.17. Comparison of LC GHG emissions calculated for the steel and magnesium grille opening reinforcement design using the MIF and FRV methods (source: Kim et al., 2015)

As seen in the three left-hand bars of Figure 2.17., the MIF method captures the absolute and relative benefit of lightweighting by providing GHG emissions for both the baseline (steel) and lightweighted (Mg) designs and it differentiates the cases of PMR only and SE. The MIF method estimates a 11 kg CO_2-eq increase and 15 kg CO_2-eq decrease of LC GHG emissions, without and with SEs respectively. In case of SE the FRV method gives the same result as the MIF method (11 kg CO2-eq increase). The higher percent increase in the FRV method (9% versus 7%) for the same absolute increase (+11 kg CO2-eq) reflects the lower baseline FC in the FRV method (124 versus 162 kg CO2-eq). The authors arrive to the following conclusions:

- the FRV method has a lower complexity, but it does not distinguish between scenarios with and without SEs. The MIF method is the more complex but it provides results for the two combinations of component perspective with, and without SEs. LCA practitioners have to select the method that meets their needs;
- *FRV* does not include engine friction loss; this latter is considered as inherent energy use neither induced by mass nor aerodynamic drag and it remains unchanged upon mass change without SEs;
- taking into account thermodynamic, transmission, and engine friction losses as FC, *MIF* values are consistent with total energy efficiency of modern ICE vehicles in literature (~20%).

Other existing studies investigate the relationship between energy consumption and mass in a wider context with respect to the mere automotive lightweight LCA and they extend the analysis to

- several powertrain technologies (ICE and other alternative technologies)
- different typologies of interventions for implementation of secondary effects.

Below a brief description of these researches is reported making reference to the only ICE technology.

Pagerit et al. (2006) evaluate the impact of mass reduction for several vehicle platforms and advanced powertrain technologies in comparison with conventional ICE cars. The sensitivity to mass of FC is defined as the ratio $\frac{dm_{fuel}}{dm_{vehicle}}$ where m_{fuel} is the total mass of fuel consumed and $m_{vehicle}$ is the vehicle mass. The calculation of FC is performed by using the Powertrain System Analysis Toolkit (PSAT), a vehicle-modeling package for simulation of performance and fuel economy; the UDDS and HWFET driving cycles are simulated as hot starts and combined by using 55/45 weighting factors to obtain a mixed value. Calculations are performed for three different reference vehicles representative of compact, SUV and midsize vehicle classes. The sensitivity to mass of FC is evaluated for two different cases:

- without powertrain resizing: the drivetrain maximum power is fixed and the vehicle mass is reduced by decreases of 10% (all vehicle classes: compact, midsize and SUV);
- with powertrain resizing: on the basis of mass reduction, drivetrain maximum power is recalculated in order to have the same 0-60 mph acceleration (only midsize vehicle class).

Table 2.3. reports technical features of both reference and resized powertrain vehicles.

		Compact vehicle	**SUV vehicle**	**Mid-size vehicle**					
				0%	**10%**	**20%**	**30%**	**40%**	**50%**
Engine	Power [kW]	113	170	118	111	105	98	91	84
	Specific power [W/kg]	89.2	83.1	76.0	76.6	78.0	78.8	79.8	81.0
	Engine peak efficiency [%]	33.3	33.5	33.5	33.5	33.5	33.5	33.5	33.5
Transmission	Type	4 speed	5 speed	5 speed	5 speed	5 speed	5 speed	5 speed	5 speed
	Final drive ratio [null]	4.07	3.55	4.44	4.44	4.44	4.44	4.44	4.44
Masses	Glider (body and chassis) [kg]	740	1258	988	889	790	692	593	494
	ICE [kg]	113	213	74	69	66	61	57	53
	Cargo & Driver [kg]	136	136	136	136	136	136	136	136
	Total [kg]	1267	2045	1552	4149	1346	1243	1140	1037
Vehicle	Frontal area [kg]	2.18	2.46	2.2	2.2	2.2	2.2	2.2	2.2
	Drag coefficient [kg]	0.3	0.41	0.3	0.3	0.3	0.3	0.3	0.3
	Rolling resistance coefficient [null]	0.008	0.0084	0.008	0.008	0.008	0.008	0.008	0.008
	Wheel radius [m]	0.307	0.368	0.317	0.317	0.317	0.317	0.317	0.317
Accessories	Mechanical [W]	300	700	300	300	300	300	300	300
	Electrical [W]	300	500	300	300	300	300	300	300

Table 2.3. Characteristics of reference and resized powertrain vehicles considered by Pagerit et al. (2006)

Table 2.4. reports performance (time for the 0-60 [mph]), FC and FRV for both the resized and non-resized vehicles: it has to be noted that the highest FRV refers to the compact class while the implementation of powertrain resizing (midsize class) involves a 22% growth of the FRV.

	Compact vehicle		**SUV vehicle**		**Mid-size vehicle**			
Mass reduction [%]	**0-60 mph[s]**	**FC [l/100km]**	**0-60 mph[s]**	**FC [l/100km]**	**Non resized**		**Resized**	
					0-60 mph[s]	**FC [l/100km]**	**0-60 mph[s]**	**FC [l/100km]**
0	9.9	6.43	9.9	11.59	10.1	7.92	0.1	7.74
10	9.0	6.12	9.0	11.2	9.3	7.59	0.1	7.35
20	8.1	5.84	8.1	10.79	8.3	7.26	0.1	6.98
30	7.2	5.57	7.2	10.41	7.3	6.98	0.1	6.59
40	6.3	5.3	6.3	10.09	6.4	6.66	0.1	6.21
FRV [l/100km*100kg]	0.38		0.30		0.32		0.39	

Table 2.4. Performance, FC and FRV for resized and non-resized vehicles of Pagerit et al. (2006)

Casadei and Broda (2007) investigate the relationship between mass and FC for different vehicle types (small car, mid-size car, small SUV and large SUV), propulsion systems (gasoline and diesel) and driving cycles (Federal Test Procedure 75, FTP75 and HighWay Fuel Economy Driving Schedule, HWFET). The generic vehicle characteristics are chosen in order to represent the variety of vehicle weights and engine sizes in the U.S. passenger vehicle fleet. FC reduction achievable through light-weighting is determined by simulation modelling of car FC for three levels of lightening: 5%, 10% and 20% with respect to basis vehicles. The simulations are conducted for vehicles with base weight, reduced weight and reduced weight with resized powertrain; the chosen performance criterion for powertrain resizing is the 50-70 [mph] elasticity. For calculation of FC, 50-70 [mph] elasticity and powertrain resizing the simulation software MSC.EASY5 is used. Table 2.5. summarizes mass and engine power for both basis and lightweight configurations of vehicles.

		Gasoline							
		Engine power [kW]				Mass [kg]			
	Vehicle configuration	**Small car**	**Mid-size car**	**Small SUV**	**Large SUV**	**Small car**	**Mid-size car**	**Small SUV**	**Large SUV**
Gasoline	Basis vehicle	87	163	189	215	1304	1644	1927	2381
	5% mass reduction	87	163	189	215	1239	1562	1831	2262
	10% mass reduction	87	163	189	215	1174	1480	1734	2143
	20% mass reduction	87	163	189	215	1043	1315	1542	1905
	5% mass reduction (resizing)	83	157	182	207	1239	1562	1831	2262
	10% mass reduction (resizing)	80	151	175	199	1174	1480	1734	2143
	20% mass reduction (resizing)	74	140	160	181	1043	1315	1542	1905
Diesel	Basis vehicle	123	130	154	228	1304	1644	1927	2381
	5% mass reduction	123	130	154	228	1239	1562	1831	2262
	10% mass reduction	123	130	154	228	1174	1480	1734	2143
	20% mass reduction	123	130	154	228	1043	1315	1542	1905
	5% mass reduction (resizing)	118	125	148	218	1239	1562	1831	2262
	10% mass reduction (resizing)	114	120	142	214	1174	1480	1734	2143
	20% mass reduction (resizing)	104	109	129	206	1043	1315	1542	1905

Table 2.5. Engine power of basis and lightweight vehicle configurations of Casadei and Broda (2007)

Table 2.6. reports FC reduction obtained by calculations: for the case of mass reduction only the values are comprised within the range 0.14-0.20 [l/100km*100kg] while for powertrain resizing they notably grow (range: 0.24-0.36 [l/100km*100kg]).

	FC reduction [l/100km*100kg]						
	Gasoline				Diesel		
	Small car	**Mid-size car**	**Small SUV**	**Large SUV**	**Mid-size car**	**Small SUV**	**Large SUV**
Mass reduction only	0.203	0.151	0.149	0.157	0.142	0.156	0.168
Powertrain resizing	0.311	0.358	0.320	0.314	0.241	0.260	0.250

Table 2.6. Values of FC reduction obtained by Casadei and Broda (2007)

Cheah et al. (2007) examine the opportunity to increase fuel economy given by several technology options applied to new U.S. naturally-aspirated gasoline cars and light-trucks by model year 2035. Three technology options are evaluated:

- improvements in efficiency of future vehicles in order to reduce FC rather than improving vehicle performance;
- increasing market share of diesel, turbocharged gasoline and hybrid electric-gasoline propulsion systems;
- reducing vehicle weight and vehicle size.

For the scope of the present treatise only the first and third options are reviewed. Technical features of cars assumed as reference are reported in Table 2.7.; they are obtained by averaging data of all new vehicles introduced in the U.S. during the year 2006.

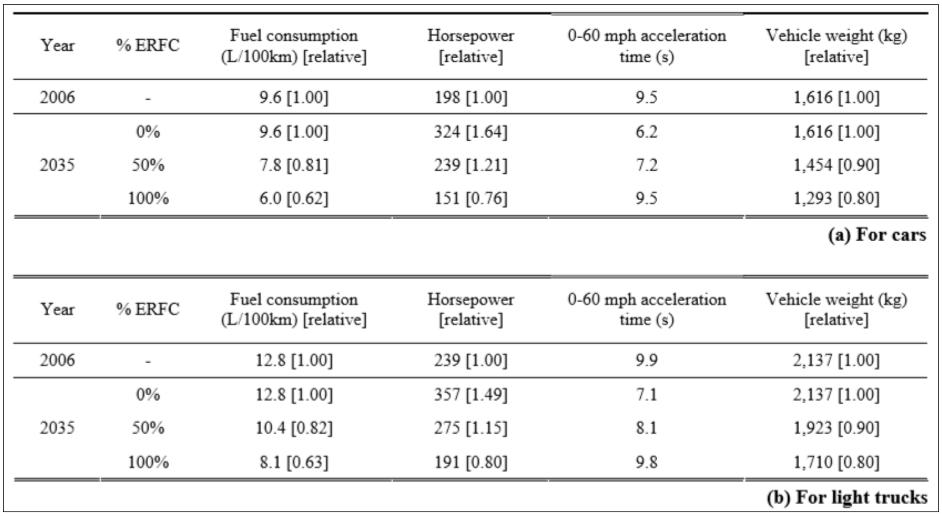
Year	Fuel consumption [l/100km * 100kg]	Horsepower [hp]	0-100 km/h acceleration [s]	Mass [kg]
2006	9.6	198	9.5	1616
2006	12.8	239	9.9	2137

Table 2.7. Technical features of reference vehicles adopted by Cheah et al. (2007)

Considering the first option, Cheah defines the index Emphasis on Reducing Fuel Consumption (ERFC) as:

$$\% ERFC = \frac{Future\ fuel\ consumption\ reduction\ realized}{Future\ fuel\ consumption\ reduction\ possible\ with\ constant\ size\ and\ performance} \qquad \text{Eq. 2.29.}$$

At 100% ERFC, vehicle weight decreases by 20% and all steady improvements in conventional technology are assumed to realize reduced FC while the 0-100 [km/h] acceleration remains constant. In contrast, without any emphasis on reducing FC (0% ERFC), consumption of new vehicles remains at today’s values, no weight reduction occurs, and all of the efficiency gains from steady technology improvements are channelled to better horsepower and acceleration performance. At 50% ERFC it is assumed that the 0-100 [km/h] time is the average between the 0% ERFC level and the 100% ERFC one. The engine power of the different vehicle configurations is determined in order to match the 0-100 km/h acceleration on the basis of the ERFC index. Performances and FC are simulated using the AVL ADVISOR software; FC is obtained through a combination of FTP75 and HWFET driving cycles by 55/45 weighting factors. Table 2.8. reports a summary of technical features, performances and FC of current and future vehicle configurations: for every 100 kg mass decrease the average FC reduction is very high, about 1.1 [l/100km*100kg] both for cars and light trucks.



Year	% ERFC	Fuel consumption (L/100km) [relative]	Horsepower [relative]	0-60 mph acceleration time (s)	Vehicle weight (kg) [relative]
2006	-	9.6 [1.00]	198 [1.00]	9.5	1,616 [1.00]
2035	0%	9.6 [1.00]	324 [1.64]	6.2	1,616 [1.00]
	50%	7.8 [0.81]	239 [1.21]	7.2	1,454 [0.90]
	100%	6.0 [0.62]	151 [0.76]	9.5	1,293 [0.80]

(a) For cars

Year	% ERFC	Fuel consumption (L/100km) [relative]	Horsepower [relative]	0-60 mph acceleration time (s)	Vehicle weight (kg) [relative]
2006	-	12.8 [1.00]	239 [1.00]	9.9	2,137 [1.00]
2035	0%	12.8 [1.00]	357 [1.49]	7.1	2,137 [1.00]
	50%	10.4 [0.82]	275 [1.15]	8.1	1,923 [0.90]
	100%	8.1 [0.63]	191 [0.80]	9.8	1,710 [0.80]

(b) For light trucks

Table 2.8. Technical features of current and future vehicle assumed by Cheah et al. (2007)

The second option considers to obtain FC saving through a 35% weight reduction beyond what has been assumed at different levels of ERFC. The future vehicles are simulated in AVL ADVISOR software taking into account that the only difference with respect to reference vehicles is the weight reduction. Results show that for every 100 kg mass reduction, the adjusted FC decreases by 0.3 [l/100km] for cars and 0.4 [l/100km] for light trucks (Figure 2.18.).

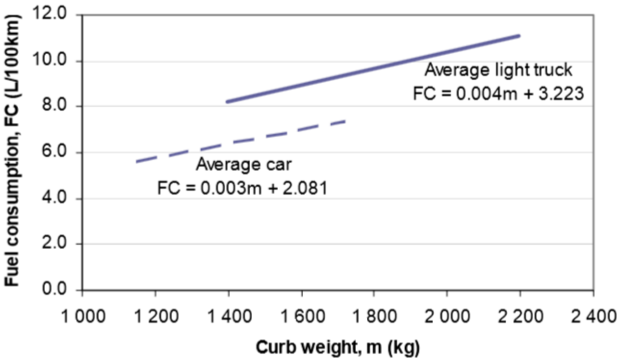


Figure 2.18. Mass-FC relationship for future vehicles in case of emphasis on weight reduction obtained by Cheah et al. (2007)

Wohlecker et al. (2007) investigate the relationship between mass and FC through simulation modelling of three vehicle types (compact, mid-size, SUV), five propulsion systems (gasoline, diesel, gasoline hybrid, diesel hybrid, fuel cell) and two driving cycles (NEDC, HYZEM). Technical features of vehicles assumed as reference for calculations are shown in Table 2.9.

	Gasoline		**Diesel**	
Vehicle type	**Power [kW]**	**Mass [kg]**	**Power [kW]**	**Mass [kg]**
Compact	85	1260	100	1260
Mid-size	181	1640	170	1640
SUV	235	2195	220	2195

Table 2.9. Technical features of vehicles assumed by Wohlecker et al. (2007)

The simulation approach takes into account both primary and secondary mass saving:

- primary weight reduction is considered to be achieved through a lightening of body-in-white (mass of body-in-white for typical cars of the considered classes are reported in table 2.10). Two lightweight configurations are defined: minimum mass reduction (20% saving of body-in-white mass) and maximum mass reduction (40% saving of body in white mass).
- secondary mass saving is assumed to be 30% of primary mass saving; this further mass reduction is considered to be originated by lightening other vehicle components thanks to the lighter body-in-white. The values of mass and mass reduction are reported in Table 2.10.

Class	**Body-in-white mass [kg]**	**Primary mass saving [kg]**		**Secondary mass saving [kg]**	
		Min	**Max**	**Min**	**Max**
Compact	360	72	144	22	43
Mid-size	400	80	160	24	48
SUV	540	108	216	32	65

Table 2.10. Values of mass and mass reduction considered by Wohlecker et al. (2007)

Wohlecker performs the simulations for vehicles with base weight, reduced weight and reduced weight with re-sized powertrain. Powertrain resizing consists in the adaptation of powertrain to the lower weight in order to achieve the same 0-100 [km/h] acceleration as the basis vehicle. For calculation of 0-100 [km/h] acceleration, FC and powertrain configurations the simulation tool Matlab/Simulink is used. Table 2.11. summarizes vehicle mass and engine power for the considered vehicle classes.

	Gasoline						**Diesel**					
	Mass [kg]			**Engine power [kW]**			**Mass [kg]**			**Engine power [kW]**		
Vehicle configuration	**Compact**	**Mid-size**	**SUV**	**Compact**	**Mid-size**	**SUV**	**Compact**	**Mid-size**	**SUV**	**Compact**	**Mid-size**	**SUV**
Basis vehicle	1260	1640	2195	85	181	235	1260	1640	2195	100	170	220
Minimum mass reduction	1166	1536	2055	85	181	235	1166	1536	2055	100	170	220
Maximum mass reduction	1073	1432	1914	85	181	235	1073	1432	1914	100	170	220
Minimum mass reduction (resizing)	1166	1536	2055	79	170	222	1166	1536	2055	94	161	209
Maximum mass reduction (resizing)	1073	1432	1914	74	160	207	1073	1432	1914	87	152	197

Table 2.11. Vehicle mass and engine power of basis and lightweight vehicle configurations considered by Wohlecker et al. (2007)

Table 2.12. reports FC reduction obtained by calculations expressed in [l/100km*100kg].

		FC reduction [l/100km*100kg]					
		Gasoline			**Diesel**		
		Compact	**Mid-size**	**SUV**	**Compact**	**Mid-size**	**SUV**
NEDC	Mass reduction only	0.13	0.12	0.15	0.13	0.12	0.11
	Powertrain resizing	0.35	0.50	0.45	0.27	0.34	0.29
HYZEM	Mass reduction only	0.16	0.16	0.16	0.13	0.12	0.13
	Powertrain resizing	0.28	0.34	0.30	0.20	0.23	0.22

Table 2.12. FC reduction obtained by Wohlecker et al., 2007

The results obtained by Wohlecker are commented as follows:

- Powertrain resizing. For gasoline cars the influence on FC reduction of powertrain re-sizing depends on driving cycle: in the HYZEM it is about as important as weight reduction while in the NEDC it is more than twice. The difference is due to the low load profile of the NEDC with respect to the HYZEM. For diesel vehicles the powertrain re-sizing is slightly less effective due to the higher part load efficiency which results from the lack of throttling losses;
- Vehicle segment. The dependency of absolute consumption reduction on vehicle segment is mainly influenced by characteristic weight and motorization of the

different case studies. The highest absolute consumption improvement is achieved in the heaviest vehicle segment, with the most powerful engine (SUV); on the other hand the lowest reduction is reached in the smallest segment, the compact class;

- Driving cycle. The absolute consumption reduction obtained by powertrain re-sizing is smaller in the HYZEM with respect to the NEDC; this is due to the higher engine base efficiency which is a result of the higher load profile of the cycle. On the other hand weight reduction is more important in the HYZEM because the more dynamic run entails that the mass dependent acceleration resistance takes a bigger share of total resistance;
- When talking about weight sensitivity the used boundary conditions have to be strongly considered, as the results are influenced by many parameters.

Redelbach et al. (2012) analyze the impact of weight reduction on energy consumption and related costs for different advanced electric powertrain concepts: several hybrid architectures (parallel/serial hybrid, with/without external charging) and a full battery electric vehicle are assessed and compared to a conventional ICE car on the basis of the NEDC driving cycle. To build up and model the different powertrain architectures the DLR Modelica library is applied. Considering only conventional ICE car, a midsize passenger car sold on the German auto market is chosen as reference (see Table 2.13.) while the simulation model is composed by two modules:

- internal combustion engine: an engine characteristic map based on a real-world engine is used in order to determine FC and torque as a function of accelerator pedal position and engine speed;
- driver: the driver adapts the accelerator pedal position by comparing at any time the requested velocity from driving cycle with car actual velocity.

Vehicle architecture	**Power engine [kW]**	**Curb mass [kg]**
Gasoline engine, direct ignition 2-wheel drive, 6-speed automatic transmission	100	1400

Table 2.13. Technical features of conventional ICE car assumed by Redelbach et al. (2012)

The effect on FC of weight reduction is carried out through a series of simulation runs in which the mass is changed in discrete steps while all other parameters are kept constant. Simulations show a nearly linear relationship resulting in a value of FC reduction of 0.245 [l/100km*100kg].

Carlson et al. (2013) determine the impact of vehicle mass on vehicle road load and energy consumption for different vehicle powertrain architectures (conventional internal combustion powertrain, hybrid electric and all-electric) through coastdown testing and chassis dynamometer testing. The three vehicles used in testing are a 2012 Ford Fusion V6, a 2012 Ford Fusion Hybrid and a 2011 Nissan Leaf. Testing includes coastdown testing on a test track to determine the drag forces and road load at each test weight for each vehicle. Chassis dynamometer testing was conducted over standard driving cycles on each vehicle at multiple test weights to determine the energy consumption impact caused by change in vehicle mass. The considered driving cycles are the Urban Dynamometer Drive Schedule

(UDDS), Highway Fuel Economy Test (HWFET) and US06 (United States Environmental Protection Agency, 2015). Considering the only ICE vehicle, dynamometer testing shows that

- the road load presents a slightly non-linear trend of decreasing road load with decreasing mass;
- a 10% mass reduction results in a FC reduction of 3.4, 2.1 and 3.8 [%] respectively for UDDS, HWFET and US06 driving cycles.

2.3. Critical analysis of current use stage LCA practices

In the light of the review of existing literature, a critical analysis of current use stage LCA practices is reported below. Similarly to previous paragraphs, the treatment is conducted separately for the three main typologies of study.

LCA of an entire vehicle

The practice is to assume the FC declared by the manufacturer which is based on standardized driving cycles for homologation testing. The fact that the automotive LCAs are aligned on the same driving cycles is surely an advantage in terms of consistency, transparency and comparability between the various studies; in this regard Koffler and Rodhe-Branderburger (2010) state that “one should generally utilize the legally binding driving cycles”. On the other hand the point of criticism is that the use stage is assessed on the basis of single cycles without evaluating additional driving behaviours and patterns.

LCA of a specific vehicle component

Below points of criticism are reported separately for Incremental and Proportional method.

Incremental method. The Incremental method takes into account only the influence on consumption of the mass by the proportionality constant *c*. Therefore it bases on values which can be measured (e.g. by removing the component from the car), and such a verifiability represents the main advantage of the method. On the other hand the points of criticism are:

- the mass-orientation limits its application to components which have no effect on vehicle efficiency;
- the method would lead to unrealistic conclusions when masses which represent high percentages of total car mass are considered. Indeed, if the mass of the component (m_{comp} in Eq. 2.1) is assumed to be equal to the mass of the entire vehicle, the result is not the actual car FC, but only the weight-related portion of it;
- the method needs a proportionality constant *c* fixed a priori. Many of the existing LCAs adopt the value 0.6, as suggested by Lynne Ridge (1997). As such studies deal with cars belonging to different vehicle classes that differ in terms of engine technology, mass, maximum power and power-to-weight ratio, the point of criticism is represented by the adoption of the same value for the proportionality constant. Indeed considering the same *c* involves that the ratio

$\frac{FC_{comp}/FC_{veh}}{m_{comp}/m_{veh}}$ (ratio between the quota of consumption and the quota of mass attributed to the component) is the same for a wide range of vehicles beyond technical features that characterize the specific application.

Proportional method. The Proportional method takes into account all the aspects of motion resistance considering, additionally to the mass-dependent quota, also the share of FC independent of weight. An advantage in the use of this method is that a proportionality constant is not required since the determination of component consumption is assumed to be proportional to the mass. Another advantage is that the sum of the energy consumption of all the components yields an amount which is identical with the consumption of the entire car and consequently the energy conservation is respected. On the other hand the point of criticism are:

- the component FC cannot be verified by measurements; therefore the method is rejected by scientists and experts who consider the parameters of the travelling resistance equation (as there are the aerodynamic, rolling friction and accelerating components) are simply taken into account by a mass proportional key;
- the ratio $\frac{FC_{comp}/FC_{veh}}{m_{comp}/m_{veh}}$ (ratio between the quota of consumption and the quota of mass attributed to the component) is the same for a wide range of vehicles beyond technical features that characterize the specific application.

Comparative LCA between a reference and an innovative lightweight alternative

The FRVs used by current comparative LCAs are comprised within a wide range (0.02 – 1.00 [l/100km*100kg]) and this leads to an excessive margin of inaccuracy that strongly limits the validity of the results. The values of FRV are from other studies which investigate the relationship between FC and vehicle mass:

- Kim and Wallington (2013a) and Kim et al., (2015) present a method for calculating the FRV of a specific vehicle basing on an analytical modelling of mass-induced FC. The model provides reliable and truthful results; on the other hand it needs detailed vehicle technical parameters that unlikely are available to LCA practitioners;
- the other researches determine the mass-induced FC for a limited set of car models through simulation modelling and propose reference values of FRV for the comparative lightweight LCAs.

From the review of such a typology of works, the following considerations emerge:

- Vehicle range. The researches are based on simulation modelling of a very restricted number of case studies belonging to determined vehicle classes: Eberle and Franze (1998) investigate car models within the BMW's 1998 model range (D-class), Koffler (2010) applies his analysis to a limited number of B-class gasoline and diesel vehicles while the other researches assume only one/two vehicle case studies as representative of the entire class they belong to. It can be concluded that the resulting FRVs depend on technical features of the considered case studies without being really representative of the entire class or engine technology they belong to. Additionally the existing works are focused on vehicle models belonging to specific classes; in particular it does not exist a systematic analysis which investigates a wide range of classes with respect to the actual car market. Finally despite the naturally aspirated engine family has been widely investigated in the past, for the turbocharged one large margins of examination exist (there are no researches with regard to gasoline turbocharged vehicles);

- Age of the study. The existing studies are dated. The development of new models and the advance in research make that vehicle technical features (engine technology, mass, maximum power and power-to-weight ratio) change during years and fuel economy performance of new cars are better with respect to old ones. Additionally new systems recently introduced in the market are not considered in previous works; this is the case of the “Start and Stop (S&S)” system which has a not negligible influence on car FC and whose effect on FRV has to be investigated (Matsuura and Tanaka, 2004; Wishart and Shirk, 2012). Therefore FRVs obtained 10-15 years ago for a specific vehicle class nowadays are not really representative of it. At the same time the European studies are based on the NEDC driving cycle which is going to become obsolete in the next future. Indeed at the moment a new homologation test procedure is in phase of development and it will substitute the current one within 2017. This is the new Worldwide harmonized Light Test Procedure (WLTP) which will define a global harmonized standard for Europe;
- Driving cycle. Some studies determine the FRV basing on a single driving cycle. Considering only one cycle as the basis for the calculation involves a relevant limitation in terms of reliability of the results as no further driving pattern is evaluated;
- Comparability. The existing studies determine the FRV basing on a reference driving cycle which usually is the standardized cycle effective in the geographic area where the research is conducted (the American researches generally refer to the Federal Test Procedure driving cycles while the European ones to the NEDC). Consequently the adopted cycles change passing from one study to the other and this involves a relevant limitation in terms of comparability of the FRV.

2.4. Objective of the work

In the light of critical analysis, the present research focuses on two of the three main typologies of automotive LCA study that have been reviewed: LCA of a specific vehicle component and comparative LCA between a reference and an innovative lightweight alternative. The choice of such typologies of study is based on

- the notable room for improvement they present;
- the large number of developing case studies which can take advantage from improvement.

The objective of the work is to create a tool for the assessment of the use stage in application to turbocharged vehicles, both gasoline and diesel. From a practical point of view the tool is constituted by a series of environmental models that

- can be adopted by LCA practitioners for application to real case studies
- are flexible and tailorable for any generic case study
- overcome, or at least reduce the limitations and criticisms of current LCA practices presented in the previous paragraph.

Below the enhancements with respect to existing literature that the tool intends to fulfil are reported separately per typology of study.

- <u>LCA of a specific vehicle component</u>. The allocation of impact to the component is performed abandoning the rigid proportions between mass and consumption typical of the Incremental and Proportional methods. In particular the consumption attributed to the component is determined taking into account as much as possible vehicle characteristics (engine technology, vehicle class and technical features) that case by case characterize the specific case study;
- <u>Comparative LCA between a reference and an innovative lightweight alternative</u>. The calculation of impact saving during operation achievable through light-weighting is performed by taking into account the fuel reduction value that is closest to the specific application in terms of engine technology, vehicle class and technical features.

To achieve these targets, the research is composed by two sections: simulation and environmental modelling. The simulation modelling performs an in-depth calculation of weight-induced FC whose outcomes are implemented within the environmental modelling. In particular the calculation of weight-induced FC complies the following requirements:

- calculation is performed for both gasoline and diesel turbocharged vehicles;
- within a specific engine technology and vehicle class (i.e. gasoline naturally aspirated B-class) calculation is performed for a wide range of vehicle models in terms of mass, maximum power, power to mass ratio, engine displacement, aerodynamic profile, specific FC, etc, according to the tendency of 2015 European car market. By so doing the calculation of mass-induced FC reduction is customizable for the single vehicle classes and within the classes the dependence on main vehicle technical features can be investigated. This allows the tool to characterize in-depth any generic case study and provide results as much as possible tailored for the specific application;
- calculation is performed referring to technical features typical of current car models (year 2015) for each one of the considered vehicle classes. The effect that the “Start and Stop (S&S)” system has on FC and mass-induced FC reduction is also evaluated;
- the driving cycles on which calculation is performed are representative as much as possible of the driving behaviour in real driving conditions;
- calculation is performed basing on the most globally widespread driving cycles in order that results are comparable with the ones of other studies;
- calculation is based on the modeling of the entire vehicle drive train: vehicle dynamics, driver, engine, and gearbox. This is needed in order to evaluate the effect that interaction of each component with another has on the overall car consumption and, consequently, on the mass-induced FC reduction;

- calculation is performed considering both primary mass reduction only and implementation of secondary effects. In case of implementation of secondary effects a valid criterion for their definition has to be identified.

3. Tool for the environmental assessment of the use stage

As shown in chapter 2

- the aim of the research is to conceive a reliable tool for the assessment of the use stage within real LCA applications to turbocharged vehicles;
- the tool is constituted by a series of environmental models able to treat with the needs of the different typologies of LCA study and to achieve specific enhancements with respect to existing literature;
- the research is founded on an in-depth calculation of weight-induced FC whose outcomes are implemented within the environmental models in order to overcome the points of criticism that affect current LCA practices.

Following paragraph describes the stages of work needed in order to conceive the tool.

3.1. Construction of the tool

The construction of the tool is articulated into three main stages:

- **Stage 1: calculation of use stage FC**. The first stage envisages the calculation of FC for various mass-configurations of a certain number of vehicle case studies. The calculation is performed through simulation modelling. The output of the stage is constituted exclusively by vehicle FC;

- **Stage 2: evaluation of mass-induced FC**. The second stage evaluates the mass-induced FC starting from the output of the first stage; basing on values of FC of the different mass-configurations, the mass-induced FC is determined through the relation between consumption and mass;

- **Stage 3: environmental modelling**. The third stage consists in the conception of tailored LCA models which implement the mass-induced FC calculated in stage 2 and provide as output the LCIA impacts. These models are the end result of the work and they aim to represent a support instrument for LCA practitioners in application to real case studies.

The first two stages constitute the simulation modelling section. Figure 3.1. schematizes the construction of the tool evidencing the partition in stages.

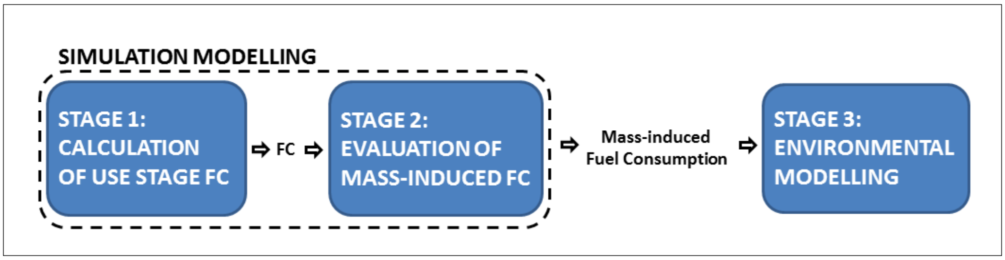


Figure 3.1. Construction of the tool evidencing the partition in stages

In the following paragraphs the three stages are qualitatively illustrated trying to evidence how each stage contributes in order to achieve the final targets of the research.

3.1.1. Stage 1: Calculation of use stage FC

The use stage FC is calculated through a simulation model developed by the software AMESim (Siemens PLM software, 2015; Smolders, 2010). The output of the model is exclusively the values of FC expressed in liters per kilometre. The model reproduces the complete drive train of the vehicle and it estimates the torque at the wheels needed in order to achieve the desired velocity by sending commands to different components, such as engine throttle position, clutch displacement, engaged gearbox ratio, and mechanical braking of the wheels. As components react to commands realistically, it is possible to model a driver who follows a predefined speed cycle by taking into account transient effects like engine starting, clutch engagement/disengagement, or shifting. The modelling of the complete drive train is aimed to consider as much as possible all elements which influence FC (and consequently mass-induced FC) in real driving conditions.

3.1.1.1. Description of the model

The model is constituted by a complete automotive network subdivided into two sections which in turn are composed by single sub-models:

- Control logic section (sub-models: *Mission profile & Ambient data, Driver, Control unit*);
- Drive train section (sub-models: *Engine, Clutch, Gearbox, Vehicle dynamics*).

A brief qualitative overview of sub-models for each model section is reported below while a detailed description of equations/logic which govern model operation and parameters setting is available in chapter 4.

Control logic section comprehends the following sub-models:

- *Mission profile & ambient data*. The sub-model defines mission profile for vehicle velocity and ambient conditions;
- *Driver*. Basing on mission profile for vehicle velocity and inputs coming from *Vehicle dynamics* (effective vehicle linear velocity) and *Engine* (engine speed), the sub-model determines gearbox, clutch, load and braking control signals respectively to *Gearbox, Clutch, Control Unit* and *Vehicle dynamics*;
- *Control unit*. Basing on inputs coming from *Engine* (engine speed) and *Driver* (load control signal), the sub-model determines the effective load control signal to *Engine*.

Drive train section comprehends following sub-models:

- *Engine*. Basing on input coming from *Control unit* (effective load control signal to the engine), the sub-model determines the engine torque. The effective load and engine torque identify the operating point within the specific FC map; as specific FC is expressed in g/kWh, the FC (expressed in l/100km) is obtained instant by instant through the energy required for motion;
- *Clutch*. Basing on inputs coming from *Engine* (engine torque) and *Gearbox* (torque of gearbox primary shaft), the sub-model determines the speed of both engine and gearbox primary shaft;
- *Gearbox*. Basing on inputs coming from *Clutch* (speed of gearbox primary shaft) and *Vehicle dynamics* (wheel speed), the sub-model determines the driving torque;
- *Vehicle dynamics*. Basing on inputs coming from *Driver* (braking control signal) and *Gearbox* (driving torque), the sub-model determines the linear velocity of the vehicle. The calculation takes into account aerodynamic, rolling and acceleration driving resistances.

Figure 3.2. reports a complete scheme of the use stage simulation model.

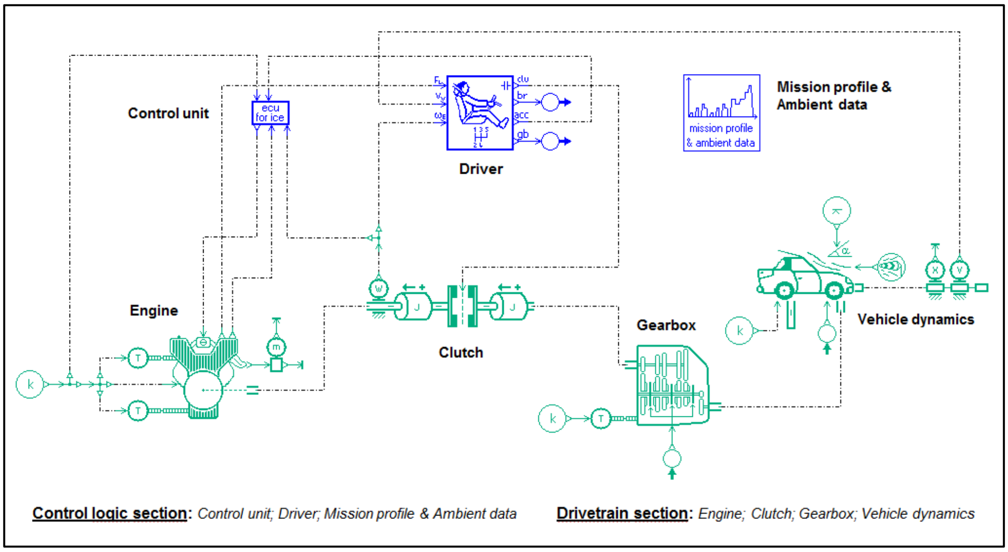


Figure 3.2. Complete scheme of use stage simulation model

3.1.1.2. Driving cycles

The model performs calculations for various legislation driving cycles. Legislation driving cycles are standard cycles that all mass produced cars are subjected to before being authorized for sale in market. The total mass of emissions produced during a particular cycle must be below a set limit decided by the legislating authority. While many standardized cycles exist throughout the world (including special cycles used for research only), the most common ones are the ones used by the U.S. Environmental Protection Agency (EPA) (United States Environmental Protection Agency, 2015) and the United Nations Economic Commission for Europe (UNECE) (United Nations Economic Commission for Europe, 2015). In the U.S.A., federal emissions standards are set by EPA whereas Californian standards are set by the Air Resources Board (ARB) (Air Resources Board, 2015). European laws are developed and enforced by the following institutions:

- European Parliament: elected by people of Member States;
- Council: representing the governments of Member States. The Council of Environment Ministers oversees the area of environmental regulations;
- Commission: the executive and the body having the right to initiate legislation.

The standardized driving cycles over which the use stage simulation model performs the calculations are:

- Federal Test Procedure 72 (FTP72);
- Japanese driving Cycle 08 (JC08).
- New European Driving Cycle (NEDC);
- Worldwide harmonized Light Test Cycle (WLTC).

The choice to utilize legally binding standardized cycles is dictated by reasons of transparency, consistency and comparability with results of existing studies. On the other hand considering four cycles allows to assess the entire vehicle LC on various use stage scenarios permitting to evaluate the effect of diverse routes and driving styles. Below a brief description of each cycle is reported.

Federal Test Procedures 72 (FTP72). The EPA has a number of driving cycles used for various legislation purposes. The FTP72 is a mandated dynamometer test used for emission certification and fuel economy testing of cars and light duty trucks (Barlow et al., 2009). This cycle is a compilation of various real-world driving routes performed on the streets of Los Angeles in California. The FTP72 consists of two phases. The first one (0-505 s) simulates a highway route of 5.78 [km] which subjects the car to a relatively high load; the second one (506-1372 s) represents an urban driving including frequent stops over a distance of 6.29 [km]. A common variant of the test is the FTP75 which is derived from the FTP72 by adding the third phase of 505s, identical to the first phase of FTP72. The FTP72 cycle is known in Australia as the ADR 27 (Australian Design Rules) cycle and in Sweden as the A10 or CVS (Constant Volume Sampler) cycle. Figure 3.3. reports an overview of the speed profile of the FTP72 driving cycle.

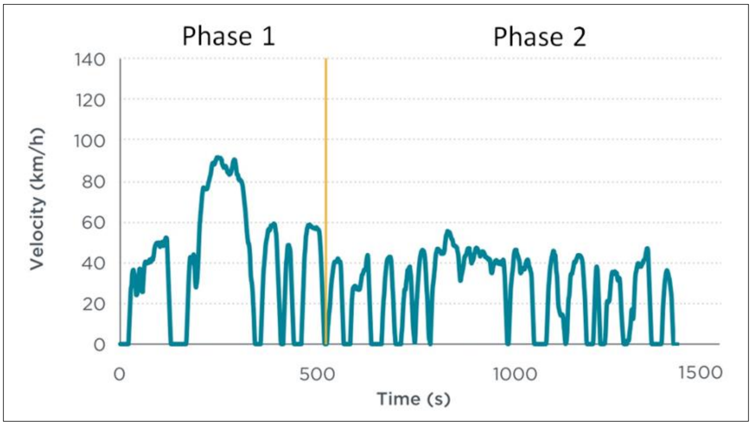


Figure 3.3. Driving schedule of Federal Test Procedure72 (FTP72)

Japanese driving Cycle 08 (JC08). To date the 10-15 mode driving cycle test is the official fuel economy and emission certification test for new light duty vehicles in Japan. A new more demanding test, called Japanese driving Cycle 08 (JC08), was established by Japanese emission regulation in December 2006 and since 2008 it is also used for emission certification and fuel economy for new cars (Kuhlwein et al., 2009). Such a test is significantly longer and more rigorous than the 10-15 mode; the economy ratings are lower and they are expected to be more real world. The JC08 corresponds to driving conditions in congested city traffic, including idling periods and frequently alternating acceleration and deceleration: the running pattern stretches out to 1200 [s] and the top speed is 82 [km/h]. Figure 3.4. reports an overview of the speed profile of the JC08 driving cycle.

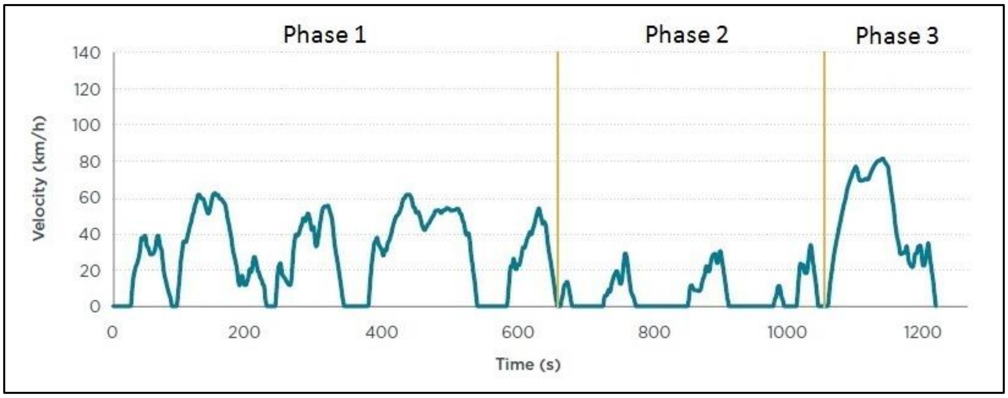


Figure 3.4. Driving schedule of the Japanese driving Cycle 08 (JC08)

New European Driving Cycle (NEDC). The New European Driving Cycle (NEDC) is a driving cycle designed to assess the emission levels of car engines and the fuel economy of passenger cars (excluding light trucks and commercial vehicles) in Europe (Barlow et al., 2009; United Nations Economic Commission for Europe, 2011, 2013). It is also referred to as MVEG cycle (Motor Vehicle Emissions Group). The NEDC is supposed to represent the typical usage of a car in Europe. The total duration of the cycle is 1180 [s]: the first phase of 780 [s] consist of four repeated Economic Commission for Europe urban driving cycles (ECE) while the last 400 seconds consist of one Extra-Urban Driving Cycle (EUDC). The ECE-15 was introduced first in 1970 and has been designed to represent typical driving conditions of busy European cities; it is characterized by low engine load, low exhaust gas temperature, and a maximum speed of 50 [km/h]. The EUDC, introduced by ECE R101 in 1990, has been designed to represent more aggressive, high speed driving modes with a maximum speed of 120 [km/h] (the low-powered vehicles are limited to 90 [km/h]). Figure 3.5. reports an overview of the speed profile of the NEDC driving cycle.

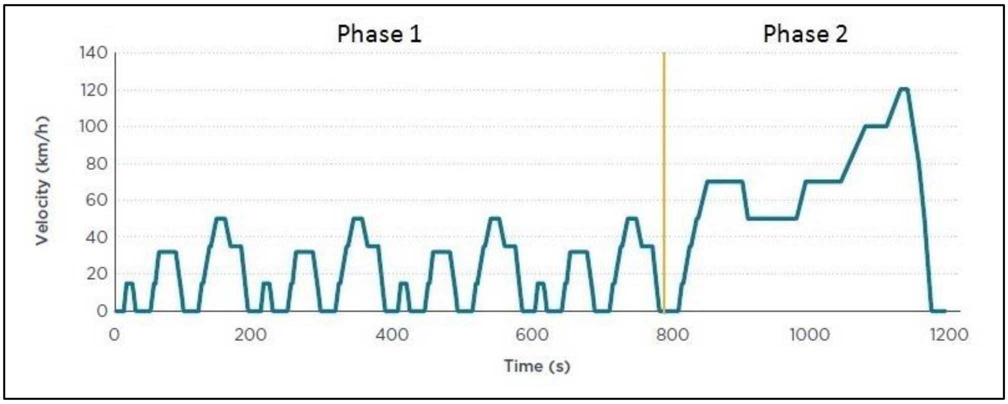


Figure 3.5. Driving schedule of the New European Driving Cycle (NEDC)

Worldwide harmonized Light-duty Test Cycle (WLTC). The Worldwide harmonized Light-duty Test Cycle (WLTC) is being developed by the Working Party on Pollution and Energy group (GRPE) within the framework of the Worldwide harmonized Light Vehicles Test Procedure (WLTP) (Marotta and Tutuianu, 2012; Mock et al., 2014; Tutuianu et al., 2013). The WLTC is expected to replace the European NEDC procedure for type approval testing of light-duty vehicles with the transition to the Euro 6 emission standards in September 2017. The WLTP procedure includes three test cycles applicable to vehicle categories of different Power-to-Mass Ratios, PMR (Table 3.1.). The cycle definitions may also depend on the maximum speed (v_{max}) which is the maximum speed of the vehicle as declared by the manufacturer and not any use restriction or safety based limitation.

WLTC driving cycle			
Category	**PMR [W/kg]**	**Speed phases**	**Comments**
Class 1	PMR ≤ 22	Low, Middle	If $v_{max} \geq$ 70 km/h, phase “Low” is repeated after phase “Middle”. If $v_{max} <$ 70 km/h, phase “Middle” is replaced by a repetition of phase “Low”
Class 2	PMR ≥ 34 > 22	Low, Middle, High	If $v_{max} <$ 90 km/h, phase “High” is replaced by a repetition of phase “Low”
Class 3	PMR > 34	Low, Middle, High, Extra-High	If $v_{max} <$ 135 km/h, phase “Extra-High” is replaced by a repetition of phase “Low”

Table 3.1. Test cycles of Worldwide harmonized Light Vehicles Test Procedure (WLTP) (source: Kuhlwein et al., 2009)

Class 3 includes vehicles with the highest PMR and it is representative of cars driven in Europe, U.S. and Japan. It consists of four phases: low (phase 1: 0-589 s), middle (phase 2: 590-1022 s), high (phase 3: 1023-1477 s) and extra-high (phase 4: 1478-1800 s) load (Figure 3.6.).

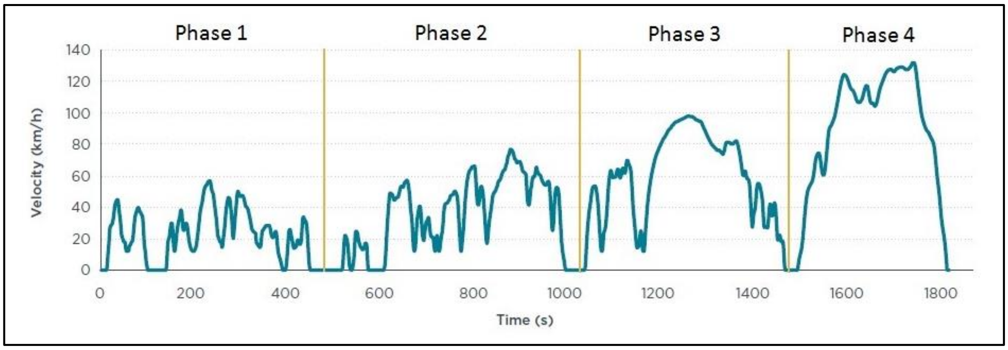


Figure 3.6. Driving schedule of the Worldwide harmonized Light-duty Test Cycle (WLTC)

Table 3.2. gives an overview of the considered driving cycles by reporting their main descriptive parameters.

		Descriptive parameters of driving cycles				
		Unit	**FTP72**	**JC08**	**NEDC**	**WLTC**
General	**Duration**	s	1369	1204	1180	1800
	Distance	km	12.00	8.17	11.03	23.27
	Mean velocity	km/h	31.6	24.40	33.60	46.50
	Max. velocity	km/h	91.2	81.6	120.0	131.3
	Stop phases	null	14	12	14	9
Durations	**Stop**	s	189	346	280	226
	Constant driving	s	247	21	475	66
	Acceleration	s	506	432	247	789
	Deceleration	s	427	405	178	719
Shares	**Stop**	%	13.8	28.7	23.7	12.6
	Constant driving	%	18.0	1.7	40.3	3.7
	Acceleration	%	37.0	35.9	20.9	43.8
	Deceleration	%	31.2	33.6	15.1	39.9
Dynamic	**Mean positive acceleration**	m/s^2	0.429	0.42	0.59	0.41
	Max. positive acceleration	m/s^2	1.47	1.69	1.04	1.67
	Mean positive "vel * acc" (acceleration phases)	m^2/s^3	3.46	3.34	4.97	4.54
	Mean positive "vel * acc" (whole cycle)	m^2/s^3	1.41	1.20	1.04	1.99
	Max positive "vel * acc"	m^2/s^3	18.28	11.60	9.22	21.01
	Mean deceleration	m/s^2	-0.46	-0.45	-0.82	-0.45
	Min. deceleration	m/s^2	-1.47	-1.29	-1.39	-1.50
	Relative positive acceleration	m/s^2	0.1652	0.1707	0.1114	0.1524

Table 3.2. Descriptive parameters of the considered driving cycles (source: Kuhlwein et al., 2009)

Evaluating FC and mass-induced FC in more than one driving cycle allows to obtain results characterized by a wide comparability with respect to existing literature. Additionally the inclusion of the WLTC aligns the present research with the coming type test approval procedure and it ensures that the outcomes can be used as a reliable yardstick for future analyses.

3.1.1.3. Extension of the analysis: vehicle model range

In this paragraph the extension of the analysis is described in terms of both engine technology, vehicle class and case study.

Engine technology. With respect to engine technology the modelling is extended to:

- Gasoline Turbocharged vehicles (GT vehicles);
- Diesel Turbocharged vehicles (DT vehicles).

Vehicle class. The selection of vehicle classes is based on car model range within the European car market of the year 2015. For both the cited engine technologies, the following vehicle classes are taken into account:

- A-class
- B-class
- C-class
- D-class

As cars belonging to A and B classes present similar features in terms of mass, engine displacement and maximum power, they are considered as aggregate for both GT and DT technologies. The extension of the analysis to the cited classes allows to investigate a wide extent in terms of vehicle model range for both technologies. The complete set of vehicle classes is described in Table 3.3.

Vehicle classes					
GT			**DT**		
A/B	C	D	A/B	C	D

Table 3.3. Summary of vehicle classes considered in the study

Case study. The tool performs the calculation of FC for several vehicle case studies. Assuming only one case study as representative of a class would lead to results strongly influenced by technical features (car mass, engine displacement, power and power-to-weight ratio) of the specific car models. Therefore in order to determine FCs which are really representative of the investigated classes, the modelling is applied to a certain number of vehicle case studies within each class. Additionally it has to be kept in mind that the core of the tool is the quantification of the mass-induced FC (stage 2 of the construction of the tool): analysing various case studies allows to estimate the mass-induced FC of each class not by a single value but by a range, thus considering a certain variability of vehicle technical features within the class.

With the scope to obtain realistic FCs, the different vehicle case studies are characterized as much as possible by parameters of real car models from the European car market of the year 2015. Table 3.4. describes the extension of the analysis in terms of number of considered case studies. It has to be noted that the number of case studies within each class depends exclusively on the availability in literature of data needed for the setting of the simulation model.

	Extension of the analysis: vehicle classes and case studies					
	GT			**DT**		
	A/B-class	**C-class**	**D-class**	**A/B-class**	**C-class**	**D-class**
N° of case studies	10	11	11	10	12	10
	32			32		
	64					

Table 3.4. Number of considered vehicle case studies within each vehicle class

3.2. Stage 2: Evaluation of mass-induced FC

In this paragraph the calculation of mass-induced FC is described for the two considered typologies of LCA study. It has to be noted that hereinafter the typology “comparative LCA between a reference and an innovative lightweight alternative” is treated separately between the cases of Primary Mass Reduction only (PMR) and implementation of Secondary Effects (SE).

3.2.1. LCA of a specific vehicle component & Comparative LCA in case of PMR

In the case of LCA of a specific vehicle component the target of the tool is to determine the quantity of FC imputable to the component starting from the knowledge of the component mass. On the other hand in the case of comparative LCA where only PMR is taken into account, the target is to determine the reduction of FC starting from the knowledge of the saved mass. Considering the allocation of FC to a specific vehicle component, if it is assumed

- to calculate the FC imputable to the component as the mass-induced FC
- to determine the mass-induced FC as the difference between FC of vehicle with its reference mass and FC of vehicle lessened than the component mass

the issue can be treated as a lightening. Consequently for both the typologies of study the mass-induced FC can be determined as the consumption saving achievable through mass reduction. The relation between FC and car mass is expressed by the FRV coefficient which quantifies the FC reduction due to a 100kg mass reduction. Once the FRV is determined, FC imputable to the component and FC reduction involved by PMR are calculated by analogous relations:

$$FC_{use\_comp} = FRV_{PMR} * m_{comp} \qquad \text{Eq. 3.1.}$$

$$FC_{use\_sav\_PMR} = FRV_{PMR} * m_{sav} \qquad \text{Eq. 3.2.}$$

Where:
FC_{use_comp} = amount of Fuel Consumption during operation attributed to the component [l/100km];
FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction only [l/100km*100kg];
$FC_{use\_sav\_PMR}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in case of Primary Mass Reduction only [l/100km];
m_{sav} = saved mass thanks to light-weighting [100kg];
m_{comp} = component mass [100kg].

The determination of FRV is based on FCs calculated by the use stage simulation model in the first stage of the construction of tool. For each vehicle case study the calculation of FC is performed for the following five mass-configurations:

- Reference (*Reference mass-configuration*);
- 5% light-weighting (*PMR mass-configuration 5%*);
- 10% light-weighting (*PMR mass-configuration 10%*);
- 15% light-weighting (*PMR mass-configuration 15%*);
- 20% light-weighting (*PMR mass-configuration 20%*).

Once the FC is calculated for the mass-configurations defined above, five points in the diagram “FC – Mass” are known: the FRV is determined as the slope of the regression line of consumption in function of mass.

The determination of FRV is performed for each one of the 64 vehicle case studies defined in paragraph 3.1.1.3. Figure 3.7. reports an exemplifying diagram of consumption in function of mass with the corresponding regression line and FRV.

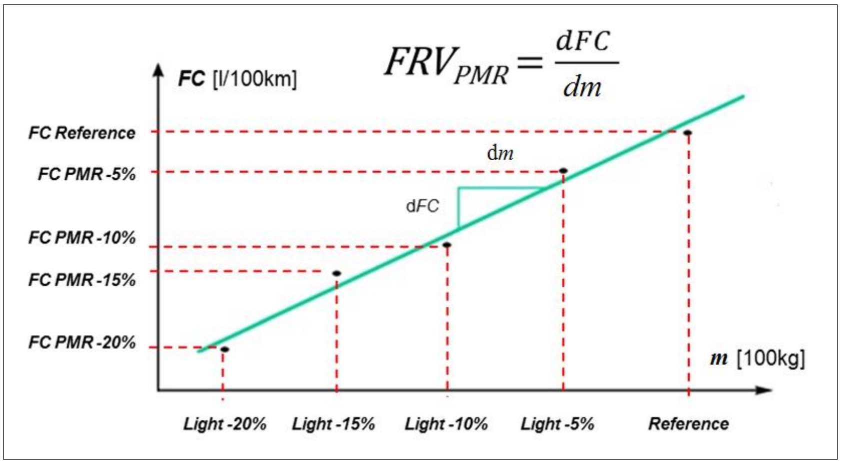


Figure 3.7. Exemplifying diagram of FC in function of mass with corresponding FRV for LCA of a specific vehicle component & comparative LCA with PMR only

With respect to both typologies of LCA study it has to be noted that:

- the percent lightening is referred to the tare mass of the reference mass-configuration as the mass of fluids, fuel, tool kit, spare wheel and driver/luggage of the PMR mass-configurations remains the same with respect to the reference one;
- FC of the PMR mass-configurations is calculated using the same simulation model adopted for the reference configuration where the only change is represented by car mass. Indeed as the final target is to evaluate the effect on FC of mass reduction, all other specifications remain unaltered;
- mass reduction makes that performance of vehicle in the PMR mass-configurations grows in terms of both acceleration and top speed. This is due to the higher torque available for accelerating the vehicle, meaning a bigger difference between the driving and the resistance force; indeed, while the engine torque remains unaltered, the force required to drive the wheels (calculated as the sum of the aerodynamic, rolling and acceleration resistances) decreases.

On the other hand some observations have to be made with respect to the case of comparative LCA with PMR only:

- mass reduction entails that the absolute FC of the PMR mass-configurations is lower with respect to the reference one. On the contrary it has to be considered that despite a lower absolute FC, the specific consumption increases. This is due to the fact that the mass saving involves a reduction of engine load shifting the operating point towards areas of the specific FC map characterized by lower efficiency (Eq. 3.3.).

$$t_E = load_E * t_{E\_max} = \frac{F_{req} * R_W}{\alpha_f * \alpha_G * \eta_f * \eta_G} \qquad \text{Eq. 3.3.}$$

Where:
t_E = Engine torque;

$load_E$ = Engine load;
t_{E_max} = maximum Engine torque for a given engine speed;
F_{req} = Force required to drive the wheels;
R_w = wheel Radius;
α_f = final transmission ratio;
α_G = Gear transmission ratio;
η_f = efficiency of final transmission;
η_G = Gear efficiency.

- the comparison between the alternatives is performed basing on the same functional unit: as vehicle performance increases passing from the reference to the innovative lightweight alternative, car performance cannot be included in the functional unit.

3.2.2. Comparative LCA with implementation of SE

In this case the mass-induced FC is determined as the consumption saving achievable through car mass reduction with further implementation of SE. Similarly to the case of comparative LCA with PMR only, it has to be identified the relation which gives FC in function of car mass. Once again the answer is represented by the FRV coefficient. In order to distinguish the two cases, the Fuel Reduction Value with implementation of Secondary Effects is identified by the acronym FRV_{SE}.

The amount of FC reduction achievable through mass reduction is calculated by the following relation:

$$FC_{use\_sav\_SE} = FRV_{SE} * m_{sav} \qquad \text{Eq. 3.4.}$$

Where:
$FC_{use\_sav\_SE}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in case of Secondary Effects [l/100km];
FRV_{SE} = Fuel Reduction Value in case of Secondary Effects [l/100km*100kg];
m_{sav} = saved mass thanks to light-weighting [100kg].

FRV_{SE} is determined starting from calculations of FC performed by the use stage simulation model in the first stage of the construction of the tool. For each vehicle case study the calculation of FC is performed for the following five mass-configurations:

- Reference (*Reference configuration*);
- 5% light-weighting & Secondary Effects (*SE mass-configuration 5%*);
- 10% light-weighting & Secondary Effects (*SE mass-configuration 10%*);
- 15% light-weighting & Secondary Effects (*SE mass-configuration 15%*);
- 20% light-weighting & Secondary Effects (*SE mass-configuration 20%*).

It has to be noted that the percent lightening is referred to the tare mass of the reference mass-configuration (see paragraph 3.2.1.) and that SE are implemented at four different levels (5%, 10%, 15%, 20%).

Similarly to the case of LCA with PMR only, once FC is calculated for the mass-configurations defined above, five points in the diagram “FC – Mass” are known, and the FRV_{SE} is determined as the slope of the regression line of consumption in function of mass. It has to be noted that the reference mass-configuration is the same with respect to the case of PMR only.

The determination of FRV_{SE} is performed for each one of the 64 vehicle case studies identified in paragraph 3.1.1.3. Figure 3.8. reports an exemplifying diagram of consumption in function of mass with the corresponding regression line and FRV_{SE}.

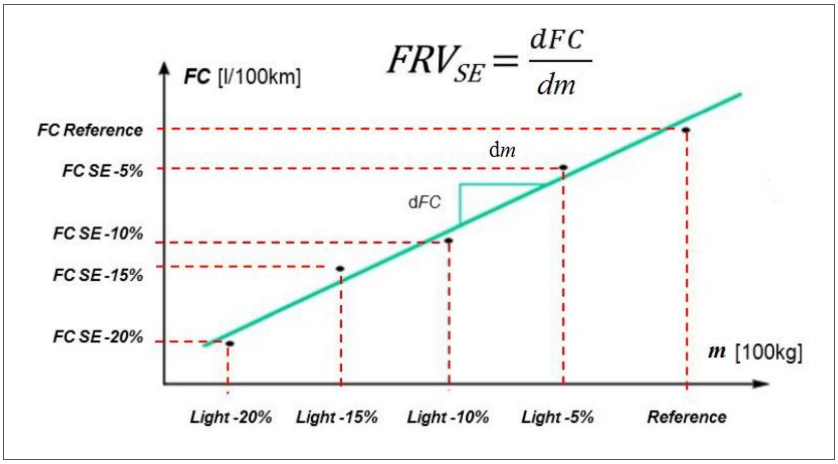


Figure 3.8. Exemplifying diagram of FC in function of mass and corresponding FRV for comparative LCA with implementation of SE

3.2.2.1. Secondary effects

As said in paragraph 3.2.1., car mass reduction involves on one hand a reduction of the absolute FC and on the other hand an improvement in the driving performance. In the only perspective of FC reduction, performance improvement is considered an useless effect which involves an unjustified energy expenditure. Thus the implementation of SEs in the lightweight mass-configurations is aimed to use mass reduction in order to achieve exclusively reduction of consumption instead of improving performance.

The concept of performance cannot be reduced to one single factor, but is rather made up of a multitude of different criteria. Usually car journals base their tests on “acceleration times from 0 to 100 km/h”; indeed such a performance criterion is very influential on the customers and represents a hardly relevant parameter in practice. In addition to time from 0 to 100 [km/h], many other criteria are commonly used in order to assess the performance level of a car: acceleration from 0 to 60 [mph], elasticity from 80 to 120 [km/h], time to travel a kilometre, top speed, etc. Rather than acceleration from 0 to a given velocity, elasticity within a certain speed range covers a situation commonly encountered on the road. More specifically, accelerating at high velocity is an usual operation to pass other vehicles in highway and represents a risk factor to be minimized by keeping the process as short as possible. So that, the chosen performance criterion for the present treatise is the “elasticity from 80 to 120 [km/h] in the upper gear ratio”.

In addition to the conservation of the performance, it is assumed that vehicles in the SE mass-configurations maintain the same technological level of the engine with respect to the reference mass-configuration. The parameters chosen as representative of the engine technological level are reported below:

- Maximum Brake Mean Effective Pressure ($BMEP_{max}$);
- Stroke to Bore Ratio (SBR);
- Mean Piston Speed (MPS).

Following equations report the analytical expression of such parameters:

$$BMEP_{max} = \frac{T_{E\_tr\_max} * 4\pi}{100\,V} \qquad \text{Eq. 3.5.}$$

$$SBR = \frac{stroke}{bore} \qquad \text{Eq. 3.6.}$$

$$MPS = \frac{stroke * \omega_E}{30000} \qquad \text{Eq. 3.7.}$$

Where:
$BMEP_{max}$ = maximum Brake Mean Effective Pressure [bar];
$t_{E\_tr\_max}$ = maximum tractive Engine torque [Nm];
V = engine displacement [l];
SBR = Stroke to Bore Ratio [null];
$stroke$ = engine stroke [mm];
$bore$ = engine bore [mm];
MPS = Mean Piston Speed [m/s];
ω_E = Engine speed [rpm].

It has to be noted that in a comparative LCA study the comparison between the alternatives is performed basing on the same functional unit. Considering that

- car mass reduction is completely used in order to decrease FC without any improvement of performance
- the technological level of the engine remains unaltered passing from the reference to the SE mass-configurations

both performance and technological level can be included in the functional unit.

3.3. Stage 3: Environmental modelling

Stage 2 of the construction of the tool quantifies the mass-induced FC in terms of FRV: FRV_{PMR} (LCA of a specific vehicle component & Comparative LCA with PMR only) and FRV_{SE} (Comparative LCA with implementation of SE). The environmental modelling consists in the conception of tailored LCA models which implement the values of mass-induced FC and provides as output the LCIA impacts; these latter represent the final output of the tool. The modelling is performed through the environmental software GaBi6 (Thinkstep, 2015); following paragraph provides a brief description of the software while the next ones illustrate the modelling for the considered typologies of LCA study.

3.3.1. The environmental software GaBi6

The GaBi6 software is a tool created in order to perform LC balances. It provides support when managing large data sets and modelling product LCs. As a method for the assessment of environmental impacts of systems (products and services), comprehensive balances can be used to fulfil LC analyses. In the realisation of a LCA study the support of the software is mainly located in the LCI and LCIA phases.

LCI phase. In the LCI all inputs and outputs of the system identified in the goal and scope definition are quantified in terms of material and energy elementary flows. With respect to the LCI phase, three object types represent the basis of GaBi6 modelling: “*Flow*”, “*Process*” and “*Plan*”.

- *Flows* model LCI elementary flows and are representative of actual material and energy flows. GaBi6 database has a comprehensive hierarchical division of flow definitions called “flow group hierarchy”. The hierarchy provides a large pre-defined set of flows categorized by type which constitutes the GaBi6 flow database. In the development of a model, material and energy flows are assigned to processes and they represent the link between each one of them. Values assigned to flows of the same name are totalled by the software during balance calculation;
- *Processes* are representative of actual processes, technical procedures and groups of procedures. Process corresponds to the term “process unit” in the ISO 14040. Like flows, processes in GaBi6 system are hierarchically grouped and stored. The hierarchy provides a large pre-defined set of processes categorized by type which constitutes the GaBi6 process database;
- *Plans* are used to assemble processes in order to create product systems. Essentially a plan is the process map which visually depict a stage or sub-stage in the system. In order to model complex systems, plans can be nested creating plans of higher level.

LCIA phase. The impact assessment evaluates the effects on the environment caused by resources consumption and emissions determined in the inventory. The assessment is divided into two sub-steps: assigning LC balance data to LC impact categories (classification) and modelling the LC balance data within the LC impact categories (characterization). GaBi6 performs the assessment using specific LCIA methods. At this regard the software makes available a wide range of LCIA methods such as Eco-indicator 95/99 (Goedkoop and Spriensma, 2000), CML (University of Leiden, 2013), Impact 2002+ (Jolliet et al., 2003) and ReCiPe (Goedkoop et al., 2009). In order to summarize balances to aid in decision-making, GaBi6 gives also the possibility to perform weighting of results using weighting sets provided by a wide range of LCIA methods.

3.3.2. Environmental modelling: use stage GaBi6 plan

As shown in paragraph 1.2., the use stage is composed by the two sub-stages WTT (fuel transformation processes upstream to FC) and TTW (FC for car driving). In order to include both quota, an use stage plan composed by the WTT and TTW processes is conceived. As all GaBi6 processes, TTW and WTT processes are environmentally characterized by their input and output flows: through the characterization of such flows the correlation between mass and LCIA impacts is performed. Below TTW and WTT processes are described for the two considered typologies of LCA study.

3.3.2.1. Use stage GaBi6 plan – LCA of a specific vehicle component

WTT process. The inputs of the process are material and energy flows needed by the fuel production processes. The output is the amount of FC during operation attributed to the component (FC_{use_comp}).

TTW process. The input flow of the TTW process is the amount of FC during the entire LC attributed to the specific component. This latter is expressed through the following relation:

$$FC_{use\_comp} = \frac{FRV_{PMR} * m_{comp} * mileage_{use}}{10000} * \rho_{fuel} \qquad \text{Eq. 3.8.}$$

Where:

FC_{use_comp} = amount of Fuel Consumption during operation attributed to the component [kg];

FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction only calculated in stage 2 of the construction of the tool [l/100kg*100km];

m_{comp} = component mass [kg];
$mileage_{use}$ = vehicle mileage during operation [km];
ρ_{fuel} = fuel density [kg/l].

The output flows of the TTW process are the air emissions during the entire vehicle LC caused by the combustion of FC attributed to the component. The output flows are characterized by the following equations:

$$emiss\_i_{use\_comp} = emiss\_i_{veh\_km} * mileage_{use} * \frac{FC_{use\_comp}}{FC_{use\_veh}} \qquad \text{Eq. 3.9.}$$

$$FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel} \qquad \text{Eq. 3.10.}$$

Where:
$emiss\_i_{use\_comp}$ = amount of emission i during operation attributed to the component (considered emissions: benzene [g], CH_4 [g] , CO [g], CO_2 [g], N_2O [g], NH_3 [g], NMVOC [g], NO [g], NO_2 [g], particulate [g], SO_2 [kg]);
$emiss\_i_{veh\_km}$ = per-kilometre amount of emission i ([g/km], [kgSO_2/km]);
FC_{use_comp} = amount of Fuel Consumption during operation attributed to the component [kg];
FC_{use_veh} = amount of Fuel Consumption during operation of entire vehicle [kg];
FC_{veh_100km} = per-100kilometre Fuel Consumption of vehicle [l/100km];
FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction [l/100km*100kg];
$mileage_{use}$ = vehicle mileage during operation [km];
ρ_{fuel} = fuel density [kg/l].

3.3.2.2. Use stage GaBi6 plan – Comparative LCA between a reference and an innovative lightweight alternative

For the comparative LCA the composition of the use stage plan is unaltered with respect to the LCA of a specific vehicle component (WTT and TTW processes). Below the use stage plan is described separately for the cases of PMR and SE.

Comparative LCA with PMR

WTT process. The inputs of the process are material and energy flows needed by the fuel production processes. The output is the amount of FC saved during operation thanks to lightweighting ($FC_{use\_sav\_PMR}$).

TTW process. The input flow of the TTW process is the amount of Fuel Consumption saved during the entire LC thanks to car mass reduction. The amount of FC saved during vehicle LC is expressed through the following equation:

$$FC_{use\_sav\_PMR} = \frac{FRV_{PMR} * m_{sav} * mileage_{use}}{10000} * \rho_{fuel} \qquad \text{Eq. 3.11.}$$

Where:
$FC_{use\_sav\_PMR}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in case of Primary Mass Reduction only [kg];
FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction only calculated in stage 2 of the construction of the tool [l/100kg*100km];
m_{sav} = saved mass thanks to light-weighting [kg];

$mileage_{use}$ = vehicle mileage during operation [km].

The output flows of the TTW process are the air emissions avoided during the entire LC thanks to the reduction of vehicle mass. The output flows are characterized by the following equations:

$$emiss\_i_{use\_sav\_PMR} = emiss\_i_{veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_PMR}}{FC_{use\_veh}} \quad \text{Eq. 3.12.}$$

$$FC_{use\_veh} = \frac{FC_{veh\_100km} * mileage_{use}}{100} * \rho_{fuel} \quad \text{Eq. 3.13.}$$

Where:
$emiss\_i_{use\_sav\_PMR}$ = amount of emission *i* saved during operation thanks to light-weighting in case of Primary Mass Reduction only (considered emissions: CO_2 [g] and SO_2 [kg]);
$emiss\_i_{veh\_km}$ = per-kilometre emission *i* of reference vehicle ([gCO_2/km], [$kgSO_2$/km]);
FC_{use_veh} = amount of Fuel Consumption during operation of reference vehicle [kg];
FC_{veh_100km} = per-100kilometre Fuel Consumption of reference vehicle [l/100km];
ρ_{fuel} = fuel density [kg/l].

Comparative LCA with implementation of SE

For the comparative LCA with implementation of SE both use stage plan composition and equations which govern TTW process remain the same with respect to comparative LCA with PMR; the only dissimilarity is represented by the use of FRV_{SE} instead of FRV_{PMR}.

WTT process. The inputs of the process are material and energy flows needed by the fuel production processes. The output is the amount of FC saved during operation thanks to lightweighting ($FC_{use\_sav\_SE}$).

TTW process. The input flow of the TTW process is the amount of FC saved during the entire vehicle LC thanks to both car mass reduction and implementation of SE. The amount of FC saved during LC is expressed through the following equation:

$$FC_{use\_sav\_SE} = \frac{FRV_{SE} * m_{sav} * mileage_{use}}{10000} * \rho_{fuel} \quad \text{Eq. 3.14.}$$

Where:
$FC_{use\_sav\_SE}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in case of Secondary Effects [kg];
FRV_{SE} = Fuel Reduction Value in case of Secondary Effects calculated in stage 2 of the construction of the tool [l/100kg*100km];
m_{sav} = saved mass thanks to light-weighting [kg];
$mileage_{use}$ = vehicle mileage during operation [km].

The output flows of the TTW process are the air emissions avoided during the entire vehicle LC thanks to both mass reduction and implementation of SE. The output flows are characterized by the following equations:

$$emiss\_i_{use\_sav\_SE} = emiss\_i_{veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_SE}}{FC_{use\_veh}} \quad \text{Eq. 3.15.}$$

$$FC_{use\_veh} = \frac{FC_{veh\_100km} * mileage_{use}}{100} * \rho_{fuel} \quad \text{Eq. 3.16.}$$

Where:
$emiss\_i_{use\_sav\_SE}$ = amount of emission *i* saved during operation thanks to light-weighting in case of Secondary Effects (considered emissions: CO_2 [g] and SO_2 [kg]);
$emiss\_i_{veh\_km}$ = per-kilometre emission *i* of reference vehicle ([gCO_2/km], [kgSO_2/km]);
FC_{use_veh} = amount of Fuel Consumption during operation of reference vehicle [kg];
FC_{veh_100km} = per-100kilometre Fuel Consumption of reference vehicle [l/100km];
ρ_{fuel} = fuel density [kg/l].

Below some notes regarding the environmental modelling are reported:

- TTW process represents the core of the use stage plan. On one hand the output flows constitute the LCI elementary flows according to which TTW impact is quantified; on the other hand the input flow determines the quantity of fuel whose production is assessed by WTT process;
- air emissions during the entire vehicle LC scale linearly with the amount of FC (Eq. 3.9., 3.12., 3.15.). As FC scales linearly with mass (Eq. 3.8., 3.11., 3.14.), also emissions scale linearly with mass;
- for both the LCA of a specific component and the comparative LCAs the target of the tool is to quantify the LCIA impacts ascribable to a certain mass. On one hand in the case of LCA of a specific vehicle component it is referred to the component mass and the quantified LCIA impact represent the quota of overall vehicle use stage impact attributed to the component. Therefore all the typologies of vehicle air emissions are considered in the assessment. On the other hand in the case of comparative LCAs it is referred to vehicle mass reduction and the quantified LCIA impacts are the environmental burdens avoided thanks to the light-weighting. Hence only CO_2 and SO_2 are taken into account as they scale linearly with amount of FC based on fuel C and S content while all other emissions (so-called “limited emissions) depend exclusively on the number of travelled kilometres as they are treated by the exhaust gas treatment system;
- the added value of the environmental modelling is the implementation within the environmental model of the FRVs determined in stage 2 of the construction of the tool. The possibility to select the value for the FRV which is closest to the generic case study (see chapter 6) makes the environmental model a reliable tool for applications to real case studies.

Figure 3.9. reports a scheme which describes the structure and operation method of the tool: the interaction between simulation modelling and environmental modelling is showed for the two typologies of LCA study.

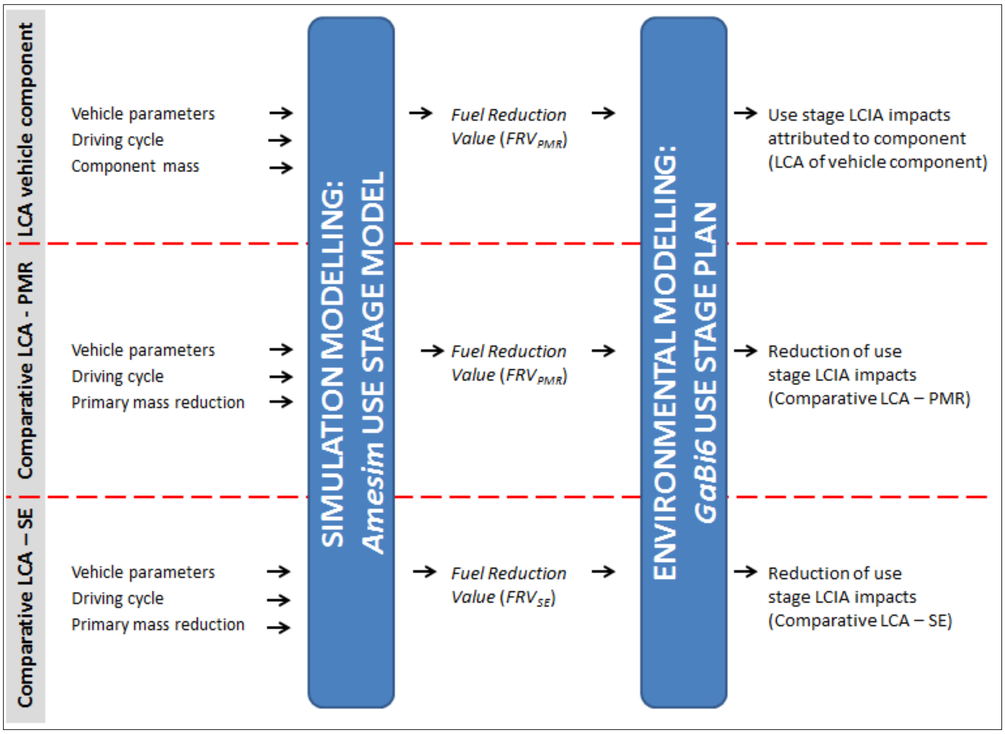


Figure 3.9. Structure and operation method of the tool: interaction between simulation and environmental modelling for the two typologies of LCA study

4. Use stage simulation model

This chapter describes the use stage simulation model including equations, logic and parameters which govern its operation. Parameters setting is reported in paragraph 4.3.

4.1. Simulation environment

The model is running in the AMESim simulation environment. Three different capabilities of the environment are used:

- Data management. The model is interfaced with external sources using AMESim capabilities for data import and export of any kind. An example of imported data is constituted by the diagram of engine torque in function of engine speed: torque and speed are introduced in the model throughout lookup tables;
- System control and functional logic implementation. The capabilities are implemented in AMESim using standard blocks library called “component sub-models”. Each component sub-model is defined by its inputs and outputs;
- Physical models. The model is mainly based on simplified component sub-models. Depending on the needs, physical components have been built using standard AMESim blocks which define component equations in explicit, causal form.

4.2. Description of the model

The model considers as much as possible all the elements which influence car FC in real driving conditions. The automotive network is modeled by two sections; each section is composed by sub-models which in turn are constituted by component sub-models. Model sections, sub-models and component sub-models are summarized in Table 4.1.:

Use stage simulation model		
Model section	**Sub-model**	**Component sub-model**
Drive train	ENGINE	Engine
	CLUTCH	Rotary load (Engine)
		Rotary Coulomb friction
		Rotary load (Gearbox)
	GEARBOX	Gearbox
	VEHICLE DYNAMICS	Vehicle dynamics
Control logic	MISSION PROFILE & AMBIENT DATA	Mission profile & Ambient data
	DRIVER	Driver
	CONTROL UNIT	Control unit

Table 4.1. Sections, sub-models and component sub-models of the use stage simulation model

Following paragraphs report a detailed description of the logic and equations which govern model operation; the description is performed separately for each one of component sub-models.

4.2.1. Drive train section

The drive train section is composed by the following sub-models: ENGINE, CLUTCH, GEARBOX and VEHICLE DYNAMICS. Figure 4.1. reports a scheme of sub-models and component sub-models which constitute the drive train section.

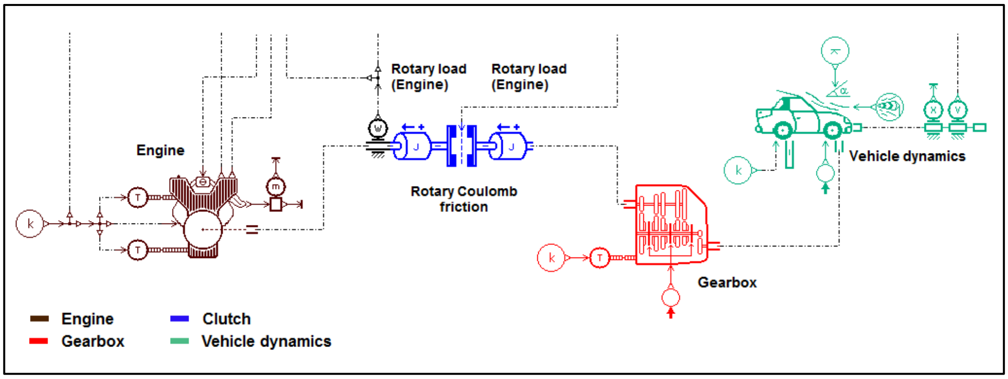


Figure 4.1. Sub-models and component sub-models of the Drive train section

ENGINE sub-model

ENGINE sub-model is constituted by the only **Engine component sub-model** which models an internal combustion engine at hot start. Moment by moment the component sub-model calculates the torque needed to follow the velocity profile imposed by the driving cycle. The instantaneous FC is computed by an energy modelling of efficiency at different engine speeds. Table 4.2. reports inputs and outputs of Engine component sub-model including component sub-models of origin and destination.

***Engine* component sub-model**					
Input			**Output**		
Parameter	**Unit**	**Origin**	**Parameter**	**Unit**	**Destination**
Effective Load control signal (sig_{L_eff})	null	Control unit	*Effective Engine torque (t_{E_eff})*	Nm	Rotary load (Engine)
Engine speed (ω_E)	rpm	Rotary load (Engine)			

Table 4.2. Input and output parameters which characterize *Engine* component sub-model

Following equations govern the operation of Engine component sub-model (equations referring to output parameters are highlighted by bold type).

$$\boldsymbol{t_{E\_eff} = t_E\,(sig_{L_{eff}})} \qquad \text{Eq. 4.1.}$$

$$BMEP = \frac{4\Pi * t_{E\_eff}}{100 * V} \qquad \text{Eq. 4.2.}$$

$$P_E = \frac{t_{E_{eff}} * \omega_E * 2\pi}{60000} \qquad \text{Eq. 4.3.}$$

$$df = \frac{cons * P_E}{3600} \qquad \text{Eq. 4.4.}$$

$$df_{idle} = \frac{cons_{idle}}{3600} \qquad \text{Eq. 4.5.}$$

$$FC = \frac{\int df * dt}{100 * \rho_{fuel} * km_{DC}} \qquad \text{Eq. 4.6.}$$

Where:
BMEP = Brake Mean Effective Pressure [bar];
t_E = Engine torque [Nm];
t_{E_eff} = effective Engine torque [Nm];
sig_{L_eff} = effective Load control signal [null];
ω_E = Engine speed [rpm];
V = engine displacement [l];
P_E = effective Engine Power [kW];
df = fuel mass flow rate [g/s];
df_{idle} = fuel mass flow rate [g/s];
$cons$ = specific fuel consumption [g/kWh];
$cons_{idle}$ = idle fuel consumption [g/h];
FC = per-100 kilometres Fuel Consumption [l/100km];
ρ_{fuel} = fuel density [kg/m^3];
km_{DC} = mileage of Driving Cycle [km].

In order to solve model equations and characterize operation of Engine component sub-model, parameters reported in Table 4.3. have to be set.

Parameter settings for *Engine* component sub-model			
Parameter	**Unit**	**Parameter**	**Unit**
Engine displacement (V)	l	*Idle FC ($cons_{idle}$)*	g/h
Engine torque (t_E)	Nm	*Specific FC (cons)*	g/kWh
Fuel density (ρ_{fuel})	kg/m^3		
Idle engine speed (ω_{idle})	rpm		

Table 4.3. Parameters setting for *Engine* component sub-model

It has to be noted that both *Engine torque* (t_E) and *specific FC* (*cons*) are set through lookup tables. t_E is given in function of *Engine speed* (ω_E) through a 2D lookup table (torque-rpm). Two (t_E - ω_E) lookup tables are provided: one referring to maximum engine load (sig_{L_eff} = 1) representing driving torque (t_{E_dr}) and one referring to minimum engine load (sig_{L_eff} = -0.1) representing resistive torque (t_{E_res}). *Specific FC* (*cons*) is set through a 3D lookup table (rpm-BMEP-specific FC) in which it is provided in function of *Brake Mean Effective Pressure* (*BMEP*) at discrete values of *Engine speed* (ω_E).

CLUTCH sub-model

CLUTCH sub-model is modelled by the following component sub-models: Rotary load (Engine), Rotary Coulomb friction, Rotary load (Gearbox). The friction is modelled as Coulomb friction only; the rotary loads simulate respectively engine and gearbox inertias.

Rotary load (Engine) component sub-model models the engine inertia; Table 4.4. reports inputs and outputs including component sub-models of origin and destination.

***Rotary load (Engine)* component sub-model**					
Input			**Output**		
Parameter	**Unit**	**Origin**	**Parameter**	**Unit**	**Destination**
Clutch Cover torque (t_{CC})	Nm	Rotary Coulomb friction	*Clutch Cover speed (ω_{CC})*	rpm	Rotary Coulomb friction
Effective Engine torque (t_{E_eff})	Nm	Engine	*Engine speed (ω_E)*	rpm	Control unit Driver Engine

Table 4.4. Inputs and outputs which characterize *Rotary load (Engine)* component sub-model

The equations that govern operation of Rotary load (Engine) component sub-model are reported below (equations referring to output parameters are highlighted by bold type):

$$\dot{\omega} = \frac{t_{CC} - t_{E\_eff}}{I_E} \qquad \text{Eq. 4.7.}$$

$$\boldsymbol{\omega_{CC} = \omega_{CC}\,(t_0) + 60/2\Pi \int_{to}^{t} \dot{\omega} * dt} \qquad \text{Eq. 4.8.}$$

$$\boldsymbol{\omega_{E} = \omega_{E}\,(t_0) + 60/2\Pi \int_{to}^{t} \dot{\omega} * dt} \qquad \text{Eq. 4.9.}$$

Where:

$\dot{\omega}$ = angular acceleration [rad/s^2];
I_E = Engine Inertia [kg*m^2];
ω_{CC} (t_0) = Clutch Cover speed at time $t = t_0$ [rpm];
ω_E (t_0) = Engine speed at time $t = t_0$ [rpm].

In order to solve model equations, *Engine inertia* (I_E) has to be set.

Rotary Coulomb friction component sub-model models rotary friction between two rotating bodies with a common axis of rotation; Table 4.5. reports inputs and outputs including component sub-models of origin and destination.

***Rotary Coulomb friction* component sub-model**					
Input			**Output**		
Parameter	**Unit of measure**	**Origin**	**Parameter**	**Unit of measure**	**Destination**
Clutch control signal (sig_C)	null	Driver	*Clutch Cover torque (t_{CC})*	Nm	Rotary load (Engine)
Clutch Cover speed (ω_{CC})	rpm	Rotary load (Engine)	*Clutch Disc torque (t_{CD})*	Nm	Rotary load (Gearbox)
Clutch Disc speed (ω_{CD})	rpm	Rotary load (Gearbox)			

Table 4.5. Inputs and outputs which characterize *Rotary Coulomb friction* component sub-model

Following equations govern operation of Rotary Coulomb friction component sub-model (equations referring to output parameters are highlighted by bold type):

$$t_{C\_fr} = t_C * tanh\ (\ 2 * \frac{\omega_{C\_rel}}{\omega_{C\_thr}}\ ) \qquad \text{Eq. 4.10.}$$

$$t_C = t_{C\_max} * sig_C \qquad \text{Eq. 4.11.}$$

$$\omega_{C\_rel} = \omega_{CD} - \omega_{CC} \qquad \text{Eq. 4.12.}$$

$$\boldsymbol{t_{C\_fr} = t_{CC} = t_{CD}} \qquad \text{Eq. 4.13.}$$

Where:
t_{C_fr} = Clutch friction torque developed at the contact [Nm];
t_C = Coulomb friction torque of the Clutch [Nm];
t_{C_max} = maximum Coulomb friction torque of the Clutch [Nm];
ω_{C_rel} = relative speed between cover and disc of the Clutch [rpm];
ω_{C_thr} = rotary speed threshold (Clutch) [rpm].

In order to solve model equations, *maximum Coulomb friction torque of the Clutch* (t_{C_max}) and *rotary speed threshold (Clutch)* (ω_{C_thr}) have to be set.

Rotary load (Gearbox) component sub-model models gearbox inertia; Table 4.6. reports inputs and outputs including component sub-models of origin and destination.

***Rotary load (Gearbox)* component sub-model**					
Input			**Output**		
Parameters	**Unit of measure**	**Origin**	**Parameters**	**Unit of measure**	**Destination**
Clutch Disc torque (t_{CD})	Nm	Rotary Coulomb friction	*Clutch Disc speed* (ω_{CD})	rpm	Rotary Coulomb friction
Gearbox Primary shaft torque (t_{GP})	Nm	Gearbox	*Gearbox Primary shaft speed* (ω_{GP})	rpm	Gearbox

Table 4.6. Inputs and outputs which characterize *Rotary load (Gearbox)* component sub-model

Following equations govern operation of Rotary load (Gearbox) sub-model (equations referring to output parameters are highlighted by bold type):

$$\dot{\omega} = \frac{t_{GP} - t_{CD}}{I_G} \qquad \text{Eq. 4.14.}$$

$$\boldsymbol{\omega_{GP} = \omega_{GP}(t_0) + 2\Pi \int_{to}^{t} \dot{\omega} * dt} \qquad \text{Eq. 4.15.}$$

$$\boldsymbol{\omega_{CD} = \omega_{CD}(t_0) + 2\Pi \int_{to}^{t} \dot{\omega} * dt} \qquad \text{Eq. 4.16.}$$

Where:
$\dot{\omega}$ = angular acceleration [rad/s^2];
I_G = Gearbox Inertia [kg*m^2];
$\omega_{GP}(t_0)$ = Gearbox Primary shaft speed at time $t = t_0$ [rpm];
$\omega_{CD}(t_0)$ = Clutch Disc speed at time $t = t_0$ [rpm].

In order to solve model equations, *Gearbox inertia* (I_G) has to be set.

GEARBOX sub-model

GEARBOX sub-model is composed by the only **Gearbox component sub-model** which models a n-ratio manual gearbox; Table 4.7. reports inputs and outputs including component sub-models of origin and destination.

***Gearbox* component sub-model**					
Input			**Output**		
Parameter	**Unit**	**Origin**	**Parameter**	**Unit**	**Destination**
Gearbox Primary shaft speed (ω_{GP})	rpm	Rotary load (Gearbox)	*Gearbox Primary shaft torque* (t_{GP})	Nm	Rotary load (Gearbox)
Wheel rotary speed (ω_w)	rpm	Vehicle dynamics	*Driving torque* (t_{dr})	Nm	Vehicle dynamics
Gearbox control signal (sig_G)	null	Driver			

Table 4.7. Inputs and outputs which characterise *Gearbox* component sub-model

Following equations govern operation of Gearbox component sub-model (equations referring to output parameters are highlighted by bold type):

$$\boldsymbol{t_{GP}} = \frac{-\,\boldsymbol{t_{GS}}}{\boldsymbol{\eta_{G,i}} * \boldsymbol{\alpha_{G,i}}} \qquad \text{Eq. 4.17.}$$

$$t_{GS} = t_{GS\_max} * tanh\left(2 * \frac{\omega_{G\_rel}}{\omega_{S\_thr}}\right) \qquad \text{Eq. 4.18.}$$

$$\omega_{G\_rel} = -\frac{\omega_{GP}}{\alpha_{G,i}} + \omega_{GS} \qquad \text{Eq. 4.19.}$$

$$\omega_{GS} = -\,\omega_{w} * \alpha_{f} \qquad \text{Eq. 4.20.}$$

$$\boldsymbol{t_{dr}} = -\,\boldsymbol{\alpha_{f}} * \boldsymbol{t_{GS}} * \boldsymbol{\eta_{f}} \qquad \text{Eq. 4.21.}$$

Where:
t_{GS} = Gearbox Secondary shaft torque [Nm];
$\alpha_{G,i}$ = transmission ratio of Gear *i* [null];
$\eta_{G,i}$ = efficiency of Gear *i* [null];
t_{GS_max} = maximum Coulomb friction torque on Gearbox Secondary shaft [Nm];
ω_{G_rel} = relative speed between Gearbox primary and secondary shafts [rpm];
ω_{S_thr} = rotary speed threshold (Synchronizer) [rpm];
ω_{GS} = Gearbox Secondary shaft speed [rpm];
α_{f} = final transmission ratio [null];
η_{f} = efficiency of final transmission [null].

In order to solve model equations, vehicle sub-model parameters reported in Table 4.8. have to be set.

Parameter settings for *Gearbox* component sub-model			
Parameter	**Unit**	**Parameter**	**Unit**
Maximum Coulomb friction torque on Gearbox Secondary shaft (t_{GS_max})	Nm	*Efficiency of final transmission (η_f)*	null
Number of gear ratios (n°_{ratios})	null	*Efficiency of Gear i ($\eta_{G,i}$)*	null
Rotary speed threshold (synchronizer) (ω_{G_thr})	rpm	*Final transmission ratio (α_f)*	null
Transmission ratio of Gear i ($\alpha_{G,i}$)	null		

Table 4.8. Parameters setting for *Gearbox* component sub-model

VEHICLE DYNAMICS sub-model

VEHICLE DYNAMICS sub-model is composed by the only **Vehicle dynamics component sub-model** which models a simple vehicle load without longitudinal slip between tyre and ground. The vehicle is considered as a single translational mass; the distinction between sprung and non-sprung masses, lateral dynamics and load variation between front and rear axles are not considered. The sub-model calculates moment by moment car linear displacement, velocity and acceleration. Table 4.9. reports inputs and outputs of Vehicle dynamic including component sub-models of origin and destination.

***Vehicle dynamics* component sub-model**					
Input			**Output**		
Parameters	**Unit**	**Origin**	**Parameters**	**Unit**	**Destination**
Braking control signal (sig_B)	null	Driver	*Vehicle linear velocity (V_{veh})*	m/s	Driver
Driving torque (t_{dr})	Nm	Gearbox	*Wheel rotary speed (ω_w)*	rpm	Gearbox
Road slope (β_{road})	%	MP & AD			

Table 4.9. Inputs and outputs which characterise *Vehicle dynamic* component sub-model

Following equations govern operation of Vehicle dynamics component sub-model (equations referring to output parameters are highlighted by bold type).

$$A_{veh} = \frac{(F_{dr} - (F_{br} + F_{res}))}{m_{veh\_corr}}$$ Eq. 4.22.

$$\boldsymbol{V_{veh} = V_{veh}(t_0) + \int_{to}^{t} A_{veh} * dt}$$ Eq. 4.23.

$$\boldsymbol{\omega_w = \frac{60\, V_{veh}}{2\, \Pi\, R_w}}$$ Eq. 4.24.

$$F_{dr} = \frac{t_{dr}}{R_w}$$ Eq. 4.25.

$$R_w = 0.5 * D_{rim} * 0.0254 + \frac{0.01 * H_{tyre} * W_{tyre}}{1000}$$ Eq. 4.26.

$$F_{br} = \frac{t_{br}}{R_w}$$ Eq. 4.27.

$$t_{br} = t_{br\_dyn} * \tanh \frac{2\omega_w}{\omega_{w\_thr}}$$ Eq. 4.28.

$$t_{br\_dyn} = t_{br\_max} * sig_B$$ Eq. 4.29.

$$F_{res} = F_{cl} + F_{aero} + F_{roll}$$ Eq. 4.30.

$$F_{cl} = m_{veh} * 9.81 * \sin(\arctan(\beta_{road}))$$ Eq. 4.31.

$$F_{aero} = 0.5 * \rho_a * C_D * A_D * {V_{veh}}^2$$ Eq. 4.32.

$$F_{roll} = m_{veh} * 9.81 * (f_S + f_D * V_{veh})$$ Eq. 4.33.

$$m_{veh\_corr} = m_{veh} + 4\frac{I_w}{{R_w}^2}$$ Eq. 4.34.

Where:
F_{dr} = driving Force applied to the vehicle [N];
F_{br} = braking Force applied to the vehicle [N];

F_{res} = resistive Force applied to the vehicle [N];
m_{veh_corr} = corrected vehicle mass [kg];
R_w = wheel Radius [m];
D_{rim} = wheel rim Diameter [in];
H_{tyre} = tyre Height [%];
W_{tyre} = tyre Width [mm];
t_{br} = braking torque [Nm];
t_{br_dyn} = dynamic braking torque [Nm];
t_{br_max} = maximum braking torque; [Nm];
F_{cl} = climbing resistance Force [N];
F_{aero} = aerodynamic drag Force [N];
F_{roll} = rolling friction Force [N];
m_{veh} = vehicle mass [kg];
ρ_a = air density [kg/m^3];
C_D = aerodynamic Drag coefficient [null];
A_D = active Area in aerodynamic Drag [m^2];
f_S = Static friction coefficient [null];
f_D = Dynamic friction coefficient [1/(m/s)];
I_w = wheel Inertia [kg*m^2];
ω_{w_thr} = rotary speed threshold (Wheel) [rpm];
$V_{veh}(t_0)$ = vehicle linear Velocity at time $t = t_0$ [m/s].

In order to solve model equations, Vehicle dynamics parameters reported in Table 4.10. have to be set.

Parameter settings for *Vehicle dynamics* component sub-model			
Parameter	**Unit**	**Parameter**	**Unit**
Active area in aerodynamic Drag (A_D)	m^2	*Tyre height (H_{tyre})*	kg*m^2
Aerodynamic Drag coefficient (C_D)	null	*Tyre width (W_{tyre})*	%
Static friction coefficient (f_S)	null	*Dynamic friction coefficient (f_D)*	1/(m/s)
Maximum braking torque (t_{br_max})	Nm	*Wheel inertia (I_w)*	kg*m^2
Rotary speed threshold (Wheel) (ω_{w_thr})	rpm	*Wheel rim diameter (D_{rim})*	in
Total vehicle mass (m_{veh})	kg		

Table 4.10. Parameters setting for *Vehicle dynamics* component sub-model

4.2.2. Control logic section

The control logic section is composed by the following component sub-models: MISSION PROFILE & AMBIENT DATA, DRIVER and CONTROL UNIT. Figure 4.2. reports a scheme of sub-models and component sub-models which constitute the control logic section.

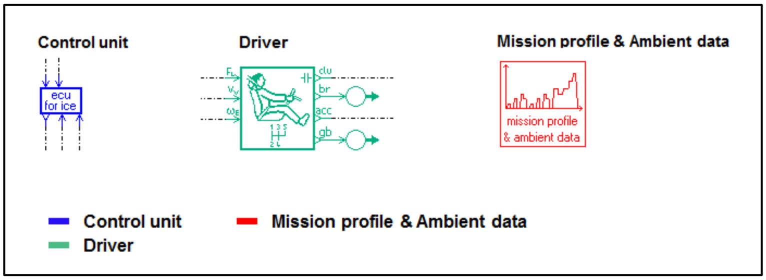


Figure 4.2. Sub-models and component sub-models of the Control logic section

MISSION PROFILE & AMBIENT DATA sub-model

MISSION PROFILE & AMBIENT DATA sub-model is composed by the only **Mission profile & Ambient data component sub-model.** Mission profile is specified in terms of vehicle linear velocity and ambient conditions; these data are implemented as internal parameters within the Engine and Driver component sub-models. Mission profile & Ambient data parameters reported in Table 4.11. have to be set.

Parameter settings for *Mission profile & Ambient data* component sub-model	
Parameter	**Unit**
Ambient temperature (T_a)	°C
Air density (ρ_a)	kg/m^3
Mission Profile Vehicle linear velocity (V_{MP})	m/s
Road slope (β_{road})	%

Table 4.11. Parameters setting for *Mission profile* component sub-model

It has to be noted that *Mission Profile Vehicle linear velocity* (V_{MP}) is set through a 2D lookup table as function of time (velocity-time).

DRIVER sub-model

DRIVER sub-model is composed by the only **Driver component sub-model** which performs several controls: acceleration, braking, clutch engagement and gearbox ratio. Table 4.12. reports inputs and outputs of Driver including component sub-models of origin and destination.

***Driver* component sub-model**					
Input			**Output**		
Parameter	**Unit**	**Origin**	**Parameter**	**Unit**	**Destination**
Vehicle linear velocity (V_{veh})	m/s	Vehicle dynamics	*Gearbox control signal* (sig_G , sig_{G_PA})	null	Gearbox
Engine speed (ω_E)	rpm	Rotary load (Engine)	*Clutch control signal* (sig_C , sig_{C_PA})	null	Rotary Coulomb friction
			Load control signal (sig_L , sig_{L_PA})	null	Control unit
			Braking control signal (sig_B , sig_{B_PA})	null	Vehicle dynamics

Table 4.12. Inputs and outputs which characterize *Driver* component sub-model

Below the determination of outputs is described for both operation modalities ($V_{veh} > 0$) and ($V_{veh} = 0$).

$V_{veh} > 0$

Gearbox control signal (sig_G) is calculated from *Engine speed* (ω_E), *Downshift Engine speed* (ω_{E_Down}) and *Upshift engine speed* (ω_{E_Up}). When $\omega_E > \omega_{E\_Up}$ the higher gear is selected; when $\omega_E < \omega_{E\_Down}$ the lower gear is selected. It has to be noted that ω_{E_Up} and ω_{E_Down} remain the same for each one of gear ratios. A delay of Δt seconds is forced between two gears:

$$\Delta t = time_{diseng\_C} + time_{eng\_G} + time_{eng\_C} \qquad \text{Eq. 4.35}$$

Where:
$time_{diseng\_C}$ = time for disengaging the Clutch [s];
$time_{eng\_G}$ = time for engaging Gearbox ratio [s];
$time_{eng\_C}$ = time for engaging the Clutch [s].

For vehicle velocity lower than *critical vehicle Velocity* (V_{veh_crit}) the gear ratio is forced at neutral.

Clutch control signal (sig_C) is set by default to 1 (engaged clutch). When a gear shifting is detected, the disengaging phase begins and the clutch control signal passes linearly from 1 to 0 in $time_{diseng\_C}$ seconds. Then the clutch control signal is constant at 0 for $time_{eng\_G}$ seconds (disengaged clutch); during this time period the gear shifting occurs. Lastly in the engaging phase the clutch control signal passes linearly from 0 to 1 in $time_{eng\_C}$ seconds. Figure 4.3. shows clutch control during gear shifting.

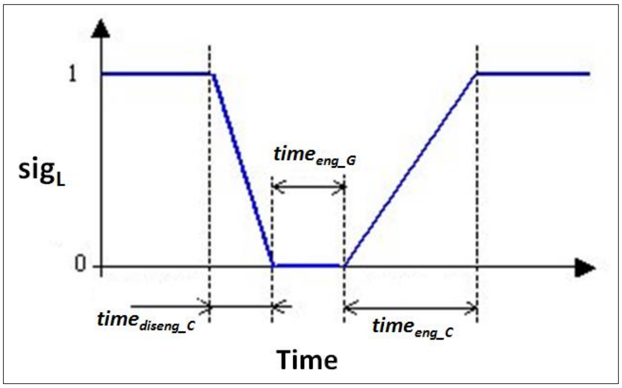


Figure 4.3. Clutch control during gear shifting

Load control signal (sig_L) and *Braking control signal* (sig_B) are determined through the following equations:

$$sig_L = GP_L * err + GI_L * \int err\ dt + GA_L * \left(\frac{V_{MP\ ant} - V_{MP}}{time_{ant}}\right) \quad \text{Eq. 4.36.}$$

$$sig_B = -GP_B * err - GI_B * \int err\ dt - GA_B * \left(\frac{V_{MP\ ant} - V_{MP}}{time_{ant}}\right) \quad \text{Eq. 4.37.}$$

Where:
$err = (V_{MP} - V_{veh})$ [m/s];
GP_L = Proportional Gain for Load control loop [1/(m/s)];
GI_L = Integral Gain for Load control loop [1/m];
GA_L = Anticipative Gain for Load control loop [1/(m/s/s)];
GP_B = Proportional Gain for Braking control loop [1/(m/s)];
GI_B = Integral Gain for Braking control loop [1/m];
GA_B = Anticipative Gain for Braking control loop [1/(m/s/s)];
V_{MP_ant} = Mission Profile vehicle linear Velocity at time (t + $time_{ant}$) [m/s];
$time_{ant}$ = time interval [s].

V_{veh} = 0 (Pull away)

Pull away is detected when *Mission Profile vehicle linear Velocity (V_{MP})* drops to 0. Pull away is composed by eight phases:

1) Clutch disengagement;
2) Clutch disengaged;
3) First gear engaged;
4) Beginning of clutch engagement (increase acceleration);
5) Beginning of clutch engagement (constant acceleration);
6) Clutch synchronization;
7) Final part of clutch synchronization;
8) Final part of clutch engagement.

The determination of *gearbox, clutch and load control signals during pull away* ($sig_{G\ PA}$, $sig_{C\ PA}$, $sig_{L\ PA}$) is graphically illustrated in Figure 4.4. and Table 4.13. for each phase.

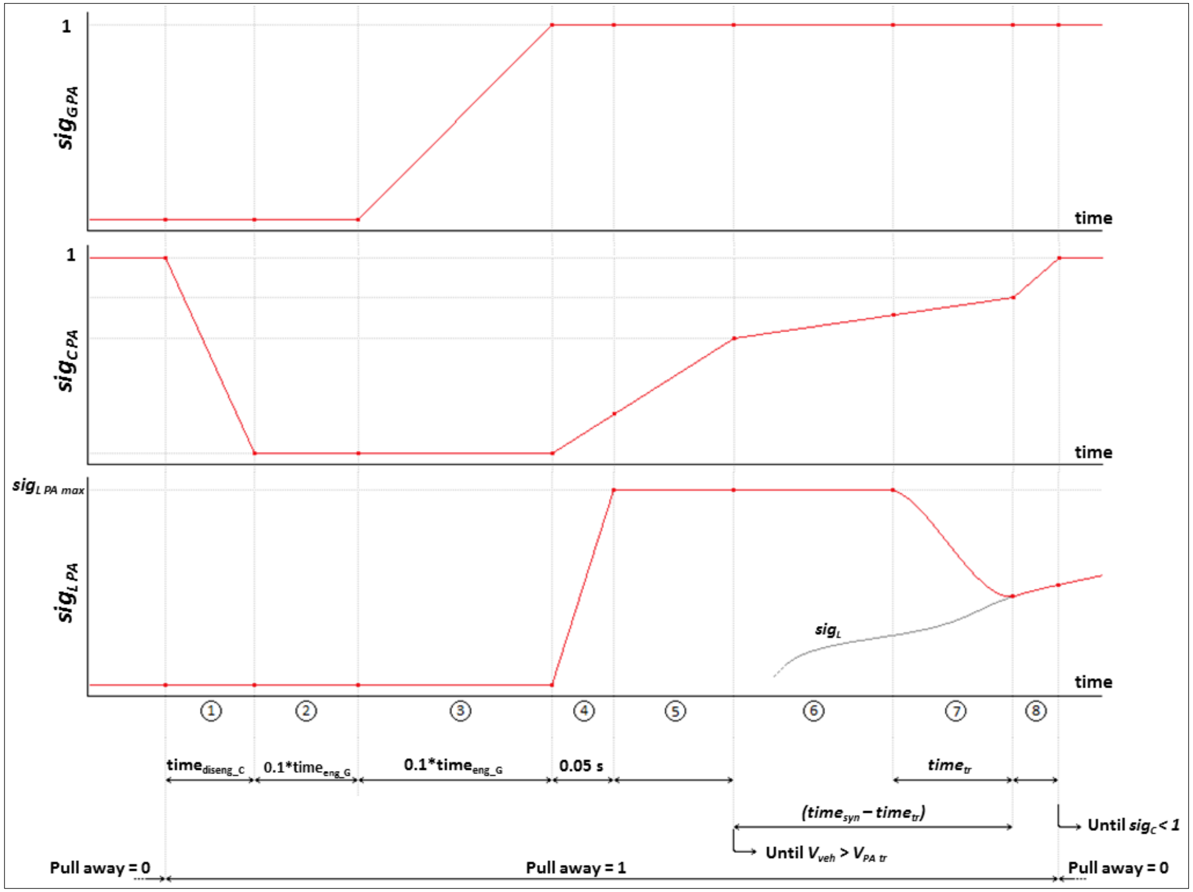


Figure 4.4. Gearbox, clutch and load control signals during each phase of pull away in function of time

		Pull away phases							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
		Clutch disengagement	**Clutch disengaged**	**First gear engaged**	**Beginning of clutch engagement (incr. acc)**	**Beginning of clutch engagement (cons. acc.)**	**Clutch synchronisation**	**Final part of clutch synchronisation**	**Final part of clutch engagement**
	Phase duration	$time_{diseng\_C}$	$0.1*time_{eng\_G}$	$0.9*time_{eng\_G}$	0.05 s	Until $V_{veh} > V_{PA\_tr}$	$(time_{syn} – time_{tr})$	$time_{tr}$	Until $sig_C < 1$
Control signals	**Gearbox**	No gear engaged	No gear engaged	Linear increase from 0 to 1	First gear engaged	First gear engaged	First gear engaged	First gear engaged	First gear engaged
	Clutch	Linear drop from 0 to 1	Set to 0	Set to 0	Linear increase ($slope = 0.1*A_{MP\_2s}$)	Linear increase ($slope = 0.1*A_{MP\_2s}$)	Linear increase ($slope = 0.1*G_{syn}$)	Linear increase ($slope = 0.1* G_{syn}$)	Linear increase ($slope =5$)
	Load	Set to 0	Set to 0	Set to 0	Linear increase from 0 to $sig_{L\_PA\_max}$	$sig_{L\_PA\_max}$	$sig_{L\_PA\_max}$	Weighted average between $sig_{L\_PA\_max}$ and sig_L	$sig_{L\_PA} = sig_L$

Table 4.13. Parameters which characterize pull away phases and control signals

Where:
V_{PA_tr} = treshold vehicle Velocity for clutch Pull Away;
$time_{syn}$ = time duration for clutch synchronization;
$time_{tr}$ = time duration for acceleration transition;
A_{MP_2s} = Mission Profile vehicle Acceleration after 2 seconds from the beginning of pull away;
G_{syn} = Gain for synchronization during pull away;
$sig_{L\_PA\_max}$ = maximum value for Load control signal during Pull Away.

In order to determine Driver control signals, parameters reported in Table 4.14. have to be set.

Parameter settings for *Driver* component sub-model							
Parameter	**Unit**	**Parameter**	**Unit**	**Parameter**	**Unit**	**Parameter**	**Unit**
Downshift Engine speed (ω_{E_Down})	rpm	*Anticipative Gain for Load control loop* (GA_L)	1/(m/s/s)	*Time for disengaging the Clutch* $(time_{diseng\_C})$	s	*Time duration for acceleration transition* $(time_{tr})$	s
Upshift Engine speed (ω_{E_Up})	rpm	*Proportional Gain for Braking control loop* (GP_B)	1/(m/s)	*Time for engaging Gearbox ratio* $(time_{eng\_G})$	s	*Gain for synchronization during pull away* (G_{syn})	null
Critical vehicle Velocity (V_{veh_crit})	m/s	*Integral Gain for Braking control loop* (GI_B)	1/m	*Time for engaging the Clutch* $(time_{eng\_C})$	s	*Maximum value for Load control signal during Pull Away* $(sig_{L\_PA\_max})$	null
Proportional Gain for Load control loop (GP_L)	1/(m/s)	*Anticipative Gain for Braking control loop* (GA_B)	1/(m/s/s)	*Treshold vehicle velocity for clutch Pull Away* (V_{PA_tr})	m/s		
Integral Gain for Load control loop (GI_L)	1/m	*Time interval* $(time_{ant})$	s	*Time duration for clutch synchronization* $(time_{syn})$	s		

Table 4.14. Parameters setting for *Driver* component sub-model

CONTROL UNIT sub-model

CONTROL UNIT sub-model is composed by the only **Control unit component sub-model** which computes the *effective Load control signal* ($sig_{L\ eff}$) and the *controlled idle speed* (ω_{idle}). Table 4.15. reports inputs and outputs of Control unit including component sub-models of origin and destination.

***Control unit* component sub-model**					
Input			**Output**		
Parameter	**Unit**	**Origin**	**Parameter**	**Unit**	**Destination**
Engine speed (ω_E)	rpm	Rotary load (Engine)	*Effective Load control signal* (sig_{L_eff})	null	Engine
Load control signal (sig_L)	null	Driver			

Table 4.15. Inputs and outputs which characterise *Control unit* component sub-model

Based on inputs *Engine speed* (ω_E) and *Load control signal* (sig_L), logic reported in Table 4.16. is adopted in order to determine the *effective Load control signal* ($sig_{L\ eff}$).

	Calculation of effective load control signal ($sig_{L\ eff}$)			
	$\omega_E < \omega_{idle}$	$\omega_{idle} < \omega_E < \omega_{fr}$	$\omega_{fr} < \omega_E < \omega_{max}$	$\omega_{max} < \omega_E$
$sig_L > 0$	Pull away mode: $sig_{L\_eff} = sig_L + G_{idle\_PA} * (\omega_{idle} - \omega_E)$	Driving mode: $sig_{L\_eff} = sig_L$		Maximum speed regulation mode: $sig_{L\ eff} = sig_L - G_{max} * (\omega_E - \omega_{max})$
$sig_L = 0$	Idle speed regulation mode: $sig_{L\_eff} = G_{idle} * (\omega_{idle} - \omega_E)$	Engine braking regulation mode: $sig_{L\ eff} = -0.1 * (\omega_E - \omega_{idle}) / (\omega_{fr} - \omega_{idle})$	Max engine braking mode: $sig_{L\_eff} = -0.1$	

Table 4.16. Logic of control unit for calculation of *effective Load control signal* ($sig_{L\ eff}$)

Below acronyms in Table 4.16. are reported in extenso:

ω_{fr} = fuel resume mode speed [rpm];
ω_{max} = maximum engine speed [rpm];
G_{idle} = Gain for idle speed regulation [null];
G_{idle_PA} = Gain for idle speed regulation during Pull Away [null];
G_{max} = Gain for maximum speed regulation [null].

In order to determine *effective Load control signal* (sig_{L_eff}), parameters reported in Table 4.17. have to be set.

Parameter settings for *Control unit* component sub-model	
Parameter	**Unit**
Fuel resume mode engine speed (ω_{fr})	rpm
Gain for idle engine speed regulation (G_{idle})	null
Gain for idle engine speed regulation during pull away (G_{idle_PA})	null
Gain for maximum engine speed regulation (G_{max})	null
Maximum engine speed (ω_{max})	rpm

Table 4.17. Parameters setting for *Control unit* component sub-model

4.3. Mass-configurations and parameters setting

As shown in chapter 3, the FRV is determined as the slope of the regression line of FC in function of mass for a wide range of vehicle case studies. Within each case study the calculation of FC is performed for

- one reference mass-configuration;
- four lightweight mass-configurations with PMR only;
- four lightweight mass-configurations with implementation of SE.

Overall, considering both GT and DT case studies the research involves:

- 64 reference mass-configurations (*Reference mass-configurations*);
- 256 lightweight mass-configurations with PMR only (*PMR mass-configurations*);
- 256 lightweight mass-configurations with implementation of SE (*SE mass-configurations*).

Following paragraphs describe the setting of model parameters; the three typologies of mass-configuration defined above are treated separately.

4.3.1. Reference mass-configurations

Model parameters which characterize the reference mass-configurations are subdivided into two groups:

- Fixed model parameters: parameters which assume the same value for all vehicle case studies;
- Variable model parameters: parameters which change value passing from a vehicle case study to another.

Following paragraphs list both fixed and variable model parameters, describe the logic adopted for their quantification and report the numerical values for each case study.

4.3.1.1. Fixed model parameters

Fixed model parameters are listed in the following tables subdivided between sub-models and component sub-models: Table 4.18. refers to Drive train section while Table 4.19. to Control logic section.

	Sub-model	Component sub-model	Reference mass-configurations - Fixed model parameters
DRIVE TRAIN	**ENGINE**	**Engine**	*Fuel density* (ρ_{fuel})
			Idle engine speed (ω_{idle})
	CLUTCH	**Rotary Coulomb friction**	*Maximum Coulomb friction torque of Clutch* (t_{C_max})
			Rotary speed threshold (Clutch) (ω_{C_thr})
		Rotary load (Gearbox)	*Gearbox Inertia* (I_G)
	GEARBOX	**Gearbox**	*Maximum Coulomb friction torque on Gearbox Secondary shaft* (t_{GS_max})
			Rotary speed threshold (Synchronizer) (ω_{S_thr})
			Threshold speed between Gearbox primary and secondary shafts (ω_{G_thr})
			Efficiency of gear i ($\eta_{G,i}$)
			Efficiency of final transmission (η_f)
	VEHICLE DYNAMICS	**Vehicle dynamics**	*Maximum braking torque* (t_{br_max})
			Static friction coefficient (f_s)
			Dynamic friction coefficient (f_D)
			Rotary speed threshold (Wheel) (ω_{W_thr})

Table 4.18. Reference mass-configurations - Fixed model parameters (Drive train section)

			Reference mass-configuration - Fixed model parameters
CONTROL LOGIC	**MISSION PROFILE & AMBIENT DATA**	**Mission profile & Ambient data**	*Mission Profile vehicle linear velocity* (V_{MP})
			Road slope (β_{road})
			Ambient temperature (T_a)
			Air density (ρ_a)
	DRIVER	**Driver**	*Critical vehicle Velocity* (V_{veh_crit})
			Proportional Gain for Load control loop (GP_L)
			Integral Gain for Load control loop (GI_L)
			Anticipative Gain for Load control loop (GA_L)
			Proportional Gain for Braking control loop (GP_B)
			Integral Gain for Braking control loop (GI_B)
			Anticipative Gain for Braking control loop (GA_B)
			Time interval ($time_{ant}$)
			Time for disengaging the Clutch ($time_{diseng\_C}$)
			Time for engaging Gearbox ratio ($time_{eng\_G}$)
			Time for engaging the Clutch ($time_{eng\_C}$)
			Threshold vehicle Velocity for clutch Pull Away (V_{PA_tr})
			Time duration for clutch synchronisation ($time_{syn}$)
			Time duration for acceleration transition ($time_{tr}$)
			Gain for synchronisation during pull away (G_{syn})
			Maximum value for Load control signal during Pull Away ($sig_{L\_PA\_max}$)
	CONTROL UNIT	**Control unit**	*Fuel resume mode speed* (ω_{fr})
			Maximum engine speed (ω_{max})
			Gain for idle speed regulation (G_{idle})
			Gain for idle speed regulation during Pull Away (G_{idle_PA})
			Gain for maximum speed regulation (G_{max})

Table 4.19. Reference mass-configurations - Fixed model parameters (Control logic section)

Tables SI4.2.1. and SI4.2.2. in SI appendix-chapter 4 report the numerical value assigned to fixed model parameters for both GT and DT case studies.

4.3.1.2. Variable model parameters

Variable model parameters are reported in Table 4.20. subdivided between sub-model components.

	Reference mass-configuration - Variable model parameters				
	Vehicle dynamics	**Engine**	**Gearbox**	**Driver**	**Rotary load (Engine)**
Variable model parameters	*Vehicle mass* (m_{veh})	*Engine displacement (V)*	*Number of gear ratios* ($n°_{ratios}$)	*Downshift engine speed* (ω_{Down})	*Engine Inertia* (I_E)
	Tyre Height (H_{tyre})	*Driving Engine torque* (t_{E_dr})	*Transmission ratio of Gear i* ($\alpha_{G,i}$)	*Upshift engine speed* (ω_{Up})	
	Tyre Width (W_{tyre})	*Resistive Engine torque* (t_{E_res})	*Final transmission ratio* (α_f)		
	Wheel rim Diameter (D_{rim})	*Specific FC (cons)*			
	Wheel Inertia (I_w)	*Idle FC* ($cons_{idle}$)			
	Aerodynamic Drag Coefficient (C_D)				
	Active Area in aerodynamic Drag (A_D)				

Table 4.20. Reference mass-configurations - Variable model parameters

As said above, variable model parameters change passing from a vehicle case study to another: for each case study the quantification of variable parameters is based on a specific vehicle model taken from the 2015 European car market. Tables 4.21. and 4.22. report car models chosen as reference for the considered case studies respectively for GT and DT case studies.

Reference mass-configurations - Variable model parameters: reference car models (GT)					
A/B-class		**C-class**		**D-class**	
Case study	**Vehicle model**	**Case study**	**Vehicle model**	**Case study**	**Vehicle model**
1	*A. ROMEO Mito 0.9 TA T 105cv*	*11*	*A. R. Giulietta 1.4 TB 105cv*	*22*	*AUDI A4 1.8 TFSI 120cv*
2	*AUDI A1 1.0 TFSI 95cv*	*12*	*A. R. Giulietta 1.4 TB 170cv*	*23*	*AUDI A4 1.8 TFSI 170cv*
3	*AUDI A1 1.4 TFSI 125cv*	*13*	*AUDI A3 1.2 TFSI 110cv*	*24*	*BMW 318i 134cv*
4	*AUDI A1 1.4 TFSI 150cv*	*14*	*AUDI A3 1.4 TFSI 150cv*	*25*	*BMW 320i 181cv*
5	*DACIA Sandero Tce Eco2 90cv*	*15*	*AUDI A3 1.8 TFSI 180cv*	*26*	*CITROEN C5 1.6 THP 155cv*
6	*FIAT Panda TA T 85cv*	*16*	*FIAT Bravo 1.4 T-jet 120cv*	*27*	*FORD Mondeo 1.0 EB 125cv*
7	*FIAT Punto TA T 85cv*	*17*	*FIAT Bravo 1.4 T-jet 140cv*	*28*	*FORD Mondeo 1.5 EB 160cv*
8	*FIAT Punto T-jet MA 135cv*	*18*	*FORD Focus 1.0 EB 100cv*	*29*	*FORD Mondeo 2.0 EB 203cv*
9	*FORD Fiesta 1.0 EB 100cv*	*19*	*FORD Focus 1.0 EB 125cv*	*30*	*FORD Mondeo 2.0 EB 240cv*
10	*FORD Fiesta 1.0 EB 125cv*	*20*	*FORD Focus 1.5 EB 150cv*	*31*	*MERCEDES C 180 154cv*
		21	*FORD Focus 1.5 EB 182 cv*	*32*	*MERCEDES C 180 181cv*

Table 4.21. Reference mass-configurations – Variable model parameters: car models chosen as reference (GT case studies)

Reference mass-configurations - Variable model parameters: reference car models (DT)					
A/B-class		**C-class**		**D-class**	
Case study	**Vehicle model**	**Case study**	**Vehicle model**	**Case study**	**Vehicle model**
1	*A. R. MiTo 1.6 JTDm 120cv*	*11*	*A. R. Giulietta 1.6 JTDm 105cv*	*23*	*BMW 318d 2.0 150cv*
2	*CITROEN C3 1.4 HDi 70cv*	*12*	*A. R. Giulietta 2.0 JTDm 150cv*	*24*	*BMW 320d 2.0 163cv*
3	*CITROEN C3 1.6 HDi 115cv*	*13*	*A. R. Giulietta 2.0 JTDm 175cv*	*25*	*BMW 320d 2.0 190cv*
4	*FIAT Cinquecento 1.3 MJT 95cv*	*14*	*CITROEN C4 1.6 HDi 90cv*	*26*	*BMW 325d 2.0 218cv*
5	*FIAT Panda 1.3 MJT 75cv*	*15*	*CITROEN C4 1.6 HDi 115cv*	*27*	*CITROEN C5 1.6 HDi 115cv*
6	*FIAT Punto 1.3 MJT 75cv*	*16*	*CITROEN C4 2.0 HDi 150cv*	*28*	*CITROEN C5 2.0 HDi 140cv*
7	*FIAT Punto 1.3 MJT 85cv*	*17*	*FIAT Bravo 1.6 MJT 90cv*	*29*	*CITROEN C5 2.0 HDi 165cv*
8	*FIAT Punto 1.3 MJT 95cv*	*18*	*FIAT Bravo 1.6 MJT 120cv*	*30*	*FORD Mondeo 1.6 TDCi 115cv*
9	*FORD Fiesta 1.5 TDCi 75cv*	*19*	*FIAT Bravo 1.6 MJT 165cv*	*31*	*FORD Mondeo 2.0 TDCi 150cv*
10	*FORD Fiesta 1.6 TDCi 95cv*	*20*	*FORD Focus 1.5 TDCi 95 cv*	*32*	*FORD Mondeo 2.0 TDCi 180cv*
		21	*FORD Focus 1.5 TDCi 120cv*		
		22	*FORD Focus 2.0 TDCi 150cv*		

Table 4.22. Reference mass-configurations – Variable model parameters: car models chosen as reference (DT case studies)

It has to be noted that reference car models are selected in order to cover range of mass, engine displacement, engine power and Power-to-Mass Ratio (PMR) representative of the considered vehicle classes. On the other hand the number of case studies within the classes and the choice of the specific car models depend exclusively on the availability in literature of data needed to set the simulation model.

Variable model parameters are subdivided into three groups:

- Model-specific parameters: parameters for which the setting is performed starting from data of reference car models reported in Tables 4.21. and 4.22.;
- Rebuilt parameters: parameters for which the setting is performed starting from data of other car models;
- Operative parameters: parameters which define the operative conditions of the vehicle.

Below the setting of variable parameters is presented separately between the three cited groups.

Model-specific parameters

Model-specific parameters are listed in Table 4.23.:

Model-specific parameters	
Active Area in aerodynamic Drag (A_D)	*Transmission ratio of Gear i* ($\alpha_{G,i}$)
Aerodynamic Drag Coefficient (C_D)	*Tyre Height* (H_{tyre})
Driving Engine torque (t_{E_dr})	*Tyre Width* (W_{tyre})
Engine displacement (V)	*Vehicle mass* (m_{veh})
Final transmission ratio (α_f)	*Wheel Inertia* (I_w)
Number of gear ratios ($n°_{ratios}$)	*Wheel rim Diameter* (D_{rim})

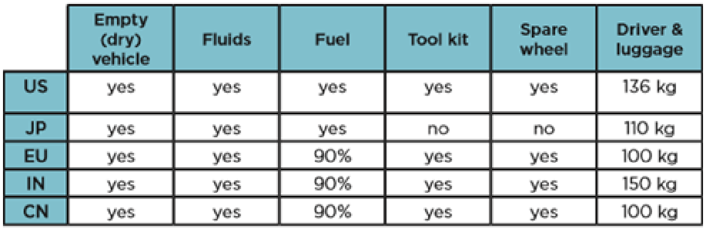
Table 4.23. Model-specific parameters

Below the logic by which model-specific parameters are quantified for the different vehicle case studies is described in detail.

Active Area in aerodynamic Drag **(A_D)*****, aerodynamic Drag Coefficient*** **(C_D)*****, engine displacement*** **(V)*****, final transmission ratio*** **(α_f)*****, number of gear ratios*** **($n°_{ratios}$)*****, driving Engine torque*** **(t_{E_dr})*****, transmission ratio of Gear i*** **(α_{Gi})*****, tyre Height*** **(H_{tyre})*****, tyre Width*** **(W_{tyre})*****, vehicle mass*** **(m_{veh})*****, wheel Inertia*** **(I_w)** and ***wheel rim Diameter*** **(D_{rim})**. For these parameters the setting is performed through the exact value which refers to the reference car models reported in Tables 4.21. and 4.22.; the literature source from which data are from is Automobile-Catalog (2015).

Below an additional note has to be done with respect to model parameters *vehicle mass* (m_{veh}) and *driving Engine torque* (t_{E_dr}) is reported.

Vehicle mass (m_{veh}). A clear reference in order to quantify car mass for simulations has to be identified. In literature many references exist: Table 4.24. reports various definitions of vehicle mass adopted by type test approval procedures all around the world (Mock, 2011).



	Empty (dry) vehicle	Fluids	Fuel	Tool kit	Spare wheel	Driver & luggage
US	yes	yes	yes	yes	yes	136 kg
JP	yes	yes	yes	no	no	110 kg
EU	yes	yes	90%	yes	yes	100 kg
IN	yes	yes	90%	yes	yes	150 kg
CN	yes	yes	90%	yes	yes	100 kg

Table 4.24. Definition of vehicle mass adopted by type test approval procedures all around the world (Mock, 2011)

In the present treatise the US definition is assumed as reference because it is considered to represent more accurately the real car driving conditions. As shown in Table 4.24., the chosen definition takes into account following contributions: empty and dry car, fluids (engine coolant, engine oil, gear oil, AC coolant, liquid for window cleaning, etc), fuel, tool kit, spare wheel, driver and luggage. The starting point for the quantification of m_{veh} is the curb mass of the car (m_{curb}); this latter is available in literature (source: Automobile-Catalog, 2015) for each one of reference car models reported in Tables 4.21. and 4.22.. Considering that m_{curb} includes

- empty and dry car
- fluids (engine coolant, engine oil, gear oil, AC coolant, liquid for window cleaning, etc)
- tool kit
- spare wheel

model parameter *vehicle mass* (m_{veh}) is determined through the following equation:

$$m_{veh} = m_{curb} + (m_{driver\,\&\,luggage} + m_{fuel}) \qquad \text{Eq. 4.38.}$$

Where:
m_{veh} = vehicle mass [kg];
m_{curb} = curb mass of vehicle [kg];
$m_{driver\,\&\,luggage}$ = mass of driver and luggage [kg];
m_{fuel} = mass of fuel [kg].

For the mass of fuel it is assumed full fuel tank:

$$m_{fuel} = tank\ capacity * \rho_{fuel} \qquad \text{Eq. 4.39.}$$

Where:
tank capacity = fuel tank capacity [l];
ρ_{fuel} = fuel density [kg/l].

The capacity of fuel tank is available in literature (source: Automobile-Catalog, 2015) for each one of reference car models reported in Tables 4.21. and 4.22.. *Tank capacity* and m_{curb} are reported respectively in Tables SI4.2.13. - SI4.2.14. and SI4.3.1. - SI4.3.6. of SI appendix-chapter 4 for each one of vehicle case studies.

Driving Engine torque (t_{E_dr}). In order to perform simulations within the AMESim simulation environment, the diagram of engine driving torque is required in the form of 2D lookup table (rpm-torque). This is performed by scanning the torque diagrams of reference car models reported in Tables 4.21. and 4.22. (source: Automobile-Catalog, 2015) through the software “Plot Digitizer”; for the discretization a variable step of acquisition on the rpm-axis is adopted.

Wheel Inertia (I_w). Model parameter I_w is not available in literature for reference car models reported in Tables 4.21. and 4.22.. Therefore the parameter is quantified basing on assumptions which regard number, geometry, dimensions, mass and mass distribution of elements that compose the wheel.

The first assumption consists in the subdivision of the wheel into three components: rim, tyre and brake disk.

The second assumption regards the geometry of the wheel components:

- the rim is assumed to be composed by two parts: a homogeneous solid cylinder reproducing the spokes (spokes cylinder) and a homogeneous hollow cylinder reproducing the external crown (rim crown cylinder);

- the brake disk is assumed as a homogeneous solid cyclinder (brake disk cylinder);
- the tyre is assumed as a homogeneous hollow cylinder.

The third assumption regards the dimensions of the wheel components:

- the diameter of the spokes cylinder and the internal diameter of the rim crown cylinder are both assumed equal to model parameter *wheel rim Diameter* (D_{rim}) lessened than 6 centimetres;
- the external diameter of the rim crown cylinder is assumed equal to model parameter *wheel rim Diameter* (D_{rim});
- the Diameter of the brake disk cylinder (D_{disk}) is assumed as the arithmetic mean of front disk Diameter (D_{disk_front}) and rear disk Diameter (D_{disk_rear}). D_{disk_front} and D_{disk_rear} refer to specific disks which are effectively mounted on reference car models reported in Tables 4.2.1. and 4.2.2. and they are from the Brembo catalog (Brembo, 2015). D_{disk_front} and D_{disk_rear} are reported in Tables 4.2.13. and 4.2.14. of SI appendix-chapter 4 for each one of vehicle case studies;
- the internal diameter of the tyre cylinder is assumed equal to model parameter *wheel rim Diameter* (D_{rim});
- the internal diameter of the tyre cylinder is assumed equal to the *wheel rim Diameter* (D_{rim});
- the external diameter of the tyre cylinder (D_{tyre_ext}) is assumed equal to the diameter of the wheel and it is determined starting from model parameters *wheel rim Diameter* (D_{rim}), *tyre Height* (H_{tyre}) and *tyre Width* (W_{tyre}) through the following equation:

$$D_{tyre\_ext} = D_{rim} * 0.0254 + \frac{0.02 * H_{tyre} * W_{tyre}}{1000} \qquad \text{Eq. 4.40.}$$

Where:
D_{tyre_ext} = external Diameter of tyre cylinder [m];
D_{rim} = wheel rim Diameter [in];
H_{tyre} = tyre Height [%];
W_{tyre} = tyre Width [mm].

The fourth assumption regards the mass of the wheel components:

- the mass of the rim (m_{rim}) is assumed basing on tyre internal diameter: Table 4.25. reports the mass of the rim in function of its diameter. m_{rim} is reported in Tables SI4.2.13. and SI4.2.14. of SI appendix-chapter 4 for each one of vehicle case studies;

Wheel rim diameter (D_{rim}) [in]	Rim mass (m_{rim}) [kg]
13	7.0
14	7.5
15	8.0
16	8.5
17	9.0

Table 4.25. Values assumed for rim mass in function of wheel rim diameter

- the tyres of each vehicle case study are assumed to be of the brand “General Tyre” model “General Altimax RT43”. The choice of the brand depends exclusively on the availability of tyre sizes for the various case studies considered in the research. The assumption to consider a single brand assures that the difference in tyre mass between case studies depends exclusively on tyre dimensions and not on technical features of the specific brand. The parameter *tyre mass* (m_{tyre}) refers to the specific tyres which are effectively mounted on reference car models reported in Tables 4.21. and 4.22. and it is from the Tyre Rack catalog (Tyre Rack, 2015). m_{tyre} is reported in Tables SI4.2.13. and SI4.2.14. of SI appendix-chapter 4 for each one of case studies;
- the mass of the brake disk (m_{disk}) is assumed as the arithmetic mean of masses of front and rear brake disk (m_{disk_rear}, m_{disk_rear}). m_{disk_front} and m_{disk_rear} refer to the specific brake disks which are effectively mounted on reference car models reported in Tables 4.21. and 4.22. and they are from the Brembo catalog (Brembo, 2015). m_{disk_front} and m_{disk_rear} are reported in Tables SI4.2.13. and SI4.2.14. of SI appendix-chapter 4 for each one of vehicle case studies.

The fifth assumption refers to mass distribution of the rim between the spokes disk and the rim crown disk:

- 35% of total rim mass is assumed to be located in the spokes cylinder;
- 65% of total rim mass is assumed to be located in the rim crown cylinder.

Based on assumptions described above, the parameter *wheel Inertia* (I_w) is calculated as the sum of the inertias of rim, brake disk and tyre:

$$I_w = I_{rim} + I_{tyre} + I_{disk} \qquad \text{Eq. 4.41.}$$

$$I_{rim} = I_{rim\_spokes} + I_{rim\_crown} \qquad \text{Eq. 4.42.}$$

$$I_{rim\_spokes} = 0.5 * 0.35 * m_{rim} * \left(\frac{D_{rim} * 0.0254 - 0.06}{2}\right)^2 \qquad \text{Eq. 4.43.}$$

$$I_{rim\_crown} = 0.5 * 0.65 * \ m_{rim} * \left(\left(\frac{D_{rim} * 0.0254 - 0.06}{2}\right)^2 + \left(\frac{D_{rim} * 0.0254}{2}\right)^2\right) \qquad \text{Eq. 4.44.}$$

$$I_{disk} = 0.5 * m_{disk} * \left(\frac{D_{disk}}{2}\right)^2 \qquad \text{Eq. 4.45.}$$

$$I_{tyre} = 0.5 * m_{tyre} * \left(\left(\frac{D_{rim} * 0.0254}{2} \right)^2 + \left(\frac{D_{rim} * 0.0254 + \frac{0.02 * H_{tyre} * W_{tyre}}{1000}}{2} \right)^2 \right) \quad \text{Eq. 4.46.}$$

Where:
I_w = total Inertia of the wheel [kg*m^2];
I_{rim} = total Inertia of the rim [kg*m^2];
I_{tyre} = total Inertia of the tyre [kg*m^2];
I_{disk} = Inertia of the brake disk [kg*m^2];
I_{rim_spokes} = Inertia of the spokes cylinder [kg*m^2];
m_{rim} = mass of the rim [kg];
I_{rim_crown} = Inertia of the rim crown cylinder [kg*m^2];
m_{tyre} = mass of the tyre [kg];
m_{disk} = mass of the brake disk [kg];
D_{disk} = Diameter of the brake disk cylinder [m];
D_{rim} = wheel rim Diameter [in].

Rebuilt parameters

Rebuilt parameters are: *resistive Engine torque* (t_{E_res}), *specific FC* (*cons*), *idle FC* ($cons_{idle}$) and *Engine Inertia* (I_E). Below the logic by which rebuilt parameters are quantified for the various vehicle case studies is described in detail.

Resistive Engine torque (t_{E_res}). Model parameter t_{E_res} is not available in literature for reference car models reported in Tables 4.21. and 4.22.. The logic adopted in order to quantify t_{E_res} envisages to assume a reference diagram from literature and to obtain the diagram of the generic case study through a scaling of y-axis (torque). The scaling is performed in order that for any point (torque-rpm) of the map the following relation is respected:

$$\frac{BMEP_{res\_i}}{BMEP_{res\_L}} = \frac{BMEP_{dr\_max\_i}}{BMEP_{dr\_max\_L}} \quad \text{Eq. 4.47.}$$

Therefore t_{E_res} is determined through the following expressions:

$$BMEP_{res\_i} = BMEP_{res\_L} * \frac{BMEP_{dr\_max\_i}}{BMEP_{dr\_max\_L}} \quad \text{Eq. 4.48.}$$

$$t_{E\_res\_i} = \frac{100 * BMEP_{res_i} * V_i}{4 * \pi} \quad \text{Eq. 4.49.}$$

Where:
$BMEP_{res\_i}$ = resistive Brake Mean Effective Pressure of generic case study *i* [bar];
$BMEP_{res\_L}$ = resistive Brake Mean Effective Pressure of reference diagram from literature [bar];
$BMEP_{dr\_max\_i}$ = maximum driving Brake Mean Effective Pressure of generic case study *i* [bar];
$BMEP_{dr\_max\_L}$ = maximum driving Brake Mean Effective Pressure of reference diagram from Literature [bar];

$t_{E\_res\_i}$ = resistive Engine torque of generic case study *i* [Nm];
V_i = displacement of Reference mass-Configuration of generic case study *i* [l].

Two distinct resistive torque diagrams from literature are adopted as reference (one for GT case studies and one for DT case studies). The reference diagram from literature for GT case studies refers to a 2.0l 89kW ($BMEP_{max}$ = 10.7 bar) gasoline naturally aspirated car and it is from the demo file “AME / demo / solutions / Automotive / Vehicle Integration / Conventional Vehicle00 _ Bat Alt Loads Reg Braking.ame” of AMESim Rev.13 library (Siemens PLM software, 2015). The reference diagram from literature for DT case studies refers to a 1.6l 50kW ($BMEP_{max}$ = 14.6 bar) diesel car and it is from the demo file “AME / demo / Libraries / Drv / Diesel Vehicle With Clutch.ame” of AMESim Rev.13 library (Siemens PLM software, 2015). Both reference diagrams are in the form of 2D lookup table (rpm-torque) in which the torque is given at discrete values of rpm; they are reported in Table SI4.1.1. of SI Appendix-chapter 4.

***Specific FC* (*cons*)**. Model parameter *cons* is not available in literature for reference car models reported in Tables 4.21. and 4.22. In absence of such a data, it is assumed to identify as reference a specific FC map from literature and to obtain the map of the various case studies through a scaling process. At this scope two distinguished FC maps from literature are assumed as reference respectively for GT and DT case studies. For GT case studies the engine whose map is chosen as reference is the VOLKSWAGEN group EA113 2.0l TFSI (Van Basshuysen, 2013) while for DT case studies it is the VOLKSWAGEN group EA189 2.0l TDI (Van Basshuysen, 2013). Table 4.26. reports main technical features of the cited engines while Figures 4.5. and 4.6. show FC map respectively for GT and DT case studies.

	GT	**DT**
	EA113 2.0l TFSI	**EA189 2.0l TDI**
Displacement [cm^3]	1984	1968
Stroke [mm]	92.8	95.5
Bore [mm]	82.5	81.0
SBR [null]	1.125	1.179
Max power [kW]	147 (5100-6000rpm)	105 (4200rpm)
Max torque [Nm]	280 (1700-5000rpm)	320 (1750-2500rpm)

Table 4.26. Main technical features of engines from literature chosen as reference for FC map (GT and DT case studies)

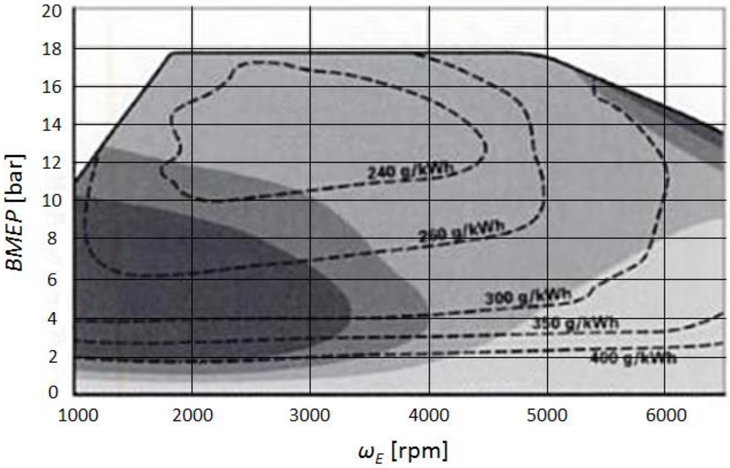


Figure 4.5. FC map of VOLKSWAGEN group EA113 2.0l TFSI engine chosen as reference for GT case studies (source: Van Basshuysen, 2013)

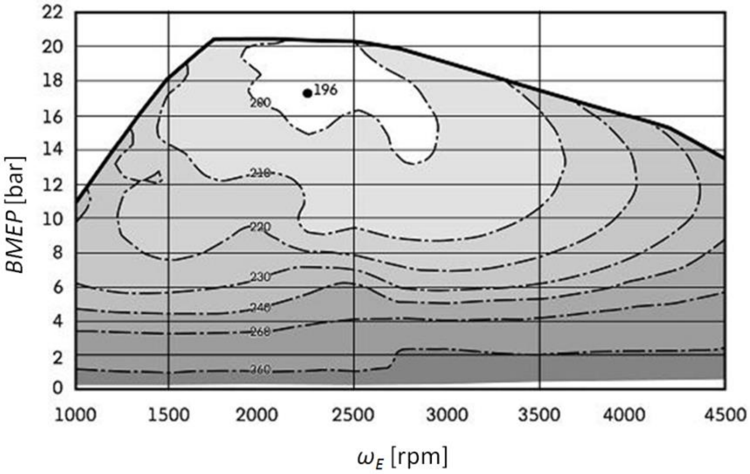


Figure 4.6. FC map of VOLKSWAGEN group EA189 2.0l TDI engine chosen as reference for DT case studies (source: Van Basshuysen, 2013)

As shown in Figures 4.5. and 4.6., the specific FC map presents

- engine speed on x-axis (expressed in rpm)
- BMEP on y-axis (expressed in bar)

while the areas within the map are defined by the so-called iso-consumption curves (specific FC expressed in g/kWh).

FC map of each study is obtained by applying a scaling process to both the axes of the reference map from literature. Below the implementation of the scaling process is described in detail separately for x and y axes.

With respect to x-axis (engine speed)

- reference FC map from literature is defined between the extremes ω_{min_L} (minimum engine speed of reference FC map from Literature) and ω_{max_L} (maximum engine speed of reference FC map from Literature);
- FC map of reference mass-configuration of generic case study *i* is defined between the extremes ω_{min_i} (minimum engine speed of FC map of case study *i*) and ω_{max_i} (maximum engine speed of FC map of case study *i*). It has to be noted that $\omega_{min\_RC\_i}$ and $\omega_{max\_RC\_i}$ are identified by the range of engine speed within which model parameter *driving Engine torque* (t_{E_dr}) is defined.

The scaling process is applied in order to pass from the range $\omega_{min\ \_L} - \omega_{max\_L}$ to the range $\omega_{min\_i} - \omega_{max\_i}$ by maintaining constant the following ratio:

$$\omega_{ratio} = \frac{\omega - \omega_{min}}{\omega_{max} - \omega_{min}} \qquad \text{Eq. 4.50.}$$

Where:
ω = generic engine speed between ω_{min} and ω_{max} [rpm];
ω_{min} = minimum engine speed of torque diagram [rpm];
ω_{max} = maximum engine speed of torque diagram [rpm].

With respect to y-axis (BMEP) the scaling is performed basing on maximum BMEP and it is realized through a fixed scaling factor defined as follows:

$$SF_{BMEP} = \frac{BMEP_{\max\_RC\_i}}{BMEP_{\max\_L}} \qquad \text{Eq. 4.51.}$$

Where:
SF_{BMEP} = Scaling Factor for BMEP [null];
$BMEP_{max\_i}$ = maximum BMEP of case study *i* [bar];
$BMEP_{max\_L}$ = maximum BMEP of reference engine from Literature [bar].

A brief description of the operative method adopted in order both to scan data from literature sources and perform the scaling process is reported below.

The reference FC maps from literature are discretized by the software “Plot Digitizer”. The discretization is performed using a variable step of acquisition on the x-axis. The result of the discretization process is represented by a lookup table in which a couple of values (BMEP, specific FC) corresponds to each value of rpm. The lookup tables of reference FC maps from literature are reported in Tables SI4.1.2. and SI4.1.3. of SI Appendix-chapter 4.

The scaling process is applied to each value of engine speed and to the corresponding value of BMEP:

- the scaled value of engine speed is obtained through the following expression:

$$\omega_i = \omega_{\min\_i} + \omega_{ratio\_L} * \left(\omega_{\max\_i} - \omega_{\min\_i}\right) \qquad \text{Eq. 4.52.}$$

Where:
ω_i = generic engine speed between ω_{min} and ω_{max} of case study *i* [rpm];

ω_{min_i} = minimum engine speed within driving torque diagram of case study *i* [rpm];
ω_{ratio_L} = ω_{ratio} evaluated for reference FC map from Literature [rpm];
ω_{max_i} = maximum engine speed within driving torque diagram of case study *i* [rpm].

- the scaled value of BMEP is obtained through the following expression:

$$BMEP_i = BMEP_L * SF_{BMEP} \qquad \text{Eq. 4.53.}$$

Where:
$BMEP_i$ = Brake Mean Effective Pressure of case study *i* [bar];
$BMEP_L$ = Brake Mean Effective Pressure of reference FC map from Literature [bar];
SF_{BMEP} = Scaling Factor for Brake Mean Effective Pressure [null].

***Idle FC* (*cons_{idle}*)**. Model parameter $cons_{idle}$ is not available in literature for reference car models reported in Tables 4.21. and 4.22. In order to determine $cons_{idle}$, for each case study, it is assumed that

- idle consumption depends exclusively on engine displacement (Gaines et al., 2012; Huff et al., 2013; Johnson et al., 2012; Lim, 2002; Mellios et al., 2014; Naik et al., 2014; Pal and Sarkar, 2012; Parida and Gangopadhyay, 2008; Rahman, 2013; Taylor, 2003);
- the analytical expression which gives idle consumption in function of engine displacement is obtained through a linear interpolation of measured data (Argonne National Laboratory, 2015; Gordon and Taylor, 2003);
- data are obtained through data collection performed on a limited number of 2015 vehicle models.

With regard to data collection, it has to be noted that:

- idle consumption is measured at idle rpm with hot engine and without any auxiliary load activated;
- additionally to idle consumption following parameters are recorded: ambient temperature, engine temperature and engine speed;
- data are determined as the arithmetic mean of 600 measurements (measurement time of 10 minutes with a time-step of 1s);
- a separate survey for both GT and DT vehicles is performed;
- within each engine technology the survey concerns A/B, C and D classes (see Table 4.27.).

Table 4.27. reports the complete set of measured data for each one of the investigated vehicle models.

	Vehicle class	**Vehicle model**	**Engine displacement [l]**	**Ambient temperature [°C]**	**Engine temperature [°C]**	**Engine speed [rpm]**	**Idle FC [g/h]**
GT vehicle models	A/B	CITROEN C3 1.2 PureTech 110cv	1.199	17.5	90.5	848	480
		FIAT Punto 0.9 T-Air 105cv	0.875	19.0	91.0	834	417
		FORD Fiesta 1.0 Ecoboost 101cv	0.999	19.5	93.5	815	405
		SMART For-two 0.9T 90cv	0.898	18.0	92.0	826	408
	C	ALFA ROMEO Giulietta M-Air 150cv	1.368	15.5	94.0	789	500
		OPEL Astra 1.4 Turbo 140cv	1.364	16.0	92.5	812	473
		PEUGEOT 308 1.2 PureTech 131cv	1.199	17.0	95.0	822	430
		VOLKSWAGEN Golf 1.2 TSI 86cv	1.197	20.0	92.5	798	470
	D	AUDI A4 1.8 TFSI 170cv	1.798	18.0	90.0	786	540
		FORD Mondeo 1.5 Ecoboost 160cv	1.498	15.5	91.5	801	503
		PEUGEOT 508 1.6 THP 165cv	1.598	13.0	91.0	778	555
		VOLKSWAGEN Passat 1.4 TSI 150cv	1.390	14.5	92.5	743	490
DT vehicle models	A/B	*CITROEN C3 1.4 HDi 90cv*	1.398	19.5	89.5	782	400
		FIAT Punto 1.3 MJT 75cv	1.248	19.0	87.5	809	390
		FORD Fiesta 1.6 TDCi 95cv	1.560	17.5	90.5	752	400
		SMART For-two 800 Cdi 54cv	0.799	16.5	88.0	764	300
	C	*AUDI A3 Sportback 1.6 TDI 90cv*	1.598	17.5	91.0	810	425
		AUDI A3 Sportback 2.0 TDI 150cv	1.968	14.5	92.5	735	456
		FIAT Bravo 1.6 MJT 120cv	1.598	13.5	91.5	786	390
		VOLKSWAGEN Golf 1.6 TDI 105cv	1.598	12.0	89.0	811	445
	D	*CITROEN C5 1.6 HDi 115cv*	1.560	19.5	92.5	740	400
		FORD Mondeo 2.0 TDCi 150cv	1.997	21.5	87.5	822	490
		VOLKSWAGEN Passat 2.0 TDI 150cv	1.968	17.0	93.5	783	474
		SAAB 9-3 1.9 TiD 150cv	1.910	18.0	91.0	806	440

Table 4.27. Data collection for idle fuel consumption; complete set of measured data (GT vehicle models)

Figure 4.7. shows measured data, regression lines and corresponding coefficient of determination R^2.

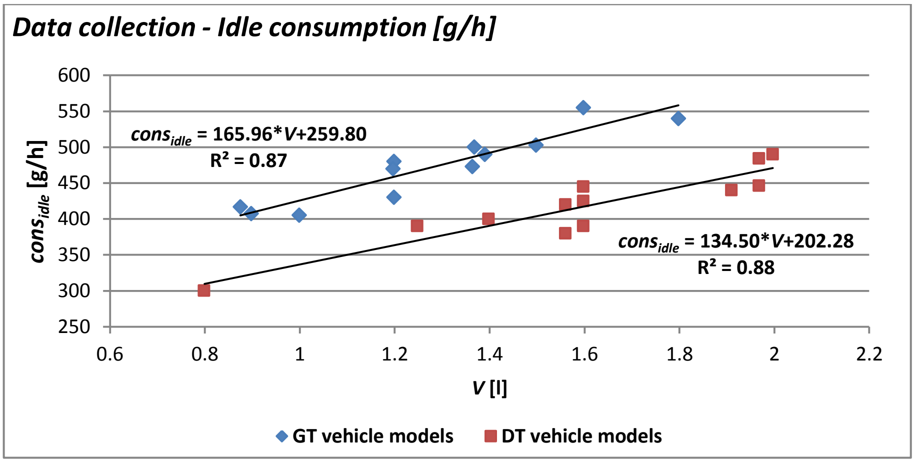


Figure 4.7. Data collection for idle consumption; measured data, regression lines and corresponding coefficient of determination R^2

Table 4.28. reports the equations of regression lines of idle consumption in function of engine displacement and the corresponding coefficients of determination R^2.

	Regression line ***Idle FC ($cons_{idle}$) – Engine displacement (V)***	**Coefficient of determination R^2**
GT case studies	$cons_{idle}$ = 166 * V + 260 [g/h]	0.87
DT case studies	$cons_{idle}$ = 135 * V + 202 [g/h]	0.88

Table 4.28. Rebuilt parameters - Idle FC ($cons_{idle}$): equations of regression lines of measured data and corresponding coefficients of determination R^2

Engine Inertia (I_E). Model parameter I_E is not available in literature for reference car models reported in Tables 4.21. and 4.22. The logic adopted in order to quantify I_E for the various case studies envisages to assume as reference a value of engine inertia from literature and scale it on the basis of engine displacement.

The reference value from literature for I_E is 0.183 [kg*m^2]; it refers to a 1.6 [l] naturally aspirated gasoline car and it is from the demo file "AME / demo / solutions / Automotive / Vehicle Integration / Conventional Vehicle00 _ Bat Alt Loads Reg Braking.ame" of AMESim Rev.13 library (Siemens PLM software, 2015). The value of I_E for both GT and DT case studies is determined through the following expression:

$$I_{E\_i} = 0.183 * \frac{V_i}{1.6} \qquad \text{Eq. 4.54.}$$

Where:
I_{E_i} = engine Inertia of case study i [kg*m^2];
V_i = engine displacement of case study i [l].

Operative parameters

Operative parameters are *Downshift engine speed* (ω_{Down}) and *Upshift engine speed* (ω_{Up}). The chosen criterion in order to quantify ω_{Down} and ω_{Up} for the various case studies is the minimum FC. Such parameters are determined by calculating FC for each one of possible combinations (ω_{Down} - ω_{Up}) within a certain range of engine speed. For both GT and DT case studies the range of engine speed is

- 900-1600 [rpm] (ω_{Down})
- 1500-2500 [rpm] (ω_{Up})

with a step of 100 [rpm]. Therefore for each case study the determination of parameters ω_{Down} and ω_{Up} requires 88 simulations; considering that the process has to be performed separately for each one of the four driving cycles (FTP72, JC08, NEDC and WLTC), the overall number of simulations per case study is 352.

The numerical values assigned to variable model parameters of reference mass-configuration are reported in Tables SI4.2.3. - SI4.2.8. of SI appendix-chapter 4 for each one of case studies with the exception of *driving Engine torque* (t_{E_dr}), *resistive Engine torque* (t_{E_res}) and *specific FC (cons).* These latter are reported in SI appendix-chapter 4 for a limited number of case studies:

- t_{E_dr} and t_{E_res} are reported in Tables SI4.2.9. and SI4.2.10. in the form of 2D lookup table (rpm-torque) for the following vehicle case studies: GT n°9, 17, 28 and DT n°7, 21, 31;
- *cons* is reported in Tables SI4.2.11. and SI4.2.12. in the form of 3D lookup table (rpm – BMEP – specific FC) for the following vehicle case studies: GT n°9, 17, 28 and DT n°7, 21, 31.

The complete set of t_{E_dr} and t_{E_res} and *cons* for vehicle case studies is reported in the CD attached to the thesis (folder “Reference mass-configurations – Variable parameters”).

4.3.2. PMR mass-configurations

For the PMR mass-configurations all model parameters (both fixed and variable) remain unchanged with respect to reference mass-configuration with the only exception of *vehicle mass* (m_{veh}). PMR mass-configurations are obtained starting from reference mass-configuration through the following four steps of lightening: 5%, 10%, 15% and 20%.

As shown in paragraph 4.3.1.2., m_{veh} refers to the fueled vehicle with standard equipment and 136 kg of driver and luggage. Car mass reduction is originated by weight reduction of vehicle components while the mass of fuel, standard equipment, driver and luggage remain unchanged; therefore the percent mass reduction defined above refers to tare mass. At this regard a specific note has to be done with respect to the determination of tare mass. As said above, Automobile-Catalog (2015) furnishes only the curb mass (m_{curb}) and this latter includes the mass of the empty and dry car (m_{tare}), tool kit ($m_{tool\ kit}$), fluids (m_{fluids}) and spare wheel ($m_{spare\ wheel}$). As the source does not specify the mass of single contributions, it is assumed to determine m_{tare} by equation below

$$m_{tare} = m_{curb} - (m_{tool\ kit} + m_{fluids} + m_{spare\ wheel}) \quad \text{Eq. 4.55.}$$

where the following assumptions are considered for all case studies:

- m_{fluids} = 15 [kg];
- $m_{tool\ kit}$ + $m_{spare\ wheel}$ = 40 [kg].

Tables SI4.3.1. - SI4.3.6 in SI appendix-chapter 4 report the numerical value of vehicle parameters

- m_{curb} (only reference mass-configuration)
- m_{tare} and m_{veh} (both reference and PMR mass-configurations)

for each one of case studies.

4.3.3. SE mass-configurations

4.3.3.1. Equivalence criteria between reference and SE mass-configurations

The implementation of SEs is performed in order that lightweight mass-configurations preserve the equivalence of both performance and technological level with respect to reference mass-configuration. As shown in chapter 3.2.2., the criterion chosen as representative of performance level is the *elasticity 80-120 km/h* ($t_{80\text{-}120km/h}$) in the upper gear ratio. On the other hand the parameters assumed as representative of technological level are *Maximum Brake Mean Effective Pressure* ($BMEP_{max}$), *Stroke-to-Bore Ratio (SBR)* and *Mean Piston Speed (MPS).* The analytical expression of such parameters is:

$$BMEP_{max} = \frac{t_{E\_max} * 4\pi}{100 * V} \quad \text{Eq. 4.56.}$$

$$SBR = \frac{stroke}{bore} \quad \text{Eq. 4.57.}$$

$$MPS = \frac{stroke * \omega_E}{30000} \quad \text{Eq. 4.58.}$$

Where:
$BMEP_{max}$ = maximum Brake Mean Effective Pressure [bar];
t_{E_max} = maximum Engine torque [Nm];
V = engine displacement [l];
stroke = engine stroke [mm];
bore = engine bore [mm];
MPS = Mean Piston Speed [m/s];
ω_E = Engine speed [rpm].

The quantification of parameters representative of performance and technological levels for reference mass-configurations is described in detail in SI appendix-chapter 4:

- the analytical procedure for calculating $t_{80\text{-}120km/h}$ in the upper gear ratio is reported in paragraph SI4.5. “Analytical modelling”.

- Tables SI4.2.13. and SI4.2.14. report $BMEP_{max}$, *elasticity 80-120km/h* and *Stroke-to-Bore Ratio* (*SBR*) of reference mass-configuration for each one of vehicle case studies.

4.3.3.2. Implementation of secondary effects

The equivalence of performance and technological levels involves that passing from reference to SE mass-configurations following vehicle parameters are affected by SEs:

- *Engine torque* (t_{E_dr} and t_{E_res})*;
- *engine displacement (V)**;
- *engine stroke (stroke)*;
- *engine bore (bore)*;
- *specific FC (cons)**;
- *idle FC* ($cons_{idle}$)*.

(* = model parameters)

Below it is described in detail the procedure adopted to quantify the mentioned parameters in the SE mass-configurations.

1. Performance level: equivalence of elasticity 80-120 km/h. The starting point is that mass reduction involves an improvement in performance level of the lightweight configuration with respect to the reference one. In order to maintain the same *elasticity 80-120 km/h in the upper gear ratio*, the torque diagram of SE mass-configuration is obtained by down-scaling the torque diagram of the reference mass-configuration by a Scaling Factor FS_{torque}. While the torque (y-axis) is scaled by a fixed factor, the engine speed (x-axis) remains unaltered.

2. Technological level: equivalence of $BMEP_{max}$. The downscaling of the torque by FS_{torque} involves that also $BMEP_{max}$ of SE mass-configuration is scaled by the same factor with respect to $BMEP_{max}$ of reference mass-configuration (see Eq. 4.56.). As the first requirement for equivalence of technological level imposes equality of $BMEP_{max}$, the displacement of SE-mass-configuration is obtained by downscaling the displacement of reference mass-configuration once again by FS_{torque}.

3. Technological level: equivalence of *SBR*. The second requirement for equivalence of technological level imposes that reference and SE mass-configurations have the same *SBR*. Assuming that the number of engine cylinders remains constant, the following system of equations allows to determine engine stroke and bore of SE mass-configuration.

$$\frac{stoke_{RC\_i}}{bore_{RC\_i}} = \frac{stroke_{SE\_i}}{bore_{SE\_i}} \qquad \text{Eq. 4.59.}$$

$$V_{SE\_i} = \frac{{bore_{SE\_i}}^{2} * stroke_{SE_i} * n°_{cyl} * \pi}{4000000} \qquad \text{Eq. 4.60.}$$

Where:
V_{SE_i} = engine displacement of SE mass-configuration of generic case study *i* [l];
$stroke_{RC\_i}$ = engine stroke of Reference mass-Configuration of generic case study *i* [mm];

$bore_{RC\_i}$ = engine bore of Reference mass-Configuration of generic case study *i* [mm];
$stroke_{SE\_i}$ = engine stroke of SE mass-configuration of generic case study *i* [mm];
$bore_{SE\_i}$ = engine bore of SE mass-configuration of generic case study *i* [mm];
$n°_{cyl}$ = number of engine cylinders [null].

Consequently $stroke_{SE\_i}$ and $bore_{SE\_i}$ are obtained by a scaling respectively of $stroke_{RC\_i}$ and $bore_{RC\_i}$ by a factor $FS_{torque}{}^{1/3}$. Tables 4.2.13. and 4.2.14. in SI appendix-chapter 4 report $n°_{cyl}$ for reference mass-configuration of each vehicle case study.

4. Technological level: equivalence of *MPS*. The third requirement for equivalence of technological level imposes that reference and SE mass-configurations have the same *MPS*. As $stroke_{SE}$ is obtained by a scaling of $stroke_{RC}$ by $FS_{torque}{}^{1/3}$, the engine speed is scaled by a factor $FS_{torque}{}^{-1/3}$.

The scaling of the engine speed involves that the x-axis (rpm) of the torque diagram is also scaled. In this way the engine power of SE mass-configuration grows and the equivalence of elasticity 80-120km/h is not still valid. The problem is solved through an iterative process which leads to identify the torque scaling factor that guarantees the simoultaneous equivalence of both performance and technological levels. The MATLAB files used in order to implement the iterative process are reported in the CD attached to the thesis (folder “SE mass-configurations – Torque Scaling Factor”).

5. Sub-effects. SEs described above involve that passing from reference to SE mass-configuration other model parameters change: as such modifications are originated by SEs, these latter can be seen as “sub-effects”. The first sub-effect regards model parameter *specific FC (cons)*. Considering that engine speed is scaled basing on the same *MPS* by $FS_{torque}{}^{-1/3}$, FC map of SE mass-configuration is obtained by applying the same scaling process to the x-axis (engine speed) of FC map of reference mass-configuration.

The second sub-effect regards model parameter *idle FC* ($cons_{idle}$). For this latter a linear dependence on engine displacement is assumed; the regression lines ($cons_{idle} – V$) obtained from data collection described in paragraph 4.3.1.2. are used in order to determine $cons_{idle}$ of SE mass-configurations.

Tables in SI appendix-chapter 4 report the numerical value that vehicle parameters affected by SEs assume in the SE mass-configurations:

- Tables SI4.4.13. - SI4.4.18 report *driving Engine torque* (t_{E_dr}) and *resistive Engine torque* (t_{E_res}) in the form of 2D lookup table (rpm-torque) for the following vehicle case studies: GT n°9, 17, 28 and DT n°7, 21, 31 (the same data are also reported in the form of diagram (rpm-torque) in Figures SI4.4.25. and SI4.4.26. of SI appendix-chapter 4). The CD attached to the thesis reports t_{E_dr} and t_{E_res} in the form of 2D lookup table (rpm-torque) for all GT and DT case studies (folder “SE mass-configurations – Torque diagrams”);
- Tables SI4.4.19. – SI4.4.24. report *specific FC* (*cons*) in the form of 3D lookup table (rpm-BMEP-specific FC) for the following vehicle case studies: GT n°9, 17, 28 and DT n°7, 21, 31. The CD attached to the thesis reports *specific FC* (*cons*) in the form of 3D lookup table (rpm-BMEP-specific FC) for all GT and DT case studies (folder “SE mass-configurations – Specific FC”);

- Tables SI4.4.1. – SI4.4.12. report *engine displacement* (*V*), *idle FC* ($cons_{idle}$), *Engine Inertia* (I_E), *engine stroke* (*stroke*) and *engine bore* (*bore*) for all SE mass-configurations of each vehicle case study;
- Tables 4.2.13. and 4.2.14. report *number of cylinders* ($n°_{cyl}$) for all SE mass-configurations of each vehicle case study.

Tables 4.29. and 4.30. report maximum power for both reference and SE mass-configurations of each vehicle case study.

Reference and SE mass-configurations – Maximum power [kW] (GT case studies)						
Class	**Case study**	**Reference**	**SE 5%**	**SE 10%**	**SE 15%**	**SE 20%**
A/B	**1**	77.0	75.3	73.6	71.9	70.3
	2	70.0	68.5	67.0	65.6	64.1
	3	92.0	90.0	88.0	85.9	83.9
	4	110.0	107.4	104.9	102.1	99.4
	5	66.0	64.9	63.8	62.5	61.3
	6	62.5	61.2	59.9	58.5	57.1
	7	62.5	61.2	59.9	58.6	57.3
	8	99.0	96.6	94.3	91.9	89.6
	9	73.5	72.0	70.5	69.0	67.5
	10	92.0	90.1	88.3	86.4	84.4
C	**11**	77.0	75.1	73.2	71.3	69.4
	12	125.0	122.1	119.3	116.3	113.4
	13	81.0	79.3	77.6	75.8	74.0
	14	110.0	107.4	104.9	102.1	99.4
	15	132.0	128.8	125.7	122.4	119.1
	16	88.0	85.9	83.9	81.8	79.6
	17	103.0	100.5	98.0	95.3	92.7
	18	73.5	71.9	70.2	68.5	66.9
	19	92.0	90.1	88.1	86.1	84.1
	20	110.0	107.4	104.9	102.3	99.7
	21	134.0	130.9	127.9	124.7	121.4
D	**22**	88.0	85.9	83.8	81.6	79.4
	23	125.0	121.9	118.8	115.6	112.4
	24	100.0	97.7	95.3	92.8	90.4
	25	135.0	131.6	128.2	124.6	121.0
	26	115.0	112.3	109.6	106.8	104.1
	27	92.0	90.0	88.0	86.0	83.9
	28	118.0	115.9	113.7	111.5	109.2
	29	149.0	145.9	142.8	139.6	136.4
	30	176.5	171.4	166.2	162.3	158.4
	31	115.0	112.3	109.6	106.9	104.2
	32	135.0	131.6	128.3	125.0	121.7

Table 4.29. Maximum power of reference and SE mass-configurations for each vehicle case study (GT)

Reference and SE mass-configurations – Maximum power [kW] (DT case studies)

Class	Case study	Reference	SE 5%	SE 10%	SE 15%	SE 20%
A/B	**1**	88.0	85.7	83.4	81.1	78.8
	2	50.0	48.9	47.9	46.8	45.8
	3	84.0	82.1	80.2	78.2	76.2
	4	70.0	68.4	66.7	65.1	63.5
	5	55.0	53.8	52.6	51.3	50.0
	6	55.0	53.7	52.5	51.2	49.9
	7	62.5	61.0	59.6	58.1	56.7
	8	70.0	68.3	66.7	65.0	63.3
	9	55.0	53.9	52.7	51.5	50.3
	10	70.0	68.6	67.1	65.6	64.1
C	**11**	77.0	75.2	73.5	71.8	70.0
	12	110.0	107.5	105.0	102.3	99.7
	13	129.0	125.8	122.7	119.5	116.3
	14	68.0	66.5	64.9	63.4	61.8
	15	84.0	82.3	80.5	78.8	77.0
	16	110.0	107.7	105.3	102.9	100.4
	17	66.0	64.5	62.9	61.4	59.9
	18	88.0	85.8	83.6	81.5	79.4
	19	121.0	118.1	115.2	112.3	109.5
	20	70.0	68.4	66.8	65.2	63.5
	21	88.0	86.0	84.1	82.1	80.0
	22	110.0	107.7	105.3	102.9	100.4
D	**23**	110.0	107.4	104.7	102.1	99.4
	24	120.0	117.4	114.8	112.2	109.6
	25	140.0	136.7	133.5	130.2	127.0
	26	160.0	155.8	151.7	147.4	143.0
	27	84.0	82.0	80.0	77.9	75.8
	28	103.0	100.8	98.5	96.3	94.1
	29	120.0	117.4	114.8	112.1	109.4
	30	84.5	82.7	80.8	79.0	77.1
	31	110.0	107.8	105.7	103.5	101.3
	32	132.0	129.3	126.7	124.0	121.3

Table 4.30. Maximum power of reference and SE mass-configurations for each vehicle case study (DT)

5. Results

The results of the study are presented subdivided into two main sections:

- simulation modelling: values of FC and FRV obtained respectively in the first stage (calculation of use stage FC) and in the second stage (evaluation of mass-induced FC) of the construction of the tool;
- environmental modelling: environmental models for the treatment of the use stage within the considered typologies of LCA study (third stage of the construction of the tool).

5.1. Simulation modelling

The results of the simulation modelling comprehend

- FCs calculated by use stage simulation model for each mass-configuration of the considered vehicle case studies;
- FRVs calculated for each one of the considered vehicle case studies.

5.1.1. Fuel consumption

The values of FC are reported in Tables (SI5.1.1. – SI5.1.6.) and (SI5.1.7. – SI5.1.12) of SI appendix-chapter 5 respectively for GT and DT case studies. Data, expressed in liters per 100 kilometers, refer to

- all case studies within the investigated vehicle classes;
- both reference and lightweight mass-configurations;
- both PMR and SE lightweight mass-configurations;
- all the considered driving cycles.

5.1.2. Fuel Reduction Value

Before presenting the complete set of FRVs obtained for all case studies, FC in function of mass, regression lines and resulting FRV coefficients are showed by way of example for two single case studies (one GT and one DT case study). Figures 5.1 and 5.2 refer, respectively for the case of PMR and SE, to GT case study n°1; Figures 5.3 and 5.4

report the same elements referring to DT case study n°1. In the figures the FRV coefficient (in bold) is identified by the slope of the regression line of FC in function of mass.

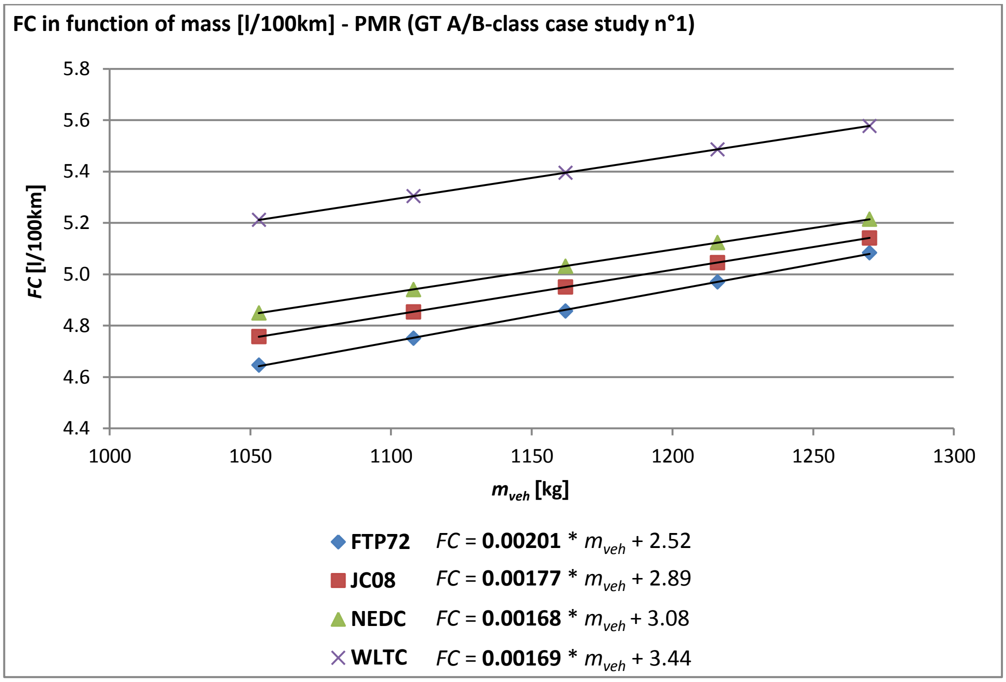


Figure 5.1. FC in function of mass and regression lines [l/100km] – PMR (GT A/B-class case study n°1)

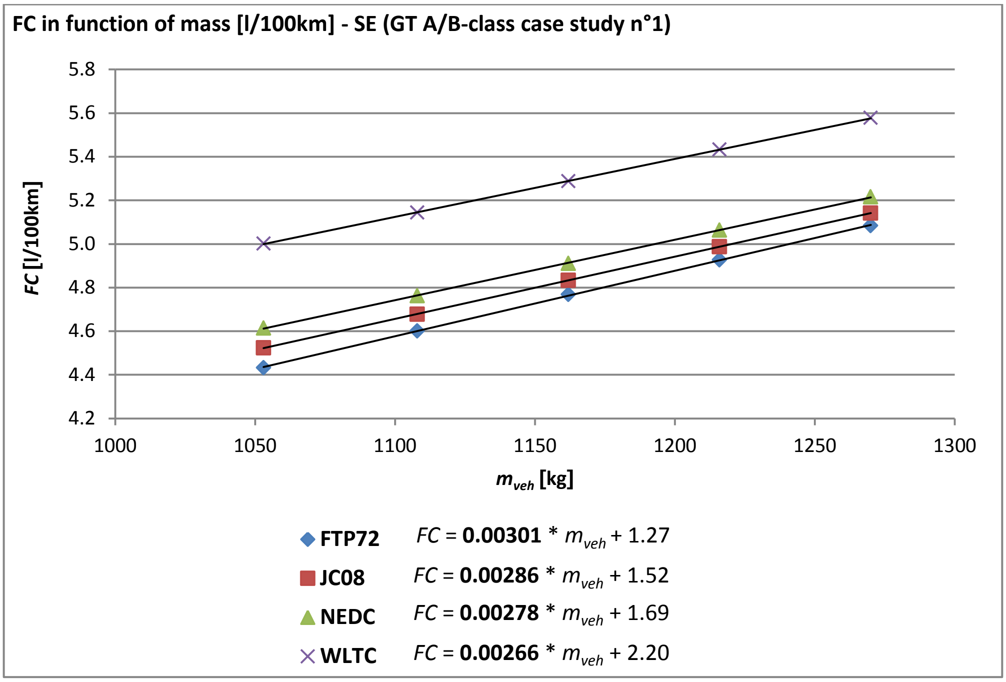


Figure 5.2. FC in function of mass and regression lines [l/100km] – SE (GT A/B-class case study n°1)

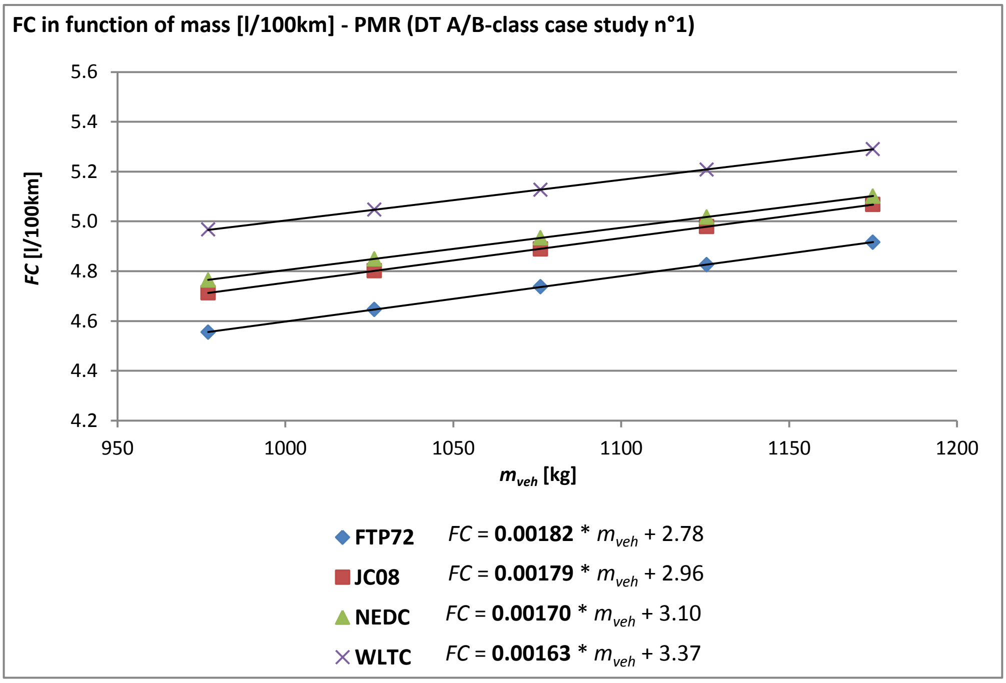


Figure 5.3. FC in function of mass and regression lines [l/100km] – PMR (DT A/B-class case study n°1)

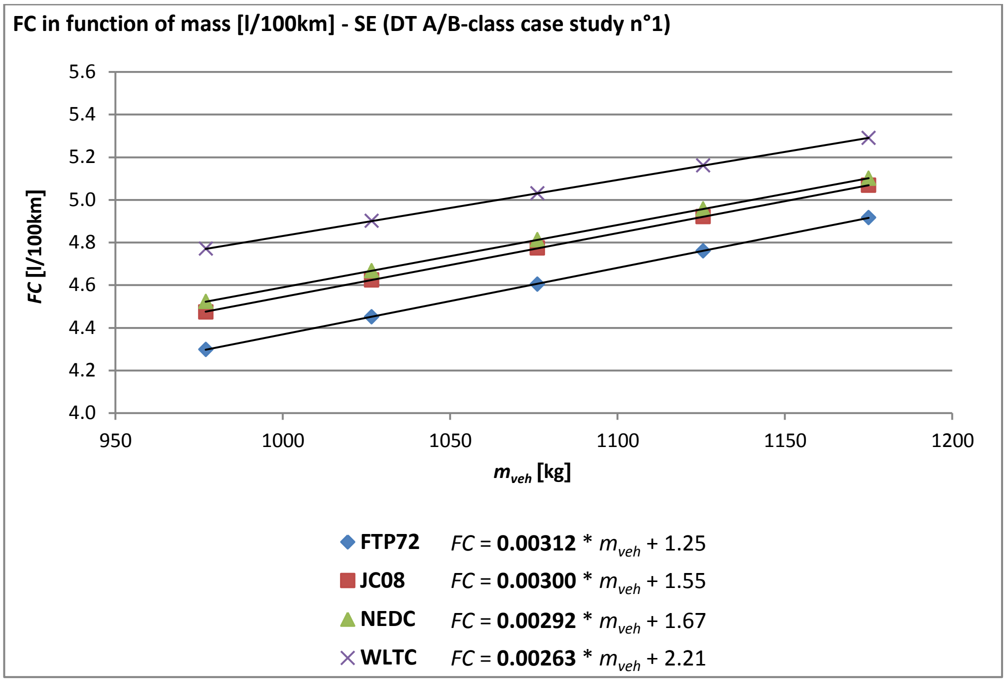


Figure 5.4. FC in function of vehicle mass and regression lines [l/100km] – SE (DT A/B-class case study n°1)

Once the calculation procedure for the FRV has been exemplified, the complete set of results is presented. Tables 5.1 and 5.2 report the FRVs in terms of l/100km*100kg respectively for GT and DT case studies; each row of the tables refers to a specific case study. Data are presented for both the cases of PMR only (FRV_{PMR}) and SE (FRV_{SE}). For each one of them five values are reported:

- four values calculated with respect to the driving cycles assumed as reference for the study (FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC})
- one value calculated as the arithmetic mean of FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} ($FRV_{MeanCycles}$).

In summary, for each case study the complete set of results is composed by 10 values of FRV:

- PMR: FRV_{FTP72_PMR}, FRV_{JC08_PMR}, FRV_{NEDC_PMR}, FRV_{WLTC_PMR}, $FRV_{MeanCycles\_PMR}$;
- SE: FRV_{FTP72_SE}, FRV_{JC08_SE}, FRV_{NEDC_SE}, FRV_{WLTC_SE}, $FRV_{MeanCycles\_SE}$.

		***FRV* [l/100km*100kg] (GT)**									
		PMR					**SE**				
Vehicle Class	**Case study**	**FTP72 (FRV_{FTP72_PMR})**	**JC08 (FRV_{JC08_PMR})**	**NEDC (FRV_{NEDC_PMR})**	**WLTC (FRV_{WLTC_PMR})**	**Mean cycles ($FRV_{MeanCycles\_PMR}$)**	**FTP72 (FRV_{FTP72_SE})**	**JC08 (FRV_{JC08_SE})**	**NEDC (FRV_{NEDC_SE})**	**WLTC (FRV_{WLTC_SE})**	**Mean cycles ($FRV_{MeanCycles\_SE}$)**
A/B	**1**	0.201	0.177	0.168	0.169	0.179	0.301	0.286	0.278	0.266	0.283
	2	0.182	0.179	0.170	0.163	0.174	0.312	0.300	0.292	0.263	0.292
	3	0.166	0.171	0.166	0.163	0.167	0.345	0.329	0.321	0.294	0.322
	4	0.189	0.174	0.162	0.173	0.175	0.407	0.393	0.389	0.346	0.384
	5	0.203	0.176	0.176	0.170	0.181	0.274	0.259	0.252	0.233	0.255
	6	0.193	0.178	0.176	0.169	0.179	0.304	0.287	0.274	0.267	0.283
	7	0.198	0.184	0.170	0.172	0.181	0.291	0.275	0.259	0.255	0.270
	8	0.182	0.172	0.165	0.174	0.173	0.349	0.337	0.336	0.301	0.331
	9	0.177	0.180	0.172	0.161	0.173	0.317	0.314	0.293	0.263	0.297
	10	0.175	0.173	0.168	0.162	0.170	0.318	0.312	0.296	0.268	0.299
C	**11**	0.185	0.174	0.171	0.170	0.175	0.341	0.335	0.327	0.314	0.329
	12	0.189	0.172	0.166	0.181	0.177	0.353	0.339	0.332	0.325	0.337
	13	0.177	0.177	0.162	0.167	0.171	0.315	0.303	0.293	0.273	0.296
	14	0.182	0.169	0.164	0.169	0.171	0.389	0.363	0.365	0.329	0.362
	15	0.175	0.163	0.161	0.168	0.167	0.384	0.359	0.354	0.332	0.357
	16	0.187	0.172	0.168	0.174	0.175	0.342	0.328	0.324	0.310	0.326
	17	0.183	0.168	0.161	0.170	0.171	0.373	0.368	0.358	0.342	0.360
	18	0.178	0.180	0.163	0.163	0.171	0.304	0.292	0.286	0.269	0.288
	19	0.179	0.181	0.169	0.163	0.173	0.298	0.287	0.282	0.265	0.283
	20	0.181	0.168	0.171	0.171	0.173	0.384	0.365	0.363	0.323	0.359
	21	0.178	0.175	0.170	0.176	0.175	0.379	0.369	0.361	0.325	0.359
D	**22**	0.180	0.183	0.168	0.182	0.178	0.350	0.339	0.326	0.310	0.331
	23	0.237	0.200	0.191	0.184	0.203	0.477	0.420	0.409	0.354	0.415
	24	0.182	0.184	0.170	0.173	0.177	0.344	0.331	0.319	0.303	0.324
	25	0.184	0.173	0.159	0.171	0.172	0.405	0.387	0.382	0.349	0.381
	26	0.182	0.184	0.172	0.180	0.180	0.375	0.352	0.338	0.314	0.345
	27	0.182	0.181	0.169	0.166	0.175	0.290	0.283	0.270	0.262	0.276
	28	0.185	0.203	0.187	0.168	0.186	0.337	0.343	0.316	0.279	0.319
	29	0.210	0.188	0.174	0.183	0.189	0.462	0.434	0.429	0.345	0.418
	30	0.216	0.192	0.178	0.186	0.193	0.468	0.441	0.441	0.348	0.425
	31	0.182	0.188	0.175	0.176	0.180	0.373	0.362	0.345	0.315	0.349
	32	0.206	0.191	0.182	0.187	0.192	0.436	0.406	0.388	0.352	0.396

Table 5.1. FRVs for GT case studies [l/100km*100kg]

		***FRV* [l/100km*100kg] (DT)**									
		PMR					**SE**				
Vehicle class	**Case study**	**FTP72 (FRV_{FTP72_PMR})**	**JC08 (FRV_{JC08_PMR})**	**NEDC (FRV_{NEDC_PMR})**	**WLTC (FRV_{WLTC_PMR})**	**Mean cycles ($FRV_{MeanCycles\_PMR}$)**	**FTP72 (FRV_{FTP72_SE})**	**JC08 (FRV_{JC08_SE})**	**NEDC (FRV_{NEDC_SE})**	**WLTC (FRV_{WLTC_SE})**	**Mean cycles ($FRV_{MeanCycles\_SE}$)**
A/B	**1**	0.173	0.165	0.148	0.146	0.158	0.295	0.284	0.270	0.253	0.276
	2	0.153	0.140	0.143	0.115	0.138	0.217	0.212	0.194	0.142	0.191
	3	0.174	0.157	0.145	0.148	0.156	0.281	0.275	0.259	0.220	0.259
	4	0.149	0.150	0.137	0.117	0.138	0.253	0.245	0.224	0.214	0.234
	5	0.145	0.151	0.146	0.122	0.141	0.239	0.237	0.218	0.173	0.217
	6	0.147	0.149	0.136	0.116	0.137	0.235	0.235	0.215	0.202	0.222
	7	0.150	0.153	0.130	0.120	0.138	0.246	0.240	0.213	0.225	0.231
	8	0.150	0.148	0.129	0.117	0.136	0.250	0.241	0.221	0.223	0.234
	9	0.149	0.143	0.137	0.129	0.140	0.227	0.226	0.207	0.166	0.207
	10	0.149	0.150	0.137	0.117	0.138	0.253	0.245	0.224	0.214	0.234
C	**11**	0.168	0.159	0.148	0.141	0.154	0.262	0.253	0.235	0.214	0.241
	12	0.180	0.167	0.154	0.152	0.163	0.294	0.282	0.266	0.240	0.271
	13	0.171	0.161	0.149	0.143	0.156	0.291	0.280	0.270	0.243	0.271
	14	0.154	0.146	0.142	0.137	0.145	0.245	0.247	0.233	0.206	0.233
	15	0.166	0.157	0.149	0.138	0.153	0.261	0.252	0.231	0.206	0.238
	16	0.174	0.160	0.156	0.144	0.159	0.281	0.266	0.252	0.214	0.253
	17	0.165	0.153	0.140	0.138	0.149	0.289	0.269	0.246	0.233	0.259
	18	0.167	0.159	0.149	0.136	0.153	0.273	0.259	0.245	0.220	0.249
	19	0.179	0.170	0.154	0.150	0.163	0.294	0.283	0.269	0.239	0.271
	20	0.160	0.154	0.141	0.133	0.147	0.273	0.258	0.240	0.216	0.247
	21	0.166	0.157	0.153	0.137	0.153	0.259	0.246	0.234	0.196	0.234
	22	0.179	0.162	0.163	0.147	0.163	0.286	0.268	0.249	0.216	0.255
D	**23**	0.187	0.168	0.158	0.150	0.166	0.297	0.273	0.259	0.224	0.263
	24	0.220	0.189	0.170	0.175	0.189	0.340	0.298	0.278	0.253	0.292
	25	0.226	0.188	0.172	0.168	0.189	0.346	0.305	0.287	0.249	0.297
	26	0.243	0.182	0.168	0.173	0.192	0.388	0.320	0.300	0.292	0.325
	27	0.156	0.149	0.143	0.131	0.145	0.243	0.246	0.232	0.197	0.230
	28	0.169	0.161	0.153	0.149	0.158	0.257	0.259	0.244	0.212	0.243
	29	0.184	0.170	0.158	0.156	0.167	0.294	0.277	0.261	0.232	0.266
	30	0.166	0.159	0.151	0.141	0.154	0.266	0.260	0.244	0.207	0.244
	31	0.197	0.170	0.160	0.148	0.169	0.291	0.264	0.243	0.208	0.252
	32	0.212	0.184	0.171	0.169	0.184	0.323	0.294	0.271	0.237	0.281

Table 5.2. FRVs for DT case studies [l/100km*100kg]

5.2. Environmental modelling

As shown in paragraph 3.3., the conceived environmental models consist in use stage plans developed by the software GaBi6 and composed by the two processes WTT (Well-To-Tank) and TTW (Tank-To-Wheel). In the construction of the model the TTW process has been completely modelled from the beginning by an analytical parametrization of input/output flows while the WTT process has been directly taken from the GaBi6 process database (section “Energy conversion – Fuel production – Refinery products”) without any modification. For this reason in the following pages the only TTW process is described in detail in terms of input/output flows and equations which model the flows. As usually the treatment is conducted separately for the typologies of LCA study *LCA of a specific vehicle component* and *comparative LCA between a reference and an innovative lightweight alternative*; this latter is treated separately between the cases of PMR only and SE.

5.2.1. LCA of a specific vehicle component

The input and output flows of TTW process are reported in Table 5.3.: for each flow a qualitative description and the reference from GaBi6 database are reported.

	LCA of a specific vehicle component: flows of TTW process	
	Description	**GaBi6 database**
INPUT	Amount of Fuel Consumption during operation attributed to the component (FC_{use_comp})	*Gasoline (Diesel) - Refinery products* [kg]
OUTPUT	Amount of benzene emission during operation attributed to the component ($benzene_{use\_comp}$)	*Benzene – Group NMVOC to air* [g]
	Amount of CH_4 emission during operation attributed to the component (CH_{4use_comp})	*Methane – Organic emissions to air (group VOC)* [g]
	Amount of CO emission during operation attributed to the component (CO_{use_comp})	*Carbon monoxide – Inorganic emissions to air* [g]
	Amount of biogenic CO_2 emission during operation attributed to the component ($CO_{2BIO\_use\_comp}$)	*Carbon dioxide (biotic) – Inorganic emissions to air* [g]
	Amount of fossil CO_2 emission during operation attributed to the component ($CO_{2FOS\_use\_comp}$)	*Carbon dioxide (fossil) – Inorganic emissions to air* [g]
	Amount of N_2O emission during operation attributed to the component ($N_2O_{use\_comp}$)	*Nitrous oxide (laughing gas) – Inorganic emissions to air* [g]
	Amount of NH_3 emission during operation attributed to the component (NH_{3use_comp})	*Ammonia – Inorganic emissions to air* [g]
	Amount of NMVOC emission during operation attributed to the component ($NMVOC_{use\_comp}$)	*NMVOC (unspecified) – Group NMVOC to air* [g]
	Amount of NO emission during operation attributed to the component (NO_{use_comp})	*Nitrogen monoxide – Inorganic emissions to air* [g]
	Amount of NO_2 emission during operation attributed to the component (NO_{2use_comp})	*Nitrogen dioxide – Inorganic emissions to air* [g]
	Amount of particulate emission during operation attributed to the component ($particulate_{use\_comp}$)	*Dust (PM2.5) – Particles to air* [g]
	Amount of SO_2 emission during operation attributed to the component ($SO_{2\_use\_comp}$)	*Sulphur dioxide – Inorganic emissions to air* [kg]

Table 5.3. Environmental model – LCA of a specific vehicle component: inputs/outputs and related GaBi6 flows of TTW process

The basic equations of TTW process are reported for each flow in Table 5.4.:

		LCA of a specific vehicle component: basic equations of TTW process
INPUT	FC_{use_comp}	$FC_{use\_comp} = \frac{FRV_{PMR} * m_{comp} * mileage_{use}}{10000} * \rho_{fuel}$ Eq. 5.1.
OUTPUT	$benzene_{use\_comp}$	$emiss\_i_{use\_comp} = emiss\_i_{veh\_km} * mileage_{use} * \frac{FC_{use\_comp}}{FC_{use\_veh}}$ Eq. 5.2. Where: $emiss\_i_{veh\_km} = share_{mw} * emiss\_i_{veh\_km\_mw} + share_{mw} * emiss\_i_{veh\_km\_mw} + share_{mw} * emiss\_i_{veh\_km\_mw}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$CH_{4\_use\_comp}$	
	CO_{use_comp}	
	$N_2O_{use\_comp}$	
	$NH_{3\_use\_comp}$	
	$NMVOC_{use\_comp}$	
	NO_{use_comp}	
	$NO_{2\_use\_comp}$	
	$particulate_{use\_comp}$	
	$CO_{2BIO\_use\_comp}$	$CO_{2BIO\_use\_comp} = CO_{2BIO\_veh\_km} * mileage_{use} * \frac{FC_{use\_comp}}{FC_{use\_veh}}$ Eq. 5.3. Where: $CO_{2BIO\_veh\_km} = CO_{2\_veh\,km} * share\ CO_{2BIO}$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$CO_{2FOS\_use\_comp}$	$CO_{2FOS\_use\_comp} = CO_{2FOS\_veh\_km} * mileage_{use} * \frac{FC_{use\_comp}}{FC_{use\_veh}}$ Eq. 5.4. Where: $CO_{2FOS\_veh\_km} = CO_{2\_veh\_km} * (1 - share\ CO_{2BIO})$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$SO_{2\_use\_comp}$	$SO_{2\_use\_comp} = SO_{2\_veh\_km} * mileage_{use} * \frac{FC_{use\_comp}}{FC_{use\_veh}}$ Eq. 5.5. Where: $SO_{2\_veh\_km} = \frac{ppm_{sulphur}}{1000000} * 2 * \frac{FC_{veh\_100km}}{100} * \rho_{fuel}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$

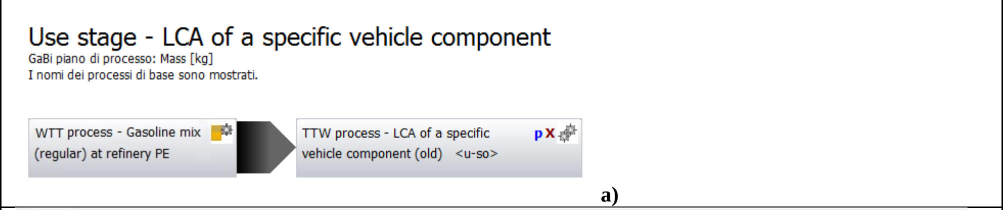
Table 5.4. Environmental model – LCA of a specific vehicle component: basic equations of TTW process

Where:
$CO_{2BIO\_use\_comp}$ = amount of biogenic CO_2 emission during operation attributed to the component [g];
$CO_{2BIO\_veh\_km}$ = per-kilometre biogenic CO_2 emission [g/km];
$CO_{2FOS\_use\_comp}$ = amount of fossil CO_2 emission during operation attributed to the component [g];
$CO_{2FOS\_veh\_km}$ = per-kilometre fossil CO_2 emission [g/km];

$CO_{2\_veh\_km}$ = per-kilometre CO_2 emission [g/km];
$CO_{2\_veh\_km\_mw}$, $CO_{2\_veh\_km\_ru}$, $CO_{2\_veh\_km\_ur}$ = per-kilometre CO_2 emission respectively for motorway, rural and urban route [g/km];
$emiss\_i_{veh\_km}$ = per-kilometre amount of emission *i*: benzene [g/km], CH_4 [g/km] , CO [g/km], N_2O [g/km], NH_3 [g/km], NMVOC [g/km], NO [g/km], NO_2 [g/km], particulate [g/km];
$emiss\_i_{veh\_km\_mw}$, $emiss\_i_{veh\_km\_ru}$, $emiss\_i_{veh\_km\_ur}$ = per-kilometre amount of emission i respectively for motorway, rural and urban route [g/km];
FC_{use_comp} = amount of Fuel Consumption during operation attributed to the component [kg];
FC_{use_veh} = amount of Fuel Consumption during operation of entire vehicle [kg];
$emiss\_i_{use\_comp}$ = amount of emission *i* during operation attributed to the component: benzene [g], CH_4 [g] , CO [g], N_2O [g], NH_3 [g], NMVOC [g], NO [g], NO_2 [g], particulate [g];
FC_{veh_100km} = per-100kilometre Fuel Consumption of vehicle [l/100km];
FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction only [l/100km*100kg];
m_{comp} = component mass [kg];
$mileage_{use}$ = vehicle mileage during operation [km];
ppm_{suphur} = sulphur content in fuel [ppm];
$share\ CO_{2\ BIO}$ = share of biogenic C in fuel [null];
$share_{mw}$, $share_{ru}$, $share_{ur}$ = share of total mileage respectively of motorway, rural and urban route [null];
$SO_{2\_use\_comp}$ = amount of SO_2 emission during operation attributed to the component [kg];
$SO_{2\_veh\_km}$ = per-kilometre SO_2 emission [kg/km];
ρ_{fuel} = fuel density [kg/l].

Figure 5.5. describes the use stage plan by imagines directly taken from the GaBi6 software which report:

- composition of the overall plan
- process database window of TTW process.



Use stage - LCA of a specific vehicle component

GaBi piano di processo: Mass [kg]

I nomi dei processi di base sono mostrati.

a)

Parametro

Parametro	Formula	Commento, unitá, default
benz_use_comp	benz_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gBenzene]
benz_veh_km	((share_mw*benz_veh_km_mw)+(share_ru*benz_veh_km_ru)+(share_ur*benz_veh_km_ur))	[gBenzene/km]
benz_veh_km_mw		[gBenzene/km]
benz_veh_km_ru		[gBenzene/km]
benz_veh_km_ur		[gBenzene/km]
CH4_use_comp	CH4_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gCH4]
CH4_veh_km	((share_mw*CH4_veh_km_mw)+(share_ru*CH4_veh_km_ru)+(share_ur*CH4_veh_km_ur))	[gCH4/km]
CH4_veh_km_mw		[gCH4/km]
CH4_veh_km_ru		[gCH4/km]
CH4_veh_km_ur		[gCH4/km]
CO_use_comp	CO_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gCO]
CO_veh_km	((share_mw*CO_veh_km_mw)+(share_ru*CO_veh_km_ru)+(share_ur*CO_veh_km_ur))	[gCO/km]
CO_veh_km_mw		[gCO/km]
CO_veh_km_ru		[gCO/km]
CO_veh_km_ur		[gCO/km]
CO2_veh_km	((share_mw*CO2_veh_km_mw)+(share_ru*CO2_veh_km_ru)+(share_ur*CO2_veh_km_ur))	[gCO2/km]
CO2_veh_km_mw		[gCO2/km]
CO2_veh_km_ru		[gCO2/km]
CO2_veh_km_ur		[gCO2/km]
CO2BIO_use_comp	CO2BIO_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gCO2BIO]
CO2BIO_veh_km	CO2_veh_km*share_CO2BIO	[gCO2BIO/km]
CO2FOS_use_comp	CO2FOS_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gCO2FOS]
CO2FOS_veh_km	CO2_veh_km*(1-share_CO2BIO)	[gCO2FOS/km]
FC_veh_100km		[l/100km]
FCuse_comp	((FRV_PMR*mass_comp*mileage_use)/10000)*ro_fuel	[kg]
FCuse_veh	((FC_veh_100km/100)*mileage_use)*ro_fuel	[kg]
FRV_PMR		[l/100km*100kg]
mass_comp		[kg]
mileage_use		[km]
N2O_use_comp	N2O_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gN2O]
N2O_veh_km	((share_mw*N2O_veh_km_mw)+(share_ru*N2O_veh_km_ru)+(share_ur*N2O_veh_km_ur))	[gN2O/km]
N2O_veh_km_mw		[gN2O/km]
N2O_veh_km_ru		[gN2O/km]
N2O_veh_km_ur		[gN2O/km]
NH3_use_comp	NH3_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gNH3]
NH3_veh_km	((share_mw*NH3_veh_km_mw)+(share_ru*NH3_veh_km_ru)+(share_ur*NH3_veh_km_ur))	[gNH3/km]
NH3_veh_km_mw		[gNH3/km]
NH3_veh_km_ru		[gNH3/km]
NH3_veh_km_ur		[gNH3/km]
NMVOC_use_comp	NMVOC_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gNMVOC]
NMVOC_veh_km	((share_mw*NMVOC_veh_km_mw)+(share_ru*NMVOC_veh_km_ru)+(share_ur*NMVOC_veh_km_ur)	[gNMVOC/km]
NMVOC_veh_km_mw		[gNMVOC/km]
NMVOC_veh_km_ru		[gNMVOC/km]

b)

NMVOC_veh_km_ur		[gNMVOC/km]
NO_use_comp	NO_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gNO]
NO_veh_km	((share_mw*NO_veh_km_mw)+(share_ru*NO_veh_km_ru)+(share_ur*NO_veh_km_ur))	[gNO/km]
NO_veh_km_mw		[gNO/km]
NO_veh_km_ru		[gNO/km]
NO_veh_km_ur		[gNO/km]
NO2_use_comp	NO2_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gNO2]
NO2_veh_km	((share_mw*NO2_veh_km_mw)+(share_ru*NO2_veh_km_ru)+(share_ur*NO2_veh_km_ur))	[gNO2/km]
NO2_veh_km_mw		[gNO2/km]
NO2_veh_km_ru		[gNO2/km]
NO2_veh_km_ur		[gNO2/km]
part_use_comp	part_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[gParticulate matter]
part_veh_km	((share_mw*part_veh_km_mw)+(share_ru*part_veh_km_ru)+(share_ur*part_veh_km_ur))	[gParticulate matter/km]
part_veh_km_mw		[gParticulate matter/km]
part_veh_km_ru		[gParticulate matter/km]
part_veh_km_ur		[gParticulate matter/km]
ppm_sulfur		[ppm]
ro_fuel		[kg/l]
share_check	share_mw+share_ru+share_ur	[null]
share_CO2BIO		[null]
share_mw		[null]
share_ru		[null]
share_ur		[null]
SO2_use_comp	SO2_veh_km*mileage_use*(FCuse_comp/FCuse_veh)	[kgSO2]
SO2_veh_km	(ppm_sulfur/1000000)*2*(FC_veh_100km/100)*ro_fuel	[kgSO2/km]

Completezza: Nessun affermazione

Inputs

Parametro	Flusso	Unità
FCuse_comp	**Gasoline (regular) [Refinery products]**	**kg**

Outputs

Parametro	Flusso	Unità
NH3_use_comp	Ammonia [Inorganic emissions to air]	g
benz_use_comp	Benzene [Group NMVOC to air]	g
CO2FOS_use_comp	Carbon dioxide [Inorganic emissions to air]	g
CO2BIO_use_comp	Carbon dioxide (biotic) [Inorganic emissions to air]	g
CO_use_comp	Carbon monoxide [Inorganic emissions to air]	g
part_use_comp	Dust (PM2.5) [Particles to air]	g
CH4_use_comp	Methane [Organic emissions to air (group VOC)]	g
NO2_use_comp	Nitrogen dioxide [Inorganic emissions to air]	g
NO_use_comp	Nitrogen monoxide [Inorganic emissions to air]	g
N2O_use_comp	Nitrous oxide (laughing gas) [Inorganic emissions to air]	g
NMVOC_use_comp	NMVOC (unspecified) [Group NMVOC to air]	g
SO2_use_comp	Sulphur dioxide [Inorganic emissions to air]	kg

b)

Figure 5.5. Environmental model – LCA of a specific vehicle component: composition of overall use stage plan (a); Process database window of TTW process (b)

5.2.2. Comparative LCA between a reference and an innovative lightweight alternative in case of PMR only

The input and output flows of TTW process are reported in Table 5.5.: for each flow a qualitative description and the reference from GaBi6 database are reported.

	Comparative LCA in case of PMR: flows of TTW process	
	Parameters	**GaBi6 flows**
INPUT	Amount of Fuel Consumption saved during operation thanks to light-weighting in case of PMR only ($FC_{use\_sav\_PMR}$)	*Gasoline (Diesel) - Refinery products* [kg]
OUTPUT	Amount of biogenic CO_2 emission saved during operation thanks to light-weighting in case of PMR only ($CO_{2BIO\_use\_sav\_PMR}$)	*Carbon dioxide (biotic) – Inorganic emissions to air* [g]
	Amount of fossil CO_2 emission saved during operation thanks to light-weighting in case of PMR only ($CO_{2FOS\_use\_sav\_PMR}$)	*Carbon dioxide (fossil) – Inorganic emissions to air* [g]
	Amount of SO_2 emission saved during operation thanks to light-weighting in case of PMR only ($SO_{2\_use\_sav\_PMR}$)	*Sulphur dioxide – Inorganic emissions to air* [kg]

Table 5.5. Environmental model – Comparative LCA between a reference and an innovative lightweight alternative (PMR): inputs/outputs and related GaBi6 flows of TTW process

The basic equations of TTW process are reported for each flow in Table 5.6:

		Comparative LCA in case of PMR: basic equations of TTW process
INPUT	$FC_{use\_sav\_PMR}$	$FC_{use\_sav\_PMR} = \frac{FRV_{PMR} * m_{sav} * mileage_{use}}{10000} * \rho_{fuel}$ Eq. 5.6.
OUTPUT	$CO_{2BIO\_use\_sav\_PMR}$	$CO_{2BIO\_use\_sav\_PMR} = CO_{2BIO\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_PMR}}{FC_{use\_veh}}$ Eq. 5.7. Where: $CO_{2BIO\_veh\_km} = CO_{2\_veh\,km} * share\ CO_{2BIO}$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$CO_{2FOS\_use\_sav\_PMR}$	$CO_{2FOS\_use\_sav\_PMR} = CO_{2FOS\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_PMR}}{FC_{use\_veh}}$ Eq. 5.8. Where: $CO_{2FOS\_veh\_km} = CO_{2\_veh\_km} * (1 - share\ CO_{2BIO})$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$SO_{2\_use\_sav\_PMR}$	$SO_{2\_use\_sav\_PMR} = SO_{2\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_PMR}}{FC_{use\_veh}}$ Eq. 5.9. Where: $SO_{2\_veh\_km} = \frac{ppm_{sulphur}}{1000000} * 2 * \frac{FC_{veh\_100km}}{100} * \rho_{fuel}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$

Table 5.6. Environmental model – Comparative LCA between a reference and an innovative lightweight alternative (PMR): basic equations of TTW process

Where:

$CO_{2BIO\_veh\_km}$ = per-kilometre biogenic CO_2 emission of reference vehicle [g/km];
$CO_{2BIO\_use\_sav\_PMR}$ = amount of biogenic CO_2 emission saved during operation thanks to light-weighting in case of Primary Mass Reduction only [g];
$CO_{2FOS\_use\_sav\_PMR}$ = amount of fossil CO_2 emission saved during operation thanks to light-weighting in case of Primary Mass Reduction only [g];
$CO_{2FOS\_veh\_km}$ = per-kilometre fossil CO_2 emission of reference vehicle [g/km];
$CO_{2\_veh\_km}$ = per-kilometre CO_2 emission of reference vehicle [g/km];
$CO_{2\_veh\_km\_mw}$, $CO_{2\_veh\_km\_ru}$, $CO_{2\_veh\_km\_ur}$ = per-kilometre CO_2 emission of reference vehicle respectively for motorway, rural and urban route [g/km];
$FC_{use\_sav\_PMR}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in case of Primary Mass Reduction only [kg];
FC_{use_veh} = amount of Fuel Consumption during operation of reference vehicle [kg];
FC_{veh_100km} = per-100kilometre Fuel Consumption of reference vehicle [l/100km];
FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction only [l/100km*100kg];
m_{sav} = saved mass thanks to light-weighting [kg];
$mileage_{use}$ = vehicle mileage during operation [km];
ppm_{suphur} = sulphur content in fuel [ppm];
$share\ CO_{2BIO}$ = share of biogenic C in fuel [null];
$share_{mw}$, $share_{ru}$, $share_{ur}$ = share of total mileage respectively for motorway, rural and urban route [null];
$SO_{2\_use\_sav\_PMR}$ = amount of SO_2 emission saved during operation thanks to light-weighting in case of Primary Mass Reduction only [kg];
$SO_{2\_veh\_km}$ = per-kilometre SO_2 emission of reference vehicle [kg/km];
ρ_{fuel} = fuel density [kg/l].

Figure 5.6. describes the use stage plan by imagines directly taken from the GaBi6 software which report:

- composition of overall use stage plan
- process database window of TTW process.

Use stage - Comparative LCA between a reference and an innovative lightweight alternative (PMR)
GaBi piano di processo: Mass [kg]
I nomi dei processi di base sono mostrati.

WTT process - Gasoline mix (regular) at refinery PE

TTW process - Comparative LCA between a reference and an innovative lightweight alternative (PMR) <u-so>

Parametro

Parametro	Formula	Commento, unitá, default
CO2_veh_km	((share_mw*CO2_veh_km_mw)+(share_ru*CO2_veh_km_ru)+(share_ur*CO2_veh_km_ur))	[gCO2/km]
CO2_veh_km_mw		[gCO2/km]
CO2_veh_km_ru		[gCO2/km]
CO2_veh_km_ur		[gCO2/km]
CO2BIO_veh_km	CO2_veh_km*share_CO2BIO	[gCO2BIO/km]
CO2BIOusesavPMR	CO2BIO_veh_km*mileage_use*(FCuse_sav_PMR/FCuse_veh)	[gCO2BIO]
CO2FOS_veh_km	CO2_veh_km*(1-share_CO2BIO)	[gCO2FOS/km]
CO2FOSusesavPMR	CO2FOS_veh_km*mileage_use*(FCuse_sav_PMR/FCuse_veh)	[gCO2FOS]
FC_veh_100km		[l/100km]
FCuse_sav_PMR	((FRV_PMR*mass_sav*mileage_use)/10000)*ro_fuel	[kg]
FCuse_veh	(FC_veh_100km/100)*mileage_use*ro_fuel	[kg]
FRV_PMR		[l/100km*100kg]
mass_sav		[kg]
mileage_use		[km]
ppm_sulfur		[ppm]
ro_fuel		[kg/l]
share_check	share_mw+share_ru+share_ur	[null]
share_CO2BIO		[null]
share_mw		[null]
share_ru		[null]
share_ur		[null]
SO2_use_sav_PMR	SO2_veh_km*mileage_use*(FCuse_sav_PMR/FCuse_veh)	[kgSO2]
SO2_veh_km	(ppm_sulfur/1000000)*2*(FC_veh_100km/100)*ro_fuel	[kgSO2/km]

Completezza: Nessun affermazione

Inputs

Parametro	Flusso	Unità
FCuse_sav_PMR	**Gasoline (regular) [Refinery products]**	**kg**

Outputs

Parametro	Flusso	Unità
CO2FOSusesavPMR	Carbon dioxide [Inorganic emissions to air]	g
CO2BIOusesavPMR	Carbon dioxide (biotic) [Inorganic emissions to air]	g
SO2_use_sav_PMR	Sulphur dioxide [Inorganic emissions to air]	kg

Figure 5.6. Environmental model – Comparative LCA between a reference and an innovative lightweight alternative (PMR): composition of overall use stage plan (a); Process database window of TTW process (b)

5.2.3. Comparative LCA between a reference and an innovative lightweight alternative in case of SE

The input and output flows of TTW process are reported in Table 5.7.: for each flow a qualitative description and the reference from GaBi6 database are reported.

	Comparative LCA in case of SE: flows of TTW process	
	Parameters	**GaBi6 flows**
INPUT	Amount of Fuel Consumption saved during operation thanks to light-weighting in case of SE ($FC_{use\_sav\_SE}$)	*Gasoline (Diesel) - Refinery products* [kg]
OUTPUT	Amount of biogenic CO_2 emission saved during operation thanks to light-weighting in case of SE ($CO_{2BIO\_use\_sav\_SE}$)	*Carbon dioxide (biotic) – Inorganic emissions to air* [g]
	Amount of fossil CO_2 emission saved during operation thanks to light-weighting in case of SE ($CO_{2FOS\_use\_sav\_SE}$)	*Carbon dioxide (fossil) – Inorganic emissions to air* [g]
	Amount of SO_2 emission saved during operation thanks to light-weighting in case of SE ($SO_{2\_use\_sav\_SE}$)	*Sulphur dioxide – Inorganic emissions to air* [kg]

Table 5.7. Environmental model – Comparative LCA between a reference and an innovative lightweight alternative (SE): inputs/outputs and related GaBi6 flows of TTW process

The basic equations of TTW process are reported for each flow in Table 5.8.:

		Comparative LCA in case of SE: basic equations of TTW process
INPUT	$FC_{use\_sav\_SE}$	$FC_{use\_sav\_SE} = \frac{FRV_{SE} * m_{sav} * mileage_{use}}{10000} * \rho_{fuel}$ Eq. 5.10.
OUTPUT	$CO_{2BIO\_use\_sav\_SE}$	$CO_{2BIO\_use\_sav\_SE} = CO_{2BIO\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_SE}}{FC_{use\_veh}}$ Eq. 5.11. Where: $CO_{2BIO\_veh\_km} = CO_{2\_veh\ km} * share\ CO_{2BIO}$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$CO_{2FOS\_use\_sav\_SE}$	$CO_{2FOS\_use\_sav\_SE} = CO_{2FOS\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_SE}}{FC_{use\_veh}}$ Eq. 5.12. Where: $CO_{2FOS\_veh\_km} = CO_{2\_veh\_km} * (1 - share\ CO_{2BIO})$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$SO_{2\_use\_sav\_SE}$	$SO_{2\_use\_sav\_SE} = SO_{2\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav\_SE}}{FC_{use\_veh}}$ Eq. 5.13. Where: $SO_{2\_veh\_km} = \frac{ppm_{sulphur}}{1000000} * 2 * \frac{FC_{veh\_100km}}{100} * \rho_{fuel}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$

Table 5.8. Environmental model – Comparative LCA between a reference and an innovative lightweight alternative (SE): basic equations of TTW process

Where:

$CO_{2BIO\_veh\_km}$ = per-kilometre biogenic CO_2 emission of reference vehicle [g/km];
$CO_{2BIO\_use\_sav\_SE}$ = amount of biogenic CO_2 emission saved during operation thanks to light-weighting in case of Secondary Effects [g];
$CO_{2FOS\_use\_sav\_SE}$ = amount of fossil CO_2 emission saved during operation thanks to light-weighting in case of Secondary Effects [g];
$CO_{2FOS\_veh\_km}$ = per-kilometre fossil CO_2 emission of reference vehicle [g/km];
$CO_{2\_veh\_km}$ = per-kilometre CO_2 emission of reference vehicle [g/km];
$CO_{2\_veh\_km\_mw}$, $CO_{2\_veh\_km\_ru}$, $CO_{2\_veh\_km\_ur}$ = per-kilometre CO_2 emission of reference vehicle respectively for motorway, rural and urban route [g/km];
$FC_{use\_sav\_SE}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in case of Secondary Effects [kg];
FC_{use_veh} = amount of Fuel Consumption during operation of reference vehicle [kg];
FC_{veh_100km} = per-100kilometre Fuel Consumption of reference vehicle [l/100km];
FRV_{SE} = Fuel Reduction Value in case of Secondary Effects [l/100km*100kg];
m_{sav} = saved mass thanks to light-weighting [kg];
$mileage_{use}$ = vehicle mileage during operation [km];
ppm_{suphur} = sulphur content in fuel [ppm];
$share\ CO_{2BIO}$ = share of biogenic C in fuel [null];
$share_{mw}$, $share_{ru}$, $share_{ur}$ = share of total mileage respectively for motorway, rural and urban route [null];
$SO_{2\_use\_sav\_SE}$ = amount of SO_2 emission saved during operation thanks to light-weighting in case of Secondary Effects [kg];
$SO_{2\_veh\_km}$ = per-kilometre SO_2 emission of reference vehicle [kg/km];
ρ_{fuel} = fuel density [kg/l].

Figure 5.7. describes the use stage plan by imagines directly taken from the GaBi6 software which report:

- composition of overall use stage plan
- process database window of TTW process.

Parametro

Parametro	Formula	Commento, unitá, default
CO2_veh_km	((share_mw*CO2_veh_km_mw)+(share_ru*CO2_veh_km_ru)+(share_ur*CO2_veh_km_ur))	[gCO2/km]
CO2_veh_km_mw		[gCO2/km]
CO2_veh_km_ru		[gCO2/km]
CO2_veh_km_ur		[gCO2/km]
CO2BIO_veh_km	CO2_veh_km*share_CO2BIO	[gCO2BIO/km]
CO2BIOusesavSE	CO2BIO_veh_km*mileage_use*(FCuse_sav_SE/FCuse_veh)	[gCO2BIO]
CO2FOS_veh_km	CO2_veh_km*(1-share_CO2BIO)	[gCO2FOS/km]
CO2FOSusesavSE	CO2FOS_veh_km*mileage_use*(FCuse_sav_SE/FCuse_veh)	[gCO2FOS]
FC_veh_100km		[l/100km]
FCuse_sav_SE	((FRV_SE*mass_sav*mileage_use)/10000)*ro_fuel	[kg]
FCuse_veh	(FC_veh_100km/100)*mileage_use*ro_fuel	[kg]
FRV_SE		[l/100km*100kg]
mass_sav		[kg]
mileage_use		[km]
ppm_sulfur		[ppm]
ro_fuel		[kg/l]
share_check	share_mw+share_ru+share_ur	[null]
share_CO2BIO		[null]
share_mw		[null]
share_ru		[null]
share_ur		[null]
SO2_use_sav_SE	SO2_veh_km*mileage_use*(FCuse_sav_SE/FCuse_veh)	[kgSO2]
SO2_veh_km	(ppm_sulfur/1000000)*2*(FC_veh_100km/100)*ro_fuel	[kgSO2/km]

Completezza: Nessun affermazione

Inputs

Parametro	Flusso	Unità
FCuse_sav_SE	**Gasoline (regular) [Refinery products]**	**kg**

Outputs

Parametro	Flusso	Unità
CO2FOSusesavSE	Carbon dioxide [Inorganic emissions to air]	g
CO2BIOusesavSE	Carbon dioxide (biotic) [Inorganic emissions to air]	g
SO2_use_sav_SE	Sulphur dioxide [Inorganic emissions to air]	kg

Figure 5.7. Environmental model – Comparative LCA between a reference and an innovative lightweight alternative (SE): composition of overall use stage plan (a); Process database window of TTW process (b)

6. Discussion

Similarly to chapter 5 “Results”, the discussion is subdivided into the main sections simulation modelling and environmental modelling.

6.1. Simulation modelling

In this paragraph the values of FC and FRV obtained by simulation modelling are critically commented at the level of both engine technology (GT, DT) and vehicle class (A/B, C, D); special attention is paid to the FRV coefficient which represents the central element of the study.

6.1.1. Fuel consumption

Table SI6.1.1. in SI appendix-chapter 6 characterizes the values of FC of reference mass-configuration in terms of

- minimum and maximum
- size of range maximum – minimum
- arithmetic mean
- standard deviation

for both single classes and entirety of case studies. Basing on these data, some critical considerations are reported below.

The first one regards the influence on FC of vehicle class. At this scope Figure 6.1. compares the arithmetic mean of FC over case studies on the same driving cycle; the black bars identify the maximum variability of FC around the arithmetic mean.

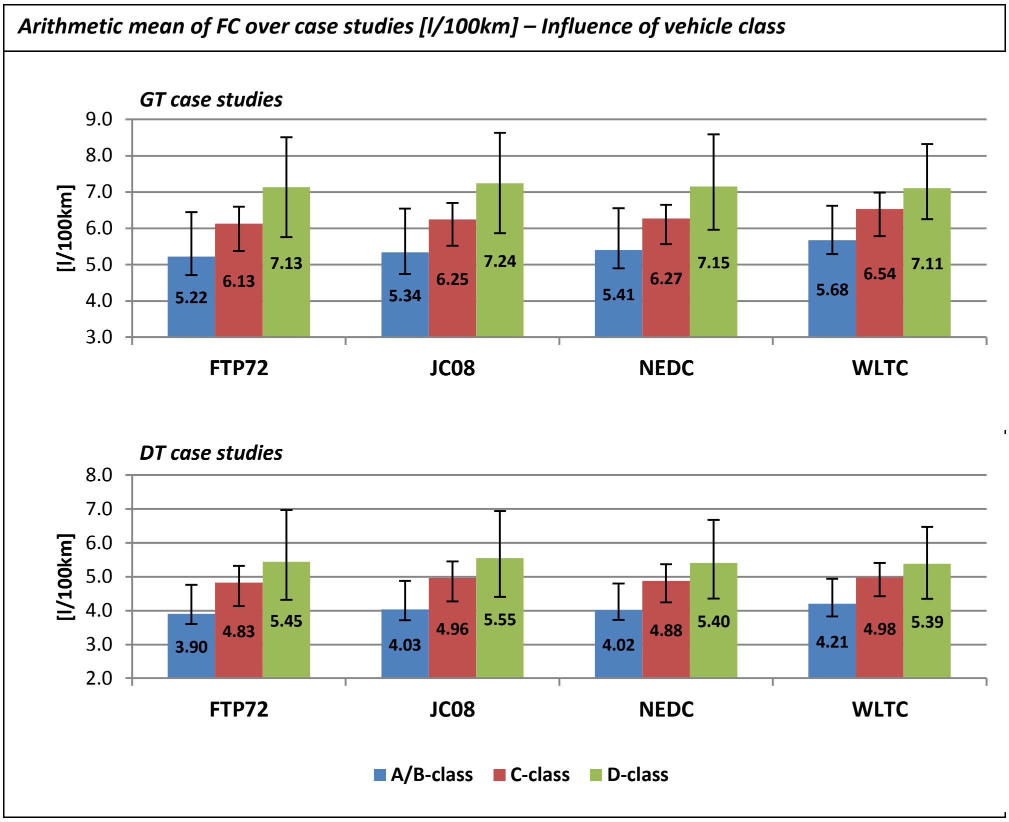


Figure 6.1. Arithmetic mean over case studies of FC of reference mass-configuration [l/100km]: influence of vehicle class (GT)

As expected, for both GT and DT technologies FC grows at vehicle class level increasing. The largest variability refers to D-class while A/B and C show similar range of variation; this is also confirmed by the values of standard deviation reported in Table SI6.1.1. of SI appendix-chapter 6.

The second critical consideration regards the influence on FC of driving cycle. At this scope Figure 6.2. compares the arithmetic mean of FC over case studies on the same vehicle class; the black bars identify the maximum variability around the arithmetic mean.

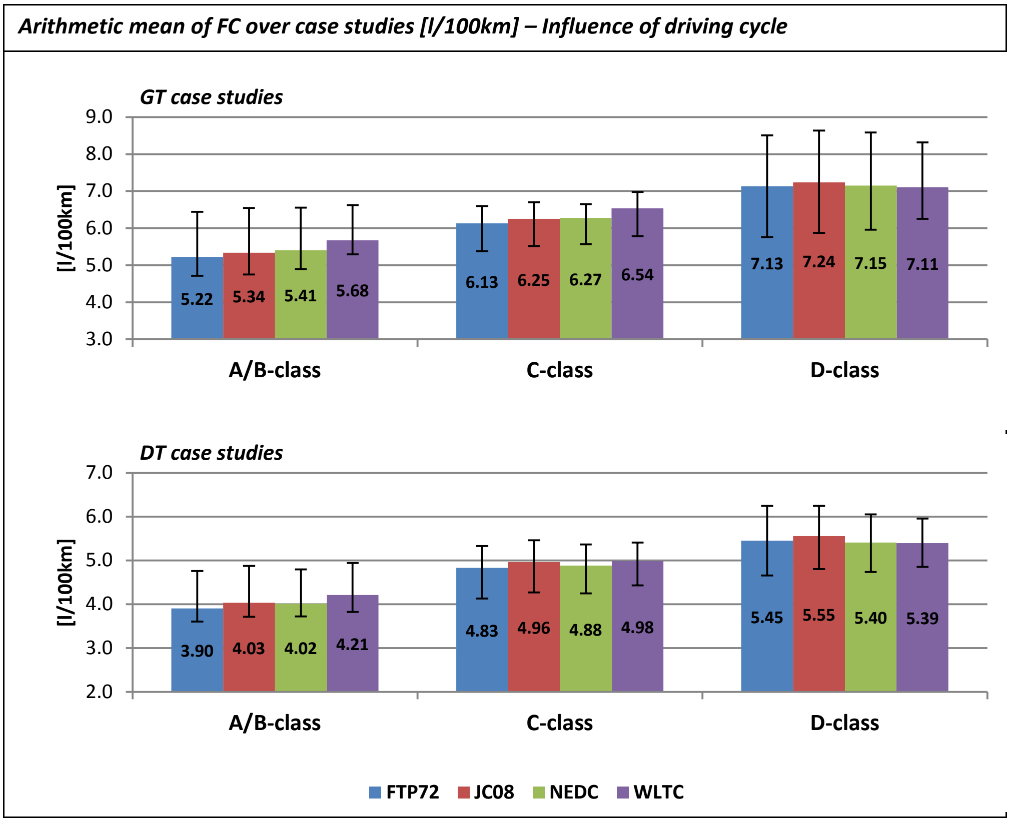


Figure 6.2. Arithmetic mean over case studies of FC of reference mass-configuration [l/100km]: influence of driving cycle (GT and DT case studies)

The influence of driving cycle is higher for A/B and C classes and this effect is more pronounced for GT vehicles. A clear trend of FC based on driving cycle is not definable; for A/B and C classes the highest FC refers to the WLTC while for the D-class the most expensive is the JC08.

6.1.2. Fuel Reduction Value

The values of FRV obtained by simulation modelling are critically commented by two sub-paragraphs which concern respectively GT and DT engine technologies. Both sub-paragraphs are structured into the following points: analysis of results, influence of vehicle class, influence of driving cycle, influence of SEs, influence of S&S system, dependence on vehicle technical features and sensitivity analysis.

6.1.2.1. FRV – GT case studies

FRV – GT case studies: analysis of results

Table SI6.2.1. in SI appendix-chapter 6 characterizes the values of FRV in terms of

- minimum and maximum

- size of range maximum – minimum
- arithmetic mean
- standard deviation

for both single classes and entirety of case studies.

Figure 6.3. reports the arithmetic mean of FRV over case studies per driving cycle: the black bars identify the range of variation around the arithmetic mean while Figure 6.4. reports the size of such a range.

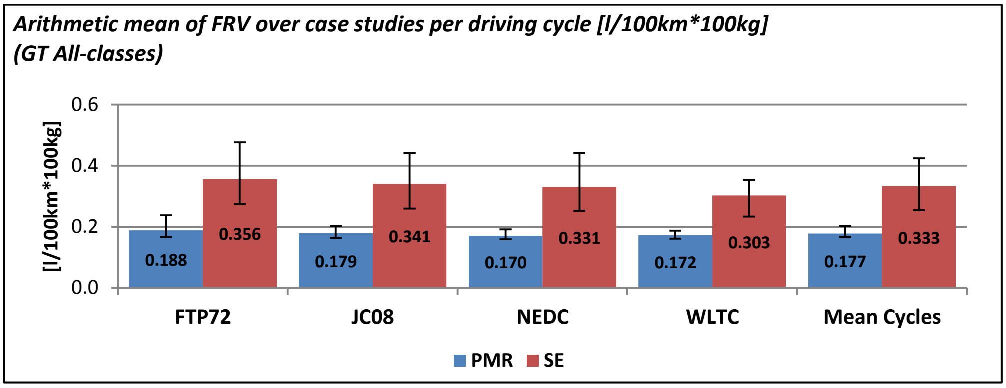


Figure 6.3. Arithmetic mean of FRV over case studies per driving cycle [l/100km*100kg] (GT – All classes)

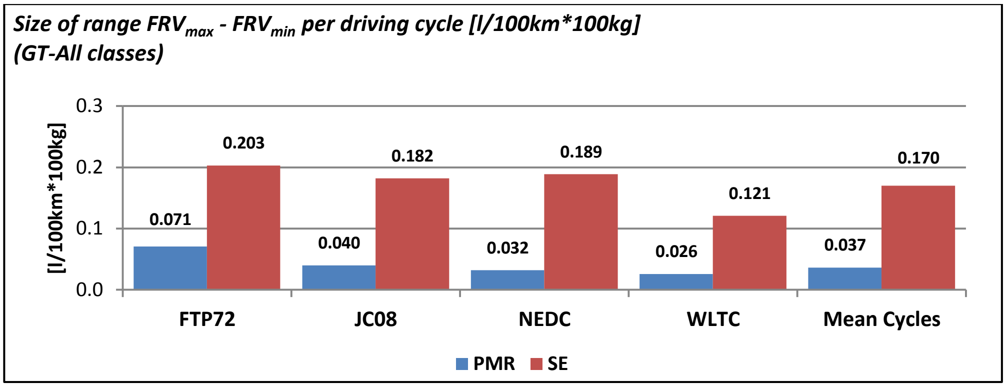


Figure 6.4. Arithmetic mean of FRV over case studies per driving cycle: size of range $FRV_{max} - FRV_{min}$ [l/100km*100kg] (GT – All classes)

Data show that:

- the arithmetic mean of FRV_{PMR} over case studies varies, depending on cycle, within the range 0.170-0.188 [l/100km*100kg]; on the other hand the arithmetic mean of FRV_{SE} is notably higher, between 0.303 and 0.356 [l/100km*100kg];
- FRV_{SE} is characterized by a higher dispersion around the arithmetic mean with respect to FRV_{PMR}: for FRV_{SE} the size of range maximum-minimum varies, depending on cycle, between 0.121 and 0.203 [l/100km*100kg] while for FRV_{PMR} it does not exceed 0.071 [l/100km*100kg]. This is also confirmed by

the higher values of standard deviation of FRV_{SE} with respect to FRV_{PMR} (Table SI6.2.1. in SI appendix-chapter 6).

FRV-GT case studies: influence of vehicle class

This section analyses the influence on FRV of vehicle class by evidencing the variation that occurs passing from one class to the other: Figure 6.5. reports the arithmetic mean of FRV within the class basing on the same driving cycle.

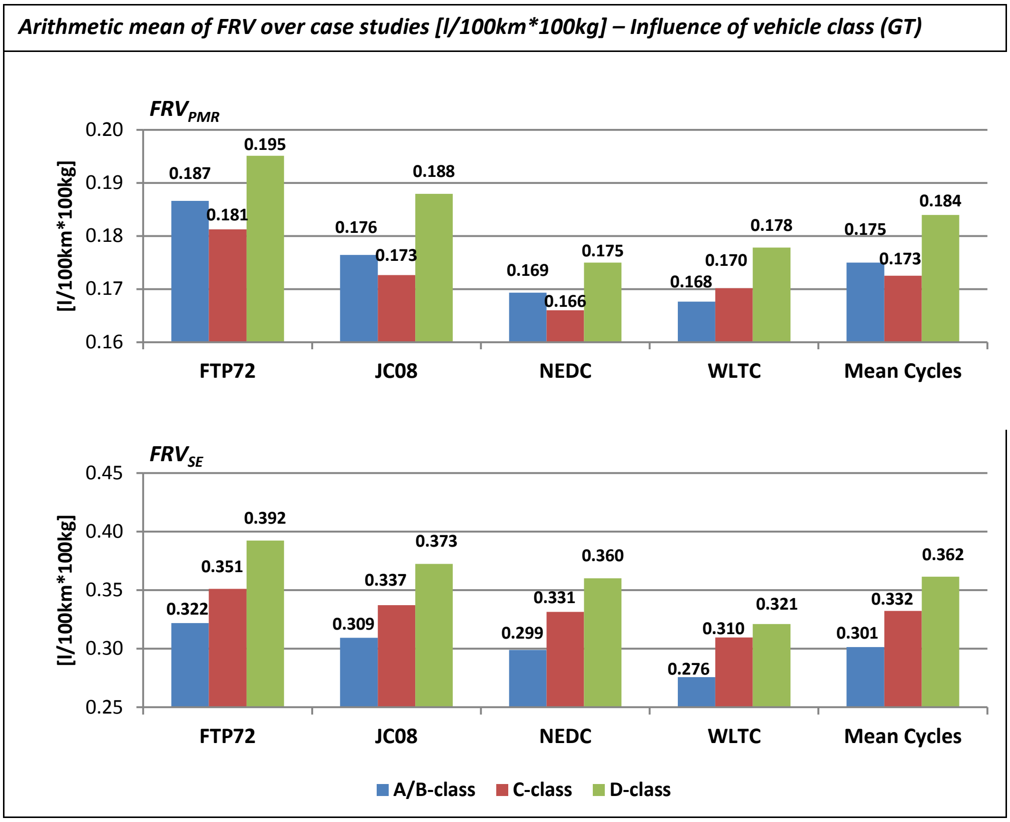


Figure 6.5. Arithmetic mean of FRV_{PMR} over case studies [l/100km*100kg]: influence of vehicle class (GT)

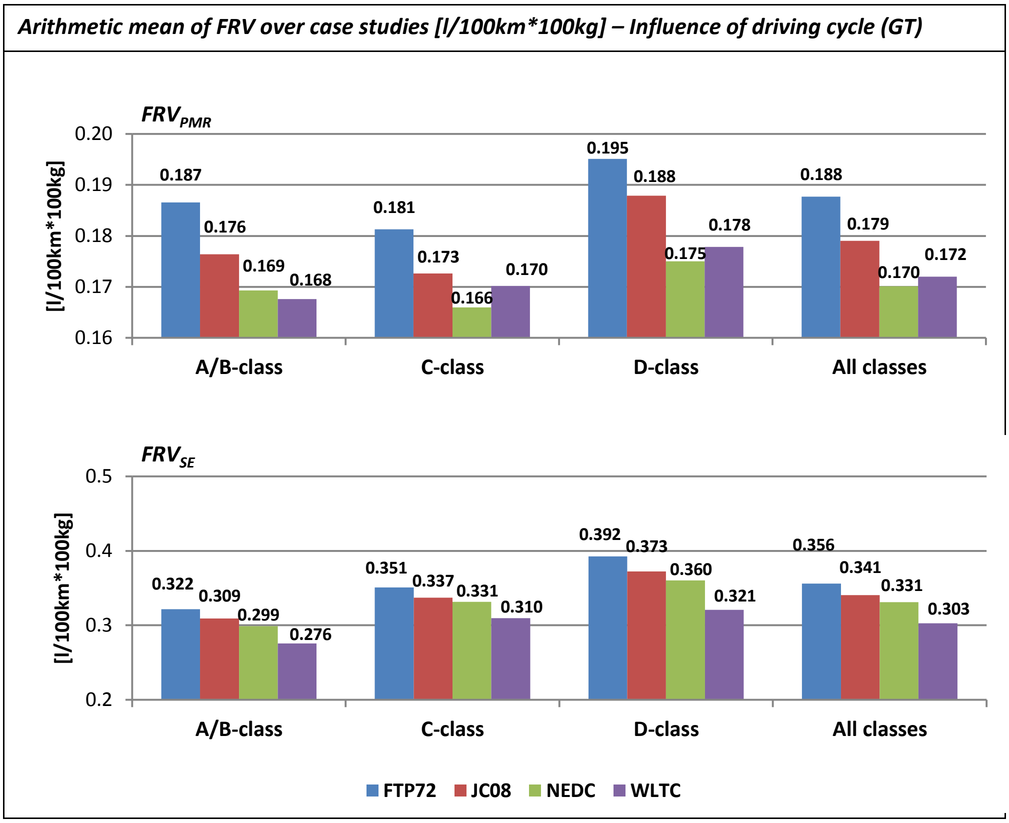
Considering the case of PMR only, for all cycles the D-class shows the highest FRVs; the lowest one refers to the C-class with the exception of WLTC. On the other hand in the case of SE for all cycles the FRV grows at vehicle class level increasing. The dependency of FRV on vehicle class is mainly influenced by the characteristic weights and motorizations of the considered case studies: as expected the highest consumption improvement is achieved in the heaviest vehicle segments with the most powerful engine (D-class) while the lowest one is reached in the smallest segment, the A/B-class.

FRV-GT case studies: influence of driving cycle

This section evaluates the influence on FRV of driving cycle and it is composed by two parts:

- All cycles: the FRVs obtained in the four driving cycles are compared with each other;
- Comparison with NEDC: the FRVs calculated in FTP72, JC08 and WLTC are compared with the ones obtained in the NEDC.

<u>All cycles</u>. The comparison between driving cycles is performed by analyzing the variation of FRV that occurs passing from one cycle to the other; Figure 6.6. evidences the influence of cycle by reporting the arithmetic mean of FRV over case studies basing on the same class.



Arithmetic mean of FRV over case studies [l/100km*100kg] – Influence of driving cycle (GT)

Figure 6.6. Arithmetic mean of FRV_{PMR} over case studies[l/100km*100kg]: influence of driving cycle (GT)

In case of PMR only the highest *FRV*s refer to the FTP72 and JC08 while the lowest ones to the NEDC and WLTC. Passing to SE, all classes show the same trend: the FTP72 has the highest values followed, in succession by JC08, NEDC and WLTC.

Despite the values of FRV depend on technical features of the specific case study, some general observations regarding the influence of driving cycle can be made. The effect on FRV of driving cycle primarily depends on the following factors:

- work per kilometer of mass-dependent resistance forces: rolling resistance (W_{roll_km}) and acceleration resistance (W_{acc_km});
- overall vehicle efficiency over the entire cycle.

Considering the first point, the work per kilometer of the mass-dependent resistance factors is higher in the FTP72, JC08 and WLTC with respect to the NEDC. This is a result of the higher W_{acc_km} of these cycles which derives from the more dynamic run.

Passing to the second point, the overall efficiency over the entire cycle results to be higher in the NEDC and WLTC. The lower values referring to the FTP72 and JC08 are explainable by the lower efficiency at which the engine operates; this is a result of the fact that the engine works in partialization for a notable share of total cycle duration due to the frequent speed fluctuations which characterize these cycles. Additionally it has to be noted that the engine base efficiency in the PMR mass-configurations is lower with respect to the reference configuration and that it decreases at mass reduction increasing. This fact is due to the lower engine load that the lightweight mass-configurations require in order to follow the velocity profile of the cycle. On the other hand in the case of SE mass-configurations, the engine base efficiency remains substantially unaltered passing from the reference to the lightweight mass-configurations. By way of example GT case study n°17 is analyzed in detail by following Table and Figures:

- Table 6.1. reports the Work per kilometer of aerodynamic Drag resistance (W_{D_km}), rolling resistance (W_{roll_km}), acceleration resistance (W_{acc_km}), mass-dependent resistance factors ($W_{mass\ dep\_km} = W_{roll\_km} + W_{acc\_km}$) and the overall vehicle efficiency (η_{veh}) for all mass-configurations and driving cycles (both PMR and SE);
- Figure 6.7. reports the share on total cycle duration of engine speed and the effective load for all driving cycles of the reference mass-configuration;
- Figures 6.8. and 6.9. report the engine operating point for all driving cycles of the reference mass-configuration.

			GT case study n°17				
			W_{D_km} [J]	**W_{roll_km}[J]**	**W_{acc_km}[J]**	**$W_{mass\ dep\_km}$[J]**	**η_{veh}[null]**
FTP72	**Reference**		47844	81773	249990	331763	0.181
	PMR	**5%**	47982	78387	240293	318680	0.178
		10%	48120	75004	230605	305609	0.175
		15%	48420	71664	219695	291359	0.171
		20%	48719	68327	208794	277121	0.167
	SE	**5%**	47883	78299	239981	318279	0.181
		10%	47923	74821	229963	304784	0.181
		15%	48018	71402	219546	290948	0.181
		20%	48113	67977	209111	277089	0.181
JC08	**Reference**		58103	91585	247718	339303	0.186
	PMR	**5%**	58078	87682	237843	325525	0.182
		10%	58054	83780	227967	311747	0.179
		15%	58116	79973	218315	298288	0.175
		20%	58179	76162	208653	284815	0.171
	SE	**5%**	58130	87752	237768	325520	0.185
		10%	58157	83911	227799	311711	0.185
		15%	58186	80022	217397	297419	0.185
		20%	58214	76128	206985	283113	0.185
NEDC	**Reference**		134410	132235	168854	301089	0.204
	PMR	**5%**	134455	126682	162880	289562	0.201
		10%	134500	121128	156907	278035	0.199
		15%	134610	115593	150665	266258	0.196
		20%	134720	110052	144417	254469	0.193
	SE	**5%**	134481	126690	162421	289111	0.205
		10%	134553	121139	155983	277122	0.206
		15%	134654	115512	148627	264138	0.207
		20%	134754	109874	141258	251131	0.208
WLTC	**Reference**		122931	89229	227740	316969	0.195
	PMR	**5%**	123115	85522	218512	304035	0.192
		10%	123299	81817	209289	291105	0.190
		15%	123677	78209	200557	278766	0.187
		20%	124054	74601	191825	266426	0.184
	SE	**5%**	123143	85536	219007	304543	0.195
		10%	123355	81840	210266	292106	0.196
		15%	123519	78179	201640	279819	0.196
		20%	123684	74512	193004	267516	0.197

Table 6.1. W_{D_km}, W_{roll_km}, W_{acc_km}, $W_{mass\ dep\_km}$ and η_{veh} for all mass-configurations (reference, PMR and SE) and driving cycles of GT case study n°17

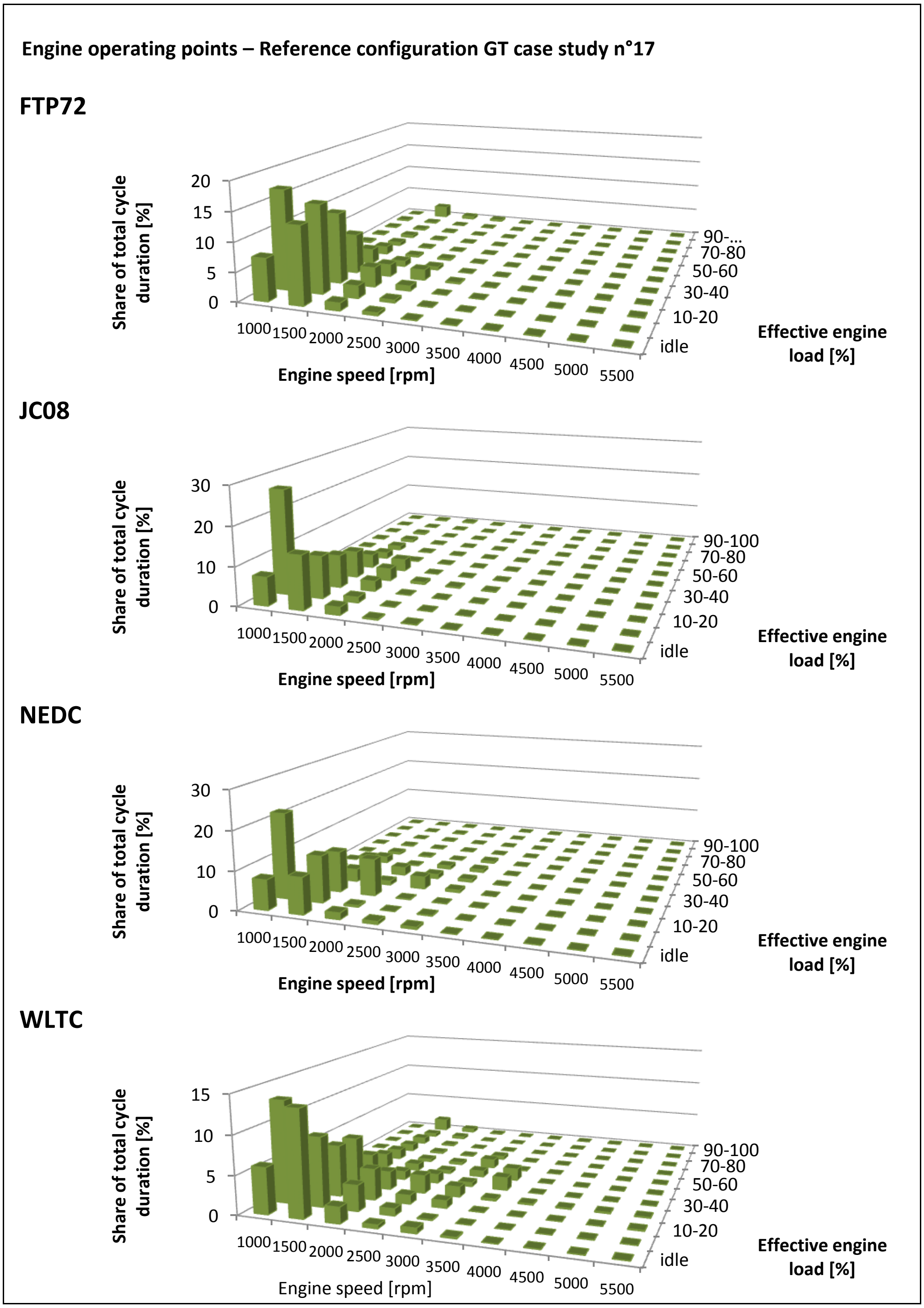


Figure 6.7. Share on total cycle duration of engine speed and effective load in the FTP72, JC08, NEDC, WLTC (reference mass-configuration GT case study n°17)

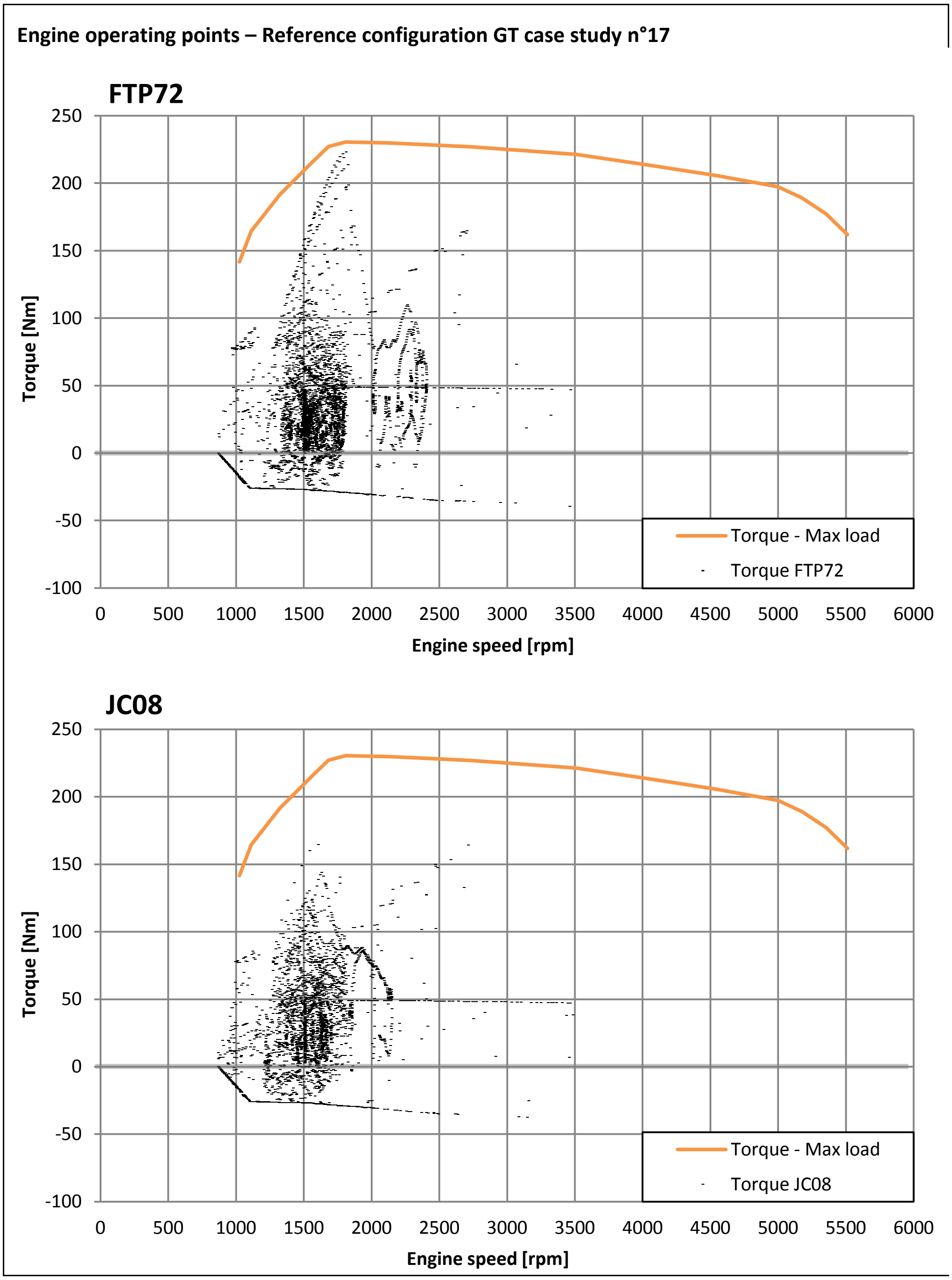


Figure 6.8. Engine operating points in the FTP72 and JC08 (reference mass-configuration GT case study n°17)

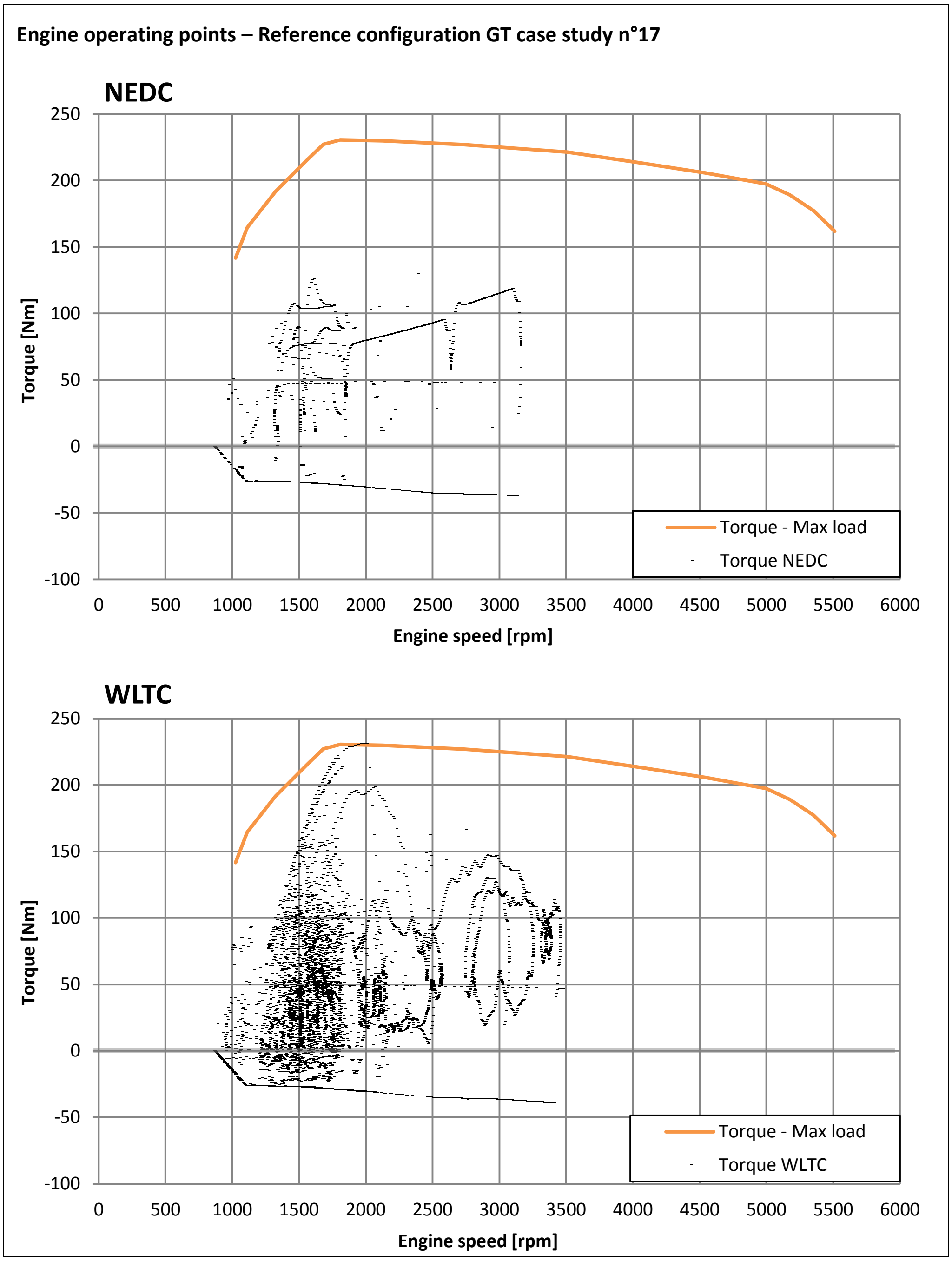


Figure 6.9. Engine operating points in the NEDC and WLTC (reference mass-configuration GT case study n°17)

Comparison with the NEDC. This section performs the comparison between the FRVs obtained in the FTP72, JC08 and WLTC with the ones calculated in the NEDC. The choice to adopt the NEDC as reference is explained by the following reasons:

- NEDC is the driving cycle currently adopted in Europe for type test approval; the comparison with other standardized cycles all around the world represents a reason of interest;
- the NEDC has been widely used in the past and many of the existing studies on FRV adopt it as reference for comparison with other cycles;
- as in the next future the NEDC will be deposed for European type test approval, the comparison with the WLTC (substitute cycle of the NEDC) appears to be of considerable interest.

The comparison of FTP72, JC08 and WLTC with the NEDC is performed basing on the arithmetic mean of FRV over case studies; Figure 6.10. reports the percent variation with respect to NEDC.

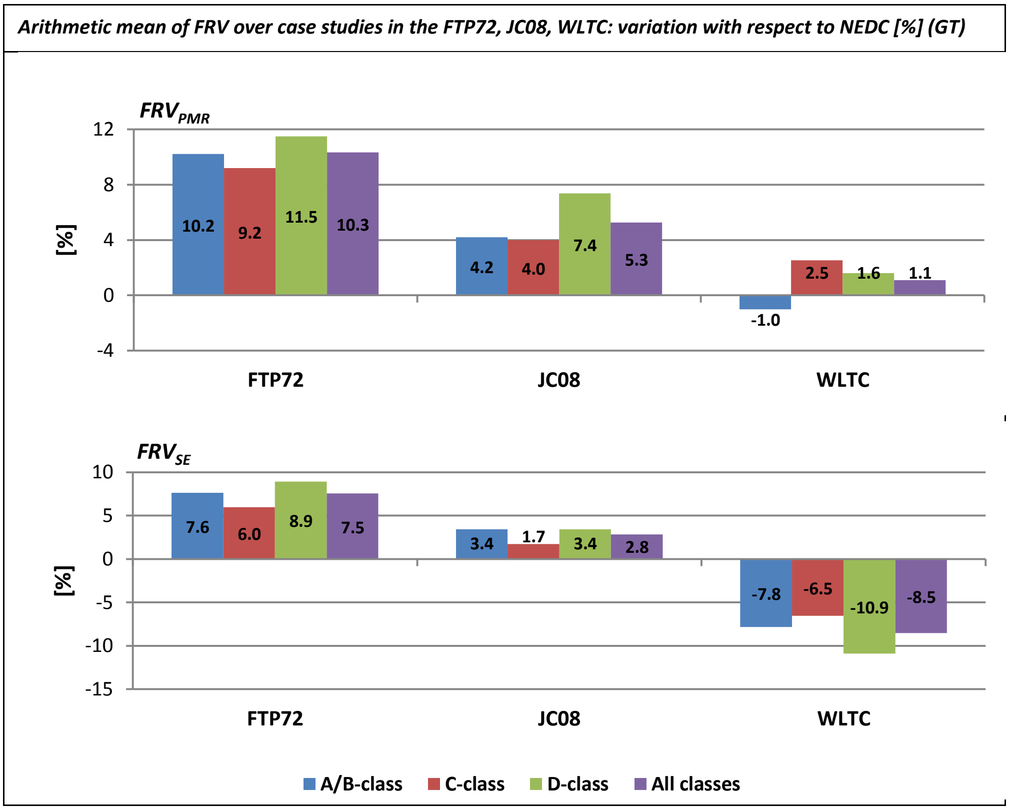

Arithmetic mean of FRV over case studies in the FTP72, JC08, WLTC: variation with respect to NEDC [%] (GT)

Figure 6.10. Arithmetic mean over case studies of *FRV*$_{PMR}$: percent variation of FTP72, JC08 and WLTC with respect to NEDC [%] (GT)

Considering FRV_{PMR}, the aggregated data "All classes" indicate an increase for each one of cycles (+10.3% for FTP72, +5.3% for JC08 and +1.1% for WLTC); for FTP72 and JC08 the increase is maintained within all classes while for WLTC the A/B-class presents a decrease (-1.0%).

Passing to FRV_{SE}, the aggregated data "All classes" indicate an increase for FTP72 and JC08 (+7.5% and +2.8% respectively) and a decrease for WLTC (-8.5%); such a trend is qualitatively confirmed within each one of the classes.

FRV-GT case studies: influence of SEs

Firstly the influence of SEs is evaluated at the engine technology level by analyzing the arithmetic mean of FRV over all case studies: Figure 6.11. reports the percent increase of FRV with respect to the case of PMR only per each one of driving cycle.

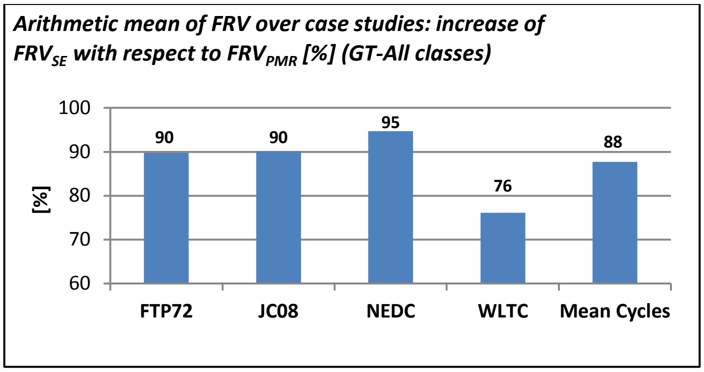


Figure 6.11. Arithmetic mean of FRV over case studies: increase of FRV_{SE} with respect to FRV_{PMR} [%] (GT-All classes)

The implementation of SE involves a notable growth of the FRV: the minimum regards the WLTC (71%) while for the other cycles it is about 90%, with a maximum of 95% for the NEDC.

FRV-GT case studies: dependence on vehicle technical features

This section is aimed to establish if any correlation between the values of FRV and the main vehicle technical features exists. The investigated parameters are *maximum Brake Mean Effective Pressure* ($BMEP_{max}$), *vehicle mass* (m_{curb}), *maximum Power* (P_{max}) and *Power-to-Mass Ratio (PMR)*. The existence of any correlation is investigated through the analysis of regression lines of FRV in function of vehicle parameters. In SI appendix-chapter 6

- Figures SI6.2.7 – SI6.2.10. report the FRV for all case studies in function of the cited parameters. For each parameter five diagrams are showed (FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC}, $FRV_{MeanCycles}$); the partition of case studies in vehicle classes is evidenced;
- Figures SI6.2.15 – SI6.2.18. report the same data with respect to Figures SI6.2.7. – SI6.2.10. including regression lines and corresponding coefficients of determination R^2. The partition in vehicle classes is not evidenced and R^2 is determined considering the entirety of case studies within the technology.

In the following:

- Figure 6.12. reports $FRV_{MeanCycles}$ in function of $BMEP_{max}$, m_{curb}, P_{max} and PMR (the partition of case studies in classes is evidenced);
- Figure 6.13. reports $FRV_{MeanCycles}$ in function of $BMEP_{max}$, m_{curb}, P_{max} and PMR with regression line and corresponding coefficient of determination R^2 (the partition in vehicle classes is not evidenced).

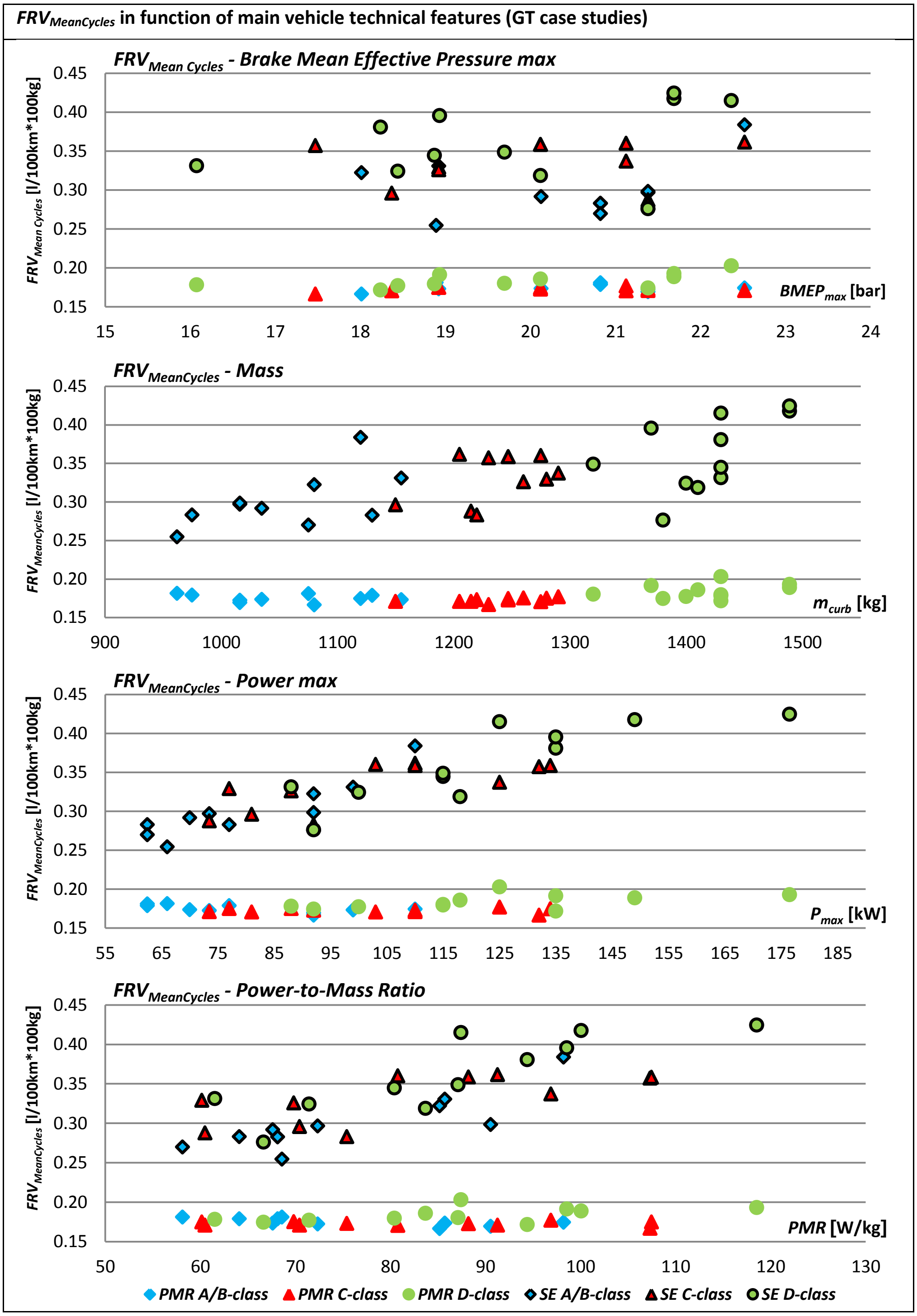


Figure 6.12. $FRV_{MeanCycles}$ of all GT case studies in function of $BMEP_{max}$, m_{curb}, P_{max} and PMR

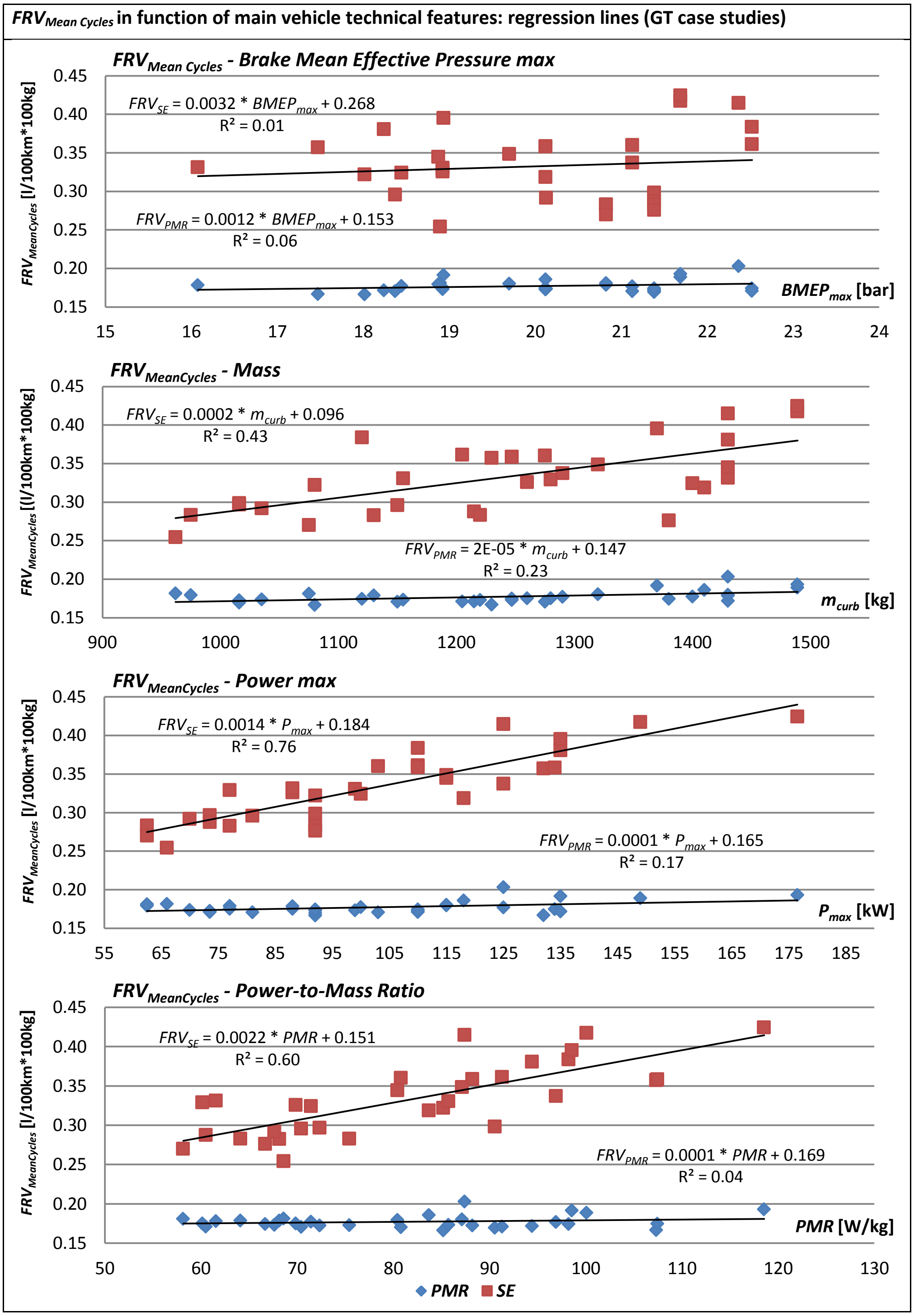


Figure 6.13. $FRV_{MeanCycles}$ of all GT case studies in function of $BMEP_{max}$, m_{curb}, P_{max} and PMR with regression lines

Table 6.2. quantifies the effectiveness of the correlation between FRV and vehicle parameters by reporting R^2 of regression lines for the various driving cycles.

	Coefficient of determination R^2									
	FRV_{FTP72}		FRV_{JC08}		FRV_{NEDC}		FRV_{WLTC}		$FRV_{MeanCycles}$	
	PMR	SE	PMR	SE	PMR	SE	PMR	SE	PMR	SE
$BMEP_{max}$	0.14	0.02	0.03	0.02	0.03	0.02	$5*10^{-3}$	$2*10^{-4}$	0.06	0.01
m_{curb}	0.09	0.41	0.23	0.44	0.07	0.41	0.44	0.42	0.23	0.43
P_{max}	0.11	0.74	0.06	0.78	0.04	0.78	0.42	0.65	0.17	0.76
PMR	0.04	0.57	$1*10^{-5}$	0.61	$4*10^{-3}$	0.62	0.20	0.50	0.04	0.60

Table 6.2. Coefficient of determination R^2 of regression lines for FRV in function of vehicle technical features

The values of R^2 in Table 6.2. evidence that for PMR only a substantial absence of correlation is detected for all the considered parameters (R^2 does not exceed 0.44). On the other hand for SE the values of R^2 definitely grow and the highest correlation is evidenced for P_{max}: in this case R^2 ranges between 0.65 (for FRV_{WLTC}) and 0.78 (for FRV_{JC08}) with a value of 0.76 for $FRV_{MeanCycles}$.

FRV-GT case studies: influence of S&S system

The study is performed considering that S&S system is off; the target of this section is to investigate the effect on the overall results of the activation of such a system.

The analysis is performed on one case study per each vehicle class; overall, considering that the study is conducted on A/B, C and D classes for both GT and DT technologies, the influence of S&S system is investigated on six case studies. The choice of the specific case studies is made in order that they are as much as possible representative of the class in terms of vehicle technical features (mass, engine displacement, maximum power, etc). Table 6.3. reports the chosen case studies with regard to GT technology:

	Analysis of influence of S&S system	
	Vehicle class	Case study
GT	A/B	9
	C	17
	D	28

Table 6.3. Analysis of influence of S&S system (GT): case studies per vehicle class

The values of FC in case S&S system is on ($FC_{S\&S}$) are obtained through an elaboration of data obtained in Reference Study (FC_{RS}). $FC_{S\&S}$ is determined by taking into account stop duration of driving cycle (t_{stop}) and idle duration that entails the same FC of a restarting (t_{eq}) through the following equation:

$$FC_{S\&S} = FC_{RS} - \left(\frac{\frac{cons_{idle}}{3600} * \left(t_{stop} - t_{eq} * n^{\circ}_{stop} \right)}{1000} * \frac{1}{\rho_{fuel}} * \frac{100}{km_{DC}} \right) \tag{Eq. 6.14.}$$

Where:
$FC_{S\&S}$ = FC in case S&S system is on [l/100km];
FC_{RS} = FC obtained in Reference Study [l/100km];
$cons_{idle}$ = idle FC [g/h];
t_{stop} = stop duration of driving cycle [s];
t_{eq} = idle duration that involves the same FC of a restarting [s];
n°_{stop} = number of stop of driving cycle [null];
ρ_{fuel} = fuel density [kg/l];
km_{DC} = total mileage of Driving Cycle [km].

Table 6.4. reports t_{stop} and n°_{stop} for the considered driving cycles.

	FTP72	**JC08**	**NEDC**	**WLTC**
t_{stop} [s]	189	346	280	226
n°_{stop} [null]	14	12	14	9
km_{DC} [km]	12.00	8.17	11.03	23.27

Table 6.4. t_{stop} and n°_{stop} for the considered driving cycles

For idle duration that entails the same FC of a restarting (t_{eq}) the value of 10 [s] is assumed. Such an assumption derives from a survey regarding the effect that S&S system has on FC of gasoline vehicles:

- Gaines et al. (2012) perform some simple experiments to provide a preliminary factual basis for recommendations on when to keep the engine on, and when to turn it off, for the minimum FC and emissions. The measurements are performed on a FORD Fusion 2.5l naturally aspirated 129kW. The work states that FC and CO_2 emissions from idling are greater than they are for restarting for idling duration over 10 seconds;
- Lohse-Busch et al. (2011) undertake a series of measurements on FC of three cars (Smart Fortwo 1.0l gasoline naturally aspirated 52kW, Mazda 3 2.0l naturally aspirated 111kW and Volkswagen Golf 2.0l TDI 103kW) in order to determine the advantages achievable through the S&S system. In the study FC on Urban Driving Cycle ECE-15 with S&S system activated ($FC_{S\&S\_ON}$) and not activated ($FC_{S\&S\_OFF}$) and the idle consumption ($cons_{idle}$) are measured. Starting from this data, the idle duration that involves the same FC of a restarting (t_{eq}) is determined through the following equation:

$$t_{eq} = \frac{t_{stop\_ECE} - \frac{\left(FC_{S\&S\_OFF} - FC_{S\&S\_ON}\right) * km_{ECE} * \rho_{fuel} * 36000}{cons_{idle}}}{n^{\circ}_{stop\_ECE}} \tag{Eq. 6.15.}$$

Where:
t_{eq} = idle duration that involves same FC of a restarting [s];
t_{stop_ECE} = stop duration of Urban Driving Cycle ECE-15 [s];
$FC_{S\&S\_OFF}$ = FC in case S&S system is not activated [l/100km];
$FC_{S\&S\_ON}$ = FC in case S&S system is activated [l/100km];
km_{ECE} = mileage of Urban Driving Cycle ECE-15 [km];
ρ_{fuel} = fuel density [kg/l];
$cons_{idle}$ = idle FC [g/h];
$n°_{stop\_ECE}$ = number of stop of Urban Driving Cycle ECE-15 [null].

Considering the gasoline vehicles investigated by Lohse-Busch, the idle duration that involves the same FC of a restarting (t_{eq}) amounts to about 8 [s] for Smart Fortwo and 10 [s] for Mazda 3.

The values of FC in case S&S system is activated ($FC_{S\&S}$) are reported in Tables SI6.1.2. and SI6.1.3. of SI appendix-chapter 6. Data, expressed in terms of liters per 100 kilometers, refer to

- both reference and lightweight mass-configurations;
- both PMR and SE lightweight mass-configurations;
- all the considered driving cycles.

Table SI6.2.3. in SI appendix-chapter 6 reports the FRVs in case of activation of S&S system ($FRV_{S\&S}$); data are presented for all the considered driving cycles and for both PMR and SE. Below the effect on FC and FRV of S&S system is described for each one of the investigated GT case studies. Figure 6.14. reports the percent variation of FC of reference mass configuration for the case of activation of S&S system with respect to the case of deactivation.

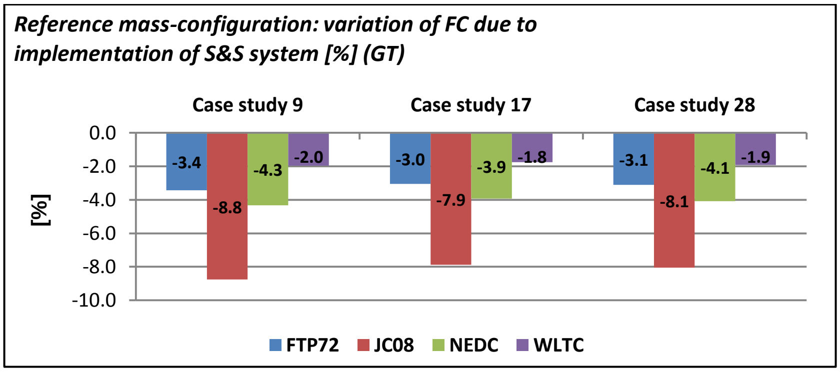


Figure 6.14. Reference mass-configuration: variation of FC due to implementation of the S&S system [%] (GT case studies)

The values of FC decrease for all case studies: the minimum decrease refers to WLTC (about 2%) while the maximum one to JC08 (8-9%); the differences between driving cycles depend on the share of total cycle duration represented by stop phases (see Table 3.2.).

Considering the FRV, the activation of S&S system has no effect on FRV_{PMR} while it involves modification of FRV_{SE}. This evidence is explainable by the fact that

- in case of PMR FC reduction involved by S&S system is the same for all the lightweight mass-configurations (idle consumption does not vary passing from a configuration to another because the engine displacement remains constant)
- in case of SE FC reduction involved by S&S system is not the same for the lightweight mass-configurations (idle consumption varies passing from a configuration to another because engine displacement is affected by SE).

Figure 6.15. reports the percent variation of FRV_{SE} for the case of activation of S&S system with respect to the case of deactivation.

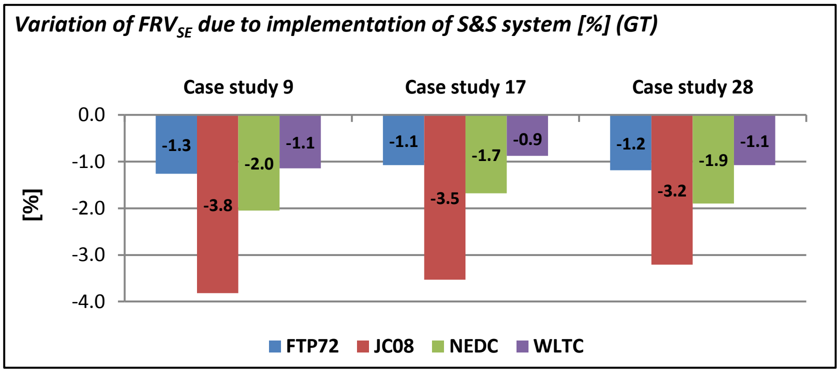


Figure 6.15. Variation of FRV_{SE} due to implementation of the S&S system [%] (GT case studies)

The results show that the values of FRV decrease for all case studies. The minimum decrease refers to WLTC and FTP72 (about 1%) while the maximum one to JC08 (3-4%); the differences between driving cycles depend on the share of total cycle duration represented by stop phases (see Table 3.2.). No specific trend imputable to vehicle class emerges.

FRV - GT case studies: sensitivity analysis

Sensitivity analysis investigates the effect on the overall results of the change of model parameter *Coulomb friction coefficient (f)* with respect to the reference value adopted in the study.

Sensitivity analysis is performed on one case study per each vehicle class; the chosen case studies are the same that have been adopted in the analysis of the influence of S&S system (GT case studies n° 9, 17 and 28).

In order to perform sensitivity analysis, the simulation modelling is completely repeated for two additional values of *Coulomb friction coefficient* f with respect to the one assumed in the reference study; Table 6.5. summarizes the considered values of f .

	Coulomb friction coefficient (f)
Sensitivity analysis (1)	0.007
Reference study	0.010
Sensitivity analysis (2)	0.013

Table 6.5. Values of *Coulomb friction coefficient f* adopted in sensitivity analysis and reference study

The change of f involves negligible modifications in the implementation of SE; consequently the values assumed by model parameters in the SE mass-configurations of reference study (see section *SI 4.4. SE mass-configurations* of SI appendix chapter 4) remain valid also for sensitivity analysis.

The values of FC obtained in sensitivity analysis for GT case studies are reported in Tables SI6.1.6. and SI6.1.7. of SI appendix-chapter 6: data, expressed in terms of liters per 100 kilometers, refer to

- both reference and lightweight mass-configurations;
- both PMR and SE lightweight mass-configurations;
- all the considered driving cycles.

Table SI6.2.5. in SI appendix-chapter 6 reports the FRVs obtained in sensitivity analysis for GT case studies; data are presented for all the considered driving cycles and for both PMR only and SE. Below the effect on FC and FRV of the change of f is described for each one of the investigated GT case studies.

Figure 6.16. reports the percent variation of FC of reference mass configuration for

- $f = 0.007$
- $f = 0.013$

with respect to the reference study ($f = 0.010$).

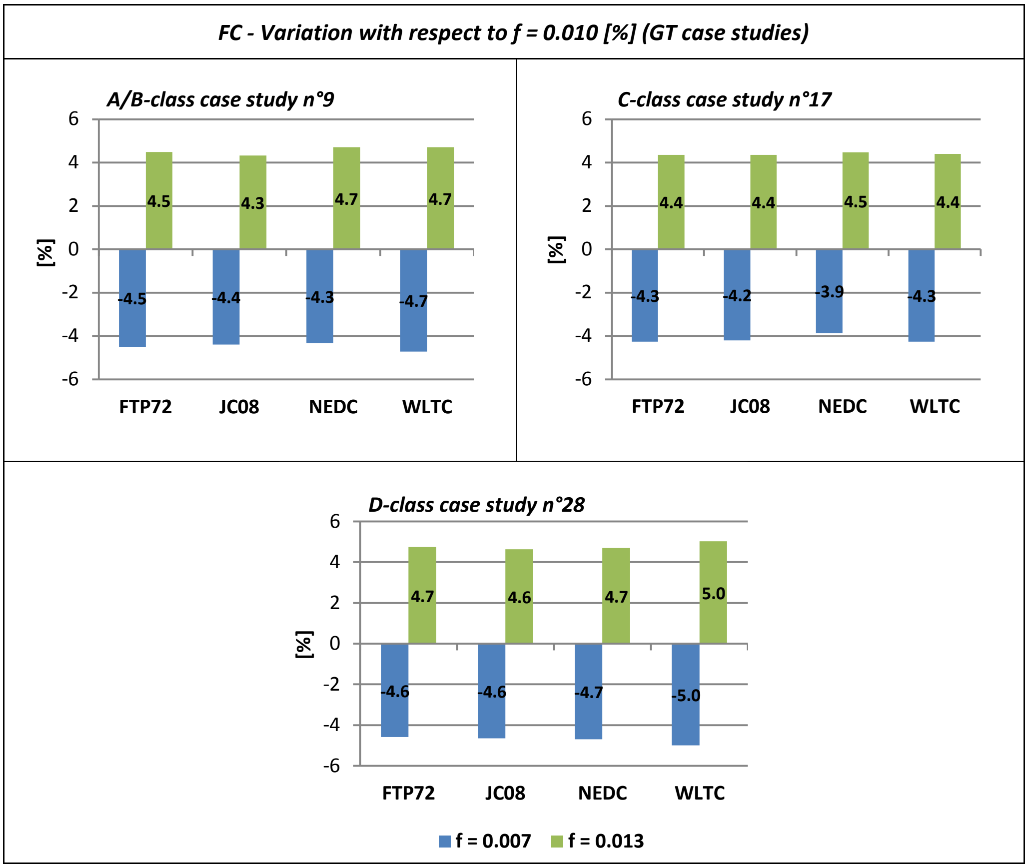


Figure 6.16. Sensitivity analysis based on *Coulomb friction coefficient (f)*. FC of reference mass-configuration: percent variation with respect to *f* = 0.010 [%] (GT A/B-class case study n°9, C-class case study n°17 and D-class case study n°28)

With regard to FC, results show that:

- *f* = 0.007. FC decreases for all case studies: depending on vehicle class and driving cycle the reductions are comprised within the range 4-5%.
- *f* = 0.013. FC grows for all case studies: depending on vehicle class and driving cycle the increases are comprised within the range 4-5%.

Figure 6.17. reports the percent variation of FRV for

- *f* = 0.007
- *f* = 0.013

with respect to the reference study (*f* = 0.010).

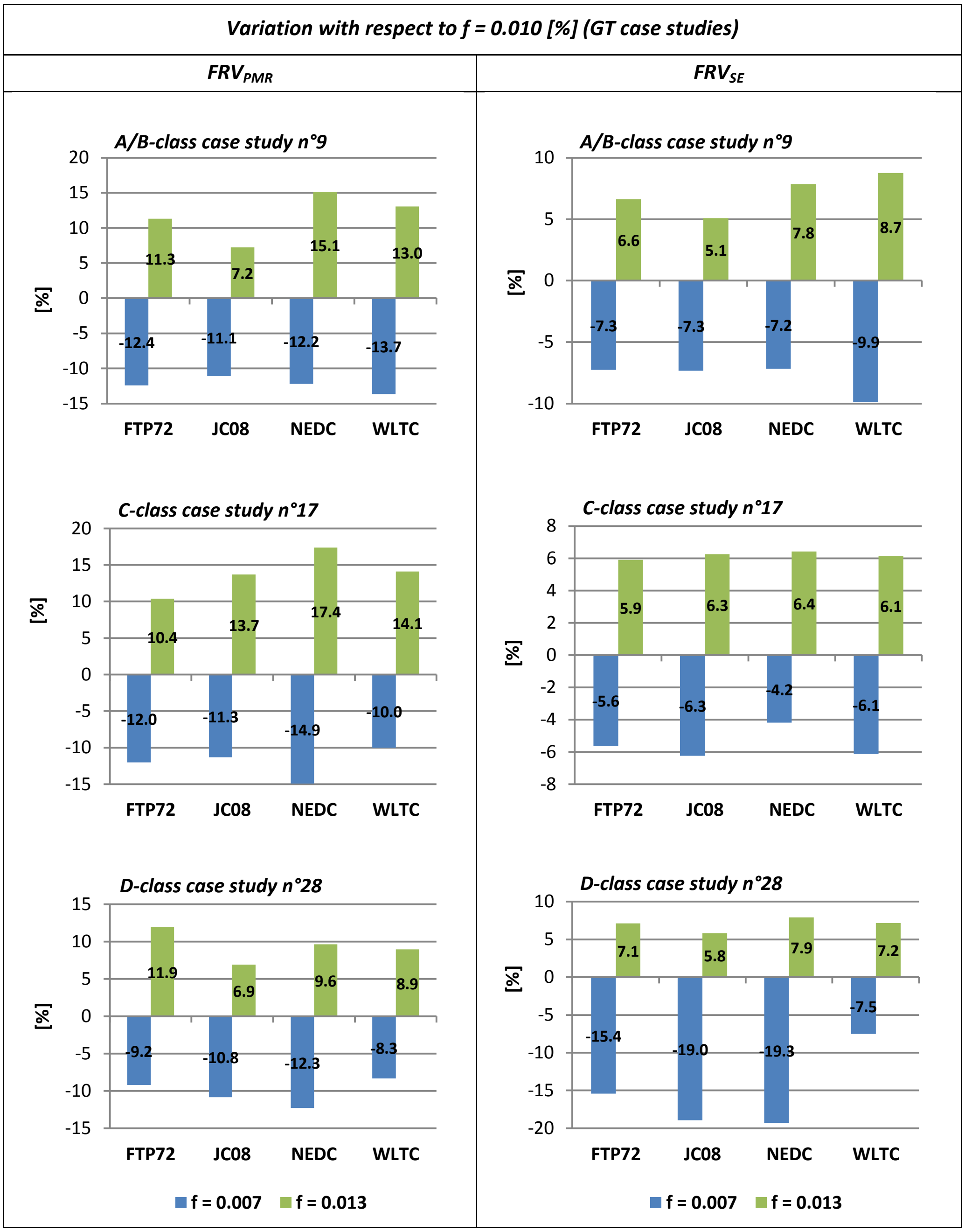


Figure 6.17. Sensitivity analysis based on *Coulomb friction coefficient (f)*. FRV_{PMR} and FRV_{SE}: percent variation with respect to $f = 0.010$ [%] (GT A/B-class case study n°9, C-class case study n°17 and D-class case study n°28)

With regard to FRV, results show that:

- *f* = 0.007 (PMR only). The FRV decreases for all case studies: depending on vehicle class and driving cycle the reduction is comprised within the range 8-15%;
- *f* = 0.007 (SE). The FRV decreases for all case studies: depending on vehicle class and driving cycle the reduction is comprised within the range 4-20%;
- *f* = 0.013 (PMR only). The FRV increases for all case studies: depending on vehicle class and driving cycle the increase is comprised within the range 6-18%;
- *f* = 0.013 (SE). The FRV increases for all case studies: depending on vehicle class and driving cycle the increase is comprised within the range 5-9%.

6.1.2.2. FRV – DT case studies

FRV – DT case studies: analysis of results

Table SI6.2.2. in SI appendix-chapter 6 characterizes the values of FRV in terms of

- minimum and maximum
- size of range maximum – minimum
- arithmetic mean
- standard deviation

for both single classes and entirety of case studies.

Figure 6.18. reports the arithmetic mean of FRV over case studies per driving cycle: the black bars identify the range of variation around the arithmetic mean while Figure 6.19. reports the size of such a range.

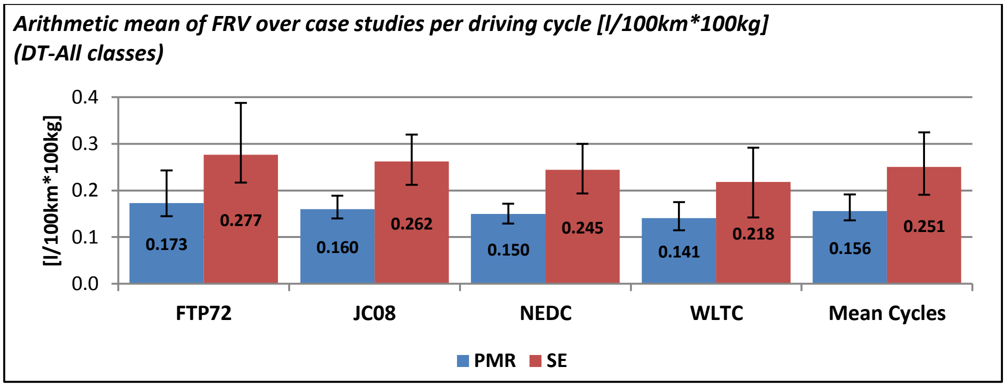


Figure 6.18. Arithmetic mean of FRV over case studies per driving cycle [l/100km*100kg] (DT – All classes)

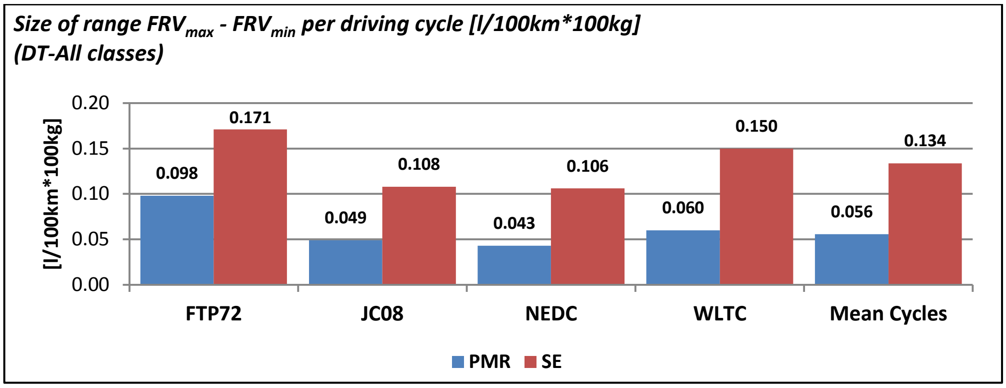


Figure 6.19. Arithmetic mean of FRV over case studies per driving cycle: size of range $FRV_{max} - FRV_{min}$ [l/100km*100kg] (DT – All classes)

Data show that:

- the arithmetic mean of FRV_{PMR} over case studies varies, depending on cycle, within the range 0.141-0.173 [l/100km*100kg]; on the other hand the arithmetic mean of FRV_{SE} is notably higher, between 0.218 and 0.277 [l/100km*100kg];
- FRV_{SE} is characterized by a higher dispersion around the arithmetic mean with respect to FRV_{PMR}: for FRV_{SE} the size of range maximum-minimum varies, depending on cycle, between 0.106 and 0.171 [l/100km*100kg] while for FRV_{PMR} it does not exceed 0.098 [l/100km*100kg]. This is also confirmed by the higher values of standard deviation of FRV_{SE} with respect to FRV_{PMR} (see Table SI6.2.2. in SI appendix-chapter 6).

FRV-DT case studies: influence of vehicle class

This section analyses the influence on FRV of vehicle class by evidencing the variation that occurs passing from one class to the other: Figure 6.20. reports the arithmetic mean of FRV within the class basing on the same driving cycle.

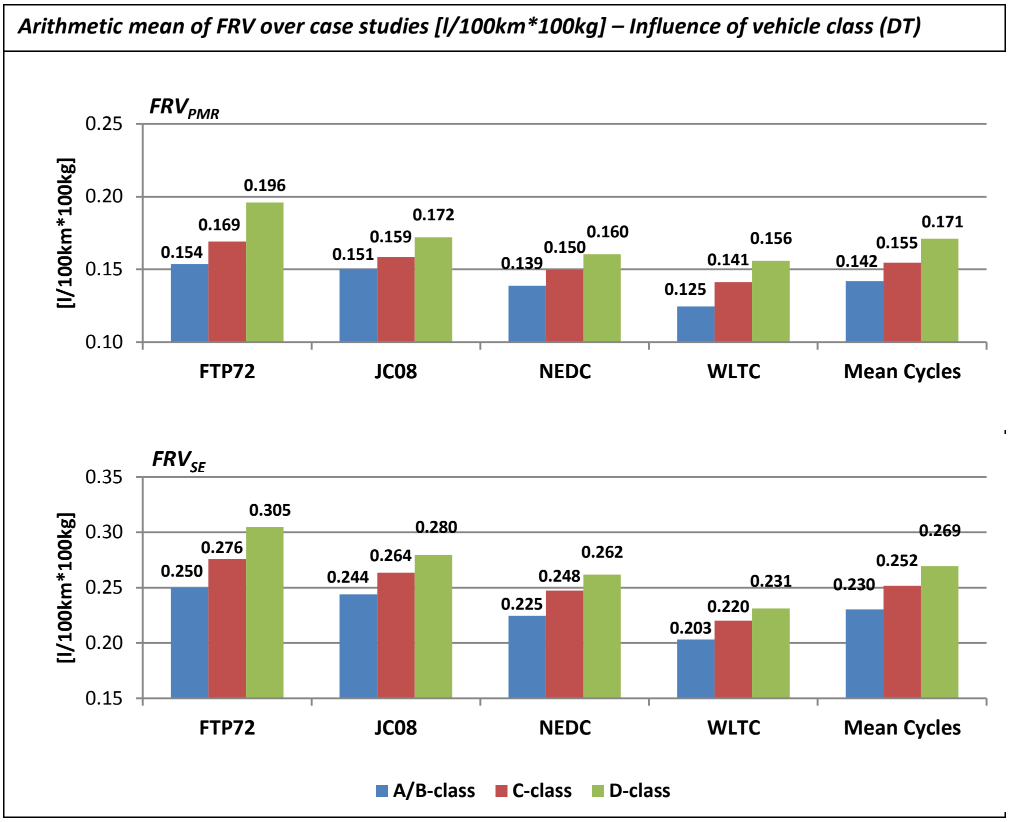


Figure 6.20. Arithmetic mean of FRV_{PMR} over case studies [l/100km*100kg]: influence of vehicle class (DT)

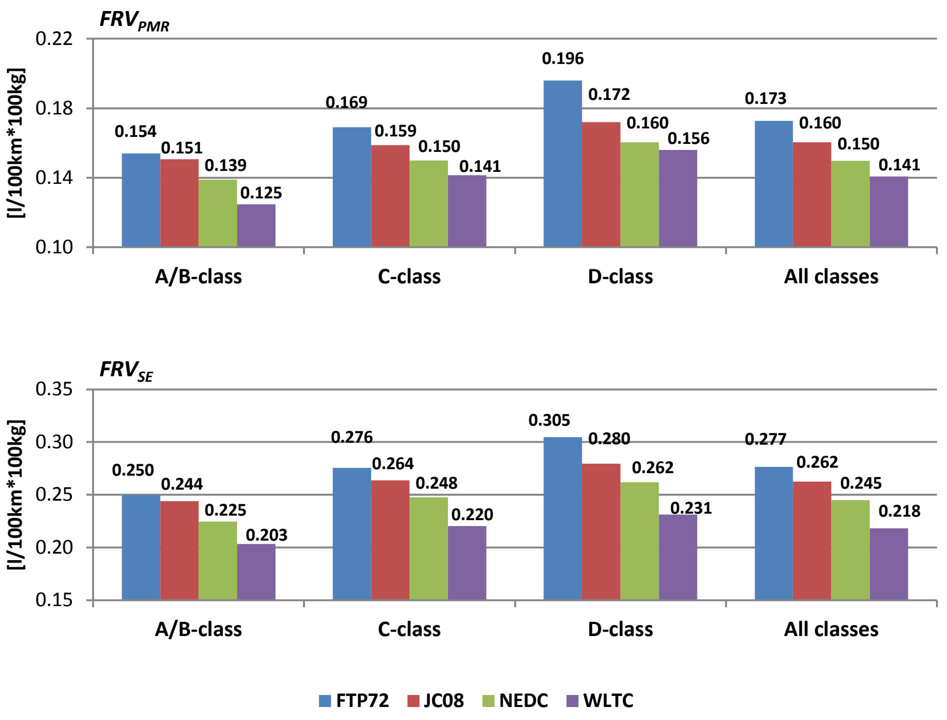
For both PMR only and SE in all cycles the FRV grows at vehicle class level increasing. The dependency of FRV on vehicle class is mainly influenced by the characteristic weights and motorizations of the considered case studies: as expected the highest consumption improvement is achieved in the heaviest vehicle segments with the most powerful engine (D-class) while the lowest one is reached in the smallest segment, the A/B-class.

FRV-DT case studies: influence of driving cycle

This section evaluates the influence on FRV of driving cycle and it is composed by two parts:

- All cycles: the FRVs obtained in the four driving cycles are compared with each other;
- Comparison with NEDC: the FRVs calculated in FTP72, JC08 and WLTC are compared with the ones obtained in the NEDC.

All cycles. The comparison between driving cycles is performed by analyzing the variation of FRV that occurs passing from one cycle to the other; Figure 6.21. evidences the influence of cycle by reporting the arithmetic mean of *FRV* over case studies basing on the same class.



Arithmetic mean of FRV over case studies [l/100km*100kg] – Influence of driving cycle (DT)

Figure 6.21. Arithmetic mean of FRV_{PMR} over case studies[l/100km*100kg]: influence of driving cycle (DT)

For both PMR only and SE all classes show the same trend: the FTP72 has the highest values followed, in succession by JC08, NEDC and WLTC.

Despite the values of FRV depend on technical features of the specific case study, some general observations regarding the influence of driving cycle can be made. The effect on FRV of driving cycle primarily depends on the following factors:

- work per kilometer of mass-dependent resistance forces: rolling resistance (W_{roll_km}) and acceleration resistance (W_{acc_km});
- overall vehicle efficiency over the entire cycle.

Considering the first point, the work per kilometer of the mass-dependent resistance factors is higher in the FTP72, JC08 and WLTC with respect to the NEDC. This is a result of the higher W_{acc_km} of these cycles which derives from the more dynamic run.

Passing to the second point, the overall efficiency over the entire cycle results to be higher in the NEDC and WLTC. The lower values referring to the FTP72 and JC08 are explainable by the lower efficiency at which the engine operates; this is a result of the fact that the engine works in partialization for a notable share of total cycle duration due to the frequent speed fluctuations which characterize these cycles. Additionally it has to be noted that the engine base efficiency in the PMR mass-configurations is lower with respect to the reference configuration and that it decreases at mass reduction increasing. This fact is due to the lower engine load that the lightweight mass-configurations require in order to follow the velocity profile of the cycle. On the other hand in the case of SE mass-configurations, the engine base efficiency remains substantially unaltered passing from the reference to the lightweight mass-configurations. By way of example DT case study n°21 is analyzed in detail by following Table and Figures:

- Table 6.6. reports the Work per kilometer of aerodynamic Drag resistance (W_{D_km}), rolling resistance (W_{roll_km}), acceleration resistance (W_{acc_km}), mass-dependent resistance factors ($W_{mass\ dep\_km} = W_{roll\_km} + W_{acc\_km}$) and the overall vehicle efficiency over the entire cycle (η_{veh}) for all mass-configurations (both PMR and SE) and driving cycles;
- Figure 6.22. reports the share on total cycle duration of engine speed and the effective load for all driving cycles of the reference mass-configuration;
- Figures 6.23. and 6.24. report the engine operating point for all driving cycles of the reference mass-configuration.

			DT case study n°21				
			W_{D_km} **[J]**	W_{roll_km}**[J]**	W_{acc_km}**[J]**	$W_{mass\ dep\_km}$**[J]**	η_{veh}**[null]**
FTP72	**Reference**		49283	82711	256459	339170	0.236
	PMR	**5%**	49438	79255	245499	324754	0.233
		10%	49593	79799	234539	310338	0.229
		15%	49519	72145	223249	295394	0.225
		20%	49445	68497	211977	280474	0.220
	SE	**5%**	49428	79375	245407	324782	0.236
		10%	49573	76033	234337	310370	0.235
		15%	49457	72394	224045	296439	0.235
		20%	49341	68751	213745	282496	0.234
JC08	**Reference**		59882	92443	254206	346648	0.241
	PMR	**5%**	59827	88443	243385	331828	0.237
		10%	59772	84452	232584	317036	0.233
		15%	59774	80441	222781	303222	0.229
		20%	59775	76431	212977	289408	0.226
	SE	**5%**	59845	88404	241634	330038	0.239
		10%	59809	84369	229074	313443	0.236
		15%	59827	80465	219713	300178	0.236
		20%	59845	76558	210343	286901	0.236
NEDC	**Reference**		137530	131792	172692	304484	0.266
	PMR	**5%**	138425	127070	163181	290251	0.264
		10%	139319	122347	153670	276017	0.261
		15%	139530	116899	147816	264715	0.260
		20%	139740	111450	141962	253413	0.258
	SE	**5%**	137533	126112	165740	291852	0.267
		10%	137535	120426	158781	279208	0.268
		15%	137544	114878	151340	266218	0.268
		20%	137553	109325	143891	253216	0.269
WLTC	**Reference**		125638	89538	231215	320573	0.261
	PMR	**5%**	126041	85668	221730	307398	0.258
		10%	126444	81980	212250	294229	0.255
		15%	126916	72299	202739	281038	0.252
		20%	127388	74621	193232	267853	0.249
	SE	**5%**	125773	85657	222335	307991	0.260
		10%	125909	81952	213447	295399	0.260
		15%	126289	78296	205032	283329	0.259
		20%	126670	74636	196607	271243	0.259

Table 6.6. W_{D_km}, W_{roll_km}, W_{acc_km}, $W_{mass\ dep\_km}$ and η_{veh} for all mass-configurations (reference, PMR and SE) and driving cycles of DT case study n°21

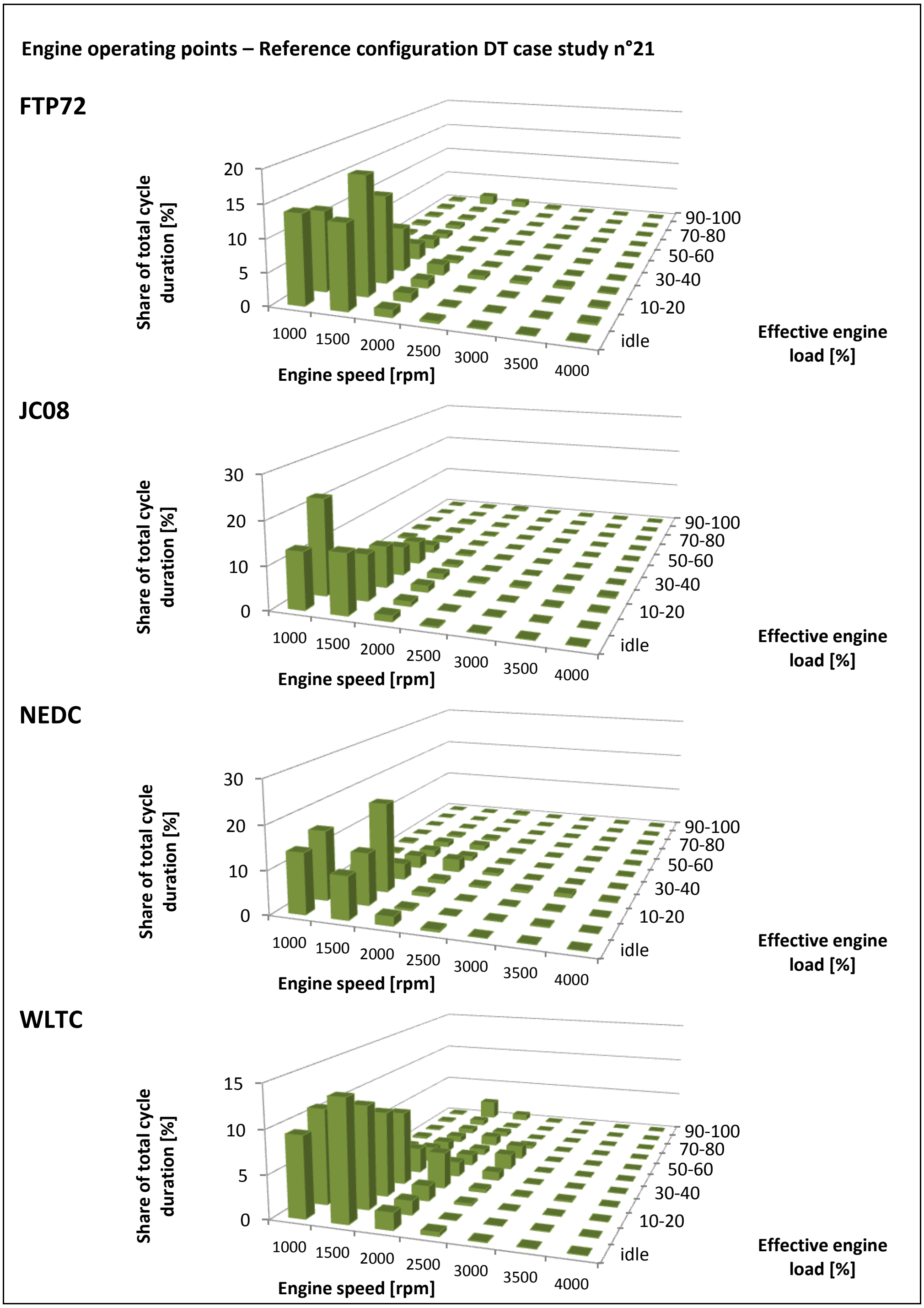


Figure 6.22. Share on total cycle duration of engine speed and effective load in the FTP72, JC08, NEDC, WLTC (reference mass-configuration DT case study n°21)

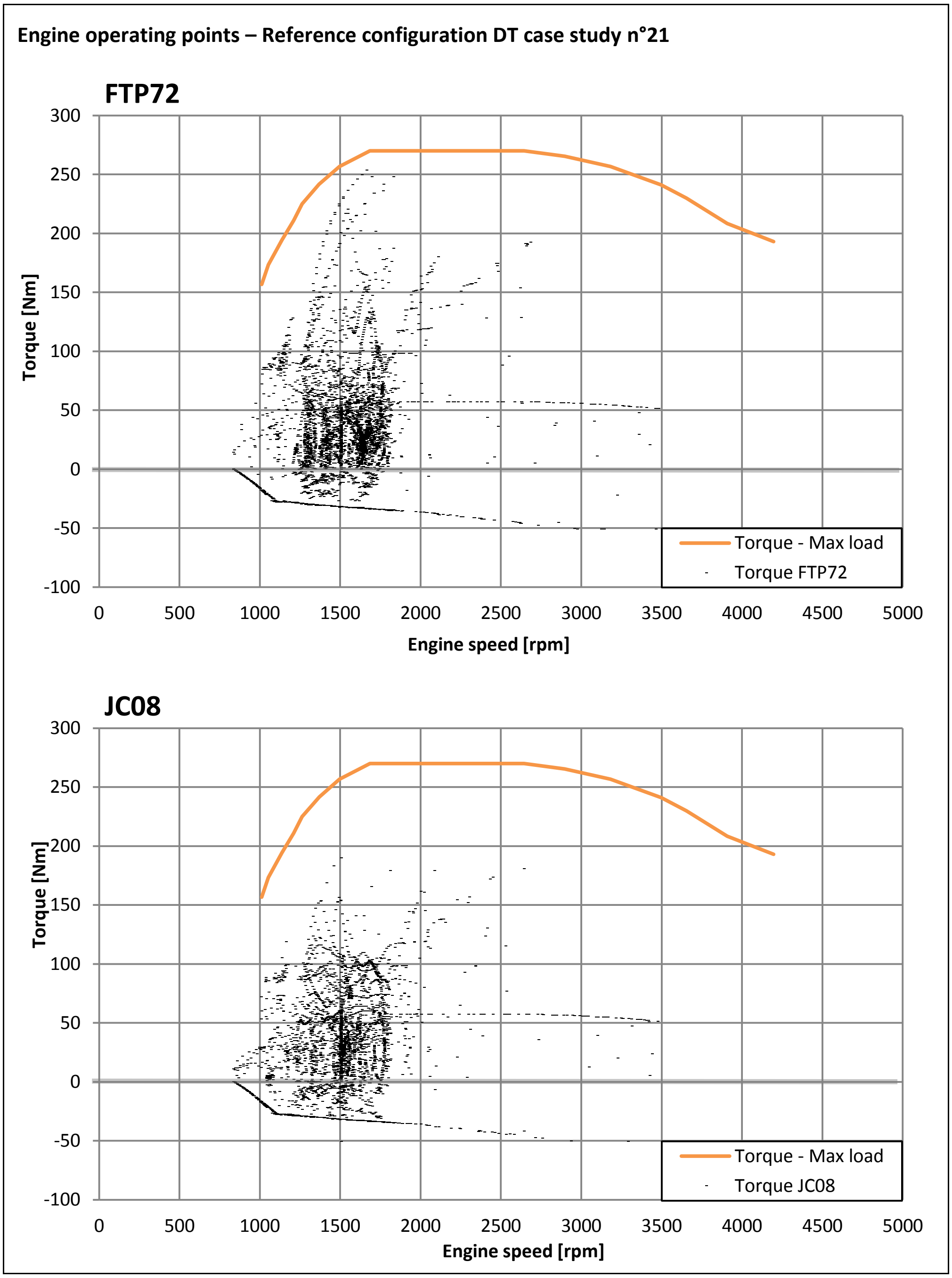


Figure 6.23. Engine operating points in the FTP72 and JC08 (reference mass-configuration DT case study n°21)

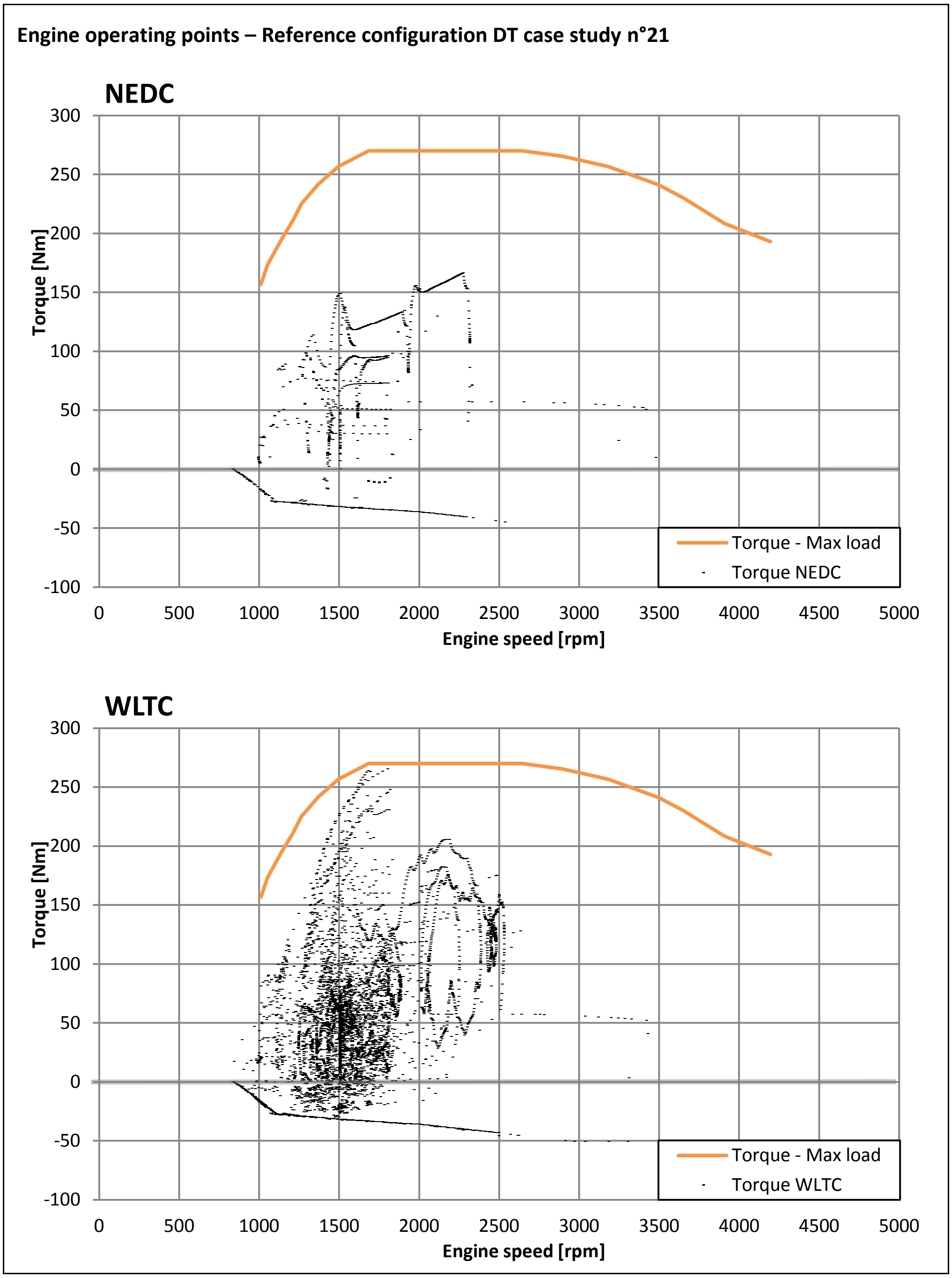


Figure 6.24. Engine operating points in the NEDC and WLTC (reference mass-configuration DT case study n°21)

Comparison with the NEDC. This section performs the comparison between the FRVs obtained in the FTP72, JC08 and WLTC with the ones calculated in the NEDC.

The comparison of FTP72, JC08 and WLTC with the NEDC is performed basing on the arithmetic mean of FRV over case studies; Figure 6.25. reports the percent variation with respect to NEDC respectively for FRV_{PMR} and FRV_{SE}.

Arithmetic mean of FRV over case studies in the FTP72, JC08, WLTC: variation with respect to NEDC [%] (DT)

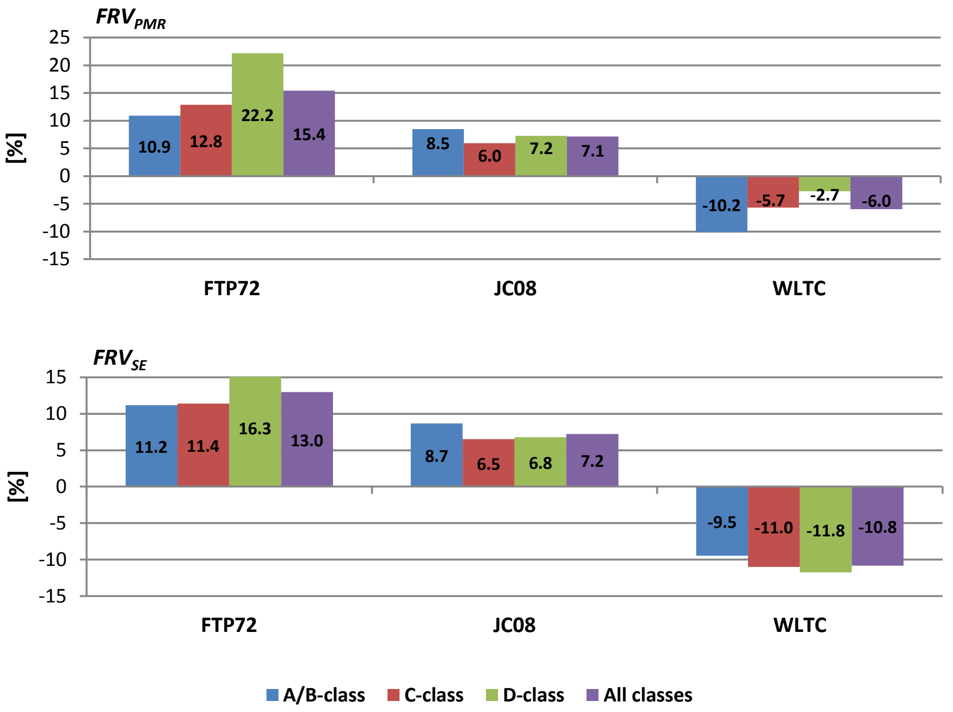


Figure 6.25. Arithmetic mean over case studies of FRV_{PMR}: percent variation of FTP72, JC08 and WLTC with respect to NEDC [%] (DT)

For both PMR only and SE the FRV shows the same trend: increase for FTP72 and JC08 and decrease for WLTC. Considering the aggregated data, the variation of FRV_{PMR} is +15.4%, +7.1% and -6.0% respectively for FTP72, JC08 and WLTC while for FRV_{SE} it is +13.0%, +7.2% and -10.8%; such a trend is qualitatively confirmed within each one of the classes.

FRV-DT case studies: influence of SE

Firstly the influence of SEs is evaluated at the engine technology level by analyzing the arithmetic mean of FRV over all case studies: Figure 6.26. reports the percent increase of FRV with respect to the case of PMR only per each one of driving cycle.

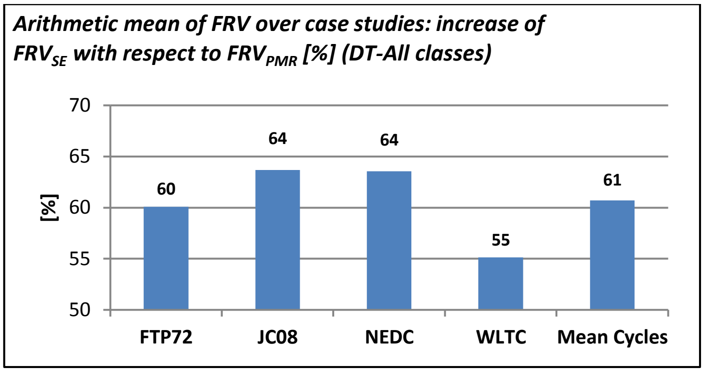


Figure 6.26. Arithmetic mean of FRV over case studies: increase of FRV_{SE} with respect to FRV_{PMR} [%] (DT-All classes)

The implementation of SE involves a notable growth of the FRV: for all the cycles the increase is about 60%.

FRV-DT case studies: dependence on vehicle technical features

This section is aimed to establish if any correlation between the values of FRV and the main vehicle technical features exists. The investigated parameters are *maximum Brake Mean Effective Pressure* ($BMEP_{max}$), *vehicle mass* (m_{curb}), *maximum Power* (P_{max}) and *Power-to-Mass Ratio (PMR)*. The existence of any correlation is investigated through the analysis of regression lines of FRV in function of vehicle parameters. In SI appendix-chapter 6

- Figures SI6.2.11. – SI6.2.14. report the FRV for all case studies in function of the cited parameters. For each parameter five diagrams are showed (FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$); the partition of case studies in vehicle classes is evidenced;
- Figures 6.2.19. – 6.2.22. report the same data with respect to Figures 6.2.11. – 6.2.14. including regression lines and corresponding coefficients of determination R^2. The partition in vehicle classes is not evidenced and R^2 is determined considering the entirety of case studies within the technology.

In the following

- Figure 6.27. reports $FRV_{MeanCycles}$ in function of $BMEP_{max}$, m_{curb}, P_{max} and *PMR* (the partition of case studies in classes is evidenced);
- Figure 6.28. reports $FRV_{MeanCycles}$ in function of $BMEP_{max}$, m_{curb} P_{max} and *PMR* with regression line and corresponding coefficient of determination R^2 (the partition in vehicle classes is not evidenced).

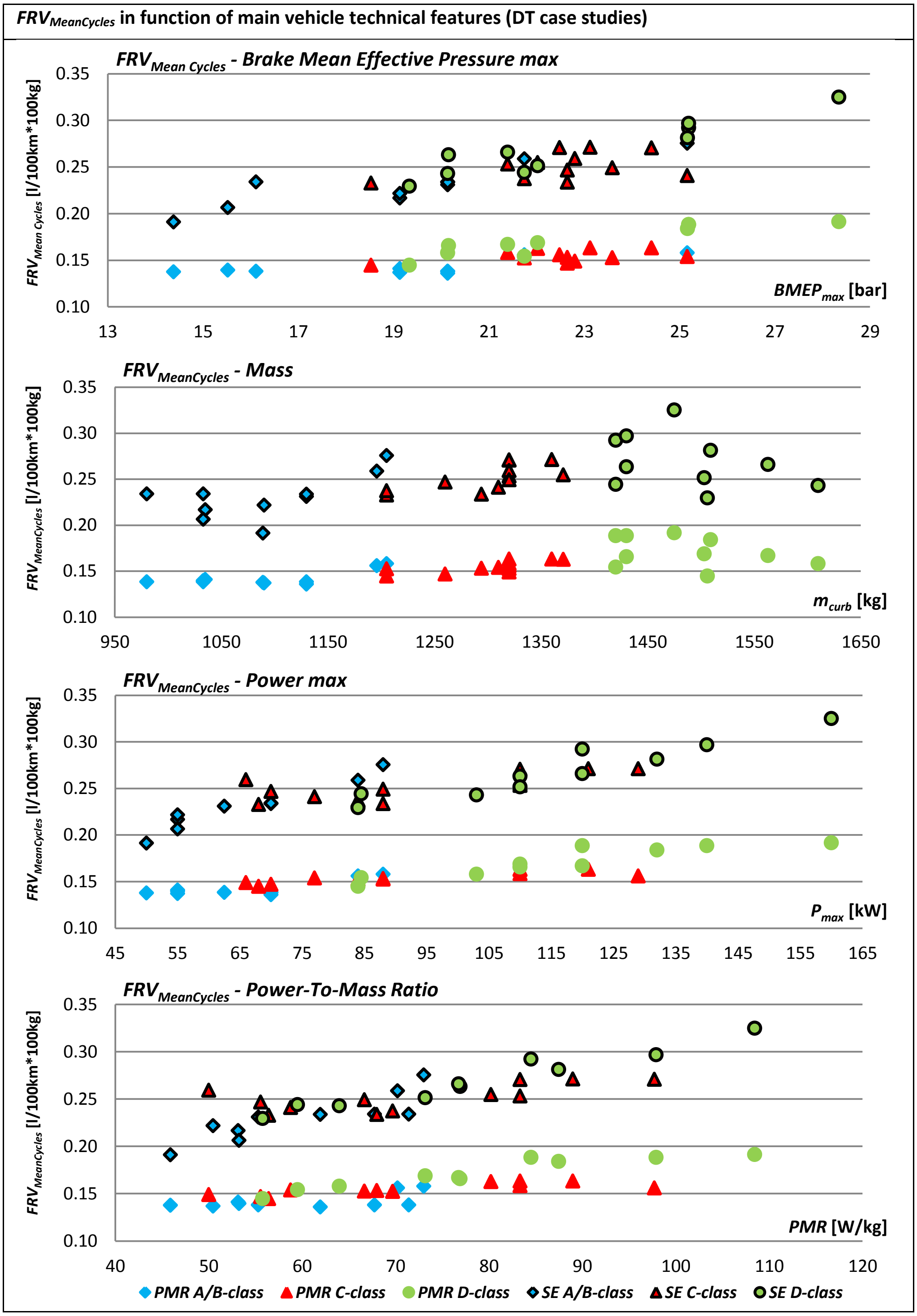


Figure 6.27. *$FRV_{MeanCycles}$* of all DT case studies in function of *$BMEP_{max}$*,*m_{curb}*, *P_{max}* and *PMR*

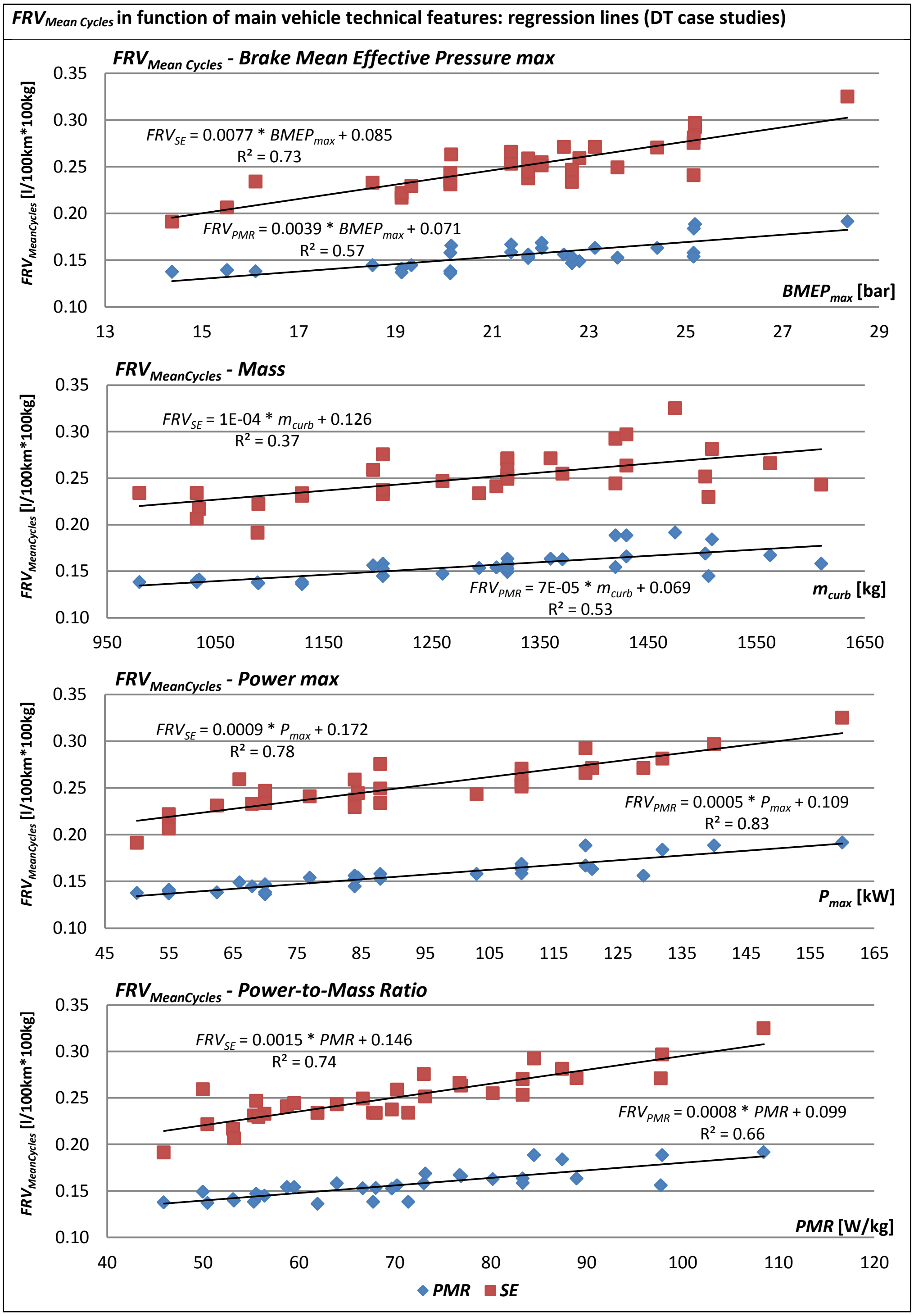


Figure 6.28. $FRV_{MeanCycles}$ of all DT case studies in function of $BMEP_{max}$, m_{curb}, P_{max} *and* PMR with regression lines

Table 6.7. quantifies the effectiveness of the correlation between FRV and vehicle parameters by reporting R^2 of regression lines for the various driving cycles.

	Coefficient of determination R^2									
	FRV_{FTP72}		FRV_{JC08}		FRV_{NEDC}		FRV_{WLTC}		$FRV_{MeanCycles}$	
	PMR	**SE**	**PMR**	**SE**	**PMR**	**SE**	**PMR**	**SE**	**PMR**	**SE**
$BMEP_{max}$	0.55	0.68	0.61	0.71	0.40	0.69	0.57	0.67	0.57	0.73
m_{curb}	0.45	0.36	0.46	0.41	0.53	0.43	0.59	0.21	0.53	0.37
P_{max}	0.79	0.78	0.78	0.80	0.74	0.82	0.78	0.55	0.83	0.78
PMR	0.65	0.72	0.66	0.73	0.56	0.75	0.58	0.57	0.66	0.74

Table 6.7. Coefficient of determination R^2 of regression lines of FRV in function of vehicle technical features

The values of R^2 in Table 6.7. evidence that for both PMR only and SE a significant correlation between FRV and vehicle technical features exists. The values of R^2 vary depending on driving cycle:

- the highest correlation is for P_{max}. R^2 is about 0.8 for all cycles (except FRV_{WLTC_SE} for which it is 0.55) with a value of 0.83 and 0.78 respectively for $FRV_{MeanCycles\_PMR}$ and $FRV_{MeanCycles\_SE}$;
- the lowest correlation is for m_{curb} (R^2 ranges between a minimum of 0.21 for FRV_{WLTC_SE} and a maximum of 0.59 for FRV_{WLTC_PMR});
- intermediate values of R^2 refer to *PMR* and *BMEP*.

FRV-DT case studies: influence of S&S system

The study is performed considering that S&S system is off; the target of this section is to investigate the effect on the overall results of the activation of such a system.

The analysis is performed on one case study per each vehicle class; the choice of the specific case studies is made in order that they are as much as possible representative of the class in terms of vehicle technical features (mass, engine displacement and maximum power, etc). Table 6.8. reports the chosen case studies with regard to DT technology:

	Analysis of influence of S&S system	
	Vehicle class	**Case study**
GT	A/B	7
	C	21
	D	31

Table 6.8. Analysis of influence of S&S system (DT): vehicle classes and case studies

The values of FC in case S&S system is on ($FC_{S\&S}$) are obtained through the same procedure adopted for the GT case studies (see paragraph 6.1.2.1.).

For idle duration that entails the same FC of a restarting (t_{eq}) the value of 12 [s] is assumed. Such an assumption comes from an elaboration of the outcomes of Lohse-Busch et al. (2011). Lohse-Bush undertakes a series of measurements on FC of three cars (Smart Fortwo 1.0l gasoline naturally aspirated 52kW, Mazda 3 2.0l naturally aspirated 111kW and Volkswagen Golf 2.0l TDI 103kW) in order to determine the advantages achievable through the S&S system. In the study FC on Urban Driving Cycle ECE-15 with S&S system activated ($FC_{S\&S\_ON}$) and not activated ($FC_{S\&S\_OFF}$) and the idle consumption ($cons_{idle}$) are measured. Starting from this data, the idle duration that involves the same FC of a restarting (t_{eq}) is determined through the following equation:

$$t_{eq} = \frac{t_{stop\_ECE} - \frac{\left(FC_{S\&S\_OFF} - FC_{S\&S\_ON}\right) * km_{ECE} * \rho_{fuel} * 36000}{cons_{idle}}}{n^{\circ}_{stop\_ECE}} \qquad \text{Eq. 6.16.}$$

Where:
t_{eq} = idle duration that involves same FC of a restarting [s];
t_{stop_ECE} = stop duration of Urban Driving Cycle ECE-15 [s];
$FC_{S\&S\_OFF}$ = FC in case S&S system is not activated [l/100km];
$FC_{S\&S\_ON}$ = FC in case S&S system is activated [l/100km];
km_{ECE} = mileage of Urban Driving Cycle ECE-15 [km];
ρ_{fuel} = fuel density [kg/l];
$cons_{idle}$ = idle FC [g/h];
$n^{\circ}_{stop\_ECE}$ = number of stop of Urban Driving Cycle ECE-15 [null].

Considering the diesel vehicle investigated by Lohse-Busch (Volkswagen Golf 2.0l TDI), the idle duration that involves the same FC of a restarting (t_{eq}) amounts to about 12 [s].

The values of FC in case S&S system is activated ($FC_{S\&S}$) are reported in Tables SI6.1.4. and SI6.1.5. of SI appendix-chapter 6. Data, expressed in terms of liters per 100 kilometers, refer to

- both reference and lightweight mass-configurations;
- both PMR and SE lightweight mass-configurations;
- all the considered driving cycles.

Table SI6.2.4. in SI appendix-chapter 6 reports the FRVs in case of activation of S&S system ($FRV_{S\&S}$); data are presented for all the considered driving cycles and for both PMR and SE. Below the effect on FC and FRV of the S&S system is described for each one of the investigated DT case studies. Figure 6.29. reports the percent variation of FC of reference mass configuration for the case of activation of S&S system with respect to the case of deactivation.

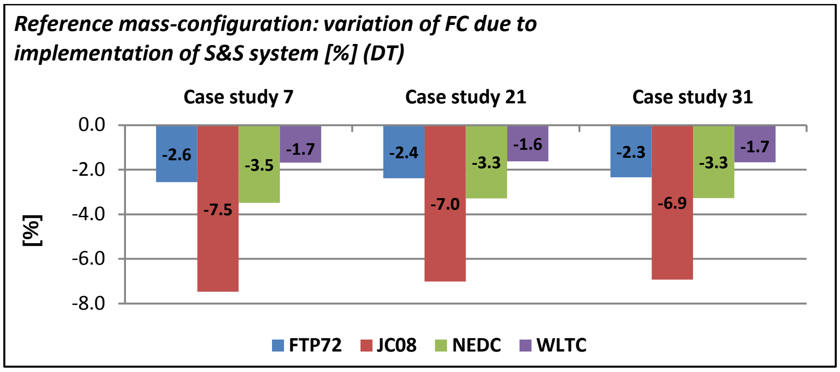


Figure 6.29. Reference mass-configuration: variation of FC due to implementation of the S&S system [%] (DT case studies n°7, 21 and 31)

The values of FC decrease for all case studies. The minimum decreases refer to WLTC (about 2%) while the maximum ones to JC08 (about 7%); the differences between driving cycles depend on the share on total cycle duration represented by stop phases (see Table 3.2.).

Considering the FRV, the activation of S&S system has no effect on FRV_{PMR} while it involves modification of FRV_{SE}. This evidence is explainable by the fact that

- in case of PMR FC reduction involved by S&S system is the same for all the lightweight mass-configurations (idle consumption does not vary passing from a configuration to another because the engine displacement remains constant)
- in case of SE FC reduction involved by S&S system is not the same for the lightweight mass-configurations (idle consumption varies passing from a configuration to another because engine displacement is affected by SE).

Figure 6.30. reports the percent variation of FRV_{SE} for the case of activation of S&S system with respect to the case of deactivation.

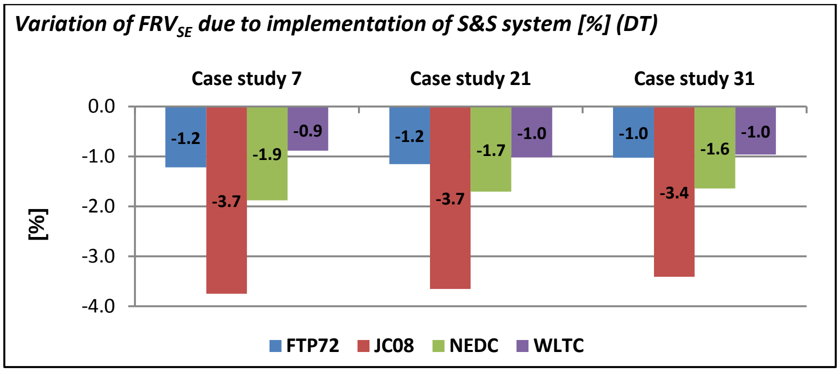


Figure 6.30. Variation of FRV_{SE} due to implementation of the S&S system [%] (DT case studies n°7, 21 and 31)

The results show that the values of FRV decrease for all case studies. The minimum decrease refers to WLTC and FTP72 (about 1%) while the maximum one to JC08 (3-4%); the differences between cycles depend on the share of total cycle duration represented by stop phases (see Table 3.2.). No specific trend imputable to vehicle class emerges.

FRV - DT case studies: sensitivity analysis

Sensitivity analysis is performed following the same operative procedure applied for the GT vehicles and the chosen case studies are the same that have been adopted in the analysis of the influence of S&S system (DT case studies n°7, 21 and 31). The change of *f* involves negligible modifications in the implementation of SE; consequently the values assumed by model parameters in the SE mass-configurations of reference study (see section *SI 4.4. SE mass configurations* of SI appendix chapter 4) remain valid also for sensitivity analysis.

The values of FC obtained in sensitivity analysis for DT case studies n°7, 21 and 31 are reported in Tables SI6.1.8. and SI6.1.9. of SI appendix-chapter 6: data, expressed in terms of liters per 100 kilometers, refer to

- both reference and lightweight mass-configurations;
- both PMR and SE lightweight mass-configurations;
- all the considered driving cycles.

Table SI6.2.6. in SI appendix-chapter 6 reports the FRVs obtained in sensitivity analysis for DT case studies; data are presented for all the considered driving cycles and for both PMR only and SE. Below the effect on FC and FRV of the change of *f* is described for each one of the investigated GT case studies.

Figures 6.31. reports the percent variation of FC of reference mass configuration for

- $f = 0.007$
- $f = 0.013$

with respect to the reference study ($f = 0.010$).

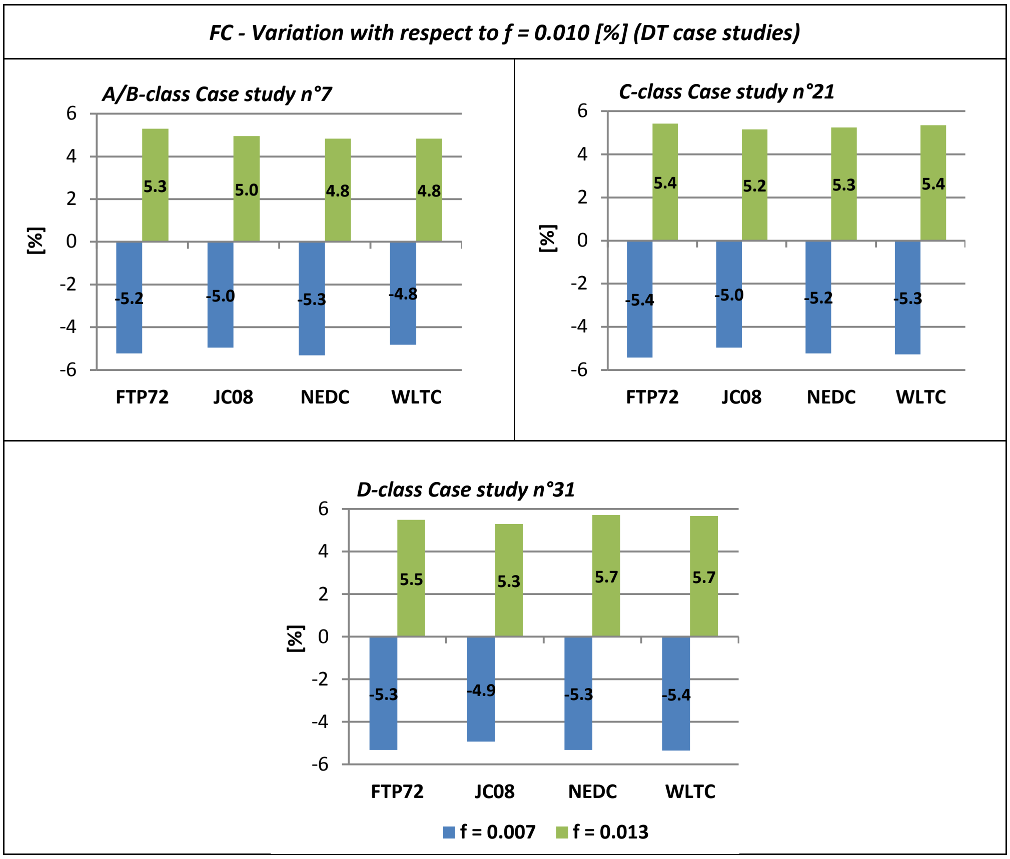


Figure 6.31. Sensitivity analysis based on *Coulomb friction coefficient (f)*. FC of reference mass-configuration: percent variation with respect to *f* = 0.010 [%] (DT A/B-class case study n°7, C-class case study n°21 and D-class case study n°31)

With regard to FC, results show that:

- *f* = 0.007. FC decreases for all case studies: depending on vehicle class and driving cycle the reductions are comprised within the range 4-6%.
- *f* = 0.013. FC grows for all case studies: depending on vehicle class and driving cycle the increases are comprised within the range 4-6%.

Figure 6.32. reports the percent variation of FRV for

- *f* = 0.007
- *f* = 0.013

with respect to the reference study (*f* = 0.010).

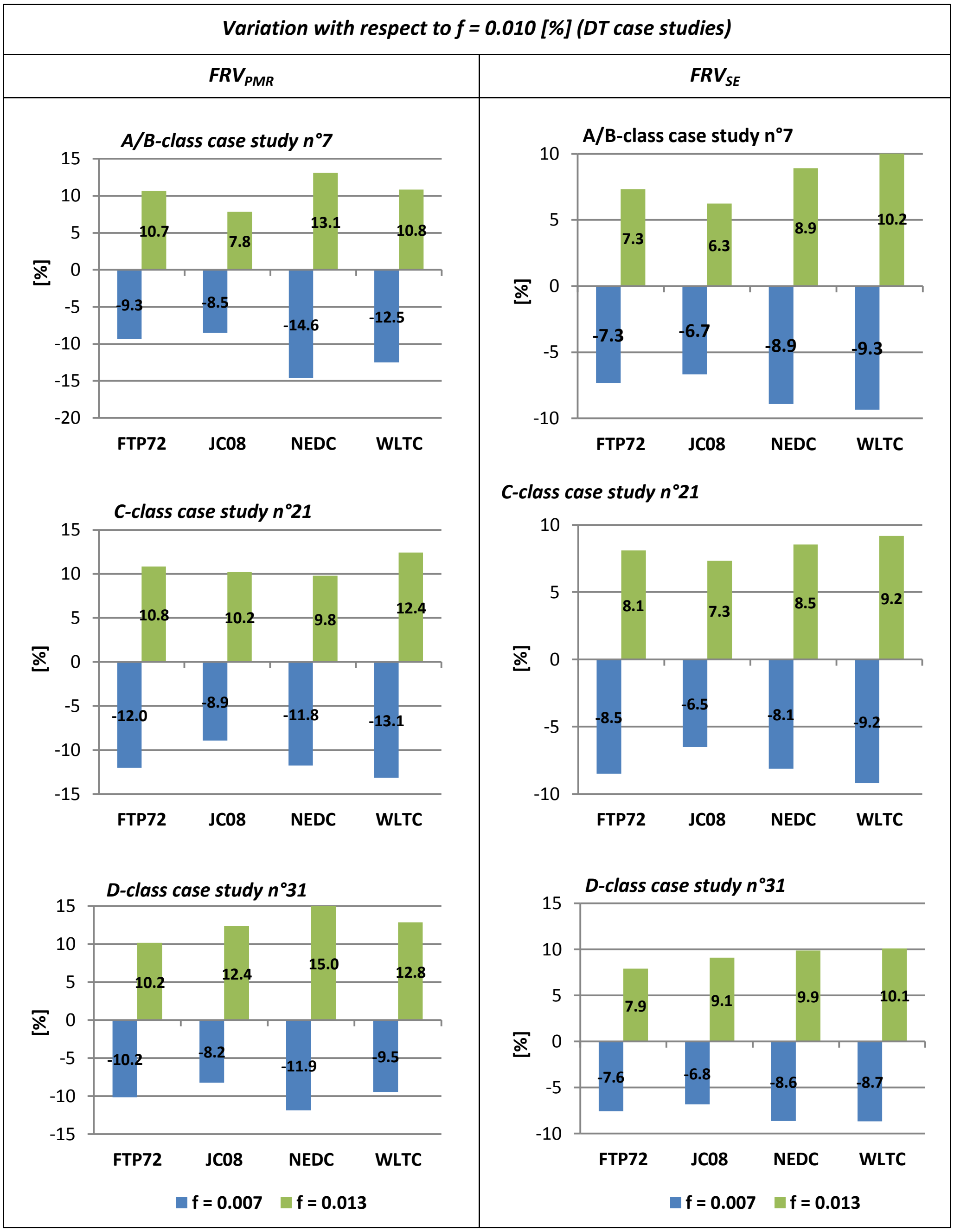


Figure 6.32. Sensitivity analysis based on *Coulomb friction coefficient (f)*. FRV_{PMR} and FRV_{SE}: percent variation with respect to $f = 0.010$ [%] (DT A/B-class case study n°7, C-class case study n°21 and D-class case study n°31)

With regard to FRV, results show that:

- *f* = 0.007 (PMR only). The FRV decreases for all case studies: depending on vehicle class and driving cycle the reduction is comprised within the range 8-15%;
- *f* = 0.007 (SE). The FRV decreases for all case studies: depending on vehicle class and driving cycle the reduction is comprised within the range 6-10%;
- *f* = 0.013 (PMR only). The FRV increases for all case studies: depending on vehicle class and driving cycle the increase is comprised within the range 7-15%;
- *f* = 0.013 (SE). The FRV increases for all case studies: depending on vehicle class and driving cycle the increase is comprised within the range 6-11%.

6.1.3. Input for environmental modelling

The aim of this section is to characterize the environmental models described in paragraph 3.3. in such a way they represent a valid reference for LCA practitioners in application to real case studies. The final target is to identify a criterion that deduces a value of FRV tailored for the generic application, starting from the entirety of FRVs obtained for the various case studies. The implementation of a such a value within the environmental models makes the tool able to treat with appropriately any real case study and it represents the meeting point between simulation and environmental modelling.

The chosen criterion struggles to take into account the variability of FRV with respect to the main vehicle technical features. Paragraphs 6.1.2.1. and 6.1.2.2. analyze the correlation between FRV and *maximum Brake Mean Effective Pressure* ($BMEP_{max}$), *vehicle mass* (m_{curb}), *maximum Power* (P_{max}) and *Power-to-Mass Ratio (PMR)* by identifying regression lines and corresponding coefficients of determination R^2. The results of the correlation analysis and the approach for the quantification of FRV for any generic application are presented separately between GT and DT vehicles.

<u>GT vehicles</u>. Basing on values of R^2 reported in Table 6.2., it has been evidenced that in case of PMR only there is a substantial absence of correlation between FRV and vehicle technical features; on the other hand in case of SE the correlation is notably higher and it is maximum for parameter P_{max}. In the light of these considerations, the refined approach for the quantification of FRV for any generic case study differs between the cases of PMR and SE:

- PMR only: the arithmetic mean over case studies within the class of $FRV_{MeanCycles\_PMR}$ is assumed (see Table 6.2.1. in SI Appendix-chapter 6);
- SE: the FRV is obtained from the regression line of $FRV_{MeanCycles\_SE}$ in function of P_{max} through the maximum power of the generic application (see Figure 6.13.).

The choice to adopt as reference $FRV_{MeanCycles}$ is justified by the fact that it is an average index of the FRVs determined in the different driving cycles.

<u>DT vehicles</u>. Basing on values of R^2 reported in Table 6.7., it has been evidenced that for both PMR only and SE the correlation between FRV and the chosen technical features is notable and it is maximum for parameter P_{max}. In the light of these considerations, the refined

approach for the quantification of FRV for any generic application is the same for both PMR only and SE:

- PMR only: the FRV is obtained from the regression line of $FRV_{MeanCycles\_PMR}$ in function of P_{max} through the maximum power of the generic application (see Figure 6.28.).
- SE: the FRV is obtained from the regression line of $FRV_{MeanCycles\_SE}$ in function of P_{max} through the maximum power of the generic application (see Figure 6.28.).

Table 6.9. summarizes the chosen approach for the quantification of FRV for any generic case study.

FRV [l/100km*100kg]	
GT vehicles	
PMR	**SE**
$FRV_{PMR} = 0.175$ (A/B-class)	$FRV_{SE} = 0.0015 * P_{max} + 0.1844$
$FRV_{PMR} = 0.173$ (C-class)	
$FRV_{PMR} = 0.184$ (D-class)	
DT vehicles	
PMR	**SE**
$FRV_{PMR} = 0.0009 * P_{max} + 0.1721$	$FRV_{SE} = 0.0005 * P_{max} + 0.1091$
Notes: P_{max} in [kW]	

Table 6.9. Input for environmental modelling: criterion for quantifying the FRV for any generic case study (GT and DT vehicles)

6.2. Environmental modelling

In this paragraph the conceived environmental models are critically analyzed in the light of final targets the research is aimed to fulfil. As usually the treatise is conducted separately for the two considered typologies of LCA study.

6.2.1. LCA of a specific vehicle component

The environmental model is the end result of the research and it incorporates the findings of both simulation and environmental modelling. One of the aims of the overall work is that the environmental model represents a valuable support instrument for LCA practitioners in application to real case studies. In this context the added value of the conceived use stage plan is that the parameters which characterize the TTW process (see Table 5.3.) are customizable on the specific application:

- $CO_{2\_km\_veh\_mw}$, $CO_{2\_km\_veh\_ru}$, $CO_{2\_km\_veh\_ur}$, $emiss\_i_{veh\_km\_mw}$, $emiss\_i_{veh\_km\_ru}$, $emiss\_i_{veh\_km\_ur}$ are from the GaBi6 process database (section "Transport-Road-Passenger car") depending on emission standard, engine size and technology of the considered vehicle;
- FRV_{PMR} is an output of the simulation modelling and it is quantified basing on vehicle technical features through the criterion defined in chapter 6.1.3.;
- ρ_{fuel}, $mileage_{use}$, $ppm_{sulphur}$, $share\ CO_{2BIO}$ are from the GaBi6 process database depending on fuel type (gasoline/diesel) of the considered vehicle;
- FC_{veh_100km}, $mass_{comp}$, $mileage_{use}$, $share_{mw}$, $share_{ru}$, $share_{ur}$ are set on the basis of the specific LCA case study.

In particular the possibility to set the FRV allows performing the allocation of component consumption taking into account as much as possible technical features of the specific case study. So that the impact allocation results to be more accurate with respect to Incremental and Proportional methods.

With respect to basic equations of TTW process (see Table 5.4.), the following observations are made:

- the amount of FC during vehicle operation attributed to the component (FC_{use_comp}) has a leading role in the economy of the overall use stage plan. On one hand FC_{use_comp} fixes the amount of fuel whose production is assessed by WTT process; on the basis of such an amount the WTT LCIA impacts attributed to the component are calculated. On the other hand FC_{use_comp} determines the amount of air emissions during operation on the basis of which TTW LCIA impacts attributed to the component are calculated (see Equations 5.2.-5.5.);
- FC_{use_comp} scales linearly with the component mass on the basis of the FRV coefficient;
- the amount of air emissions during operation attributed to the component ($emiss\_i_{use\_comp}$) scales linearly with the amount of FC during operation attributed to the component (FC_{use_comp}); as FC_{use_comp} scales linearly with component mass, also the emissions attributed to the component scale linearly with component mass;
- as the focus is to allocate to the component a quota of use stage impact, all the typologies of air emissions are considered (benzene, CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NO, NO_2, particulate and SO_2). On the other hand in the perspective of light-weighting, FC saving involved by mass reduction influences only CO_2 and SO_2 emissions whereas it has no effect on the so-called "limited emissions" (i.e. NOx, HC, etc); indeed, CO_2 and SO_2 emissions scale linearly with the amount of FC basing on fuel C and S content while the limited emissions depend exclusively on the number of travelled kilometers during operation as they are treated by the exhaust gas treatment system. Consequently in a comparative LCA between a reference and a lightweight component in which the comparison is performed by subtraction of absolute impact of the component the environmental advantages in the use stage achieved by light-weighting would be

overestimated. Therefore for the application to such a case study the conceived environmental model must be modified by removing all TTW air emissions with the exception of CO_2 and SO_2.

6.2.2. Comparative LCA between a reference and an innovative lightweight alternative (both cases of PMR and SE)

The environmental model is the end result of the research and it incorporates the findings of both simulation and environmental modelling. One of the aims of the overall work is that the environmental model represents a valuable support instrument for LCA practitioners in application to real case studies. In this context the added value of the conceived use stage plan is that the parameters which characterize the TTW process (see Tables 5.5. and 5.7.) are customizable on the specific application:

- $CO_{2\_km\_veh\_mw}$, $CO_{2\_km\_veh\_ru}$, $CO_{2\_km\_veh\_ur}$ are from the GaBi6 process database (section “Transport-Road-Passenger car”) depending on emission standard, engine size and technology of the considered vehicle;
- FRV_{PMR} (FRV_{SE}) is an output of the simulation modelling and it is quantified basing on vehicle technical features through the criterion defined in chapter 6.1.3.;
- ρ_{fuel}, $mileage_{use}$, $ppm_{sulphur}$, $share\ CO_{2BIO}$ are from the GaBi6 process database depending on fuel type (gasoline/diesel) of the considered vehicle;
- FC_{veh_100km}, $mass_{comp}$, $mileage_{use}$, $share_{mw}$, $share_{ru}$, $share_{ur}$ are set on the basis of the specific LCA case study.

In particular the possibility to set the FRV allows performing the quantification of impact reduction taking into account as much as possible technical features of the specific case study. So that the impact saving achievable through light-weighting is determined more accurately with respect to comparative studies that assume as reference a value of FRV fixed a priori.

With respect to basic equations of TTW process (see Tables 5.6. and 5.8.) the following observations are made:

- the amount of FC saved during operation (FC_{use_sav}) has a leading role in the economy of the overall use stage plan. On one hand FC_{use_sav} fixes the amount of fuel whose avoided production is assessed by WTT process; on the basis of such an amount the saving in WTT LCIA impacts is calculated. On the other hand FC_{use_sav} determines the amount of air emissions saved during operation on the basis of which the saving in TTW LCIA impacts is calculated (see Equations 5.7.-5.9. and 5.11.-5.13.);
- FC_{use_sav} scales linearly with the saved mass on the basis of the FRV coefficient;
- the amount of air emissions saved during operation ($CO_{2BIO\_use\_sav}$, $CO_{2FOS\_use\_sav}$, SO_{2use_sav}) scales linearly with the amount of FC saved during operation (FC_{use_sav}); as FC_{use_sav} scales linearly with the saved mass, also the saved emissions scale linearly with the saved mass;
- considering the typology of air emissions, only CO_2 and SO_2 are taken into account. Such a choice appears to be reasonable because FC saving involved by

mass reduction influences only CO_2 and SO_2 emissions while it has no effect on the so-called “limited emissions” (i.e. NOx, HC, etc). Indeed CO_2 and SO_2 emissions scale linearly with the amount of FC basing on fuel C and S content; on the other hand the limited emissions depend exclusively on the number of travelled kilometers as they are treated by the exhaust gas treatment system.

6.3. Peculiarities and limitations of the study

Peculiarities and limitations of the study are presented separately per each typology of LCA study considered in the research.

LCA of a specific vehicle component

1. In simulation modelling section FC is determined for five mass-configurations of the vehicle (reference configuration and four lightweight configurations: 5%, 10%, 15% and 20% lightening) and the mass-induced FC is calculated as the slope of the regression line of consumption in function of mass. As the maximum step of lightening is 20%, the calculated FRV coefficients can be considered as representative of the mass-induced FC for amount of mass that does not exceed 20% of total vehicle weight. This fact implies that in the case of LCA of a specific vehicle component the tool can be applied to case studies in which the component mass does not represent more than 20% of total vehicle weight.
2. The impact and FC attributed to the component are determined through the FRV_{PMR} coefficient; this latter represents the mass-induced FC and it is calculated from the relationship between consumption and mass only. Therefore the tool can applied exclusively to case studies in which the component has effect only on vehicle mass, all other parameters (i.e. aerodynamic drag coefficient) remaining the same.
3. In the environmental modelling all car air emissions are taken into account. On the other hand in the perspective of light-weighting, FC saving involved by mass reduction influences only CO_2 and SO_2 emissions whereas it has no effect on the so-called “limited emissions” (i.e. NOx, HC, etc); indeed, CO_2 and SO_2 emissions scale linearly with the amount of FC basing on fuel C and S content while the limited emissions depend exclusively on the number of travelled kilometers as they are treated by the exhaust gas treatment system. Consequently, in a comparative LCA between a reference and a lightweight component in which the comparison is performed by subtraction of absolute impact of the components, the environmental advantages in the use stage achieved by light-weighting would be overestimated. Hence for the application to this kind of study the conceived environmental model must be modified by removing all TTW air emissions with the exception of CO_2 and SO_2.
4. The method for quantifying the FRV proposed in paragraph 7.1.3. is valid for the only vehicle models whose technical features are within the range defined by case studies investigated in the research. Table 6.10. reports minimum-maximum range over the considered case studies for the following parameters: maximum Brake Mean Effective Pressure ($BMEP_{max}$), displacement (V), mass (m_{curb}), maximum Power (P_{max}) and Power-to-Mass Ratio (PMR).

		$BMEP_{max}$ [bar]	**V [cm^3]**	**m_{curb} [kg]**	**P_{max} [kW]**	**PMR [W/kg]**
Min-max range	**GT**	16.1 - 22.5	875 - 1999	962 - 1489	63 - 177	58.1 - 118.5
	DT	14.4 - 28.3	1248 - 1997	980 - 1610	50 - 160	45.9 - 108.5

Table 6.10. Minimum-maximum range over the considered case studies for parameters maximum Brake Mean Effective Pressure ($BMEP_{max}$), displacement (V), mass (m_{curb}), maximum Power (P_{max}) and Power-to-Mass Ratio (PMR)

For cars whose technical features are notably outside the ranges in Table 6.10., the method proposed in paragraph 7.1.3. is unreliable as it is based on simulation modelling of unappropriate vehicle models.

<u>Comparative LCA between a reference and an innovative lightweight alternative</u>

1. In simulation modelling section FC is determined for five mass-configurations of the vehicle (reference configuration and four lightweight configurations: 5%, 10%, 15% and 20% lightening) and the mass-induced FC is calculated as the slope of the regression line of consumption in function of mass. As the maximum step of lightening is 20%, the calculated FRV coefficients can be considered as representative of the mass-induced FC for amount of mass that does not exceed 20% of total vehicle weight. This fact implies that in the case of comparative LCA the tool can be applied to case studies in which mass reduction achieved through light-weighting does not exceed 20% of total vehicle weight.
2. The tool can be applied exclusively to case studies in which the innovative lightweight alternative offers advantages in terms of mass reduction only, all other vehicle parameters (i.e. aerodynamic drag coefficient) remaining the same.
3. The fourth point reported for the LCA of a specific vehicle component is equally valid in case of comparative LCA.
4. The research contemplates both cases of mass reduction only (PMR) and implementation of car re-design (SE). In this latter case the application of the conceived tool to real case studies requires the consciousness of the assumptions under which car re-sizing is performed:

    - engine resizing is applied in order that reference and lightweight mass-configurations respect at the same time two equality criteria: equivalence of performance and technological level;
    - for the performance level the chosen criterion is the elasticity 80-120 [km/h] in the upper gear ratio;
    - technical parameters assumed as representative of technological level are maximum brake mean effective pressure, bore-to-stroke ratio and mean piston speed.

6.4. Scope and future developments of the tool

The research is situated in the context of design for Sustainability (DfS). The aims of the overall work is developing a valuable tool able to support LCA practitioners in application to real case studies. Depending on the typology of LCA study, the refined tool finds application within different branches of design for sustainability and it is addressed to particular end-users:

- LCA of a specific vehicle component. The utility of the tool is included within the general definition of "design for environment", that is "evaluating the human health and environmental impacts of a process or a product". More to the point, the conceived model is functional to perform the mere environmental assessment of existing automotive concepts; here indeed the tool serves only to evaluate the eco-profile of a component as is without affecting in any way the design phase. Performing the life cycle assessment of a vehicle part can be of interest for suppliers who need providing to the parent company information regarding the eco-profile of the supply or obtaining environmental certifications/commendations for their products. At the same time, in the research world it can be the interest in evaluating the environmental performances of automotive components realized through innovative materials and technologies; in this case the entities that potentially can benefit from applying the tool to the component case study are environmental consultants, universities and research centers;
- Comparative LCA between a reference and an innovative lightweight alternative. In this case the tool can be fully located within the context of design for sustainability, specifically design for energy efficiency. The tool takes into account two fundamental aspects of a product. On one hand it addresses the energy issue, that is the energy consumption during operation attributed to the component; on the other hand, it assesses the environmental burdens caused by use stage, both WTT impacts (fuel supply chain) and TTW impacts (air emissions). As shown in chapter 1.1., a thorough design process requires that design for energy efficiency is integrated by design for manufacturing and design for recyclability, expecially when treating with concepts that involve the adoption of innovative materials or technologies; indeed, despite the undeniable environmental benefits in the use stage thanks to lower energy intensity, lightweight components usually present higher burdens in manufacturing/EoL stages and therefore a balance between advantages and disadvantages throughout the entire LC is needed. In the light of these considerations, the contribution of the conceived tool is the accurate quantification of use stage environmental benefits; more specifically, the possibility to set LC mileage within the environmental models permits to identify the break-even mileage for the effective environmental convenience of lightweight alternatives with respect to reference ones. Concluding, the added value of the tool in application to comparative LCA is incorporating the environmental concerns within materials and technologies selection process; this target is achieved through a predictive environmental assessment that can heavily influence the design phase of innovative lightweight solutions. The end-users that potentially can benefit from applying the tool to the comparative case study are mainly original equipment manufacturers that aim to insert the environmental issue between drivers of design process.

Possible future developments of the tool can be illustrated along two fronts:

- Extension to electric and hybrid vehicles. The extension of the tool to electric and hybrid cars involves to repeat both simulation and environmental modelling taking into account the peculiarities (energy absorption and air emissions) of these particular propulsion technologies. In this regard a reason of interest is the estimation of energy reduction value coefficients specific for electric and hybrid vehicles. Furthermore the integration of the tool by the two sections would enable to assess innovative solutions for different sectors (ICE, electric and hybrid vehicles), compare them and identify the most profitable one, thus providing a comprehensive overview on environmental potentialities of lightweighting within the automotive context. In view of this it can be concluded that the extension to electric and hybrid propulsion technologies would make the tool a valuable instrument in order to expand the application field of automotive LCA, take strategic decisions and direct the market toward specific directions;
- Integration with Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). The conceived tool deals with only one aspect of the sustainability, the environmental one. In order to obtain a comprehensive assessment, simply referring to environment is not enough; on the contrary it is necessary taking into account all socio-economic implications entailed by product LC. At this scope the accounted instruments are Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). LCC is a methodology aimed to assess the total cost of an asset throughout its entire life-time including planning, design, acquisition, support and any other cost directly attributable to owning or using it (New South Wales, 2004). On the other hand the scope of S-LCA is assessing the potential social and socio-economic impact, both positive and negative, of products/services throughout the life-cycle (UNEP, 2009); it allows increasing knowledge, providing information for decision makers and promoting improvement of social conditions in product life cycles (Benoit et al., 2010). In view of the above it can be concluded that integrating the existing tool by analogous instruments of socio-economic investigation would lead to a holistic approach able to take into account a wider set of aspects with respect to single-field analyses.

7. Conclusions and final remarks

The present work is aimed to refine a reliable tool for the assessment of the use stage within the two typologies of LCA study

- *LCA of a specific vehicle component;*
- *comparative LCA between a reference and an innovative alternative*.

From a practical point of view the tool is constituted by a series of environmental models developed by the software GaBi6 whose output is represented by the impacts ascribable to a certain amount of mass:

- in the case of LCA of a specific vehicle component it is referred to the component mass and the quantified impacts are the use stage impacts attributed to the component;
- in the case of comparative LCA it is referred to the saved mass and the quantified impacts are the avoided impacts thanks to light-weighting.

Below the conclusions of the study are summed up; starting from a summary of state of art and materials and methods, the utility of the tool is described evidencing the enhancements with respect to existing literature and possible future developments.

Review of existing literature

For the LCA of a specific vehicle component the focus of the use stage is to determine the quota of total use stage impact attributable to the component; at this scope a method for the allocation of component consumption is needed. In literature this issue is addressed by two main methods: Incremental and Proportional methods. Both the approaches determine the quota of FC attributed to the component (FC_{comp}) by rigid proportions between component mass (m_{comp}), vehicle mass (m_{veh}) and vehicle FC (FC_{veh}):

Incremental method: $\frac{FC_{comp}}{FC_{veh}} = \frac{m_{comp}}{m_{veh}}\, c$

Proportional method: $\frac{FC_{comp}}{FC_{veh}} = \frac{m_{comp}}{m_{veh}}$

The Incremental method needs a proportionality constant c fixed a priori and many of the existing applications adopt the value 0.6, as suggested by Lynne Ridge 1997. Since such studies deal with cars that belong to different vehicle classes and differ in terms of engine technology, mass, maximum power and power-to-mass ratio, the point of criticism is the adoption of the same value for c: this involves that the ratio $\frac{FC_{comp}/FC_{veh}}{m_{comp}/m_{veh}}$ (ratio between the quota of consumption and the quota of mass attributed to the component) is the same for a wide range of cars without taking into account technical features that case by case characterize the specific application. On the other hand the Proportional method does not need a proportionality constant fixed a priori but presents the disadvantage that, taking into account all the aspects of motion resistance, it cannot be verified by measurements; for this reason the Proportional method is rejected by scientists and experts who consider the parameters of the travelling resistance equation are simply taken into account by a mass-proportional key.

It can be concluded that the allocation of component consumption and impact performed by Incremental and Proportional methods is affected by a notable level of uncertainty.

For the comparative LCA between a reference and an innovative lightweight alternative the focus of the use stage is to determine the reduction of use stage impact achievable through car mass reduction. At this scope the quantification of FC reduction induced by mass decrease is needed. For the quantification of FC saving during operation the most widespread method is the FRV-based approach and it founds on the following relation:

$$\Delta FC = \Delta m * FRV * 0.01 \; = (m_{ref\ comp} - \; m_{light\ comp}) * FRV * 0.01 \qquad \text{Eq. 7.1.}$$

For the FRV coefficient, the value adopted by existing LCAs varies between 0.02 and 1.00 [l/100km*100kg]. This wide range involves an excessive margin of inaccuracy which strongly limits the validity of the results. Usually the reference values for the FRV are provided by other works whose aim is to investigate the relation between FC and mass. These latter are based on simulation modelling and provide reference FRVs for entire engine technologies (i.e. naturally aspirated cars) or at least for single vehicle classes (i.e. naturally aspirated C-class cars). From the review of existing works that deal with the calculation of FRV, the following considerations emerge:

- no study calculate the FRV coefficient for gasoline turbocharged vehicles;
- the calculation of FRV is performed by simulation modelling of a very restricted number of case studies: the point of criticism is that the resulting FRVs depend on technical features of the specific case studies without being really representative of entire technologies and, much less, vehicle classes;
- the existing researches are dated: FRVs determined 10-15 years ago nowadays are no more reliable. On one hand the development of new models entails a change of vehicle technical features (engine technology, mass, maximum power and power-to-weight ratio); on the other hand the advance in research makes that new cars have better fuel economy performance with respect to the old ones. Additionally the European studies determine the FRV basing on the NEDC driving cycle which is going to become obsolete as in the next years it will be substituted by the WLTC;
- some of the existing works are based on a single driving cycle: this involves a limitation in terms of reliability of the results as no additional routes and driving patterns are evaluated;
- the driving cycles adopted for calculating the FRV differ passing from one study to the another evidencing a limitation in terms of comparability.

Materials and methods

The construction of the tool is articulated into three main stages: calculation of use stage FC (stage 1), evaluation of mass-induced FC (stage 2) and environmental modelling (stage 3).

In the first stage the calculation of car FC is performed through simulation modelling of several vehicle mass-configurations: reference and four lightweight configurations (5%, 10%, 15% and 20% lightening). The lightweight configurations are evaluated for both the cases of

- Primary Mass Reduction only (PMR): the effect of the only mass reduction is evaluated;
- implementation of Secondary Effects (SE): SEs are applied in order that passing from reference to lightweight configurations two equivalence criteria are respected: performance criterion (assumed as the elasticity 80-120 [km/h] in the upper gear ratio) and technological criterion (assumed as the equivalence of brake mean effective pressure, bore-to-stroke ratio and mean piston speed).

The calculation of FC is performed for both Gasoline Turbocharged (GT) and Diesel Turbocharged (DT) vehicles; within each engine technology the analysis is extended to 32 case studies subdivided into A/B, C and D classes. The calculation is repeated for four standardized driving cycles: Federal Test Procedure 72 driving cycle (FTP72), Japan 08 driving Cycle (JC08), New European Driving Cycle (NEDC) and World Light Test driving Cycle (WLTC). The output of the first stage is constituted by the values of FC of reference and lightweight mass-configurations for all case studies with respect to the cited driving cycles.

Basing on values of FC of the different mass-configurations, the second stage evaluates the mass-induced FC as the relation between consumption and mass. For all case studies the linear regression shows coefficient of determination R^2 close to 1: therefore the slope of the regression lines is assumed as representative of the mass-induced FC and it is referred to as Fuel Reduction Value (FRV). As the calculation of FC is performed basing on four driving cycles, for both PMR and SE four values of FRV are obtained: FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC} and FRV_{WLTC}. To have a reference independent from driving cycle, an unique FRV is obtained as the arithmetic mean of the ones which refer to the single cycles and it is referred to as $FRV_{Mean\ Cycles}$. So that two values of FRV are obtained for each case study: $FRV_{Mean\ Cycles\_PMR}$ and $FRV_{Mean\ Cycles\_SE}$. The final target is that the tool represents a valid support for real LCAs; at this scope it is refined a criterion that deduces a value of FRV tailored for the generic application starting from the entirety of FRVs obtained for the various case studies. The chosen criterion struggles to take into account the variability of FRV with respect to the main vehicle technical features; for this reason the correlation between FRV_{Mean_Cycles} and parameters *maximum Brake Mean Effective Pressure* ($BMEP_{max}$), *vehicle mass* (m_{veh}), *maximum Power* (P_{max}) and *Power-to-Mass Ratio (PMR)* is investigated by an analysis based on linear regression. A good correlation between *FRV* and the chosen technical features is detected for

- DT vehicles (both cases of PMR only and SE)
- GT vehicles in the only case of SE

and it is maximum for P_{max}. On the other hand for the case of PMR of GT vehicles a substantial absence of correlation is evidenced with respect to all parameters. In the light of these considerations, the refined approach to determine the FRV for any generic case study is the following:

- DT vehicles (both PMR only and SE) & GT vehicles in the only case of SE: the FRV is obtained from the regression line of $FRV_{MeanCycles}$ in function of P_{max} through the maximum power of the generic case study;
- GT vehicles in the only case of PMR: the FRV is obtained as the arithmetic mean over case studies within the class of $FRV_{MeanCycles}$.

Table 7.1. summarizes the chosen approach to determine the FRV for any generic case study.

***FRV* [l/100km*100kg]**	
GT vehicles	
PMR	**SE**
FRV_{PMR} = 0.175 (A/B-class)	$FRV_{SE} = 0.0014 * P_{max} + 0.1844$
FRV_{PMR} = 0.173 (C-class)	
FRV_{PMR} = 0.184 (D-class)	
DT vehicles	
PMR	**SE**
$FRV_{PMR} = 0.0009 * P_{max} + 0.1721$	$FRV_{SE} = 0.0005 * P_{max} + 0.1091$
Notes: P_{max} in [kW]	

Table 7.1. Criterion for the quantification of FRV for any generic case study (GT and DT vehicles)

The third stage of the construction of the tool (environmental modelling) consists in the conception of innovative environmental models specific for the treatment of the use stage within the considered typologies of LCA study. These models assume a linear dependence of FC and emissions with respect to mass on the basis of the FRV coefficient.

- in the case of LCA of a specific vehicle component the considered amount of mass is the component mass (m_{comp}) and basing on it the amount of FC and emissions during operation attributed to the component are quantified:

$$FC_{use\_comp} = \frac{FRV_{PMR} * m_{comp} * mileage_{use}}{10000} ; \qquad \text{Eq. 7.2.}$$

$$emiss\ i_{use\_comp} = emiss\ i_{km\_veh} * mileage_{use} * \frac{FC_{use\_comp}}{FC_{use\_veh}} ; \qquad \text{Eq. 7.3.}$$

- in the case of comparative LCA the considered amount of mass is the saved mass thanks to light-weighting (m_{sav}) and basing on it the amount of FC and emissions saved thanks to light-weighting are quantified:

$$FC_{use\_saved} = \frac{FRV_{PMR} * m_{saved} * mileage_{use}}{10000}; \qquad \text{Eq. 7.4.}$$

$$emiss\ i_{use\_comp} = emiss\ i_{km\_veh} * mileage_{use} * \frac{FC_{use_{comp}}}{FC_{use_{veh}}}. \qquad \text{Eq. 7.5.}$$

Considering the implementation of the tool in real case studies, the characteristic parameters of the model (FC_{veh_100km}, $emiss\_i_{km\_veh}$, FRV, etc) are defined on the basis of the specific application. In particular the FRV is determined through the criterion identified in Table 7.1.; the possibility to set up the FRV in function of vehicle technical features represents the added value of the research.

Enhancements with respect to existing literature, utility and possible future developments of the tool

In the light of

- criticisms of current LCA practices
- review of tool structure and operation

the enhancements of the research with respect to existing literature are illustrated below. The treatise is subdivided into simulation and environmental modelling in order to evidence separately the improvements coming from the two sections the work is articulated.

Simulation modelling. The allocation of FC to a component (LCA of a specific vehicle component) and the estimation of FC reduction due to light-weighting (comparative LCA) are performed basing on the FRV coefficient. The FRV is determined through a simulation modelling that satisfies the following requirements:

- calculation is based on an use stage simulation model which reproduces the complete automotive network subdivided into two sections: drive train (sub-models: Engine, Clutch, Gearbox and Vehicle dynamics) and control logic (sub-models: Mission profile and ambient data, Driver and Control unit). The modelling of the whole network allows considering all vehicle energy expenditures and evaluating the effect that interaction of each component with another has on the overall car FC and, consequently, on FRV;
- calculation is performed taking into account not only the NEDC but also other three standardized driving cycles. On one hand the FRV based on the NEDC is useful in order to make comparisons with existing studies. On the other hand considering a broad range of driving cycles (these latter characterized by different levels of speed and acceleration) allows to evaluate the use stage on various scenarios of route and driving behavior. Additionally calculation based on different standardized driving cycles ensures to overcome the criticism that considering only the NEDC leads to unreliable results;
- calculation is performed for both GT and DT vehicles and, within the technology, for a wide range of classes and case studies according to model range of 2015 European car market;

- the characterization of FRV for a wide range of vehicle case studies allows to examine as much as possible in detail each specific application, thus obtaining more accurate results with respect to both Incremental/Proportional methods and FRV-based approach.

<u>Environmental modelling</u>. Environmental modelling refines a series of environmental models able to both allocate component impact (LCA of a specific vehicle component) and estimate impact reduction thanks to light-weighting (comparative LCA). The models are based on values of FRV obtained by simulation modelling and tailored for any generic application:

- in the case of LCA of a specific vehicle component a quota of the overall vehicle use stage impact is allocated to the component. At this scope all air emissions of the vehicle are considered in the assessment;
- in the case of comparative LCA the amount of use stage impact saved thanks to light-weighting is estimated. At this scope only the FC-dependent emissions (CO_2 and SO_2) are considered in the assessment.

From a practical point of view, the application of the tool to real case studies translates the points illustrated above to tangible enhancements:

- LCA of a specific vehicle component. The allocation of component impact is performed by taking into account the value of FRV which is closest to the specific application in terms of vehicle class, size and technical features. This remarkable modularity allows to obtain more accurate results with respect to both Incremental/Proportional methods and FRV-based approach;
- Comparative LCA between a reference and an innovative lightweight alternative. The potentiality to reduce FC through light-weighting is estimated by taking into account the value of FRV which is closest to the specific application in terms of vehicle class, size and technical features. This remarkable modularity allows to obtain more accurate results with respect to current applications of the FRV-based approach. The accurate quantification of use stage impact reduction achievable by lightweight solutions enables to perform a balance between the opposite effects that the use of innovative materials and technologies involves on the different stages of component LC (higher energy-intensity/emissions during production and reduced FC during operation). Furthermore the possibility to set LC mileage within the environmental models permits to identify the break-even mileage for the effective environmental convenience of the lightweight alternative with respect to the reference one. At this regard the tool is able to perform assessments both in case the light-weighting does not involve interventions on the vehicle (comparative LCA with mass reduction only) and in case car re-design is applied (comparative LCA with implementation of secondary effects).

The utility of the research is located within the context of Design for Sustainability (DfS), more specifically the branch “design for energy efficiency”. The conceived tool investigates two aspects of automotive use stage which are strictly connected to each other, the energy and the environment. Since a thorough design phase requires that recommendations coming from design for environment and energy efficiency are corroborated by a series of interconnected aspects such as manufacturability, material usage, durability, reliability and recyclability, the contribution of the tool can be intended as incorporating energy and environmental issues into the selection process of materials and technologies when developing lightweight design solutions.

The possible end-users of the tool are represented by practitioners of advanced LCA in the context of automotive light-weighting (environmental consultants, research centers, universities) and original equipment manufacturers that want to assume the environmental concern as a driver of design process.

Possible future developments of the work can be outlined following two distinct fronts: extension to electric and hybrid vehicles and integration with Life Cycle Costing (LCC) / Social Life Cycle Assessment (S-LCA) analyses. On one hand the inclusion of electric and hybrid vehicles would give a comprehensive overview on the environmental potentialities of light-weighting within the automotive context. On the other hand the integration of environmental and socio-economic instruments would allow evaluating, still in phase of design, aspects not strictly technical but equally essential; this would lead to an inclusive tool able to holistically assess the sustainability of an automotive asset.

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SI appendix

SI appendix – chapter 4

SI 4.1. Reference data from literature

Reference resistive torque diagram from literature			
GT		**DT**	
***rpm* [1/rpm]**	**t_{E_res} [Nm]**	***rpm* [1/rpm]**	**t_{E_res} [Nm]**
0	0.00	0	0.00
600	-19.60	1000	-18.00
1000	-19.60	1500	-22.00
1500	-20.40	2000	-25.00
2000	-23.20	2500	-30.00
2500	-26.60	3000	-35.00
3000	-27.58		
3500	-30.10		
4000	-30.80		
4500	-32.76		
5000	-33.32		
5500	-35.98		
6000	-37.24		

Table SI4.1.1. Reference resistive torque diagram for GT case studies

Reference FC map from literature (GT)		
***rpm* [rpm]**	***BMEP* [bar]**	***cons* [g/kWh]**
1019	1.89	400
	2.80	350
	3.83	300
	5.51	280
1217	1.85	400
	2.75	350
	3.83	300
	4.99	280
	6.88	260
	12.69	260
1471	1.76	400
	2.67	350
	3.74	300
	4.90	280
	6.19	260
	9.72	250
	12.73	250
1736	1.63	400
	2.67	350
	3.87	300
	4.99	280
	6.24	260
	8.30	250
	11.61	240
2001	1.68	400
	2.75	350
	3.91	300
	4.90	280
	6.28	260
	8.17	250
	10.24	240
	15.18	240
2244	1.68	400
	2.75	350
	3.96	300
	4.99	280
	6.45	260
	8.22	250
	9.98	240
	15.96	240
2497	1.72	400
	2.80	350
	3.91	300
	5.03	280
	6.62	260
	8.39	250
	10.15	240
	17.20	240
2748	1.89	400
	2.88	350
	4.00	300
	5.16	280
	6.80	260
	8.56	250
	10.37	240
	17.16	240
2996	1.98	400
	2.97	350
	3.91	300
	5.20	280
	7.05	260
	8.77	250
	10.62	240
	16.86	240
3236	2.02	400
	2.97	350
	3.96	300
	5.25	280
	7.18	260
	8.86	250
	10.71	240
	16.60	240
3488	2.06	400
	3.05	350
	3.96	300
	5.51	280
	7.35	260
	9.29	250
	10.97	240
	16.30	240
	17.72	250
3725	2.02	400
	2.97	350
	4.04	300
	5.59	280
	7.57	260
	9.42	250
	11.05	240
	15.83	240
	17.20	250
3980	2.15	400
	3.01	350
	4.09	300
	5.81	280
	7.66	260
	9.59	250
	11.18	240
	15.27	240
	16.34	250
	17.46	260
4237	2.15	400
	3.05	350
	4.26	300
	5.85	280
	7.87	260
	9.81	250
	11.48	240
	14.37	240
	15.74	250
	16.90	260
4484	2.19	400
	3.10	350
	4.39	300
	6.24	280
	8.09	260
	10.15	250
	12.77	240
	14.71	250
	16.17	260
4742	2.24	400
	3.10	350
	4.52	300
	6.45	280
	8.56	260
	15.23	260
	17.68	280
4994	2.32	400
	3.18	350
	4.65	300
	6.88	280
	10.19	260
	16.17	280
5233	2.28	400
	3.18	350
	4.86	300
	7.74	280
	14.67	280
5477	2.41	400
	3.18	350
	5.89	300
	11.70	280
	15.23	300
5730	2.37	400
	3.23	350
	6.71	300
	13.98	300
5981	2.37	400
	3.31	350
	10.24	300
	12.09	300
6237	2.45	400
	3.66	350
6476	2.75	400
	4.26	350

Table SI4.1.2. Reference FC map for GT case studies

Reference FC map from literature (DT)		
***rpm* [rpm]**	***BMEP* [bar]**	***cons* [g/kWh]**
1004	1.15	360
	3.36	260
	4.71	240
	6.19	230
1248	1.02	360
	3.28	260
	4.47	240
	5.61	230
	8.97	220
	13.72	220
1501	0.90	360
	3.24	260
	4.38	240
	5.61	230
	7.54	220
	14.26	210
	17.29	210
1734	1.02	360
	3.24	260
	4.38	240
	5.90	230
	8.23	220
	12.29	210
1980	0.98	360
	3.32	260
	4.71	240
	6.47	230
	9.34	220
	12.58	210
	16.67	200
	20.12	200
2237	1.02	360
	3.69	260
	5.49	240
	7.13	230
	8.07	220
	9.30	210
	14.95	200
	17.29	196
2501	1.07	360
	4.06	260
	6.10	240
	6.96	230
	7.87	220
	9.38	210
	16.22	200
	20.40	200
2756	2.25	360
	4.10	260
	5.08	240
	5.90	230
	7.17	220
	8.77	210
	13.40	200
	18.27	200
3006	2.34	360
	3.97	260
	5.04	240
	5.78	230
	6.88	220
	8.69	210
3250	2.09	360
	4.01	260
	5.16	240
	5.90	230
	7.05	220
	9.18	210
3501	2.01	360
	4.14	260
	5.24	240
	6.15	230
	7.70	220
	10.57	210
	16.31	210
3736	2.13	360
	4.42	260
	5.61	240
	6.68	230
	8.69	220
	16.43	220
3977	2.21	360
	4.75	260
	6.27	240
	7.58	230
	10.86	220
	14.09	220
4235	2.21	360
	5.00	260
	6.96	240
	9.18	230
	14.38	230
4496	2.42	360
	5.74	260
	8.81	240

Table SI4.1.3. Reference FC map for DT case studies

SI 4.2. Reference mass-configurations

			Reference mass-configuration - Fixed model parameters (GT & DT case studies)	
			Parameter	**Value**
DRIVE TRAIN	**ENGINE**	**Engine**	*Fuel density* (ρ_{fuel})	0.741 [kg/m^3] (GT) 0.837 [kg/m^3] (DT)
			Idle engine speed (ω_{idle})	800 [rpm] (GT) 780 [rpm] (DT)
	CLUTCH	**Rotary Coulomb friction**	*Maximum Coulomb friction torque of Clutch* (t_{C_max})	300 [Nm]
			Rotary speed threshold (Clutch) (ω_{C_thr})	1 [Nm]
		Rotary load (Gearbox)	*Gearbox Inertia* (I_G)	0.005 [kg*m^2]
	GEARBOX	**Gearbox**	*Efficiency of final transmission* (η_f)	0.98 [null]
			Efficiency of Gear i ($\eta_{G,i}$)	0.98 [null]
			Maximum Coulomb friction torque on Gearbox Secondary shaft (t_{GS_max})	500 [Nm]
			Rotary speed threshold (Synchronizer) (ω_{S_thr})	1 [rpm]
	VEHICLE DYNAMICS	**Vehicle dynamics**	*Dynamic friction coefficient* (f_D)	0.0001 [1/(m/s)]
			Maximum braking torque (t_{br_max})	1500 [Nm]
			Static friction coefficient (f_S)	0.01 [null]
			Rotary speed threshold (Wheel) (ω_{W_thr})	0.000001 [rpm]

Table SI4.2.1. Reference mass-configuration - Fixed model parameters: numerical value assigned to GT & DT case studies (Drive train section)

			Reference mass-configuration - Fixed model parameters (GT & DT case studies)	
			Parameter	**Value**
CONTROL LOGIC	**MISSION PROFILE & AMBIENT DATA**	***Mission profile & Ambient data***	*Air density* (ρ_a)	1.214 [kg/m^3]
			Ambient temperature (T_a)	17.5 [°C]
			Mission Profile vehicle linear Velocity (V_{MP})	Driving cycle profile (V_{MP} = f(t) [m/s])
			Road slope (β_{road})	0 [%]
	DRIVER	***Driver***	*Anticipative Gain for Braking control loop* (GA_B)	0.1 [1/(m/s/s)]
			Anticipative Gain for Load control loop (GA_L)	0.5 [1/(m/s/s)]
			Critical vehicle Velocity (V_{veh_crit})	1.5 [m/s]
			Gain for synchronisation during pull away (G_{syn})	0.5 [null]
			Integral Gain for Braking control loop (GI_B)	0.1 [1/m]
			Integral Gain for Load control loop (GI_L)	0 [1/m]
			Maximum value for Load control signal during Pull Away ($sig_{L\_PA\_max}$)	0.21 [null]
			Proportional Gain for Braking control loop (GP_B)	0.2 [1/(m/s)]
			Proportional Gain for Load control loop (GP_L)	1 [1/(m/s)]
			Time duration for acceleration transition ($time_{tr}$)	1 [s]
			Time duration for clutch synchronisation ($time_{syn}$)	2 [s]
			Time for disengaging the Clutch ($time_{diseng\_C}$)	0.2 [s]
			Time for engaging Gearbox ratio ($time_{eng\_G}$)	0.2 [s]
			Time for engaging the Clutch ($time_{eng\_C}$)	0.8 [s]
			Time interval ($time_{ant}$)	2 [s]
			Threshold vehicle velocity for clutch Pull Away ($V_{PA\_ tr}$)	0.5 [m/s]
	CONTROL UNIT	***Control unit***	*Fuel resume mode speed* (ω_{fr})	1100 [rpm]
			Gain for idle speed regulation (G_{idle})	0.01 [null]
			Gain for idle speed regulation during Pull Away (G_{Pidle_PA})	0.01 [null]
			Gain for maximum speed regulation (G_{max})	0.01 [null]
			Maximum engine speed (ω_{max})	6500 (GT) [rpm] 5000 (DT) [rpm]

Table SI4.2.2. Reference mass-configuration - Fixed model parameters: numerical value assigned to GT & DT case studies (Control logic section)

			Reference mass-configuration – Variable model parameters									
			Case study (GT A/B-class)									
		Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vehicle dynamics	*Active Area in aerod. Drag* (A_D)	m^2	2.238	2.217	2.217	2.217	2.375	2.293	2.262	2.262	2.317	2.137
	Aerodynamic Drag coefficient (C_D)	null	0.29	0.31	0.31	0.31	0.34	0.32	0.34	0.34	0.328	0.328
	Tyre Height (H_{tyre})	%	55	60	60	45	65	65	65	65	55	50
	Tyre Width (W_{tyre})	mm	195	185	185	215	185	175	175	185	195	195
	Vehicle mass (m_{veh})	kg	1270	1175	1220	1260	1102	1115	1215	1295	1156	1156
	Wheel Inertia (I_w)	$kg{*}m^2$	0.811	0.716	0.716	0.926	0.734	0.558	0.667	0.755	0.719	0.762
	Wheel rim Diameter (D_{rim})	in	16	15	15	16	15	14	15	15	15	16
Engine	*Engine displacement (V)*	l	0.875	0.999	1.395	1.395	0.898	0.875	0.875	1.368	0.999	0.999
	Idle FC ($cons_{idle}$)	g/h	404	425	491	491	408	404	404	487	425	425
Gearbox	*Final transmission ratio* (α_f)	null	4.923	3.625	3.625	3.450	4.50	3.867	3.870	3.730	3.610	3.610
	Number of gear ratios (n)	null	6	5	6	6	5	5	5	5	5	5
	Transmission ratio of Gear i ($\alpha_{G,i}$)	null	4.100 2.158 1.345 0.974 0.766 0.646	3.769 1.955 1.281 0.927 0.740	3.615 1.947 1.281 0.973 0.778 0.646	3.469 2.077 1.469 1.088 0.886 0.730	3.730 1.960 1.230 0.900 0.660	4.100 2.158 1.345 0.974 0.766	4.100 2.158 1.345 0.974 0.766	3.909 2.238 1.444 1.029 0.838	3.583 1.926 1.206 0.878 0.689	3.583 1.926 1.206 0.878 0.689
Driver	*Downshift eng. speed* (ω_{Down}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1100 1000 1000 1100	1000 1100 1100 1000	1000 1000 1000 1000	1100 1000 1100 1100	1000 1000 1100 1000	1000 1100 1100 1000	1000 1000 1100 1000	1100 1000 1000 1000	1000 1000 1100 1000	1100 1100 1100 1100
	Upshift engine speed (ω_{Up}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1700 1700 1600 1700	1800 1800 1700 1700	1700 1800 1800 1700	1700 1700 1800 1700	1700 1800 1700 1700	1800 1800 1700 1700	1800 1700 1700 1600	1700 1800 1800 1700	1700 1800 1700 1600	1800 1800 1700 1800
Rotary load (Engine)	*Engine Inertia* (I_E)	$kg{*}m^2$	0.100	0.114	0.160	0.160	0.102	0.100	0.100	0.156	0.114	0.114

Table SI4.2.3. Reference mass-configuration - Variable model parameters: numerical values assigned to case studies (GT A/B-class)

			Reference mass-configuration – Variable model parameters										
			Case study (GT C-class)										
		Unit	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Vehicle dynamics	*Active Area in aerod. Drag* (A_D)	m^2	2.371	2.371	2.273	2.273	2.273	2.416	2.416	2.435	2.435	2.435	2.435
	Aerodynamic Drag coefficient (C_D)	null	0.310	0.310	0.310	0.310	0.310	0.300	0.300	0.310	0.310	0.310	0.310
	Tyre Height (H_{tyre})	%	55	55	55	55	55	55	55	55	55	55	55
	Tyre Width (W_{tyre})	mm	205	205	205	205	205	205	205	205	205	205	215
	Vehicle mass (m_{veh})	kg	1420	1430	1290	1345	1370	1400	1415	1355	1360	1387	1387
	Wheel Inertia (I_w)	kg*m^2	0.931	0.940	0.938	0.938	0.938	0.924	0.884	0.935	0.935	0.935	0.951
	Wheel rim Diameter (D_{rim})	in	16	16	16	16	16	16	16	16	16	16	16
Engine	*Engine displacement* (V)	l	1.368	1.368	1.197	1.395	1.798	1.368	1.368	0.999	0.999	1.499	1.499
	Idle FC ($cons_{idle}$)	g/h	487	487	458	491	559	487	487	425	425	509	509
Gearbox	*Final transmission ratio* (α_f)	null	4.118	3.833	4.056	3.647	3.647	3.940	4.070	4.250	4.067	3.824	3.824
	Number of gear ratios (n)	null	6	6	6	6	6	6	6	5	6	6	6
	Transmission ratio of Gear i ($\alpha_{G,i}$)	null	3.909 2.118 1.484 1.116 0.897 0.767	3.909 2.118 1.484 1.116 0.897 0.767	3.615 1.947 1.281 0.973 0.778 0.646	3.777 2.117 1.360 1.029 0.857 0.733	3.777 2.117 1.360 1.029 0.857 0.733	3.818 2.158 1.475 1.067 0.875 0.744	4.150 2.120 1.120 0.900 0.770	3.583 1.926 1.281 0.951 0.756	3.727 2.048 1.357 1.032 0.821 0.690	3.727 2.048 1.357 1.032 0.821 0.690	3.727 2.048 1.357 1.032 0.821 0.690
Driver	*Downshift eng. speed* (ω_{Down}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1100 1000 1100 1100	1000 1100 1100 1100	1100 1100 1000 1100	1100 1100 1100 1000	1100 1100 1000 1100	1000 1100 1100 1100	1100 1100 1100 1100	1100 1100 1100 1000	1100 1100 1100 1100	1100 1100 1100 1100	1100 1000 1100 1100
	Upshift engine speed (ω_{Up}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1700 1700 1800 1700	1700 1800 1700 1800	1800 1700 1700 1800	1800 1700 1700 1800	1800 1700 1800 1800	1800 1800 1700 1800	1800 1800 1800 1800	1700 1800 1800 1800	1800 1800 1800 1800	1800 1800 1800 1800	1800 1800 1700 1800
Rotary load (Engine)	*Engine Inertia* (I_E)	kg*m^2	0.156	0.156	0.137	0.160	0.206	0.156	0.156	0.114	0.114	0.171	0.171

Table SI4.2.4. Reference mass-configuration - Variable model parameters: numerical values assigned to case studies (GT C-class)

			Reference mass-configuration – Variable model parameters										
			Case study (GT D-class)										
		Unit	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Vehicle dynamics	*Active Area in aerod. Drag (A_D)*	m^2	2.345	2.345	2.329	2.329	2.428	2.470	2.470	2.470	2.470	2.349	2.349
	Aerodynamic Drag coefficient (C_D)	null	0.270	0.270	0.270	0.270	0.310	0.300	0.300	0.300	0.300	0.270	0.270
	Tyre Height (H_{tyre})	%	60	60	60	60	55	60	60	50	50	60	60
	Tyre Width (W_{tyre})	mm	205	205	205	205	225	215	215	235	235	205	205
	Vehicle mass (m_{veh})	kg	1570	1570	1540	1570	1570	1520	1550	1629	1629	1460	1510
	Wheel Inertia (I_w)	$kg*m^2$	0.957	0.957	0.949	0.966	1.184	1.040	1.042	1.230	1.230	0.933	0.950
	Wheel rim Diameter (D_{rim})	in	16	16	16	16	17	16	16	17	17	16	16
Engine	*Engine displacement (V)*	l	1.798	1.798	1.499	1.998	1.598	0.999	1.499	1.999	1.999	1.595	1.991
	Idle FC ($cons_{idle}$)	g/h	559	559	509	593	526	425	509	593	593	525	592
Gearbox	*Final transmission ratio (α_f)*	null	4.142	3.304	3.077	3.385	4.180	4.270	3.070	3.210	3.210	2.650	2.650
	Number of gear ratios (n)	null	6	6	6	6	6	6	6	6	6	6	6
	Transmission ratio of Gear i ($\alpha_{G,i}$)	null	3.400 1.905 1.276 0.941 0.737 0.625	3.778 2.050 1.321 0.970 0.811 0.692	4.552 2.548 1.659 1.230 1.000 0.830	4.551 2.548 1.659 1.230 1.000 0.830	3.540 1.920 1.320 0.980 0.760 0.650	3.727 2.048 1.357 1.032 0.821 0.690	3.727 2.048 1.258 0.919 0.738 0.622	4.584 2.964 1.912 1.446 1.000 0.746	4.584 2.964 1.912 1.446 1.000 0.746	4.750 2.460 1.620 1.240 1.000 0.790	4.750 2.460 1.620 1.240 1.000 0.790
Driver	*Downshift eng. speed (ω_{Down}) (FTP72, JC08, NEDC, WLTC)*	rpm	1100 1000 1000 1100	1000 1100 1000 1100	1100 1100 1100 1100	1100 1100 1100 1100	1000 1100 1000 1100	1100 1100 1100 1100	1100 1100 1000 1100	1100 1100 1000 1000	1100 1000 1100 1100	1100 1100 1000 1100	1100 1100 1100 1100
	Upshift engine speed (ω_{Up}) (FTP72, JC08, NEDC, WLTC)	rpm	1700 1800 1800 1700	1800 1800 1800 1800	1700 1800 1700 1800	1800 1800 1700 1800	1700 1700 1800 1700	1800 1800 1800 1800	1800 1800 1700 1800	1800 1800 1800 1800	1800 1800 1700 1800	1800 1700 1800 1800	1800 1800 1800 1800
Rotary load (Engine)	*Engine Inertia (I_E)*	$kg*m^2$	0.206	0.206	0.171	0.229	0.182	0.114	0.171	0.228	0.228	0.182	0.228

Table SI4.2.5. Reference mass-configuration - Variable model parameters: numerical values assigned to case studies (GT D-class)

			Reference mass-configuration – Variable model parameters									
			Case study (DT A/B-class)									
		Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vehicle dynamics	*Active Area in aerod. Drag (A_D)*	m^2	2.238	2.370	2.370	2.180	2.293	2.262	2.262	2.262	2.317	2.317
	Aerodynamic Drag coefficient (C_D)	null	0.290	0.310	0.310	0.325	0.320	0.340	0.340	0.340	0.328	0.328
	Tyre Height (H_{tyre})	%	55	65	55	55	65	65	65	65	65	50
	Tyre Width (W_{tyre})	mm	195	185	195	185	175	175	175	185	175	195
	Vehicle mass (m_{veh})	kg	1345	1229	1336	1120	1175	1230	1270	1270	1173	1173
	Wheel Inertia (I_w)	$kg*m^2$	0.816	0.747	0.747	0.727	0.555	0.667	0.676	0.749	0.564	0.762
	Wheel rim Diameter (D_{rim})	in	16	15	16	15	14	15	15	15	14	16
Engine	*Engine displacement (V)*	l	1.598	1.398	1.560	1.248	1.248	1.248	1.248	1.248	1.498	1.560
	Idle FC ($cons_{idle}$)	g/h	417	416	464	371	371	371	371	371	404	412
Gearbox	*Number of gear ratios (n)*	null	6	5	6	5	5	5	5	5	5	5
	Transmission ratio of Gear i ($\alpha_{G,i}$)	null	3.818 2.158 1.475 1.067 0.875 0.744	3.420 1.810 1.170 0.850 0.680	3.540 1.920 1.280 0.910 0.670 0.560	3.909 2.158 1.345 0.974 0.766	4.273 2.238 1.444 1.029 0.767	3.909 2.238 1.444 1.029 0.767	3.909 2.238 1.444 1.029 0.767	3.909 2.238 1.444 1.029 0.767	3.583 1.926 1.206 0.878 0.689	3.583 1.926 1.206 0.878 0.689
	Final transmission ratio (α_f)	null	3.421	3.940	3.420	3.440	3.150	3.560	3.560	4.070	3.370	3.370
Driver	*Downshift eng. speed (ω_{Down}) (FTP72, JC08, NEDC, WLTC)*	rpm	1100 1100 1000 1000	1000 1100 1100 1100	1100 1000 1000 1100	1100 1100 1000 1000	1000 1100 1100 1100	1100 1100 1100 1100	1100 1100 1100 1100	1100 1100 1100 1000	1100 1100 1100 1100	1100 1100 1100 1100
	Upshift engine speed (ω_{Up}) (FTP72, JC08, NEDC, WLTC)	rpm	1600 1800 1700 1700	1800 1700 1700 1800	1800 1800 1800 1800	1800 1800 1800 1800	1800 1800 1800 1700	1800 1700 1800 1800	1800 1700 1700 1800	1700 1800 1800 1800	1700 1800 1700 1800	1800 1800 1800 1800
Rotary load (Engine)	*Engine Inertia (I_E)*	$kg*m^2$	0.183	0.159	0.178	0.143	0.143	0.143	0.143	0.143	0.171	0.178

Table SI4.2.6. Reference mass-configuration - Variable model parameters: numerical values assigned to case studies (DT A/B-class)

			Reference mass-configuration – Variable model parameters											
			Case study (DT C-class)											
		Unit	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Vehicle dynamics	*Active Area in aerod. Drag* (A_D)	m^2	2.371	2.371	2.371	2.412	2.412	2.412	2.416	2.416	2.416	2.435	2.435	2.435
	Aerodynamic Drag coefficient (C_D)	null	0.310	0.310	0.310	0.300	0.300	0.300	0.300	0.300	0.300	0.310	0.310	0.310
	Tyre Height (H_{tyre})	%	55	55	55	65	65	45	65	55	45	55	55	55
	Tyre Width (W_{tyre})	mm	205	205	205	195	195	225	195	205	225	205	205	215
	Vehicle mass (m_{veh})	kg	1450	1460	1460	1345	1345	1460	1460	1460	1500	1400	1434	1511
	Wheel Inertia (I_w)	$kg*m^2$	0.931	0.94	0.94	0.775	0.779	1.093	0.767	0.924	1.073	0.933	0.933	0.654
	Wheel rim Diameter (D_{rim})	in	16	16	16	15	15	17	15	16	17	16	16	16
Engine	*Engine displacement* (V)	l	1.598	1.956	1.956	1.560	1.560	1.997	1.598	1.598	1.956	1.498	1.498	1.997
	Idle FC ($cons_{idle}$)	g/h	417	465	465	412	412	471	417	417	465	404	404	471
Gearbox	*Number of gear ratios* (n)	null	6	6	6	5	6	6	6	6	6	6	6	6
	Transmission ratio of Gear i ($\alpha_{G,i}$)	null	4.154 2.118 1.361 0.978 0.756 0.622	3.909 2.118 1.361 0.978 0.756 0.622	4.154 2.269 1.435 0.978 0.754 0.622	3.450 1.870 1.160 0.820 0.660	3.540 1.920 1.280 0.910 0.670 0.560	3.417 1.783 1.121 0.795 0.647 0.534	3.800 2.235 1.360 0.910 0.710 0.614	3.800 2.235 1.360 0.971 0.763 0.610	3.917 2.040 1.321 0.954 0.755 0.623	3.727 2.048 1.258 0.919 0.738 0.622	3.583 1.952 1.194 0.842 0.674 0.564	3.583 1.952 1.194 0.842 0.674 0.564
	Final transmission ratio (α_f)	null	3.421	3.421	3.833	3.680	3.740	4.060	3.350	3.560	3.550	3.611	4.067	3.933
Driver	*Downshift eng. speed* (ω_{Down}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1100 1100 1100 1100	1000 1100 1000 1100	1100 1100 1100 1100	1100 1100 1100 1000	1100 1100 1100 1100	1100 1000 1100 1100	1100 1000 1100 1100	1100 1100 1100 1100	1100 1000 1100 1100	1000 1100 1100 1100	1100 1100 1100 1100	1100 1100 1000 1100
	Upshift engine speed (ω_{Up}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1800 1800 1800 1800	1800 1800 1800 1800	1700 1800 1800 1800	1800 1800 1700 1800	1800 1800 1800 1800	1800 1800 1800 1800	1800 1800 1700 1800	1800 1800 1800 1800	1800 1800 1800 1800	1800 1700 1800 1800	1800 1800 1800 1800	1700 1800 1700 1800
Rotary load (Engine)	*Engine Inertia* (I_E)	$kg*m^2$	0.183	0.224	0.224	0.178	0.178	0.228	0.183	0.183	0.223	0.171	0.171	0.228

Table SI4.2.7. Reference mass-configuration - Variable model parameters: numerical values assigned to case studies (DT C-class)

			Reference mass-configuration – Variable model parameters									
			Case study (DT D-class)									
		Unit	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Vehicle dynamics	*Active Area in aerod. Drag (A_D)*	m^2	2.329	2.329	2.329	2.329	2.428	2.428	2.428	2.471	2.471	2.471
	Aerodynamic Drag coefficient (C_D)	null	0.280	0.280	0.280	0.280	0.290	0.290	0.290	0.300	0.300	0.300
	Tyre Height (H_{tyre})	%	60	60	60	50	55	55	55	60	60	60
	Tyre Width (W_{tyre})	mm	205	205	205	225	225	225	225	215	215	215
	Vehicle mass (m_{veh})	kg	1570	1560	1570	1615	1646	1750	1703	1560	1643	1649
	Wheel Inertia (I_w)	$kg*m^2$	0.967	0.967	0.967	1.151	1.184	1.184	1.192	1.040	1.040	1.040
	Wheel rim Diameter (D_{rim})	in	16	16	16	17	17	17	17	16	16	16
Engine	*Engine displacement (V)*	l	1.995	1.995	1.995	1.995	1.560	1.997	1.997	1.560	1.997	1.997
	Idle FC ($cons_{idle}$)	g/h	471	471	471	471	412	471	471	412	471	471
Gearbox	*Final transmission ratio (α_f)*	null	3.231	2.929	3.154	3.462	4.290	4.310	4.310	3.610	3.813	3.813
	Number of gear ratios (n)	null	6	6	6	6	5	6	6	6	6	6
	Transmission ratio of Gear i ($\alpha_{G,i}$)	null	4.002 2.109 1.380 1.000 0.781 0.645	4.110 2.248 1.403 1.000 0.802 0.659	4.110 2.248 1.403 1.000 0.802 0.659	4.110 2.248 1.403 1.000 0.802 0.659	3.450 1.870 1.160 0.820 0.660	3.417 1.783 1.121 0.795 0.647 0.534	3.417 1.783 1.121 0.795 0.647 0.534	3.727 2.048 1.258 0.919 0.738 0.622	3.583 1.864 1.156 0.816 0.644 0.536	3.583 1.864 1.156 0.816 0.644 0.536
Driver	*Downshift eng. speed (ω_{Down})* *(FTP72, JC08, NEDC, WLTC)*	rpm	1100 1100 1100 1000	1000 1100 1000 1100	1100 1100 1100 1100	1100 1000 1000 1100	1100 1100 1100 1100	1100 1100 1000 1100	1100 1100 1100 1100	1100 1100 1000 1000	1100 1100 1000 1100	1100 1100 1100 1100
	Upshift engine speed (ω_{Up}) *(FTP72, JC08, NEDC, WLTC)*	rpm	1700 1700 1700 1700	1800 1800 1800 1800	1800 1700 1800 1800	1700 1800 1800 1800	1800 1800 1800 1800	1800 1700 1800 1800	1800 1800 1800 1800	1800 1800 1700 1800	1800 1800 1800 1800	1800 1800 1700 1800
Rotary load (Engine)	*Engine Inertia (I_E)*	$kg*m^2$	0.227	0.227	0.227	0.227	0.178	0.228	0.228	0.178	0.228	0.228

Table SI4.2.8. Reference mass-configuration - Variable model parameters: numerical values assigned to case studies (DT D-class)

Reference mass-configuration – Variable model parameters ***Driving*** **and** ***resistive Engine torque*** **(t_{E_dr}, t_{E_res}) (GT case studies n°9, 17, 28)**					
Case study n°9		**Case study n°17**		**Case study n°28**	
rpm **[rpm]**	**t_{E_res} [Nm]**	***rpm*** **[rpm]**	**t_{E_res} [Nm]**	***rpm*** **[rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
600	-19.2	600	-26.0	600	-27.0
1000	-19.2	1000	-26.0	1000	-27.0
1500	-19.9	1500	-27.0	1500	-28.1
2000	-22.7	2000	-30.7	2000	-32.0
2500	-26.0	2500	-35.2	2500	-36.6
3000	-27.0	3000	-36.5	3000	-38.0
3500	-29.4	3500	-39.9	3500	-41.5
4000	-30.1	4000	-40.8	4000	-42.4
4500	-32.0	4500	-43.4	4500	-45.1
5000	-32.6	5000	-44.1	5000	-45.9
5500	-35.2	5500	-47.7	5500	-49.6
6000	-36.4	6000	-49.3	6000	-51.3
rpm **[rpm]**	**t_{E_tr} [Nm]**	***rpm*** **[rpm]**	**t_{E_tr} [Nm]**	***rpm*** **[rpm]**	**t_{E_tr} [Nm]**
0	0.0	0	0.0	0	0.0
1029	119.7	1025	141.7	1029	161.4
1114	137.1	1111	164.4	1143	186.4
1257	154.2	1323	191.6	1257	207.5
1414	170.0	1566	216.1	1371	224.1
2184	170.0	1683	227.2	1513	239.6
4109	170.0	1810	230.5	2000	239.6
4422	160.0	2126	229.9	2400	239.6
4779	147.4	2739	227.1	2800	239.6
5007	140.7	3509	221.4	3200	239.6
5264	133.9	4037	213.6	3600	239.6
5535	127.1	4543	205.8	4000	239.6
5834	120.7	4997	197.4	4608	239.6
6077	115.8	5176	189.0	4736	238.5
6205	111.9	5355	177.3	4993	225.2
6305	107.7	5513	161.8	5292	213.6
				5549	203.0
				5834	193.6
				6062	186.9
				6262	176.4
				6504	158.1

Table SI4.2.9. Reference mass-configuration – Variable model parameters: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case studies n°9, 17, 28)

Reference mass-configuration – Variable model parameters ***Driving*** **and** ***resistive Engine torque*** **(t_{E_dr}, t_{E_res}) (DT case studies n°7, 21, 31)**					
Case study n°7		**Case study n°21**		**Case study n°31**	
rpm **[rpm]**	**t_{E_res} [Nm]**	***rpm*** **[rpm]**	**t_{E_res} [Nm]**	***rpm*** **[rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
1000	-19.4	1000	-26.1	1000	-33.9
1500	-23.7	1500	-31.9	1500	-41.4
2000	-26.9	2000	-36.3	2000	-47.0
2500	-32.3	2500	-43.6	2500	-56.5
3000	-37.6	3000	-50.8	3000	-65.9
rpm **[rpm]**	**t_{E_tr} [Nm]**	***rpm*** **[rpm]**	**t_{E_tr} [Nm]**	***rpm*** **[rpm]**	**t_{E_tr} [Nm]**
0	0.0	0	0.0	0	0.0
1011	139.0	1011	156.7	1011	172.2
1042	150.3	1053	173.3	1074	200.0
1105	162.3	1137	194.4	1158	225.6
1179	175.8	1211	211.1	1253	251.1
1274	187.7	1263	225.0	1348	275.6
1348	194.2	1369	241.7	1464	300.6
1411	198.4	1495	256.7	1632	326.1
1506	200.0	1685	270.0	1727	338.9
1780	199.7	2644	270.0	1843	346.7
2011	198.4	2897	265.6	1980	350.0
2317	195.5	3181	256.7	2475	350.0
2654	190.7	3497	241.1	2665	349.4
2981	184.2	3655	230.0	2823	345.0
3307	176.1	3908	208.3	3012	338.3
3497	171.3			3149	330.0
3592	166.5			3286	319.4
3813	151.6			3466	303.3
				3645	289.4
				3803	276.1
				3950	265.6
				4077	255.0
				4214	240.6

Table SI4.2.10. Reference mass-configuration – Variable model parameters: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case studies n°7, 21, 31)

Reference MC – Variable model parameters *Specific FC* (*cons*) - GT case studies n°9, 17, 28								
Case study n°9			Case study n°17			Case study n°28		
rpm [rpm]	BMEP [bar]	*cons* [g/kWh]	rpm [rpm]	BMEP [bar]	*cons* [g/kWh]	rpm [rpm]	BMEP [bar]	*cons* [g/kWh]
1029	2.3	400	1025	2.3	400	1069	2.1	400
	3.4	350		3.3	350		3.2	350
	4.6	300		4.6	300		4.3	300
	6.6	280		6.6	280		6.2	280
1220	2.2	400	1188	2.2	400	1275	2.1	400
	3.3	350		3.3	350		3.1	350
	4.6	300		4.6	300		4.3	300
	6.0	280		6.0	280		5.7	280
	8.3	260		8.2	260		7.8	260
	15.3	260		15.2	260		14.4	260
1466	2.1	400	1397	2.1	400	1540	2.0	400
	3.2	350		3.2	350		3.0	350
	4.5	300		4.5	300		4.2	300
	5.9	280		5.9	280		5.6	280
	7.5	260		7.4	260		7.0	260
	11.7	250		11.6	250		11.0	250
	15.4	250		15.2	250		14.4	250
1722	2.0	400	1615	2.0	400	1817	1.9	400
	3.2	350		3.2	350		3.0	350
	4.7	300		4.6	300		4.4	300
	6.0	280		6.0	280		5.7	280
	7.5	260		7.5	260		7.1	260
	10.0	250		9.9	250		9.4	250
	14.0	240		13.9	240		13.2	240
1979	2.0	400	1833	2.0	400	2093	1.9	400
	3.3	350		3.3	350		3.1	350
	4.7	300		4.7	300		4.4	300
	5.9	280		5.9	280		5.6	280
	7.6	260		7.5	260		7.1	260
	9.9	250		9.8	250		9.3	250
	12.4	240		12.2	240		11.6	240
	18.3	240		18.1	240		17.2	240
2213	2.0	400	2032	2.0	400	2346	1.9	400
	3.3	350		3.3	350		3.1	350
	4.8	300		4.7	300		4.5	300
	6.0	280		6.0	280		5.7	280
	7.8	260		7.7	260		7.3	260
	9.9	250		9.8	250		9.3	250
	12.0	240		11.9	240		11.3	240
	19.2	240		19.1	240		18.1	240
2458	2.1	400	2240	2.1	400	2610	2.0	400
	3.4	350		3.3	350		3.2	350
	4.7	300		4.7	300		4.4	300
	6.1	280		6.0	280		5.7	280
	8.0	260		7.9	260		7.5	260
	10.1	250		10.0	250		9.5	250
	12.2	240		12.1	240		11.5	240
	20.7	240		20.5	240		19.5	240
2701	2.3	400	2447	2.3	400	2872	2.1	400
	3.5	350		3.4	350		3.3	350
	4.8	300		4.8	300		4.5	300
	6.2	280		6.2	280		5.8	280
	8.2	260		8.1	260		7.7	260
	10.3	250		10.2	250		9.7	250
	12.5	240		12.4	240		11.8	240
	20.7	240		20.5	240		19.4	240
2941	2.4	400	2651	2.4	400	3131	2.2	400
	3.6	350		3.6	350		3.4	350
	4.7	300		4.7	300		4.4	300
	6.3	280		6.2	280		5.9	280
	8.5	260		8.4	260		8.0	260
	10.6	250		10.5	250		9.9	250
	12.8	240		12.7	240		12.0	240
	20.3	240		20.1	240		19.1	240
3173	2.4	400	2849	2.4	400	3381	2.3	400
	3.6	350		3.6	350		3.4	350
	4.8	300		4.7	300		4.5	300
	6.3	280		6.3	280		6.0	280
	8.7	260		8.6	260		8.1	260
	10.7	250		10.6	250		10.0	250
	12.9	240		12.8	240		12.1	240
	20.0	240		19.8	240		18.8	240
3416	2.5	400	3055	2.5	400	3643	2.3	400
	3.7	350		3.6	350		3.5	350
	4.8	300		4.7	300		4.5	300
	6.6	280		6.6	280		6.2	280
	8.9	260		8.8	260		8.3	260
	11.2	250		11.1	250		10.5	250
	13.2	240		13.1	240		12.4	240
	19.7	240		19.5	240		18.5	240
	21.4	250		21.2	250		20.1	250
3645	2.4	400	3251	2.4	400	3891	2.3	400
	3.6	350		3.6	350		3.4	350
	4.9	300		4.8	300		4.6	300
	6.7	280		6.7	280		6.3	280
	9.1	260		9.0	260		8.6	260
	11.4	250		11.3	250		10.7	250
	13.3	240		13.2	240		12.5	240
	19.1	240		18.9	240		17.9	240
	20.7	250		20.5	250		19.5	250
3892	2.6	400	3461	2.6	400	4156	2.4	400
	3.6	350		3.6	350		3.4	350
	4.9	300		4.9	300		4.6	300
	7.0	280		6.9	280		6.6	280
	9.2	260		9.1	260		8.7	260
	11.6	250		11.5	250		10.9	250
	13.5	240		13.4	240		12.7	240
	18.4	240		18.2	240		17.3	240
	19.7	250		19.5	250		18.5	250
	21.1	260		20.8	260		19.8	260
4140	2.6	400	3672	2.6	400	4424	2.4	400
	3.7	350		3.6	350		3.5	350
	5.1	300		5.1	300		4.8	300
	7.1	280		7.0	280		6.6	280
	9.5	260		9.4	260		8.9	260
	11.8	250		11.7	250		11.1	250
	13.8	240		13.7	240		13.0	240
	17.3	240		17.2	240		16.3	240
	19.0	250		18.8	250		17.8	250
	20.4	260		20.2	260		19.1	260
4379	2.6	400	3875	2.6	400	4682	2.5	400
	3.7	350		3.7	350		3.5	350
	5.3	300		5.2	300		5.0	300
	7.5	280		7.5	280		7.1	280
	9.8	260		9.7	260		9.2	260
	12.2	250		12.1	250		11.5	250
	15.4	240		15.2	240		14.5	240
	17.7	250		17.6	250		16.7	250
	19.5	260		19.3	260		18.3	260
4629	2.7	400	4087	2.7	400	4951	2.5	400
	3.7	350		3.7	350		3.5	350
	5.5	300		5.4	300		5.1	300
	7.8	280		7.7	280		7.3	280
	10.3	260		10.2	260		9.7	260
	18.4	260		18.2	260		17.3	260
	21.3	280		21.1	280		20.0	280
4873	2.8	400	4295	2.8	400	5214	2.6	400
	3.8	350		3.8	350		3.6	350
	5.6	300		5.6	300		5.3	300
	8.3	280		8.2	280		7.8	280
	12.3	260		12.2	260		11.5	260
	19.5	280		19.3	280		18.3	280
5103	2.8	400	4491	2.7	400	5463	2.6	400
	3.8	350		3.8	350		3.6	350
	5.9	300		5.8	300		5.5	300
	9.3	280		9.2	280		8.8	280
	17.7	280		17.5	280		16.6	280
5340	2.9	400	4692	2.9	400	5718	2.7	400
	3.8	350		3.8	350		3.6	350
	7.1	300		7.0	300		6.7	300
	14.1	280		14.0	280		13.3	280
	18.4	300		18.2	300		17.3	300
5584	2.9	400	4900	2.8	400	5981	2.7	400
	3.9	350		3.9	350		3.7	350
	8.1	300		8.0	300		7.6	300
	16.9	300		16.7	300		15.8	300
5827	2.9	400	5106	2.8	400	6243	2.7	400
	4.0	350		4.0	350		3.8	350
	12.4	300		12.2	300		11.6	300
	14.6	300		14.4	300		13.7	300
6074	3.0	400	5316	2.9	400	6509	2.8	400
	4.4	350		4.4	350		4.2	350
6305	3.3	400	5513	3.3	400	6758	3.1	400
	5.1	350		5.1	350		4.8	350

Table SI4.2.11. Reference mass-configuration – Variable model parameters: *Specific FC* (*cons*) - GT case studies n°9, 17, 28

Reference mass-configuration *Specific FC* (*cons*) - DT case studies n°7, 21, 31								
Case study n°7			Case study n°21			Case study n°31		
rpm [rpm]	BMEP [bar]	*cons* [g/kWh]	rpm [rpm]	BMEP [bar]	*cons* [g/kWh]	rpm [rpm]	BMEP [bar]	*cons* [g/kWh]
1011	1.1	360	1011	1.3	360	1011	1.2	360
	3.3	260		3.7	260		3.6	260
	4.6	240		5.2	240		5.1	240
	6.1	230		6.9	230		6.7	230
1207	1.0	360	1213	1.1	360	1235	1.1	360
	3.2	260		3.6	260		3.5	260
	4.4	240		5.0	240		4.8	240
	5.5	230		6.2	230		6.1	230
	8.8	220		9.9	220		9.7	220
	13.5	220		15.2	220		14.8	220
1410	0.9	360	1424	1.0	360	1467	1.0	360
	3.2	260		3.6	260		3.5	260
	4.3	240		4.9	240		4.7	240
	5.5	230		6.2	230		6.1	230
	7.4	220		8.4	220		8.1	220
	14.0	210		15.8	210		15.4	210
	17.0	210		19.2	210		18.6	210
1597	1.0	360	1617	1.1	360	1681	1.1	360
	3.2	260		3.6	260		3.5	260
	4.3	240		4.9	240		4.7	240
	5.8	230		6.5	230		6.4	230
	8.1	220		9.1	220		8.9	220
	12.1	210		13.6	210		13.2	210
1794	1.0	360	1821	1.1	360	1906	1.1	360
	3.3	260		3.7	260		3.6	260
	4.6	240		5.2	240		5.1	240
	6.4	230		7.2	230		7.0	230
	9.2	220		10.4	220		10.1	220
	12.4	210		13.9	210		13.6	210
	16.4	200		18.5	200		18.0	200
	19.8	200		22.3	200		21.7	200
2000	1.0	360	2034	1.1	360	2142	1.1	360
	3.6	260		4.1	260		4.0	260
	5.4	240		6.1	240		5.9	240
	7.0	230		7.9	230		7.7	230
	8.0	220		8.9	220		8.7	220
	9.2	210		10.3	210		10.0	210
	14.7	200		16.6	200		16.1	200
	17.0	196		19.2	196		18.6	196
2212	1.1	360	2253	1.2	360	2384	1.2	360
	4.0	260		4.5	260		4.4	260
	6.0	240		6.8	240		6.6	240
	6.9	230		7.7	230		7.5	230
	7.8	220		8.7	220		8.5	220
	9.2	210		10.4	210		10.1	210
	16.0	200		18.0	200		17.5	200
	20.1	200		22.6	200		22.0	200
2417	2.2	360	2464	2.5	360	2618	2.4	360
	4.0	260		4.5	260		4.4	260
	5.0	240		5.6	240		5.5	240
	5.8	230		6.5	230		6.4	230
	7.1	220		7.9	220		7.7	220
	8.6	210		9.7	210		9.5	210
	13.2	200		14.8	200		14.4	200
	18.0	200		20.2	200		19.7	200
2617	2.3	360	2672	2.6	360	2847	2.5	360
	3.9	260		4.4	260		4.3	260
	5.0	240		5.6	240		5.4	240
	5.7	230		6.4	230		6.2	230
	6.8	220		7.6	220		7.4	220
	8.6	210		9.6	210		9.4	210
2813	2.1	360	2875	2.3	360	3071	2.3	360
	4.0	260		4.5	260		4.3	260
	5.1	240		5.7	240		5.6	240
	5.8	230		6.5	230		6.4	230
	6.9	220		7.8	220		7.6	220
	9.0	210		10.2	210		9.9	210
3014	2.0	360	3082	2.2	360	3301	2.2	360
	4.1	260		4.6	260		4.5	260
	5.2	240		5.8	240		5.7	240
	6.1	230		6.8	230		6.6	230
	7.6	220		8.5	220		8.3	220
	10.4	210		11.7	210		11.4	210
	16.1	210		18.1	210		17.6	210
3203	2.1	360	3278	2.4	360	3517	2.3	360
	4.4	260		4.9	260		4.8	260
	5.5	240		6.2	240		6.1	240
	6.6	230		7.4	230		7.2	230
	8.6	220		9.6	220		9.4	220
	16.2	220		18.2	220		17.7	220
3396	2.2	360	3477	2.5	360	3738	2.4	360
	4.7	260		5.3	260		5.1	260
	6.2	240		6.9	240		6.8	240
	7.5	230		8.4	230		8.2	230
	10.7	220		12.0	220		11.7	220
	13.9	220		15.6	220		15.2	220
3604	2.2	360	3692	2.5	360	3975	2.4	360
	4.9	260		5.5	260		5.4	260
	6.9	240		7.7	240		7.5	240
	9.0	230		10.2	230		9.9	230
	14.2	230		15.9	230		15.5	230
3813	2.4	360	3908	2.7	360	4214	2.6	360
	5.7	260		6.4	260		6.2	260
	8.7	240		9.8	240		9.5	240

Table SI4.2.12. Reference mass-configuration – Variable model parameters: *Specific FC* (*cons*) - DT case studies n°7, 21, 31

	Reference mass-configuration - Auxiliary parameters (GT case studies)											
Case study	***Elasticity 80-120 km/h ($t_{80-120km/h}$) [s]***	***Front disk diameter (D_{disk_front}) [mm]***	***Front disk mass (m_{disk_front}) [kg]***	***Max. Brake Mean Effective Pressure ($BMEP_{max}$) [bar]***	***Number of cylinders ($n°_{cyl}$) [null]***	***Power-to-Mass Ratio (PMR) [W/kg]***	***Rear disk diameter (D_{disk_rear}) [mm]***	***Rear disk mass (m_{disk_rear}) [kg]***	***Stroke-to-Bore Ratio (SBR) [null]***	***Tank capacity (tank capacity) [l]***	***Tyre mass (m_{tyre}) [kg]***	***Wheel rim mass (m_{rim}) [kg]***
1	16.28	257	6.1	20.83	2	68.1	251	3.7	1.068	45	7.7	8.5
2	16.27	256	5.1	20.07	3	67.6	230	2.6	1.026	45	7.7	8.0
3	14.82	256	5.1	17.99	4	85.2	230	2.6	1.074	45	7.7	8.0
4	9.96	256	5.1	22.54	4	98.2	230	2.6	1.074	45	10	8.5
5	19.47	258	3.8	18.95	3	68.6	203	3.8	1.014	50	7.7	8.0
6	15.11	257	4.3	20.89	2	64.1	203	3.5	1.068	37	6.4	7.5
7	18.06	257	5.0	20.87	2	58.1	228	3.7	1.068	45	6.8	8.0
8	10.86	284	6.1	18.93	4	85.7	264	3.7	1.167	45	7.7	8.0
9	16.63	284	6.1	21.38	3	72.3	228	3.7	1.141	42	7.7	8.0
10	16.97	284	6.1	21.34	3	90.6	228	3.7	1.141	42	7.3	8.5
11	12.25	281	6.5	18.98	4	60.2	264	3.7	1.167	60	9.1	8.5
12	11.43	305	7.5	21.18	4	96.9	264	3.7	1.167	60	9.1	8.5
13	17.75	288	7.3	18.34	4	70.4	272	3.8	1.065	50	9.1	8.5
14	10.68	288	7.3	22.55	4	91.3	272	3.8	1.074	50	9.1	8.5
15	10.90	288	7.3	17.51	4	107.3	272	3.8	1.019	50	9.1	8.5
16	13.11	284	6.0	19.01	4	69.8	251	3.5	1.167	57	9.1	8.5
17	10.42	281	6.0	21.17	4	80.8	251	3.5	1.167	57	9.1	8.5
18	14.65	278	6.6	21.37	3	60.5	271	4.3	1.141	55	9.1	8.5
19	18.24	278	6.6	21.35	3	75.4	271	4.3	1.141	55	9.1	8.5
20	12.11	278	6.6	20.12	4	88.2	271	4.3	0.968	55	9.1	8.5
21	12.42	278	6.6	20.14	4	107.5	271	4.3	0.968	55	9.1	8.5
22	15.21	314	8.4	16.07	4	61.5	300	5.2	1.019	63	8.6	8.5
23	11.47	314	8.4	22.34	4	87.4	300	5.2	1.019	63	8.6	8.5
24	16.14	300	8.1	18.44	3	71.4	296	4.9	1.154	60	8.6	8.5
25	10.00	312	8.9	18.24	4	94.4	300	6.3	1.154	60	8.6	8.5
26	14.99	304	9.9	18.89	4	80.4	290	5.0	1.114	71	10	9.0
27	20.70	300	8.7	21.39	3	66.7	302	5.5	1.141	62	9.5	8.5
28	14.26	300	8.7	20.09	4	83.7	302	5.1	0.968	62	9.5	8.5
29	13.01	300	8.7	21.65	4	100.1	302	5.1	0.950	62	10.9	9.0
30	12.07	300	8.7	21.65	4	118.5	302	5.1	1.053	62	10.9	9.0
31	16.93	288	7.1	19.65	4	87.1	278	4.1	0.888	41	8.6	8.5
32	13.49	295	8.3	18.94	4	98.5	300	5.0	1.108	41	8.6	8.5

Table SI4.2.13. Reference mass-configuration – Auxiliary parameters (GT case studies)

	Reference mass-configuration - Auxiliary parameters (DT case studies)											
Case study	***Elasticity 80-120 km/h ($t_{80-120km/h}$) [s]***	***Front disk diameter (D_{disk_front}) [mm]***	***Front disk mass (m_{disk_front}) [kg]***	***Max. Brake Mean Effective Pressure ($BMEP_{max}$) [bar]***	***Number of cylinders ($n°_{cyl}$) [null]***	***Power-to-Mass Ratio (PMR) [W/kg]***	***Rear disk diameter (D_{disk_rear}) [mm]***	***Rear disk mass (m_{disk_rear}) [kg]***	***Stroke-to-Bore Ratio (SBR) [null]***	***Tank capacity (tank capacity) [l]***	***Tyre mass (m_{tyre}) [kg]***	***Wheel rim mass (m_{rim}) [kg]***
1	8.06	281	6.1	25.21	4	73.0	251	3.7	1.013	45	7.7	8.5
2	18.92	266	4.1	14.39	4	45.9	249	5.1	1.113	45	7.7	8.0
3	11.72	266	4.1	21.76	4	70.2	249	5.1	1.177	45	7.7	8.5
4	11.19	260	5.0	20.14	4	71.4	240	3.5	1.178	35	8.2	8.0
5	14.79	257	4.3	19.10	4	53.1	203	3.5	1.178	37	6.4	7.5
6	14.03	257	5.0	19.13	4	50.5	228	3.7	1.178	45	6.8	8.0
7	13.50	284	6.1	20.14	4	55.3	228	3.7	1.178	45	6.8	8.0
8	11.58	284	6.1	20.17	4	61.9	228	3.7	1.178	45	7.7	8.0
9	16.24	258	5.1	15.53	4	53.2	253	3.35	1.201	40	6.4	7.5
10	14.92	284	6.1	16.08	4	67.8	228	3.7	1.177	40	6.8	8.5
11	11.65	281	6.5	25.13	4	58.8	264	3.7	1.013	60	9.1	8.5
12	9.31	305	7.5	24.40	4	83.3	264	3.7	1.089	60	9.1	8.5
13	8.84	305	7.5	22.49	4	97.7	264	3.7	1.089	60	9.1	8.5
14	14.02	266	6.8	18.53	4	56.4	249	5.4	1.177	60	7.7	8.0
15	14.00	283	6.8	21.72	4	69.7	249	5.4	1.177	60	7.7	8.0
16	10.89	302	7.4	21.40	4	83.3	268	5.4	1.035	60	10.0	9.0
17	14.07	284	6.0	22.81	4	50.0	251	3.5	1.013	57	7.7	8.0
18	12.37	284	6.0	23.60	4	66.7	251	3.5	1.013	57	9.1	8.5
19	9.75	281	6.8	23.09	4	89.0	251	3.5	1.089	57	10.0	9.0
20	13.60	278	6.6	22.61	4	55.6	271	4.3	1.201	53	9.1	8.5
21	13.05	278	6.6	22.65	4	68.0	271	4.3	1.201	53	6.8	8.5
22	10.81	278	6.6	21.99	4	80.2	271	4.3	1.035	60	9.1	8.5
23	13.10	312	8.9	20.16	4	76.9	300	6.3	1.071	57	8.6	8.5
24	11.40	312	8.9	25.08	4	84.5	300	6.3	1.071	57	8.6	8.5
25	10.05	312	8.9	25.18	4	97.9	300	6.3	1.071	57	8.6	8.5
26	7.81	312	8.9	28.25	4	108.5	300	6.3	1.071	57	10.0	9.0
27	14.60	304	9.9	19.37	4	55.8	290	5.0	1.177	71	10.0	9.0
28	14.79	304	9.9	20.10	4	64.0	290	5.0	1.035	71	10.0	9.0
29	13.16	330	10.0	21.40	4	76.8	290	5.0	1.035	71	10.0	9.0
30	16.03	300	8.7	21.75	4	59.5	302	5.1	1.178	62	9.5	8.5
31	14.95	300	8.7	22.02	4	73.2	302	5.1	1.035	62	9.5	8.5
32	12.43	300	8.7	25.17	4	87.5	302	5.1	1.035	62	9.5	8.5

Table SI4.2.14. Reference mass-configuration – Auxiliary parameters (DT case studies)

SI 4.3. PMR mass-configurations

PMR mass-configurations (GT A/B-class)									
Case study	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**	**Case study**	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**
1	Reference	1130	1083	1270	**7**	Reference	1075	1028	1215
	PMR 5%	-	1028	1216		PMR 5%	-	976	1164
	PMR 10%	-	974	1162		PMR 10%	-	925	1112
	PMR 15%	-	920	1108		PMR 15%	-	873	1061
	PMR 20%	-	866	1053		PMR 20%	-	822	1009
2	Reference	1035	988	1175	**8**	Reference	1155	1108	1295
	PMR 5%	-	938	1125		PMR 5%	-	1052	1240
	PMR 10%	-	889	1076		PMR 10%	-	997	1184
	PMR 15%	-	839	1026		PMR 15%	-	941	1129
	PMR 20%	-	790	977		PMR 20%	-	886	1073
3	Reference	1080	1033	1220	**9**	Reference	1016	971	1156
	PMR 5%	-	981	1168		PMR 5%	-	922	1107
	PMR 10%	-	929	1117		PMR 10%	-	874	1059
	PMR 15%	-	878	1064		PMR 15%	-	825	1010
	PMR 20%	-	826	1013		PMR 20%	-	777	962
4	Reference	1120	1073	1260	**10**	Reference	1016	971	1156
	PMR 5%	-	1019	1207		PMR 5%	-	922	1107
	PMR 10%	-	1153	1153		PMR 10%	-	874	1059
	PMR 15%	-	1099	1099		PMR 15%	-	825	1010
	PMR 20%	-	1045	1045		PMR 20%	-	777	962
5	Reference	962	911	1102					
	PMR 5%	-	865	1056					
	PMR 10%	-	820	1011					
	PMR 15%	-	774	965					
	PMR 20%	-	729	920					
6	Reference	975	933	1115					
	PMR 5%	-	887	1068					
	PMR 10%	-	840	1022					
	PMR 15%	-	793	975					
	PMR 20%	-	747	928					

Table SI4.3.1. PMR mass-configurations - *Curb mass (m_{curb}), tare mass (m_{tare}), and vehicle mass (m_{veh})*: numerical values assigned to case studies (GT A/B-class)

PMR mass-configurations (GT C-class)									
Case study	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**	**Case study**	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**
11	Reference	1280	1222	1420	**17**	Reference	1275	1219	1415
	PMR 5%	-	1161	1359		PMR 5%	-	1158	1354
	PMR 10%	-	1100	1298		PMR 10%	-	1097	1293
	PMR 15%	-	1039	1237		PMR 15%	-	1036	1232
	PMR 20%	-	977	1176		PMR 20%	-	975	1171
12	Reference	1290	1232	1430	**18**	Reference	1215	1160	1355
	PMR 5%	-	1170	1368		PMR 5%	-	1102	1297
	PMR 10%	-	1109	1307		PMR 10%	-	1044	1239
	PMR 15%	-	1047	1245		PMR 15%	-	986	1181
	PMR 20%	-	985	1184		PMR 20%	-	928	1123
13	Reference	1150	1099	1290	**19**	Reference	1220	1165	1360
	PMR 5%	-	1044	1235		PMR 5%	-	1107	1302
	PMR 10%	-	989	1180		PMR 10%	-	1049	1243
	PMR 15%	-	934	1125		PMR 15%	-	991	1185
	PMR 20%	-	879	1070		PMR 20%	-	932	1127
14	Reference	1205	1154	1345	**20**	Reference	1247	1192	1387
	PMR 5%	-	1096	1287		PMR 5%	-	1133	1327
	PMR 10%	-	1039	1230		PMR 10%	-	1073	1268
	PMR 15%	-	981	1172		PMR 15%	-	1014	1208
	PMR 20%	-	923	1114		PMR 20%	-	954	1149
15	Reference	1230	1179	1370	**21**	Reference	1247	1192	1387
	PMR 5%	-	1120	1311		PMR 5%	-	1133	1327
	PMR 10%	-	1061	1252		PMR 10%	-	1073	1268
	PMR 15%	-	1002	1193		PMR 15%	-	1014	1208
	PMR 20%	-	943	1134		PMR 20%	-	954	1149
16	Reference	1260	1204	1400					
	PMR 5%	-	1144	1340					
	PMR 10%	-	1084	1280					
	PMR 15%	-	1023	1219					
	PMR 20%	-	963	1159					

Table SI4.3.2. PMR mass-configurations - *Curb mass (m_{curb}), tare mass (m_{tare}), and vehicle mass (m_{veh})*: numerical values assigned to case studies (GT C-class)

PMR mass-configurations (GT D-class)									
Case study	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**	**Case study**	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**
22	Reference	1430	1370	1570	**28**	Reference	1410	1350	1550
	PMR 5%	-	1301	1502		PMR 5%	-	1283	1482
	PMR 10%	-	1233	1433		PMR 10%	-	1215	1415
	PMR 15%	-	1164	1365		PMR 15%	-	1148	1347
	PMR 20%	-	1096	1296		PMR 20%	-	1080	1280
23	Reference	1430	1370	1570	**29**	Reference	1489	1429	1629
	PMR 5%	-	1301	1502		PMR 5%	-	1558	1558
	PMR 10%	-	1233	1433		PMR 10%	-	1486	1486
	PMR 15%	-	1164	1365		PMR 15%	-	1415	1415
	PMR 20%	-	1096	1296		PMR 20%	-	1343	1343
24	Reference	1400	1342	1540	**30**	Reference	1489	1429	1629
	PMR 5%	-	1275	1473		PMR 5%	-	1358	1558
	PMR 10%	-	1208	1406		PMR 10%	-	1286	1486
	PMR 15%	-	1141	1339		PMR 15%	-	1215	1415
	PMR 20%	-	1073	1272		PMR 20%	-	1143	1343
25	Reference	1430	1372	1570	**31**	Reference	1320	1275	1460
	PMR 5%	-	1303	1502		PMR 5%	-	1212	1396
	PMR 10%	-	1235	1433		PMR 10%	-	1148	1332
	PMR 15%	-	1166	1365		PMR 15%	-	1084	1268
	PMR 20%	-	1097	1296		PMR 20%	-	1020	1205
26	Reference	1430	1364	1570	**32**	Reference	1370	1325	1510
	PMR 5%	-	1296	1502		PMR 5%	-	1259	1444
	PMR 10%	-	1227	1434		PMR 10%	-	1193	1377
	PMR 15%	-	1159	1365		PMR 15%	-	1127	1311
	PMR 20%	-	1091	1297		PMR 20%	-	1060	1245
27	Reference	1380	1320	1520					
	PMR 5%	-	1254	1454					
	PMR 10%	-	1188	1388					
	PMR 15%	-	1122	1322					
	PMR 20%	-	1056	1256					

Table SI4.3.3. PMR mass-configurations - *Curb mass (*m_{curb}*), tare mass (*m_{tare}*), and vehicle mass (*m_{veh}*)*: numerical values assigned to case studies (GT D-class)

PMR mass-configurations (DT A/B-class)									
Case study	**Configuration**	**Curb mass (m_{curb}) [kg]**	**Tare mass (m_{tare}) [kg]**	**Vehicle mass (m_{veh}) [kg]**	**Case study**	**Configuration**	**Curb mass (m_{curb}) [kg]**	**Tare mass (m_{tare}) [kg]**	**Vehicle mass (m_{veh}) [kg]**
1	Reference	1205	1152	1345	**7**	Reference	1130	1077	1270
	PMR 5%	-	1095	1287		PMR 5%	-	1023	1216
	PMR 10%	-	1037	1230		PMR 10%	-	970	1162
	PMR 15%	-	979	1172		PMR 15%	-	916	1108
	PMR 20%	-	922	1115		PMR 20%	-	862	1055
2	Reference	1089	1036	1229	**8**	Reference	1130	1077	1270
	PMR 5%	-	984	1177		PMR 5%	-	1023	1216
	PMR 10%	-	932	1125		PMR 10%	-	970	1162
	PMR 15%	-	881	1074		PMR 15%	-	916	1108
	PMR 20%	-	829	1022		PMR 20%	-	862	1055
3	Reference	1196	1143	1336	**9**	Reference	1033	985	1173
	PMR 5%	-	1086	1279		PMR 5%	-	935	1124
	PMR 10%	-	1029	1222		PMR 10%	-	886	1075
	PMR 15%	-	972	1165		PMR 15%	-	837	1025
	PMR 20%	-	914	1107		PMR 20%	-	788	976
4	Reference	980	936	1120	**10**	Reference	1033	985	1173
	PMR 5%	-	889	1073		PMR 5%	-	935	1124
	PMR 10%	-	842	1026		PMR 10%	-	886	1075
	PMR 15%	-	795	980		PMR 15%	-	837	1025
	PMR 20%	-	749	933		PMR 20%	-	788	976
5	Reference	1035	989	1175					
	PMR 5%	-	940	1126					
	PMR 10%	-	890	1076					
	PMR 15%	-	841	1027					
	PMR 20%	-	791	977					
6	Reference	1090	1037	1230					
	PMR 5%	-	985	1178					
	PMR 10%	-	934	1126					
	PMR 15%	-	882	1074					
	PMR 20%	-	830	1023					

Table SI4.3.4. PMR mass-configurations - *Curb mass (m_{curb}), tare mass (m_{tare}), and vehicle mass (m_{veh})*: numerical values assigned to case studies (DT A/B-class)

PMR mass-configurations (DT C-class)									
Case study	**Configuration**	***Curb mass (m_{curb})* [kg]**	***Tare mass (m_{tare})* [kg]**	***Vehicle mass (m_{veh})* [kg]**	**Case study**	**Configuration**	***Curb mass (m_{curb})* [kg]**	***Tare mass (m_{tare})* [kg]**	***Vehicle mass (m_{veh})* [kg]**
11	Reference	1310	1245	1450	**17**	Reference	1320	1257	1460
	PMR 5%	-	1183	1388		PMR 5%	-	1194	1397
	PMR 10%	-	1120	1326		PMR 10%	-	1132	1334
	PMR 15%	-	1058	1263		PMR 15%	-	1069	1271
	PMR 20%	-	996	1201		PMR 20%	-	1006	1209
12	Reference	1320	1255	1460	**18**	Reference	1320	1257	1460
	PMR 5%	-	1192	1397		PMR 5%	-	1194	1397
	PMR 10%	-	1129	1335		PMR 10%	-	1132	1334
	PMR 15%	-	1067	1272		PMR 15%	-	1069	1271
	PMR 20%	-	1004	1209		PMR 20%	-	1006	1209
13	Reference	1320	1255	1460	**19**	Reference	1360	1297	1500
	PMR 5%	-	1192	1397		PMR 5%	-	1232	1435
	PMR 10%	-	1129	1335		PMR 10%	-	1168	1370
	PMR 15%	-	1067	1272		PMR 15%	-	1103	1305
	PMR 20%	-	1004	1209		PMR 20%	-	1038	1241
14	Reference	1205	1140	1345	**20**	Reference	1260	1201	1400
	PMR 5%	-	1083	1288		PMR 5%	-	1141	1340
	PMR 10%	-	1026	1231		PMR 10%	-	1081	1280
	PMR 15%	-	969	1174		PMR 15%	-	1021	1220
	PMR 20%	-	912	1117		PMR 20%	-	961	1160
15	Reference	1205	1140	1345	**21**	Reference	1294	1235	1434
	PMR 5%	-	1083	1288		PMR 5%	-	1173	1372
	PMR 10%	-	1026	1231		PMR 10%	-	1111	1311
	PMR 15%	-	969	1174		PMR 15%	-	1049	1249
	PMR 20%	-	912	1117		PMR 20%	-	988	1187
16	Reference	1320	1255	1460	**22**	Reference	1371	1306	1511
	PMR 5%	-	1192	1397		PMR 5%	-	1240	1446
	PMR 10%	-	1129	1335		PMR 10%	-	1175	1380
	PMR 15%	-	1067	1272		PMR 15%	-	1110	1315
	PMR 20%	-	1004	1209		PMR 20%	-	1045	1250

Table SI4.3.5. PMR mass-configurations - *Curb mass (m_{curb}), tare mass (m_{tare}), and vehicle mass (m_{veh})*: numerical values assigned to case studies (DT C-class)

PMR mass-configurations (DT D-class)									
Case study	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**	**Case study**	**Configuration**	***Curb mass* (*m_{curb}*) [kg]**	***Tare mass* (*m_{tare}*) [kg]**	***Vehicle mass* (*m_{veh}*) [kg]**
23	Reference	1430	1367	1570	**29**	Reference	1563	1489	1703
	PMR 5%	-	1299	1502		PMR 5%	-	1414	1629
	PMR 10%	-	1231	1433		PMR 10%	-	1340	1554
	PMR 15%	-	1162	1365		PMR 15%	-	1265	1480
	PMR 20%	-	1094	1297		PMR 20%	-	1191	1405
24	Reference	1420	1357	1560	**30**	Reference	1420	1353	1560
	PMR 5%	-	1289	1492		PMR 5%	-	1285	1492
	PMR 10%	-	1222	1424		PMR 10%	-	1218	1425
	PMR 15%	-	1154	1356		PMR 15%	-	1150	1357
	PMR 20%	-	1086	1289		PMR 20%	-	1082	1289
25	Reference	1430	1367	1570	**31**	Reference	1503	1436	1643
	PMR 5%	-	1299	1502		PMR 5%	-	1364	1571
	PMR 10%	-	1231	1433		PMR 10%	-	1292	1499
	PMR 15%	-	1162	1365		PMR 15%	-	1221	1428
	PMR 20%	-	1094	1297		PMR 20%	-	1149	1356
26	Reference	1475	1412	1615	**32**	Reference	1509	1442	1649
	PMR 5%	-	1342	1545		PMR 5%	-	1370	1577
	PMR 10%	-	1271	1474		PMR 10%	-	1298	1505
	PMR 15%	-	1200	1404		PMR 15%	-	1226	1433
	PMR 20%	-	1130	1333		PMR 20%	-	1154	1361
27	Reference	1506	1432	1646					
	PMR 5%	-	1360	1574					
	PMR 10%	-	1288	1503					
	PMR 15%	-	1217	1431					
	PMR 20%	-	1145	1360					
28	Reference	1610	1536	1750					
	PMR 5%	-	1459	1679					
	PMR 10%	-	1382	1596					
	PMR 15%	-	1305	1520					
	PMR 20%	-	1228	1443					

Table SI4.3.6. PMR mass-configurations - *Curb mass (m_{curb}), tare mass (m_{tare}), and vehicle mass (m_{veh})*: numerical values assigned to case studies (DT D-class)

SI 4.4. SE mass-configurations

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (GT A/B-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (*I_E*) [kg*m^2]**	***Idle FC* (*$cons_{idle}$*) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
1	Reference	0.875	0.100	404	80.50	86.00
	SE 5%	0.846	0.097	399	79.59	85.03
	SE 10%	0.817	0.093	394	78.67	84.05
	SE 15%	0.789	0.090	389	77.72	83.03
	SE 20%	0.759	0.087	384	76.77	82.01
2	Reference	0.999	0.114	425	74.50	76.40
	SE 5%	0.968	0.110	420	73.71	75.59
	SE 10%	0.936	0.107	141	72.91	74.77
	SE 15%	0.905	0.103	408	72.08	73.92
	SE 20%	0.874	0.100	403	71.24	73.06
3	Reference	1.395	0.160	491	74.50	80.00
	SE 5%	1.350	0.155	483	73.68	79.12
	SE 10%	1.304	0.149	476	72.85	78.23
	SE 15%	1.258	0.144	468	71.99	77.30
	SE 20%	1.213	0.139	461	71.12	76.37
4	Reference	1.395	0.160	491	74.50	80.00
	SE 5%	1.346	0.154	483	73.61	79.04
	SE 10%	1.297	0.148	475	72.71	78.08
	SE 15%	1.248	0.143	466	71.77	77.07
	SE 20%	1.198	0.137	458	70.82	76.05
5	Reference	0.898	0.102	408	72.20	73.20
	SE 5%	0.874	0.100	404	71.54	72.54
	SE 10%	0.851	0.097	400	70.89	71.87
	SE 15%	0.827	0.094	396	70.22	71.20
	SE 20%	0.804	0.092	392	69.56	70.52
6	Reference	0.875	0.100	404	80.50	86.00
	SE 5%	0.847	0.097	399	79.63	85.07
	SE 10%	0.820	0.094	394	78.76	84.14
	SE 15%	0.792	0.090	390	77.85	83.17
	SE 20%	0.764	0.087	385	76.94	82.20

Table SI4.4.1. SE mass-configurations - Parameters affected by SE: numerical values assigned to case studies n°1-6 (GT A/B-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (GT A/B-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
7	Reference	0.875	0.100	404	80.50	86.00
	SE 5%	0.848	0.097	400	79.65	85.09
	SE 10%	0.821	0.094	395	78.80	84.18
	SE 15%	0.794	0.091	390	77.92	83.25
	SE 20%	0.767	0.088	386	77.05	82.31
8	Reference	1.368	0.156	487	72.00	84.00
	SE 5%	1.320	0.150	479	71.14	83.00
	SE 10%	1.272	0.145	471	70.28	81.99
	SE 15%	1.225	0.140	463	69.38	80.95
	SE 20%	1.177	0.135	455	68.49	79.90
9	Reference	0.999	0.114	425	71.90	82.00
	SE 5%	0.969	0.110	420	71.17	81.17
	SE 10%	0.939	0.107	414	70.44	80.33
	SE 15%	0.908	0.104	409	69.66	79.45
	SE 20%	0.879	0.101	404	68.89	78.57
10	Reference	0.999	0.114	425	71.90	82.00
	SE 5%	0.969	0.110	420	71.17	81.17
	SE 10%	0.939	0.107	414	70.44	80.33
	SE 15%	0.909	0.104	409	69.67	79.46
	SE 20%	0.879	0.101	404	68.91	78.59

Table SI4.4.2. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°7-10 (GT A/B-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (GT C-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
11	Reference	1.368	0.156	487	72.00	84.00
	SE 5%	1.318	0.150	478	71.11	82.96
	SE 10%	1.269	0.145	470	70.22	81.92
	SE 15%	1.220	0.139	462	69.29	80.84
	SE 20%	1.171	0.134	454	68.36	79.75
12	Reference	1.368	0.156	487	72.00	84.00
	SE 5%	1.321	0.151	479	71.16	83.03
	SE 10%	1.275	0.145	471	70.33	82.05
	SE 15%	1.228	0.140	463	69.46	81.04
	SE 20%	1.182	0.135	456	68.59	80.02
13	Reference	1.290	0.137	458	71.00	75.60
	SE 5%	1.235	0.133	451	70.23	74.78
	SE 10%	1.180	0.128	445	69.46	73.96
	SE 15%	1.125	0.124	438	68.66	73.11
	SE 20%	1.070	0.120	432	67.58	72.25
14	Reference	1.395	0.160	491	74.50	80.00
	SE 5%	1.346	0.154	483	73.61	79.04
	SE 10%	1.297	0.148	475	72.71	78.08
	SE 15%	1.248	0.142	466	71.76	77.06
	SE 20%	1.198	0.137	458	70.81	76.04
15	Reference	1.798	0.206	559	82.50	84.10
	SE 5%	1.734	0.198	548	81.50	83.08
	SE 10%	1.670	0.191	538	80.50	82.06
	SE 15%	1.606	0.183	527	79.44	80.99
	SE 20%	1.543	0.176	516	78.39	79.91
16	Reference	1.368	0.156	487	72.00	84.00
	SE 5%	1.320	0.150	479	71.14	83.00
	SE 10%	1.272	0.145	471	70.28	81.99
	SE 15%	1.224	0.140	462	69.37	80.93
	SE 20%	1.176	0.135	454	68.46	79.87

Table SI4.4.3. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°11-16 (GT C-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (GT C-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
17	Reference	1.368	0.156	487	72.00	84.00
	SE 5%	1.318	0.150	478	71.10	82.95
	SE 10%	1.268	0.145	470	70.19	81.89
	SE 15%	1.218	0.139	462	69.25	80.79
	SE 20%	1.168	0.134	453	68.31	79.69
18	Reference	0.999	0.114	425	71.90	82.00
	SE 5%	0.966	0.110	419	71.09	81.08
	SE 10%	0.933	0.106	413	70.29	80.16
	SE 15%	0.900	0.102	407	69.44	79.20
	SE 20%	0.867	0.099	402	68.59	78.23
19	Reference	0.999	0.114	425	71.90	82.00
	SE 5%	0.968	0.110	419	71.12	81.12
	SE 10%	0.936	0.106	414	70.35	80.23
	SE 15%	0.904	0.103	408	69.55	79.32
	SE 20%	0.873	0.100	403	68.74	78.40
20	Reference	1.499	0.171	509	79.00	76.45
	SE 5%	1.447	0.165	500	78.07	75.55
	SE 10%	1.396	0.159	491	77.14	74.65
	SE 15%	1.344	0.153	482	76.17	73.71
	SE 20%	1.293	0.148	474	75.20	72.77
21	Reference	1.499	0.171	509	79.00	76.45
	SE 5%	1.447	0.165	500	78.08	75.56
	SE 10%	1.396	0.159	492	77.15	74.66
	SE 15%	1.345	0.153	483	76.18	73.73
	SE 20%	1.294	0.148	474	75.22	72.79

Table SI4.4.4. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°17-21 (GT C-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (GT D-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
22	Reference	1.798	0.206	559	82.50	84.10
	SE 5%	1.734	0.198	549	81.49	83.07
	SE 10%	1.670	0.191	538	80.48	82.04
	SE 15%	1.606	0.183	527	79.42	80.97
	SE 20%	1.541	0.176	516	78.37	79.89
23	Reference	1.798	0.206	559	82.50	84.10
	SE 5%	1.732	0.198	548	81.46	83.04
	SE 10%	1.665	0.190	537	80.41	81.97
	SE 15%	1.598	0.183	526	79.30	80.84
	SE 20%	1.531	0.175	514	78.19	79.71
24	Reference	1.499	0.171	509	82.00	94.60
	SE 5%	1.447	0.165	500	81.02	93.47
	SE 10%	1.394	0.159	491	80.03	92.33
	SE 15%	1.341	0.153	482	79.00	91.14
	SE 20%	1.288	0.147	473	77.97	89.95
25	Reference	1.998	0.229	593	82.00	94.60
	SE 5%	1.923	0.220	580	80.94	93.38
	SE 10%	1.847	0.211	568	79.88	92.15
	SE 15%	1.772	0.202	555	78.76	90.87
	SE 20%	1.697	0.194	542	77.65	89.58
26	Reference	1.598	0.182	526	77.00	85.80
	SE 5%	1.542	0.176	517	76.08	84.78
	SE 10%	1.487	0.170	507	75.17	83.76
	SE 15%	1.431	0.163	498	74.21	82.69
	SE 20%	1.376	0.157	488	73.25	81.62
27	Reference	0.999	0.114	425	71.90	82.00
	SE 5%	0.967	0.110	420	71.12	81.11
	SE 10%	0.935	0.107	414	70.33	80.21
	SE 15%	0.902	0.103	408	69.50	79.27
	SE 20%	0.870	0.099	403	68.67	78.32

Table SI4.4.5. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°22-27 (GT D-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (GT D-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
28	Reference	1.499	0.171	509	79.00	76.45
	SE 5%	1.458	0.166	502	78.27	75.75
	SE 10%	1.417	0.162	495	77.54	75.04
	SE 15%	1.376	0.157	488	76.78	74.31
	SE 20%	1.336	0.152	481	76.02	73.57
29	Reference	1.999	0.228	593	87.50	83.10
	SE 5%	1.937	0.221	582	86.58	82.23
	SE 10%	1.875	0.214	572	85.66	81.35
	SE 15%	1.813	0.207	561	84.68	80.43
	SE 20%	1.750	0.200	551	83.71	79.50
30	Reference	1.999	0.228	593	87.50	83.10
	SE 5%	1.937	0.221	582	89.61	85.11
	SE 10%	1.873	0.214	572	91.72	87.11
	SE 15%	1.810	0.206	561	90.66	86.10
	SE 20%	1.746	0.199	550	89.60	85.09
31	Reference	1.595	0.182	525	83.00	73.70
	SE 5%	1.540	0.176	516	82.02	72.83
	SE 10%	1.484	0.170	506	81.04	71.96
	SE 15%	1.429	0.164	497	80.02	71.05
	SE 20%	1.375	0.157	488	78.99	70.14
32	Reference	1.991	0.228	592	83.00	92.00
	SE 5%	1.919	0.220	579	81.97	90.86
	SE 10%	1.846	0.211	567	80.94	89.72
	SE 15%	1.774	0.203	555	79.86	88.52
	SE 20%	1.703	0.195	543	78.78	87.32

Table SI4.4.6. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°28-32 (GT D-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (DT A/B-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
1	Reference	1.598	0.183	417	79.50	80.50
	SE 5%	1.536	0.176	409	78.45	79.44
	SE 10%	1.475	0.169	401	77.40	78.37
	SE 15%	1.413	0.162	390	76.30	77.26
	SE 20%	1.353	0.155	385	75.20	76.15
2	Reference	1.398	0.159	391	73.70	82.00
	SE 5%	1.354	0.154	385	72.90	81.11
	SE 10%	1.310	0.150	379	72.09	80.21
	SE 15%	1.266	0.144	373	71.28	79.31
	SE 20%	1.223	0.139	367	70.46	78.40
3	Reference	1.560	0.178	412	75.00	88.30
	SE 5%	1.507	0.172	405	74.13	87.28
	SE 10%	1.454	0.166	398	73.26	86.25
	SE 15%	1.402	0.160	391	72.35	85.18
	SE 20%	1.348	0.154	384	71.43	84.10
4	Reference	1.248	0.143	371	69.60	82.00
	SE 5%	1.205	0.138	365	68.79	81.04
	SE 10%	1.162	0.133	359	67.97	80.08
	SE 15%	1.121	0.128	354	67.13	79.09
	SE 20%	1.078	0.123	348	66.29	78.10
5	Reference	1.248	0.143	371	69.60	82.00
	SE 5%	1.207	0.138	365	68.81	81.08
	SE 10%	1.166	0.133	360	68.03	80.15
	SE 15%	1.125	0.128	354	67.21	79.19
	SE 20%	1.084	0.124	349	66.40	78.23
6	Reference	1.248	0.143	371	69.60	82.00
	SE 5%	1.205	0.138	365	68.79	81.05
	SE 10%	1.163	0.133	359	67.98	80.09
	SE 15%	1.121	0.128	315	67.15	79.12
	SE 20%	1.080	0.123	348	66.32	78.14

Table SI4.4.7. SE mass-configurations - Parameters affected by SE: numerical values assigned to case studies n°1-6 (DT A/B-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (DT A/B-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
7	Reference	1.248	0.143	371	69.60	82.00
	SE 5%	1.205	0.138	365	68.79	81.04
	SE 10%	1.162	0.133	355	67.97	80.08
	SE 15%	1.120	0.128	353	67.13	79.09
	SE 20%	1.078	0.123	348	66.29	78.10
8	Reference	1.248	0.143	371	69.60	82.00
	SE 5%	1.204	0.138	365	68.76	81.01
	SE 10%	1.160	0.133	355	67.92	80.02
	SE 15%	1.116	0.128	352	67.05	79.00
	SE 20%	1.073	0.123	348	66.18	77.97
9	Reference	1.498	0.171	404	73.50	88.30
	SE 5%	1.452	0.166	398	72.72	87.37
	SE 10%	1.405	0.161	392	71.94	86.43
	SE 15%	1.358	0.156	385	71.13	85.46
	SE 20%	1.312	0.150	379	70.32	84.48
10	Reference	1.560	0.178	412	75.00	88.30
	SE 5%	1.512	0.173	406	74.21	87.37
	SE 10%	1.464	0.167	400	73.42	86.44
	SE 15%	1.415	0.161	394	72.59	85.47
	SE 20%	1.367	0.156	387	71.76	84.49

Table SI4.4.8. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°7- 10 (DT A/B-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (DT C-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (*I_E*) [kg*m^2]**	***Idle FC* (*$cons_{idle}$*) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
11	Reference	1.598	0.183	417	79.50	80.50
	SE 5%	1.544	0.177	410	78.59	79.58
	SE 10%	1.491	0.171	403	77.68	78.66
	SE 15%	1.437	0.165	396	76.73	77.70
	SE 20%	1.385	0.158	389	75.79	76.74
12	Reference	1.956	0.224	465	83.00	90.40
	SE 5%	1.889	0.216	456	82.03	89.34
	SE 10%	1.822	0.208	447	81.05	88.28
	SE 15%	1.755	0.200	438	80.03	87.17
	SE 20%	1.688	0.193	429	79.02	86.06
13	Reference	1.956	0.224	465	83.00	90.40
	SE 5%	1.884	0.216	456	81.96	89.27
	SE 10%	1.814	0.207	446	80.93	88.14
	SE 15%	1.743	0.199	437	79.85	86.97
	SE 20%	1.672	0.191	427	78.77	85.79
14	Reference	1.560	0.178	412	75.00	88.30
	SE 5%	1.508	0.172	407	74.14	87.29
	SE 10%	1.456	0.166	398	73.28	86.28
	SE 15%	1.404	0.160	392	72.39	85.23
	SE 20%	1.352	0.154	385	71.50	84.18
15	Reference	1.560	0.178	412	75.00	88.30
	SE 5%	1.512	0.173	406	74.21	87.37
	SE 10%	1.464	0.167	399	73.42	86.44
	SE 15%	1.415	0.161	393	72.60	85.47
	SE 20%	1.367	0.156	387	71.77	84.50
16	Reference	1.997	0.228	471	85.00	88.00
	SE 5%	1.933	0.220	463	84.08	87.05
	SE 10%	1.870	0.213	454	83.16	86.09
	SE 15%	1.807	0.206	445	82.19	85.10
	SE 20%	1.743	0.199	437	81.23	84.10

Table SI4.4.9. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°11- 16 (DT C-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			Auxiliary parameters	
Case study (DT C-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
17	Reference	1.598	0.183	417	79.50	80.50
	SE 5%	1.543	0.177	410	78.56	79.55
	SE 10%	1.488	0.170	403	77.62	78.60
	SE 15%	1.434	0.164	395	76.67	77.64
	SE 20%	1.381	0.157	388	75.72	76.67
18	Reference	1.598	0.183	417	79.50	80.50
	SE 5%	1.537	0.176	409	78.50	79.49
	SE 10%	1.480	0.169	402	77.50	78.47
	SE 15%	1.424	0.163	394	76.50	77.46
	SE 20%	1.369	0.156	387	75.50	76.45
19	Reference	1.956	0.223	465	83.00	90.40
	SE 5%	1.887	0.215	456	81.99	89.31
	SE 10%	1.818	0.207	447	80.99	88.21
	SE 15%	1.749	0.199	438	79.95	87.08
	SE 20%	1.682	0.192	429	78.91	85.95
20	Reference	1.498	0.171	404	73.50	88.30
	SE 5%	1.447	0.165	397	72.64	87.27
	SE 10%	1.396	0.159	390	71.78	86.23
	SE 15%	1.345	0.153	384	70.89	85.16
	SE 20%	1.294	0.148	377	70.00	84.09
21	Reference	1.498	0.171	404	73.50	88.30
	SE 5%	1.448	0.165	397	72.66	87.30
	SE 10%	1.399	0.159	391	71.83	86.29
	SE 15%	1.348	0.153	384	70.95	85.24
	SE 20%	1.299	0.148	377	70.08	84.19
22	Reference	1.997	0.228	471	85.00	88.00
	SE 5%	1.933	0.221	462	84.06	87.03
	SE 10%	1.868	0.213	454	83.13	86.06
	SE 15%	1.805	0.206	445	82.17	85.07
	SE 20%	1.742	0.199	437	81.20	84.07

Table SI4.4.10. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°17- 22 (DT C-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (DT D-class)	**Mass configuration**	***Engine displacement* (*V*) [l]**	***Engine Inertia* (I_E) [kg*m^2]**	***Idle FC* ($cons_{idle}$) [g/h]**	***Engine bore* (*bore*) [mm]**	***Engine srtoke* (*stroke*) [mm]**
23	Reference	1.995	0.227	471	84.00	90.00
	SE 5%	1.925	0.219	462	82.98	88.91
	SE 10%	1.854	0.211	452	81.97	87.82
	SE 15%	1.784	0.203	443	80.91	86.69
	SE 20%	1.714	0.195	433	79.85	85.55
24	Reference	1.995	0.227	471	84.00	90.00
	SE 5%	1.930	0.220	462	83.08	89.01
	SE 10%	1.866	0.213	453	82.15	88.02
	SE 15%	1.801	0.206	444	81.20	87.00
	SE 20%	1.739	0.198	436	80.25	85.98
25	Reference	1.995	0.227	471	84.00	90.00
	SE 5%	1.927	0.219	462	83.02	88.95
	SE 10%	1.858	0.212	452	82.03	87.89
	SE 15%	1.790	0.204	443	81.01	86.80
	SE 20%	1.723	0.196	434	80.00	85.71
26	Reference	1.995	0.227	471	84.00	90.00
	SE 5%	1.918	0.218	460	82.88	88.81
	SE 10%	1.840	0.210	450	81.77	87.61
	SE 15%	1.763	0.201	440	80.59	86.35
	SE 20%	1.686	0.192	429	79.42	85.09
27	Reference	1.560	0.178	412	75.00	88.30
	SE 5%	1.504	0.171	406	74.08	87.22
	SE 10%	1.449	0.165	399	73.17	86.14
	SE 15%	1.393	0.159	391	72.21	85.01
	SE 20%	1.338	0.153	383	71.25	83.88
28	Reference	1.997	0.228	471	85.00	88.00
	SE 5%	1.933	0.220	462	84.07	87.04
	SE 10%	1.869	0.213	454	83.14	86.07
	SE 15%	1.806	0.206	445	82.18	85.08
	SE 20%	1.743	0.199	437	81.22	84.09

Table SI4.4.11. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°23- 28 (DT D-class)

		SE mass-configurations – Parameters affected by SE				
		Model parameters			**Auxiliary parameters**	
Case study (DT D-class)	**Mass configuration**	***Engine displacement (V)* [l]**	***Engine Inertia (I_E)* [kg*m^2]**	***Idle FC ($cons_{idle}$)* [g/h]**	***Engine bore (bore)* [mm]**	***Engine srtoke (stroke)* [mm]**
29	Reference	1.997	0.228	471	85.00	88.00
	SE 5%	1.933	0.220	462	84.06	87.03
	SE 10%	1.868	0.213	454	83.13	86.06
	SE 15%	1.804	0.204	445	82.15	85.05
	SE 20%	1.740	0.194	436	81.18	84.04
30	Reference	1.560	0.178	412	75.00	88.30
	SE 5%	1.509	0.172	403	74.18	87.33
	SE 10%	1.460	0.166	394	73.35	86.36
	SE 15%	1.410	0.161	385	72.50	85.36
	SE 20%	1.360	0.155	376	71.64	84.35
31	Reference	1.997	0.228	471	85.00	88.00
	SE 5%	1.939	0.221	463	84.15	87.13
	SE 10%	1.881	0.214	455	83.31	86.25
	SE 15%	1.823	0.207	447	82.44	85.35
	SE 20%	1.765	0.201	440	81.57	84.45
32	Reference	1.997	0.228	471	85.00	88.00
	SE 5%	1.937	0.221	463	84.14	87.11
	SE 10%	1.878	0.214	455	83.27	86.21
	SE 15%	1.818	0.207	447	82.37	85.28
	SE 20%	1.759	0.201	439	81.46	84.34

Table SI4.4.12. SE mass-configurations - Vehicle parameters affected by SE: numerical values assigned to case studies n°29- 32 (DT D-class)

SE mass-config. - Parameters affected by SE *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (GT case study n°9)					
Reference		**SE 10%**		**SE 20%**	
***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
600	-19.2	613	-18.0	626.4	-16.9
1000	-19.2	1021	-18.0	1044	-16.9
1500	-19.9	1532	-18.7	1566	-17.5
2000	-22.7	2042	-21.3	2088	-19.9
2500	-26.0	2553	-24.4	2610	-22.9
3000	-27.0	3063	-25.3	3132	-23.7
3500	-29.4	3574	-27.6	3654	-25.9
4000	-30.1	4084	-28.3	4176	-26.5
4500	-32.0	4595	-30.1	4698	-28.2
5000	-32.6	5105	-30.6	5220	-28.6
5500	-35.2	5616	-33.0	5742	-30.9
6000	-36.4	6126	-34.2	6264	-32.0
***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**
0	0.0	0	0.0	0	0.0
1029	119.7	1050	112.5	1073	105.3
1114	137.1	1137	128.8	1163	120.6
1257	154.2	1283	144.9	1312	135.6
1414	170.0	1443	159.8	1475	149.5
2184	170.0	2229	159.8	2279	149.5
4109	170.0	4194	159.8	4288	149.5
4422	160.0	4515	150.4	4615	140.7
4779	147.4	4879	138.5	4987	129.7
5007	140.7	5112	132.2	5226	123.7
5264	133.9	5374	125.8	5493	117.8
5535	127.1	5650	119.5	5776	111.8
5834	120.7	5956	113.4	6089	106.1
6077	115.8	6203	108.8	6342	101.9
6205	111.9	6334	105.2	6476	98.5
6305	107.7	6436	101.3	6580	94.8

Table SI4.4.13 SE mass-configurations – Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (GT case study n°9)

SE mass-config. - Parameters affected by SE *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (GT case study n°17)					
Reference		**SE 10%**		**SE 20%**	
***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
600	-26.0	616	-24.1	632	-22.2
1000	-26.0	1026	-24.1	1054	-22.2
1500	-27.0	1539	-25.0	1581	-23.1
2000	-30.7	2052	-28.5	2108	-26.2
2500	-35.2	2565	-32.7	2635	-30.1
3000	-36.5	3078	-33.9	3162	-31.2
3500	-39.9	3591	-37.0	3689	-34.0
4000	-40.8	4104	-37.8	4216	-34.8
4500	-43.4	4617	-40.2	4743	-37.1
5000	-44.1	5130	-40.9	5270	-37.7
5500	-47.7	5643	-44.2	5797	-40.7
6000	-49.3	6156	-45.7	6324	-42.1
***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**
0	0.0	0	0.0	0	0.0
1025	141.7	1052	131.3	1081	121.0
1111	164.4	1139	152.4	1171	140.4
1323	191.6	1357	177.6	1394	163.6
1566	216.1	1607	200.2	1651	184.5
1683	227.2	1726	210.5	1774	193.9
1810	230.5	1856	213.6	1908	196.8
2126	229.9	2181	213.0	2242	196.3
2739	227.1	2809	210.4	2887	193.9
3509	221.4	3599	205.2	3699	189.0
4037	213.6	4141	197.9	4255	182.4
4543	205.8	4660	190.7	4789	175.7
4997	197.4	5125	182.9	5267	168.5
5176	189.0	5309	175.2	5456	161.4
5355	177.3	5493	164.3	5645	151.4
5513	161.8	5655	149.9	5811	138.1

Table SI4.4.14. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (GT case study n°17)

SE mass-config. - Parameters affected by SE *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (GT case study n°28)					
Reference		**SE 10%**		**SE 20%**	
***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
600	-27.0	611	-25.5	623	-24.0
1000	-27.0	1019	-25.5	1039	-24.0
1500	-28.1	1529	-26.6	1559	-25.0
2000	-32.0	2038	-30.2	2078	-28.5
2500	-36.6	2548	-34.7	2598	-32.6
3000	-38.0	3057	-35.9	3117	-33.8
3500	-41.5	3567	-39.2	3637	-36.9
4000	-42.4	4076	-40.1	4156	-37.8
4500	-45.1	4586	-42.7	4676	-40.2
5000	-45.9	5095	-43.4	5195	-40.9
5500	-49.6	5605	-46.9	5715	-44.1
6000	-51.3	6114	-48.5	6234	-45.7
***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**
0	0.0	0	0.0	0	0.0
1029	161.4	1048	152.6	1069	143.9
1143	186.4	1164	176.2	1187	166.1
1257	207.5	1280	196.1	1306	184.9
1371	224.1	1397	211.9	1424	199.7
1513	239.6	1542	226.6	1573	213.6
2000	239.6	2038	226.6	2078	213.6
2400	239.6	2445	226.6	2494	213.6
2800	239.6	2853	226.6	2909	213.6
3200	239.6	3260	226.6	3325	213.6
3600	239.6	3668	226.6	3741	213.6
4000	239.6	4075	226.6	4156	213.6
4608	239.6	4695	226.6	4788	213.6
4736	238.5	4825	225.5	4921	212.6
4993	225.2	5087	212.9	5188	200.7
5292	213.6	5392	201.9	5499	190.3
5549	203.0	5654	192.0	5766	180.9
5834	193.6	5944	183.0	6062	172.5
6062	186.9	6177	176.7	6299	166.6
6262	176.4	6380	166.8	6507	157.2
6504	158.1	6627	149.5	6759	140.9

Table SI4.4.15. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (GT case study n°28)

SE mass-config. - Parameters affected by SE *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case study n°7)					
Reference		**SE 10%**		**SE 20%**	
***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
1000	-19.4	1024	-18.0	1050	-16.7
1500	-23.7	1536	-22.0	1575	-20.4
2000	-26.9	2048	-25.0	2100	-23.2
2500	-32.3	2560	-30.0	2625	-27.9
3000	-37.6	3072	-35.0	3150	-32.5
***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**
0	0.0	0	0.0	0	0.0
1011	139.0	1035	129.5	1061	120.1
1042	150.3	1067	140.0	1094	129.9
1105	162.3	1132	151.1	1161	140.2
1179	175.8	1207	163.8	1238	151.9
1274	187.7	1304	174.9	1338	162.2
1348	194.2	1380	180.9	1415	167.7
1411	198.4	1445	184.8	1481	171.4
1506	200.0	1542	186.3	1581	172.8
1780	199.7	1822	186.0	1869	172.5
2011	198.4	2060	184.8	2112	171.4
2317	195.5	2373	182.1	2433	168.9
2654	190.7	2718	177.6	2787	164.7
2981	184.2	3052	171.6	3130	159.1
3307	176.1	3387	164.1	3473	152.1
3497	171.3	3581	159.5	3672	148.0
3592	166.5	3678	155.0	3772	143.8
3813	151.6	3905	141.2	4004	131.0

Table SI4.4.16. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case study n°7)

SE mass-config. - Parameters affected by SE *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case study n°21)					
Reference		**SE 10%**		**SE 20%**	
***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
1000	-26.1	1023	-24.4	1049	-22.6
1500	-31.9	1535	-29.8	1574	-27.6
2000	-36.3	2046	-33.9	2098	-31.4
2500	-43.6	2558	-40.7	2623	-37.6
3000	-50.8	3069	-47.5	3147	-43.9
***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**
0	0.0	0	0.0	0	0.0
1011	156.7	1034	146.3	1060	135.8
1053	173.3	1077	161.8	1104	150.3
1137	194.4	1163	181.5	1193	168.6
1211	211.1	1239	197.1	1270	183.0
1263	225.0	1293	210.1	1325	195.1
1369	241.7	1401	225.6	1436	209.5
1495	256.7	1530	239.6	1568	222.5
1685	270.0	1724	252.1	1767	234.1
2644	270.0	2705	252.1	2773	234.1
2897	265.6	2964	247.9	3038	230.2
3181	256.7	3255	239.6	3336	222.5
3497	241.1	3579	225.1	3668	209.0
3655	230.0	3740	214.7	3834	199.4
3908	208.3	3999	194.5	4099	180.6

Table SI4.4.17. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case study n°21)

SE mass-config. - Parameters affected by SE *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case study n°31)					
Reference		**SE 10%**		**SE 20%**	
***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**	***rpm* [rpm]**	**t_{E_res} [Nm]**
0	0.0	0	0.0	0	0.0
1000	-33.9	1020	-31.9	1042	-29.9
1500	-41.4	1530	-39.0	1563	-36.6
2000	-47.0	2040	-44.3	2084	-41.6
2500	-56.5	2550	-53.2	2605	-49.9
3000	-65.9	3060	-62.0	3126	-58.2
***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**	***rpm* [rpm]**	**t_{E_dr} [Nm]**
0	0.0	0	0.0	0	0.0
1011	172.2	1031	162.2	1053	152.2
1074	200.0	1096	188.4	1119	176.8
1158	225.6	1181	212.4	1207	199.4
1253	251.1	1278	236.5	1306	222.0
1348	275.6	1375	259.5	1405	243.6
1464	300.6	1494	283.1	1526	265.7
1632	326.1	1665	307.1	1701	288.3
1727	338.9	1762	319.2	1800	299.6
1843	346.7	1880	326.5	1920	306.5
1980	350.0	2020	329.6	2063	309.4
2475	350.0	2525	329.6	2579	309.4
2665	349.4	2719	329.1	2777	308.9
2823	345.0	2880	324.9	2942	305.0
3012	338.3	3073	318.6	3139	299.1
3149	330.0	3213	310.8	3281	291.7
3286	319.4	3353	300.9	3424	282.4
3466	303.3	3536	285.7	3612	268.2
3645	289.4	3719	272.6	3798	255.9
3803	276.1	3880	260.0	3963	244.1
3950	265.6	4030	250.1	4116	234.8
4077	255.0	4160	240.2	4248	225.4
4214	240.6	4299	226.6	4391	212.7

Table SI4.4.18. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) (DT case study n°31)

SE mass-configurations - Parameters affected by SE *Specific FC* (*cons*) (GT case study n°9)								
Reference			**SE 10%**			**SE 20%**		
rpm [rpm]	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**
1029	2.3	400	1050	2.3	400	1074	2.3	400
	3.4	350		3.4	350		3.4	350
	4.6	300		4.6	300		4.6	300
	6.6	280		6.6	280		6.6	280
1220	2.2	400	1246	2.2	400	1273	2.2	400
	3.3	350		3.3	350		3.3	350
	4.6	300		4.6	300		4.6	300
	6.0	280		6.0	280		6.0	280
	8.3	260		8.3	260		8.3	260
	15.3	260		15.3	260		15.3	260
1466	2.1	400	1496	2.1	400	1530	2.1	400
	3.2	350		3.2	350		3.2	350
	4.5	300		4.5	300		4.5	300
	5.9	280		5.9	280		5.9	280
	7.5	260		7.5	260		7.5	260
	11.7	250		11.7	250		11.7	250
	15.4	250		15.4	250		15.4	250
1722	2.0	400	1758	2.0	400	1797	2.0	400
	3.2	350		3.2	350		3.2	350
	4.7	300		4.7	300		4.7	300
	6.0	280		6.0	280		6.0	280
	7.5	260		7.5	260		7.5	260
	10.0	250		10.0	250		10.0	250
	14.0	240		14.0	240		14.0	240
1979	2.0	400	2020	2.0	400	2065	2.0	400
	3.3	350		3.3	350		3.3	350
	4.7	300		4.7	300		4.7	300
	5.9	280		5.9	280		5.9	280
	7.6	260		7.6	260		7.6	260
	9.9	250		9.9	250		9.9	250
	12.4	240		12.4	240		12.4	240
	18.3	240		18.3	240		18.3	240
2213	2.0	400	2259	2.0	400	2310	2.0	400
	3.3	350		3.3	350		3.3	350
	4.8	300		4.8	300		4.8	300
	6.0	280		6.0	280		6.0	280
	7.8	260		7.8	260		7.8	260
	9.9	250		9.9	250		9.9	250
	12.0	240		12.0	240		12.0	240
	19.2	240		19.2	240		19.2	240
2458	2.1	400	2509	2.1	400	2565	2.1	400
	3.4	350		3.4	350		3.4	350
	4.7	300		4.7	300		4.7	300
	6.1	280		6.1	280		6.1	280
	8.0	260		8.0	260		8.0	260
	10.1	250		10.1	250		10.1	250
	12.2	240		12.2	240		12.2	240
	20.7	240		20.7	240		20.7	240
2701	2.3	400	2757	2.3	400	2818	2.3	400
	3.5	350		3.5	350		3.5	350
	4.8	300		4.8	300		4.8	300
	6.2	280		6.2	280		6.2	280
	8.2	260		8.2	260		8.2	260
	10.3	250		10.3	250		10.3	250
	12.5	240		12.5	240		12.5	240
	20.7	240		20.7	240		20.7	240
2941	2.4	400	3002	2.4	400	3069	2.4	400
	3.6	350		3.6	350		3.6	350
	4.7	300		4.7	300		4.7	300
	6.3	280		6.3	280		6.3	280
	8.5	260		8.5	260		8.5	260
	10.6	250		10.6	250		10.6	250
	12.8	240		12.8	240		12.8	240
	20.3	240		20.3	240		20.3	240
3173	2.4	400	3239	2.4	400	3311	2.4	400
	3.6	350		3.6	350		3.6	350
	4.8	300		4.8	300		4.8	300
	6.3	280		6.3	280		6.3	280
	8.7	260		8.7	260		8.7	260
	10.7	250		10.7	250		10.7	250
	12.9	240		12.9	240		12.9	240
	20.0	240		20.0	240		20.0	240
3416	2.5	400	3487	2.5	400	3565	2.5	400
	3.7	350		3.7	350		3.7	350
	4.8	300		4.8	300		4.8	300
	6.6	280		6.6	280		6.6	280
	8.9	260		8.9	260		8.9	260
	11.2	250		11.2	250		11.2	250
	13.2	240		13.2	240		13.2	240
	19.7	240		19.7	240		19.7	240
	21.4	250		21.4	250		21.4	250
3645	2.4	400	3721	2.4	400	3805	2.4	400
	3.6	350		3.6	350		3.6	350
	4.9	300		4.9	300		4.9	300
	6.7	280		6.7	280		6.7	280
	9.1	260		9.1	260		9.1	260
	11.4	250		11.4	250		11.4	250
	13.3	240		13.3	240		13.3	240
	19.1	240		19.1	240		19.1	240
	20.7	250		20.7	250		20.7	250
3892	2.6	400	3973	2.6	400	4062	2.6	400
	3.6	350		3.6	350		3.6	350
	4.9	300		4.9	300		4.9	300
	7.0	280		7.0	280		7.0	280
	9.2	260		9.2	260		9.2	260
	11.6	250		11.6	250		11.6	250
	13.5	240		13.5	240		13.5	240
	18.4	240		18.4	240		18.4	240
	19.7	250		19.7	250		19.7	250
	21.1	260		21.1	260		21.1	260
4140	2.6	400	4227	2.6	400	4321	2.6	400
	3.7	350		3.7	350		3.7	350
	5.1	300		5.1	300		5.1	300
	7.1	280		7.1	280		7.1	280
	9.5	260		9.5	260		9.5	260
	11.8	250		11.8	250		11.8	250
	13.8	240		13.8	240		13.8	240
	17.3	240		17.3	240		17.3	240
	19.0	250		19.0	250		19.0	250
	20.4	260		20.4	260		20.4	260
4379	2.6	400	4470	2.6	400	4570	2.6	400
	3.7	350		3.7	350		3.7	350
	5.3	300		5.3	300		5.3	300
	7.5	280		7.5	280		7.5	280
	9.8	260		9.8	260		9.8	260
	12.2	250		12.2	250		12.2	250
	15.4	240		15.4	240		15.4	240
	17.7	250		17.7	250		17.7	250
	19.5	260		19.5	260		19.5	260
4629	2.7	400	4725	2.7	400	4831	2.7	400
	3.7	350		3.7	350		3.7	350
	5.5	300		5.5	300		5.5	300
	7.8	280		7.8	280		7.8	280
	10.3	260		10.3	260		10.3	260
	18.4	260		18.4	260		18.4	260
	21.3	280		21.3	280		21.3	280
4873	2.8	400	4974	2.8	400	5085	2.8	400
	3.8	350		3.8	350		3.8	350
	5.6	300		5.6	300		5.6	300
	8.3	280		8.3	280		8.3	280
	12.3	260		12.3	260		12.3	260
	19.5	280		19.5	280		19.5	280
5103	2.8	400	5210	2.8	400	5326	2.8	400
	3.8	350		3.8	350		3.8	350
	5.9	300		5.9	300		5.9	300
	9.3	280		9.3	280		9.3	280
	17.7	280		17.7	280		17.7	280
5340	2.9	400	5451	2.9	400	5573	2.9	400
	3.8	350		3.8	350		3.8	350
	7.1	300		7.1	300		7.1	300
	14.1	280		14.1	280		14.1	280
	18.4	300		18.4	300		18.4	300
5584	2.9	400	5700	2.9	400	5827	2.9	400
	3.9	350		3.9	350		3.9	350
	8.1	300		8.1	300		8.1	300
	16.9	300		16.9	300		16.9	300
5827	2.9	400	5948	2.9	400	6081	2.9	400
	4.0	350		4.0	350		4.0	350
	12.4	300		12.4	300		12.4	300
	14.6	300		14.6	300		14.6	300
6074	3.0	400	6201	3.0	400	6339	3.0	400
	4.4	350		4.4	350		4.4	350
6305	3.3	400	6436	3.3	400	6580	3.3	400
	5.1	350		5.1	350		5.1	350

Table SI4.4.19. SE mass-configurations - Parameters affected by SE: *Specific FC* (*cons*) (GT case study n°9)

SE mass-configurations - Parameters affected by SE *Specific FC* (*cons*) (GT case study n°17)								
Reference			**SE 10%**			**SE 20%**		
rpm [rpm]	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**
1025	2.3	400	1051	2.3	400	1080	2.3	400
	3.3	350		3.3	350		3.3	350
	4.6	300		4.6	300		4.6	300
	6.6	280		6.6	280		6.6	280
1188	2.2	400	1218	2.2	400	1252	2.2	400
	3.3	350		3.3	350		3.3	350
	4.6	300		4.6	300		4.6	300
	6.0	280		6.0	280		6.0	280
	8.2	260		8.2	260		8.2	260
	15.2	260		15.2	260		15.2	260
1397	2.1	400	1433	2.1	400	1472	2.1	400
	3.2	350		3.2	350		3.2	350
	4.5	300		4.5	300		4.5	300
	5.9	280		5.9	280		5.9	280
	7.4	260		7.4	260		7.4	260
	11.6	250		11.6	250		11.6	250
	15.2	250		15.2	250		15.2	250
1615	2.0	400	1656	2.0	400	1702	2.0	400
	3.2	350		3.2	350		3.2	350
	4.6	300		4.6	300		4.6	300
	6.0	280		6.0	280		6.0	280
	7.5	260		7.5	260		7.5	260
	9.9	250		9.9	250		9.9	250
	13.9	240		13.9	240		13.9	240
1833	2.0	400	1880	2.0	400	1932	2.0	400
	3.3	350		3.3	350		3.3	350
	4.7	300		4.7	300		4.7	300
	5.9	280		5.9	280		5.9	280
	7.5	260		7.5	260		7.5	260
	9.8	250		9.8	250		9.8	250
	12.2	240		12.2	240		12.2	240
	18.1	240		18.1	240		18.1	240
2032	2.0	400	2085	2.0	400	2142	2.0	400
	3.3	350		3.3	350		3.3	350
	4.7	300		4.7	300		4.7	300
	6.0	280		6.0	280		6.0	280
	7.7	260		7.7	260		7.7	260
	9.8	250		9.8	250		9.8	250
	11.9	240		11.9	240		11.9	240
	19.1	240		19.1	240		19.1	240
2240	2.1	400	2298	2.1	400	2361	2.1	400
	3.3	350		3.3	350		3.3	350
	4.7	300		4.7	300		4.7	300
	6.0	280		6.0	280		6.0	280
	7.9	260		7.9	260		7.9	260
	10.0	250		10.0	250		10.0	250
	12.1	240		12.1	240		12.1	240
	20.5	240		20.5	240		20.5	240
2447	2.3	400	2510	2.3	400	2579	2.3	400
	3.4	350		3.4	350		3.4	350
	4.8	300		4.8	300		4.8	300
	6.2	280		6.2	280		6.2	280
	8.1	260		8.1	260		8.1	260
	10.2	250		10.2	250		10.2	250
	12.4	240		12.4	240		12.4	240
	20.5	240		20.5	240		20.5	240
2651	2.4	400	2720	2.4	400	2795	2.4	400
	3.6	350		3.6	350		3.6	350
	4.7	300		4.7	300		4.7	300
	6.2	280		6.2	280		6.2	280
	8.4	260		8.4	260		8.4	260
	10.5	250		10.5	250		10.5	250
	12.7	240		12.7	240		12.7	240
	20.1	240		20.1	240		20.1	240
2849	2.4	400	2922	2.4	400	3003	2.4	400
	3.6	350		3.6	350		3.6	350
	4.7	300		4.7	300		4.7	300
	6.3	280		6.3	280		6.3	280
	8.6	260		8.6	260		8.6	260
	10.6	250		10.6	250		10.6	250
	12.8	240		12.8	240		12.8	240
	19.8	240		19.8	240		19.8	240
3055	2.5	400	3134	2.5	400	3221	2.5	400
	3.6	350		3.6	350		3.6	350
	4.7	300		4.7	300		4.7	300
	6.6	280		6.6	280		6.6	280
	8.8	260		8.8	260		8.8	260
	11.1	250		11.1	250		11.1	250
	13.1	240		13.1	240		13.1	240
	19.5	240		19.5	240		19.5	240
	21.2	250		21.2	250		21.2	250
3251	2.4	400	3334	2.4	400	3427	2.4	400
	3.6	350		3.6	350		3.6	350
	4.8	300		4.8	300		4.8	300
	6.7	280		6.7	280		6.7	280
	9.0	260		9.0	260		9.0	260
	11.3	250		11.3	250		11.3	250
	13.2	240		13.2	240		13.2	240
	18.9	240		18.9	240		18.9	240
	20.5	250		20.5	250		20.5	250
3461	2.6	400	3550	2.6	400	3648	2.6	400
	3.6	350		3.6	350		3.6	350
	4.9	300		4.9	300		4.9	300
	6.9	280		6.9	280		6.9	280
	9.1	260		9.1	260		9.1	260
	11.5	250		11.5	250		11.5	250
	13.4	240		13.4	240		13.4	240
	18.2	240		18.2	240		18.2	240
	19.5	250		19.5	250		19.5	250
	20.8	260		20.8	260		20.8	260
3672	2.6	400	3766	2.6	400	3870	2.6	400
	3.6	350		3.6	350		3.6	350
	5.1	300		5.1	300		5.1	300
	7.0	280		7.0	280		7.0	280
	9.4	260		9.4	260		9.4	260
	11.7	250		11.7	250		11.7	250
	13.7	240		13.7	240		13.7	240
	17.2	240		17.2	240		17.2	240
	18.8	250		18.8	250		18.8	250
	20.2	260		20.2	260		20.2	260
3875	2.6	400	3975	2.6	400	4084	2.6	400
	3.7	350		3.7	350		3.7	350
	5.2	300		5.2	300		5.2	300
	7.5	280		7.5	280		7.5	280
	9.7	260		9.7	260		9.7	260
	12.1	250		12.1	250		12.1	250
	15.2	240		15.2	240		15.2	240
	17.6	250		17.6	250		17.6	250
	19.3	260		19.3	260		19.3	260
4087	2.7	400	4192	2.7	400	4308	2.7	400
	3.7	350		3.7	350		3.7	350
	5.4	300		5.4	300		5.4	300
	7.7	280		7.7	280		7.7	280
	10.2	260		10.2	260		10.2	260
	18.2	260		18.2	260		18.2	260
	21.1	280		21.1	280		21.1	280
4295	2.8	400	4405	2.8	400	4527	2.8	400
	3.8	350		3.8	350		3.8	350
	5.6	300		5.6	300		5.6	300
	8.2	280		8.2	280		8.2	280
	12.2	260		12.2	260		12.2	260
	19.3	280		19.3	280		19.3	280
4491	2.7	400	4606	2.7	400	4734	2.7	400
	3.8	350		3.8	350		3.8	350
	5.8	300		5.8	300		5.8	300
	9.2	280		9.2	280		9.2	280
	17.5	280		17.5	280		17.5	280
4692	2.9	400	4813	2.9	400	4946	2.9	400
	3.8	350		3.8	350		3.8	350
	7.0	300		7.0	300		7.0	300
	14.0	280		14.0	280		14.0	280
	18.2	300		18.2	300		18.2	300
4900	2.8	400	5026	2.8	400	5165	2.8	400
	3.9	350		3.9	350		3.9	350
	8.0	300		8.0	300		8.0	300
	16.7	300		16.7	300		16.7	300
5106	2.8	400	5238	2.8	400	5383	2.8	400
	4.0	350		4.0	350		4.0	350
	12.2	300		12.2	300		12.2	300
	14.4	300		14.4	300		14.4	300
5316	2.9	400	5453	2.9	400	5604	2.9	400
	4.4	350		4.4	350		4.4	350
5513	3.3	400	5655	3.3	400	5811	3.3	400
	5.1	350		5.1	350		5.1	350

Table SI4.4.20. SE mass-configurations - Parameters affected by SE: *Specific FC* (*cons*) (GT case study n°17)

SE mass-configurations - Parameters affected by SE *Specific FC* (*cons*) - GT case study n°28								
Reference			SE 10%			SE 20%		
rpm [rpm]	BMEP [bar]	*cons* [g/kWh]	rpm [rpm]	BMEP [bar]	*cons* [g/kWh]	rpm [rpm]	BMEP [bar]	*cons* [g/kWh]
1029	2.1	400	1048	2.1	400	1069	2.1	400
	3.2	350		3.2	350		3.2	350
	4.3	300		4.3	300		4.3	300
	6.2	280		6.2	280		6.2	280
1227	2.1	400	1251	2.1	400	1275	2.1	400
	3.1	350		3.1	350		3.1	350
	4.3	300		4.3	300		4.3	300
	5.7	280		5.7	280		5.7	280
	7.8	260		7.8	260		7.8	260
	14.4	260		14.4	260		14.4	260
1482	2.0	400	1510	2.0	400	1540	2.0	400
	3.0	350		3.0	350		3.0	350
	4.2	300		4.2	300		4.2	300
	5.6	280		5.6	280		5.6	280
	7.0	260		7.0	260		7.0	260
	11.0	250		11.0	250		11.0	250
	14.4	250		14.4	250		14.4	250
1748	1.9	400	1781	1.9	400	1817	1.9	400
	3.0	350		3.0	350		3.0	350
	4.4	300		4.4	300		4.4	300
	5.7	280		5.7	280		5.7	280
	7.1	260		7.1	260		7.1	260
	9.4	250		9.4	250		9.4	250
	13.2	240		13.2	240		13.2	240
2014	1.9	400	2052	1.9	400	2093	1.9	400
	3.1	350		3.1	350		3.1	350
	4.4	300		4.4	300		4.4	300
	5.6	280		5.6	280		5.6	280
	7.1	260		7.1	260		7.1	260
	9.3	250		9.3	250		9.3	250
	11.6	240		11.6	240		11.6	240
	17.2	240		17.2	240		17.2	240
2258	1.9	400	2300	1.9	400	2346	1.9	400
	3.1	350		3.1	350		3.1	350
	4.5	300		4.5	300		4.5	300
	5.7	280		5.7	280		5.7	280
	7.3	260		7.3	260		7.3	260
	9.3	250		9.3	250		9.3	250
	11.3	240		11.3	240		11.3	240
	18.1	240		18.1	240		18.1	240
2511	2.0	400	2559	2.0	400	2610	2.0	400
	3.2	350		3.2	350		3.2	350
	4.4	300		4.4	300		4.4	300
	5.7	280		5.7	280		5.7	280
	7.5	260		7.5	260		7.5	260
	9.5	250		9.5	250		9.5	250
	11.5	240		11.5	240		11.5	240
	19.5	240		19.5	240		19.5	240
2764	2.1	400	2816	2.1	400	2872	2.1	400
	3.3	350		3.3	350		3.3	350
	4.5	300		4.5	300		4.5	300
	5.8	280		5.8	280		5.8	280
	7.7	260		7.7	260		7.7	260
	9.7	250		9.7	250		9.7	250
	11.8	240		11.8	240		11.8	240
	19.4	240		19.4	240		19.4	240
3013	2.2	400	3070	2.2	400	3131	2.2	400
	3.4	350		3.4	350		3.4	350
	4.4	300		4.4	300		4.4	300
	5.9	280		5.9	280		5.9	280
	8.0	260		8.0	260		8.0	260
	9.9	250		9.9	250		9.9	250
	12.0	240		12.0	240		12.0	240
	19.1	240		19.1	240		19.1	240
3254	2.3	400	3315	2.3	400	3381	2.3	400
	3.4	350		3.4	350		3.4	350
	4.5	300		4.5	300		4.5	300
	6.0	280		6.0	280		6.0	280
	8.1	260		8.1	260		8.1	260
	10.0	250		10.0	250		10.0	250
	12.1	240		12.1	240		12.1	240
	18.8	240		18.8	240		18.8	240
3506	2.3	400	3572	2.3	400	3643	2.3	400
	3.5	350		3.5	350		3.5	350
	4.5	300		4.5	300		4.5	300
	6.2	280		6.2	280		6.2	280
	8.3	260		8.3	260		8.3	260
	10.5	250		10.5	250		10.5	250
	12.4	240		12.4	240		12.4	240
	18.5	240		18.5	240		18.5	240
	20.1	250		20.1	250		20.1	250
3744	2.3	400	3815	2.3	400	3891	2.3	400
	3.4	350		3.4	350		3.4	350
	4.6	300		4.6	300		4.6	300
	6.3	280		6.3	280		6.3	280
	8.6	260		8.6	260		8.6	260
	10.7	250		10.7	250		10.7	250
	12.5	240		12.5	240		12.5	240
	17.9	240		17.9	240		17.9	240
	19.5	250		19.5	250		19.5	250
4000	2.4	400	4075	2.4	400	4156	2.4	400
	3.4	350		3.4	350		3.4	350
	4.6	300		4.6	300		4.6	300
	6.6	280		6.6	280		6.6	280
	8.7	260		8.7	260		8.7	260
	10.9	250		10.9	250		10.9	250
	12.7	240		12.7	240		12.7	240
	17.3	240		17.3	240		17.3	240
	18.5	250		18.5	250		18.5	250
	19.8	260		19.8	260		19.8	260
4258	2.4	400	4338	2.4	400	4424	2.4	400
	3.5	350		3.5	350		3.5	350
	4.8	300		4.8	300		4.8	300
	6.6	280		6.6	280		6.6	280
	8.9	260		8.9	260		8.9	260
	11.1	250		11.1	250		11.1	250
	13.0	240		13.0	240		13.0	240
	16.3	240		16.3	240		16.3	240
	17.8	250		17.8	250		17.8	250
	19.1	260		19.1	260		19.1	260
4506	2.5	400	4590	2.5	400	4682	2.5	400
	3.5	350		3.5	350		3.5	350
	5.0	300		5.0	300		5.0	300
	7.1	280		7.1	280		7.1	280
	9.2	260		9.2	260		9.2	260
	11.5	250		11.5	250		11.5	250
	14.5	240		14.5	240		14.5	240
	16.7	250		16.7	250		16.7	250
	18.3	260		18.3	260		18.3	260
4765	2.5	400	4854	2.5	400	4951	2.5	400
	3.5	350		3.5	350		3.5	350
	5.1	300		5.1	300		5.1	300
	7.3	280		7.3	280		7.3	280
	9.7	260		9.7	260		9.7	260
	17.3	260		17.3	260		17.3	260
	20.0	280		20.0	280		20.0	280
5018	2.6	400	5112	2.6	400	5214	2.6	400
	3.6	350		3.6	350		3.6	350
	5.3	300		5.3	300		5.3	300
	7.8	280		7.8	280		7.8	280
	11.5	260		11.5	260		11.5	260
	18.3	280		18.3	280		18.3	280
5257	2.6	400	5356	2.6	400	5463	2.6	400
	3.6	350		3.6	350		3.6	350
	5.5	300		5.5	300		5.5	300
	8.8	280		8.8	280		8.8	280
	16.6	280		16.6	280		16.6	280
5502	2.7	400	5606	2.7	400	5718	2.7	400
	3.6	350		3.6	350		3.6	350
	6.7	300		6.7	300		6.7	300
	13.3	280		13.3	280		13.3	280
	17.3	300		17.3	300		17.3	300
5756	2.7	400	5864	2.7	400	5981	2.7	400
	3.7	350		3.7	350		3.7	350
	7.6	300		7.6	300		7.6	300
	15.8	300		15.8	300		15.8	300
6008	2.7	400	6121	2.7	400	6243	2.7	400
	3.8	350		3.8	350		3.8	350
	11.6	300		11.6	300		11.6	300
	13.7	300		13.7	300		13.7	300
6264	2.8	400	6382	2.8	400	6509	2.8	400
	4.2	350		4.2	350		4.2	350
6504	3.1	400	6627	3.1	400	6758	3.1	400
	4.8	350		4.8	350		4.8	350

Table SI4.4.21. SE mass-configurations - Parameters affected by SE: *Specific FC* (*cons*) (GT case study n°28)

SE mass-configurations - Parameters affected by SE *Specific FC* (*cons*) - DT case study n°7								
Reference			**SE 10%**			**SE 20%**		
rpm [rpm]	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**
1011	1.1	360	1035	1.1	360	1062	1.1	360
	3.3	260		3.3	260		3.3	260
	4.6	240		4.6	240		4.6	240
	6.1	230		6.1	230		6.1	230
1207	1.0	360	1236	1.0	360	1267	1.0	360
	3.2	260		3.2	260		3.2	260
	4.4	240		4.4	240		4.4	240
	5.5	230		5.5	230		5.5	230
	8.8	220		8.8	220		8.8	220
	13.5	220		13.5	220		13.5	220
1410	0.9	360	1444	0.9	360	1480	0.9	360
	3.2	260		3.2	260		3.2	260
	4.3	240		4.3	240		4.3	240
	5.5	230		5.5	230		5.5	230
	7.4	220		7.4	220		7.4	220
	14.0	210		14.0	210		14.0	210
	17.0	210		17.0	210		17.0	210
1597	1.0	360	1635	1.0	360	1677	1.0	360
	3.2	260		3.2	260		3.2	260
	4.3	240		4.3	240		4.3	240
	5.8	230		5.8	230		5.8	230
	8.1	220		8.1	220		8.1	220
	12.1	210		12.1	210		12.1	210
1794	1.0	360	1837	1.0	360	1884	1.0	360
	3.3	260		3.3	260		3.3	260
	4.6	240		4.6	240		4.6	240
	6.4	230		6.4	230		6.4	230
	9.2	220		9.2	220		9.2	220
	12.4	210		12.4	210		12.4	210
	16.4	200		16.4	200		16.4	200
	19.8	200		19.8	200		19.8	200
2000	1.0	360	2048	1.0	360	2100	1.0	360
	3.6	260		3.6	260		3.6	260
	5.4	240		5.4	240		5.4	240
	7.0	230		7.0	230		7.0	230
	8.0	220		8.0	220		8.0	220
	9.2	210		9.2	210		9.2	210
	14.7	200		14.7	200		14.7	200
	17.0	196		17.0	196		17.0	196
2212	1.1	360	2265	1.1	360	2323	1.1	360
	4.0	260		4.0	260		4.0	260
	6.0	240		6.0	240		6.0	240
	6.9	230		6.9	230		6.9	230
	7.8	220		7.8	220		7.8	220
	9.2	210		9.2	210		9.2	210
	16.0	200		16.0	200		16.0	200
	20.1	200		20.1	200		20.1	200
2417	2.2	360	2474	2.2	360	2537	2.2	360
	4.0	260		4.0	260		4.0	260
	5.0	240		5.0	240		5.0	240
	5.8	230		5.8	230		5.8	230
	7.1	220		7.1	220		7.1	220
	8.6	210		8.6	210		8.6	210
	13.2	200		13.2	200		13.2	200
	18.0	200		18.0	200		18.0	200
2617	2.3	360	2680	2.3	360	2748	2.3	360
	3.9	260		3.9	260		3.9	260
	5.0	240		5.0	240		5.0	240
	5.7	230		5.7	230		5.7	230
	6.8	220		6.8	220		6.8	220
	8.6	210		8.6	210		8.6	210
2813	2.1	360	2881	2.1	360	2954	2.1	360
	4.0	260		4.0	260		4.0	260
	5.1	240		5.1	240		5.1	240
	5.8	230		5.8	230		5.8	230
	6.9	220		6.9	220		6.9	220
	9.0	210		9.0	210		9.0	210
3014	2.0	360	3086	2.0	360	3165	2.0	360
	4.1	260		4.1	260		4.1	260
	5.2	240		5.2	240		5.2	240
	6.1	230		6.1	230		6.1	230
	7.6	220		7.6	220		7.6	220
	10.4	210		10.4	210		10.4	210
	16.1	210		16.1	210		16.1	210
3203	2.1	360	3280	2.1	360	3363	2.1	360
	4.4	260		4.4	260		4.4	260
	5.5	240		5.5	240		5.5	240
	6.6	230		6.6	230		6.6	230
	8.6	220		8.6	220		8.6	220
	16.2	220		16.2	220		16.2	220
3396	2.2	360	3478	2.2	360	3566	2.2	360
	4.7	260		4.7	260		4.7	260
	6.2	240		6.2	240		6.2	240
	7.5	230		7.5	230		7.5	230
	10.7	220		10.7	220		10.7	220
	13.9	220		13.9	220		13.9	220
3604	2.2	360	3690	2.2	360	3784	2.2	360
	4.9	260		4.9	260		4.9	260
	6.9	240		6.9	240		6.9	240
	9.0	230		9.0	230		9.0	230
	14.2	230		14.2	230		14.2	230
3813	2.4	360	3904	2.4	360	4004	2.4	360
	5.7	260		5.7	260		5.7	260
	8.7	240		8.7	240		8.7	240

Table SI4.4.22. SE mass-configurations - Parameters affected by SE : *Specific FC* (*cons*) (DT case study n°7)

SE mass-configurations - Parameters affected by SE *Specific FC* (*cons*) (DT case study n°21)								
Reference			**SE 10%**			**SE 20%**		
rpm [rpm]	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**
1011	1.3	360	1035	1.3	360	1060	1.3	360
	3.7	260		3.7	260		3.7	260
	5.2	240		5.2	240		5.2	240
	6.9	230		6.9	230		6.9	230
1213	1.1	360	1242	1.1	360	1273	1.1	360
	3.6	260		3.6	260		3.6	260
	5.0	240		5.0	240		5.0	240
	6.2	230		6.2	230		6.2	230
	9.9	220		9.9	220		9.9	220
	15.2	220		15.2	220		15.2	220
1424	1.0	360	1457	1.0	360	1493	1.0	360
	3.6	260		3.6	260		3.6	260
	4.9	240		4.9	240		4.9	240
	6.2	230		6.2	230		6.2	230
	8.4	220		8.4	220		8.4	220
	15.8	210		15.8	210		15.8	210
	19.2	210		19.2	210		19.2	210
1617	1.1	360	1655	1.1	360	1696	1.1	360
	3.6	260		3.6	260		3.6	260
	4.9	240		4.9	240		4.9	240
	6.5	230		6.5	230		6.5	230
	9.1	220		9.1	220		9.1	220
	13.6	210		13.6	210		13.6	210
1821	1.1	360	1863	1.1	360	1910	1.1	360
	3.7	260		3.7	260		3.7	260
	5.2	240		5.2	240		5.2	240
	7.2	230		7.2	230		7.2	230
	10.4	220		10.4	220		10.4	220
	13.9	210		13.9	210		13.9	210
	18.5	200		18.5	200		18.5	200
	22.3	200		22.3	200		22.3	200
2034	1.1	360	2081	1.1	360	2133	1.1	360
	4.1	260		4.1	260		4.1	260
	6.1	240		6.1	240		6.1	240
	7.9	230		7.9	230		7.9	230
	8.9	220		8.9	220		8.9	220
	10.3	210		10.3	210		10.3	210
	16.6	200		16.6	200		16.6	200
	19.2	196		19.2	196		19.2	196
2253	1.2	360	2306	1.2	360	2363	1.2	360
	4.5	260		4.5	260		4.5	260
	6.8	240		6.8	240		6.8	240
	7.7	230		7.7	230		7.7	230
	8.7	220		8.7	220		8.7	220
	10.4	210		10.4	210		10.4	210
	18.0	200		18.0	200		18.0	200
	22.6	200		22.6	200		22.6	200
2464	2.5	360	2522	2.5	360	2585	2.5	360
	4.5	260		4.5	260		4.5	260
	5.6	240		5.6	240		5.6	240
	6.5	230		6.5	230		6.5	230
	7.9	220		7.9	220		7.9	220
	9.7	210		9.7	210		9.7	210
	14.8	200		14.8	200		14.8	200
	20.2	200		20.2	200		20.2	200
2672	2.6	360	2734	2.6	360	2802	2.6	360
	4.4	260		4.4	260		4.4	260
	5.6	240		5.6	240		5.6	240
	6.4	230		6.4	230		6.4	230
	7.6	220		7.6	220		7.6	220
	9.6	210		9.6	210		9.6	210
2875	2.3	360	2942	2.3	360	3015	2.3	360
	4.5	260		4.5	260		4.5	260
	5.7	240		5.7	240		5.7	240
	6.5	230		6.5	230		6.5	230
	7.8	220		7.8	220		7.8	220
	10.2	210		10.2	210		10.2	210
3082	2.2	360	3154	2.2	360	3233	2.2	360
	4.6	260		4.6	260		4.6	260
	5.8	240		5.8	240		5.8	240
	6.8	230		6.8	230		6.8	230
	8.5	220		8.5	220		8.5	220
	11.7	210		11.7	210		11.7	210
	18.1	210		18.1	210		18.1	210
3278	2.4	360	3354	2.4	360	3438	2.4	360
	4.9	260		4.9	260		4.9	260
	6.2	240		6.2	240		6.2	240
	7.4	230		7.4	230		7.4	230
	9.6	220		9.6	220		9.6	220
	18.2	220		18.2	220		18.2	220
3477	2.5	360	3558	2.5	360	3647	2.5	360
	5.3	260		5.3	260		5.3	260
	6.9	240		6.9	240		6.9	240
	8.4	230		8.4	230		8.4	230
	12.0	220		12.0	220		12.0	220
	15.6	220		15.6	220		15.6	220
3692	2.5	360	3778	2.5	360	3872	2.5	360
	5.5	260		5.5	260		5.5	260
	7.7	240		7.7	240		7.7	240
	10.2	230		10.2	230		10.2	230
	15.9	230		15.9	230		15.9	230
3908	2.7	360	3999	2.7	360	4099	2.7	360
	6.4	260		6.4	260		6.4	260
	9.8	240		9.8	240		9.8	240

Table SI4.4.23. SE mass-configurations - Parameters affected by SE : *Specific FC* (*cons*) (DT case study n°21)

SE mass-configurations - Parameters affected by SE *Specific FC* (*cons*) (DT case study n°31)								
Reference			**SE 10%**			**SE 20%**		
rpm [rpm]	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**	**rpm [rpm]**	**BMEP [bar]**	***cons* [g/kWh]**
1011	1.2	360	1031	1.2	360	1053	1.2	360
	3.6	260		3.6	260		3.6	260
	5.1	240		5.1	240		5.1	240
	6.7	230		6.7	230		6.7	230
1235	1.1	360	1260	1.1	360	1287	1.1	360
	3.5	260		3.5	260		3.5	260
	4.8	240		4.8	240		4.8	240
	6.1	230		6.1	230		6.1	230
	9.7	220		9.7	220		9.7	220
	14.8	220		14.8	220		14.8	220
1467	1.0	360	1497	1.0	360	1529	1.0	360
	3.5	260		3.5	260		3.5	260
	4.7	240		4.7	240		4.7	240
	6.1	230		6.1	230		6.1	230
	8.1	220		8.1	220		8.1	220
	15.4	210		15.4	210		15.4	210
	18.6	210		18.6	210		18.6	210
1681	1.1	360	1715	1.1	360	1752	1.1	360
	3.5	260		3.5	260		3.5	260
	4.7	240		4.7	240		4.7	240
	6.4	230		6.4	230		6.4	230
	8.9	220		8.9	220		8.9	220
	13.2	210		13.2	210		13.2	210
1906	1.1	360	1945	1.1	360	1987	1.1	360
	3.6	260		3.6	260		3.6	260
	5.1	240		5.1	240		5.1	240
	7.0	230		7.0	230		7.0	230
	10.1	220		10.1	220		10.1	220
	13.6	210		13.6	210		13.6	210
	18.0	200		18.0	200		18.0	200
	21.7	200		21.7	200		21.7	200
2142	1.1	360	2185	1.1	360	2232	1.1	360
	4.0	260		4.0	260		4.0	260
	5.9	240		5.9	240		5.9	240
	7.7	230		7.7	230		7.7	230
	8.7	220		8.7	220		8.7	220
	10.0	210		10.0	210		10.0	210
	16.1	200		16.1	200		16.1	200
	18.6	196		18.6	196		18.6	196
2384	1.2	360	2433	1.2	360	2484	1.2	360
	4.4	260		4.4	260		4.4	260
	6.6	240		6.6	240		6.6	240
	7.5	230		7.5	230		7.5	230
	8.5	220		8.5	220		8.5	220
	10.1	210		10.1	210		10.1	210
	17.5	200		17.5	200		17.5	200
	22.0	200		22.0	200		22.0	200
2618	2.4	360	2671	2.4	360	2728	2.4	360
	4.4	260		4.4	260		4.4	260
	5.5	240		5.5	240		5.5	240
	6.4	230		6.4	230		6.4	230
	7.7	220		7.7	220		7.7	220
	9.5	210		9.5	210		9.5	210
	14.4	200		14.4	200		14.4	200
	19.7	200		19.7	200		19.7	200
2847	2.5	360	2905	2.5	360	2967	2.5	360
	4.3	260		4.3	260		4.3	260
	5.4	240		5.4	240		5.4	240
	6.2	230		6.2	230		6.2	230
	7.4	220		7.4	220		7.4	220
	9.4	210		9.4	210		9.4	210
3071	2.3	360	3134	2.3	360	3200	2.3	360
	4.3	260		4.3	260		4.3	260
	5.6	240		5.6	240		5.6	240
	6.4	230		6.4	230		6.4	230
	7.6	220		7.6	220		7.6	220
	9.9	210		9.9	210		9.9	210
3301	2.2	360	3368	2.2	360	3440	2.2	360
	4.5	260		4.5	260		4.5	260
	5.7	240		5.7	240		5.7	240
	6.6	230		6.6	230		6.6	230
	8.3	220		8.3	220		8.3	220
	11.4	210		11.4	210		11.4	210
	17.6	210		17.6	210		17.6	210
3517	2.3	360	3588	2.3	360	3665	2.3	360
	4.8	260		4.8	260		4.8	260
	6.1	240		6.1	240		6.1	240
	7.2	230		7.2	230		7.2	230
	9.4	220		9.4	220		9.4	220
	17.7	220		17.7	220		17.7	220
3738	2.4	360	3814	2.4	360	3895	2.4	360
	5.1	260		5.1	260		5.1	260
	6.8	240		6.8	240		6.8	240
	8.2	230		8.2	230		8.2	230
	11.7	220		11.7	220		11.7	220
	15.2	220		15.2	220		15.2	220
3975	2.4	360	4055	2.4	360	4142	2.4	360
	5.4	260		5.4	260		5.4	260
	7.5	240		7.5	240		7.5	240
	9.9	230		9.9	230		9.9	230
	15.5	230		15.5	230		15.5	230
4214	2.6	360	4299	2.6	360	4391	2.6	360
	6.2	260		6.2	260		6.2	260
	9.5	240		9.5	240		9.5	240

Table SI4.4.24. SE mass-configurations - Parameters affected by SE: *Specific FC* (*cons*) (DT case study n°31)

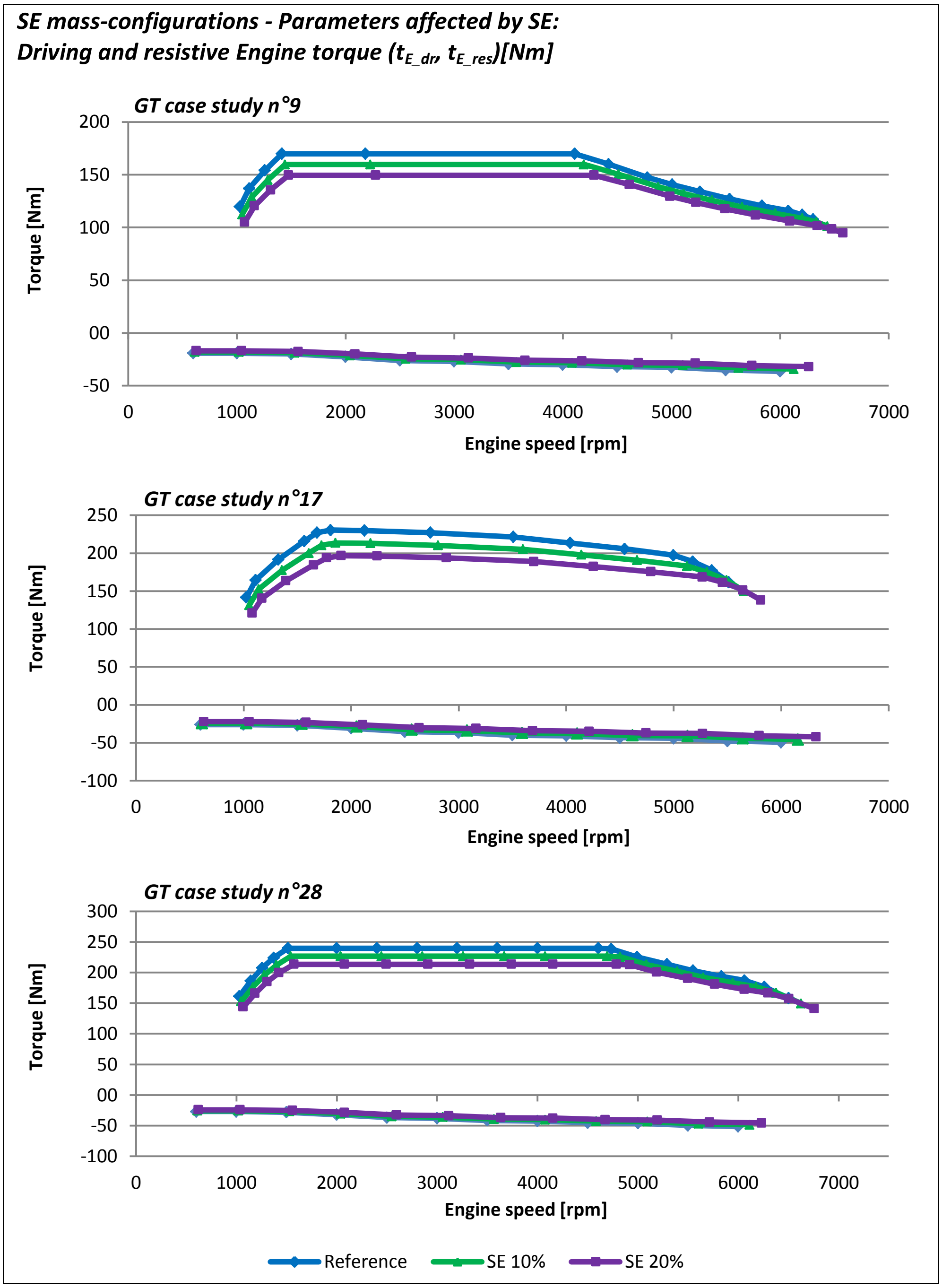


Figure SI4.4.25. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) of GT case studies n°9,17,28 (Reference, SE10% and SE20%)

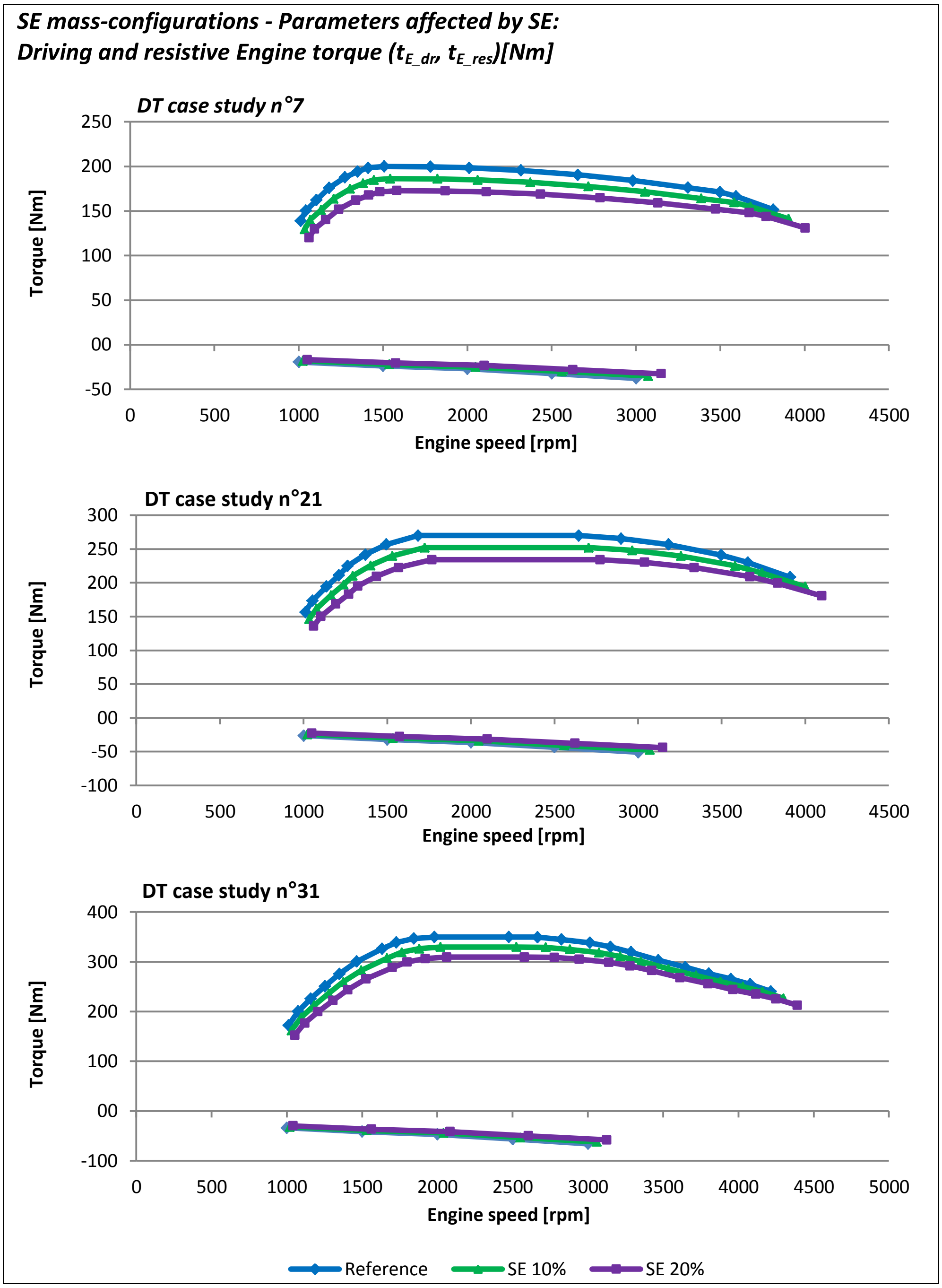


Figure SI4.4.26. SE mass-configurations - Parameters affected by SE: *Driving* and *resistive Engine torque* (t_{E_dr}, t_{E_res}) of DT case studies n°7,21,31 (Reference, SE10% and SE20%)

SI 4.5. Analytical modelling

For each vehicle case study the elasticity 80-120 km/h ($t_{80\text{-}120km/h}$) of reference mass-configuration in the upper gear ratio is determined. Below the calculation procedure is described in detail.
The first point is the modelling of

- force required to drive the wheels;
- vehicle velocity.

This is performed basing on the torque diagram of reference mass-configuration (2D look-up table “rpm-torque”).
The force required to drive the wheels is calculated from the engine torque considering the overall transmission ratio and the efficiency of drive train as well as wheel radius:

$$F_{dr} = \frac{t_{E\_dr} * \alpha_{G\_upper} * \alpha_f * \eta_{G\_upper} * \eta_f}{R_w}$$

Where:
F_{dr} = Force required to drive the wheels [N];
t_{E_dr} = driving engine torque [Nm];
α_{G_upper} = upper Gear ratio [null];
α_f = final transmission ratio [null];
η_{G_upper} = efficiency of upper Gear ratio [null];
η_f = efficiency of final transmission ratio [null];
R_w = wheel radius [m].

Vehicle velocity (v_{veh}) is determined from engine speed (ω_E) considering wheel radius and overall transmission ratio of drive train:

$$v_{veh} = \frac{2\pi * R_w * \omega_E}{60 * \left(\alpha_{upper\_gear} * \alpha_f\right)}$$

Where:
v_{veh} = vehicle velocity [m/s];
ω_E = Engine speed [rpm].

As torque diagram of reference mass-configuration is provided through a 2D look-up table (rpm-torque) of dimension n, F_{dr} and v_{veh} are vectors of dimension n.
The second point is the interpolation of F_{dr} over the range of velocity 80-120 [km/h] with a certain interpolation step. This is performed by

- defining a vector V whose components are the values of velocity between 22.22 and 33.33 [m/s] with an interpolation step of 0.1 [m/s];
- interpolating F_D over the components of vector V.

The third point is the calculation of vehicle acceleration (a_{veh}) for each value of velocity identified by components of *V* through following equations:

$$a_{veh} = \frac{F_{dr\_i} - F_{res\_i}}{m_{veh}}$$

$$F_{res} = F_{aero} + F_{roll} = (0.5 * \rho_{air} * C_D * A_D * {v_{veh}}^2) + (f_S * m_{veh} * g + f_D * m_{veh} * g * {v_{veh}}^2)$$

Where:
a_{veh} = vehicle acceleration [m/s^2];
F_{dr_i} = Force required to drive the wheels interpolated over component *i* of *V* [N];
F_{res_i} = total resistance Force over component *i* of *V* [N];
F_{aero} = aerodynamic drag Force [N];
F_{roll} = rolling friction Force [N];
ρ_{air} = air density [kg/m^3];
C_D = aerodynamic Drag Coefficient [null];
A_D = active Area for aerodynamic Drag [m^2];
f_S = Static friction coefficient [null];
f_D = Dynamic friction coefficient [1/(m/s)];
m_{veh} = vehicle mass [kg];
g = gravitational acceleration [m/s^2].

Finally the time to pass from 80 to 120 km/h is determined through expressions above:

$$t_{(80-120\ km/h)} = \frac{33.33 - 22.22}{a_{av}}$$

$$a_{av} = \frac{1}{(33.33 - 22.22)} * \int_{22.22}^{33.33} a_{veh} * dv$$

Where:
a_{av} = average vehicle acceleration in the range of velocity 80-120 km/h [m/s^2].

The calculation procedure described above has been implemented through the MATLAB software. The MATLAB file adopted for calculating elasticity 80-120 km/h is reported in the CD attached to the thesis (“folder “SE mass-configurations – Elasticity 80-120 km/h”).

SI appendix - chapter 5

	***Fuel consumption (FC)* [l/100km] (GT A/B-class)**																			
	Reference mass-configuration				**PMR mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
1	5.08	5.14	5.22	5.58	4.97	5.05	5.12	5.49	4.86	4.95	5.03	5.40	4.75	4.85	4.94	5.30	4.65	4.76	4.85	5.21
2	4.92	5.07	5.10	5.29	4.83	4.98	5.02	5.21	4.74	4.89	4.93	5.13	4.65	4.8	4.85	5.05	4.56	4.71	4.76	4.97
3	5.56	5.70	5.72	5.82	5.48	5.61	5.63	5.74	5.39	5.52	5.55	5.65	5.30	5.44	5.46	5.57	5.22	5.35	5.37	5.49
4	6.44	6.55	6.55	6.62	6.34	6.45	6.47	6.53	6.24	6.36	6.38	6.44	6.14	6.27	6.29	6.34	6.04	6.17	6.21	6.25
5	4.71	4.75	4.89	5.32	4.61	4.67	4.82	5.24	4.52	4.59	4.74	5.16	4.43	4.51	4.66	5.08	4.34	4.43	4.57	5.01
6	4.73	4.82	4.89	5.30	4.63	4.73	4.81	5.23	4.54	4.65	4.74	5.15	4.45	4.56	4.65	5.07	4.37	4.48	4.56	4.99
7	4.94	5.02	5.14	5.53	4.84	4.93	5.05	5.44	4.74	4.84	4.96	5.35	4.64	4.74	4.88	5.26	4.54	4.65	4.79	5.17
8	5.83	5.95	6.07	6.34	5.73	5.85	5.98	6.24	5.63	5.76	5.88	6.15	5.53	5.66	5.79	6.05	5.42	5.57	5.70	5.96
9	5.03	5.20	5.25	5.47	4.94	5.11	5.16	5.40	4.85	5.02	5.08	5.32	4.77	4.94	5.00	5.24	4.68	4.85	4.92	5.16
10	5.01	5.18	5.23	5.47	4.92	5.09	5.14	5.39	4.84	5.01	5.06	5.31	4.75	4.93	4.98	5.23	4.67	4.84	4.90	5.16

Table SI5.1.1. Fuel consumption of reference and PMR mass-configurations [l/100km] (GT A/B-class case studies)

	***Fuel consumption (FC)* [l/100km] (GT C-class)**																			
	Reference mass-configuration				**PMR mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
11	6.16	6.31	6.32	6.70	6.04	6.20	6.22	6.59	5.93	6.09	6.11	6.49	5.82	5.99	6.01	6.39	5.71	5.88	5.91	6.28
12	6.43	6.51	6.49	6.91	6.31	6.40	6.39	6.80	6.20	6.30	6.30	6.68	6.08	6.19	6.19	6.57	5.97	6.09	6.08	6.46
13	5.38	5.52	5.57	5.79	5.28	5.42	5.48	5.70	5.18	5.33	5.39	5.6	5.09	5.23	5.30	5.51	4.99	5.13	5.21	5.42
14	6.55	6.61	6.59	6.69	6.44	6.52	6.50	6.59	6.33	6.42	6.40	6.49	6.23	6.32	6.31	6.39	6.13	6.22	6.21	6.29
15	6.60	6.70	6.65	6.75	6.49	6.61	6.55	6.64	6.38	6.52	6.46	6.54	6.28	6.42	6.36	6.45	6.18	6.32	6.27	6.35
16	6.05	6.16	6.18	6.55	5.94	6.06	6.08	6.44	5.82	5.96	5.98	6.33	5.71	5.85	5.88	6.23	5.60	5.75	5.77	6.13
17	6.48	6.62	6.62	6.98	6.37	6.51	6.52	6.87	6.26	6.41	6.42	6.77	6.15	6.31	6.32	6.67	6.04	6.21	6.23	6.57
18	5.43	5.56	5.67	5.95	5.32	5.45	5.57	5.86	5.22	5.35	5.47	5.77	5.11	5.24	5.38	5.67	5.01	5.14	5.29	5.58
19	5.48	5.59	5.72	6.02	5.37	5.49	5.62	5.92	5.27	5.38	5.52	5.82	5.16	5.28	5.42	5.73	5.06	5.17	5.32	5.64
20	6.45	6.57	6.60	6.80	6.34	6.47	6.50	6.69	6.23	6.36	6.39	6.59	6.12	6.27	6.29	6.49	6.02	6.17	6.19	6.39
21	6.46	6.57	6.60	6.79	6.36	6.46	6.50	6.68	6.25	6.36	6.40	6.58	6.15	6.26	6.30	6.47	6.04	6.15	6.20	6.37

Table SI5.1.2. Fuel consumption of reference and PMR mass-configurations [l/100km] (GT C-class case studies)

	***Fuel consumption (FC)* [l/100km] (GT D-class)**																			
	Reference mass-configuration				**PMR mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
22	6.51	6.67	6.58	6.63	6.39	6.55	6.46	6.50	6.26	6.42	6.35	6.37	6.14	6.30	6.23	6.25	6.02	6.17	6.12	6.13
23	7.90	7.89	7.65	7.41	7.73	7.74	7.51	7.29	7.55	7.60	7.38	7.16	7.40	7.47	7.25	7.03	7.25	7.34	7.12	6.91
24	6.37	6.52	6.43	6.47	6.24	6.40	6.31	6.35	6.12	6.27	6.20	6.23	6.00	6.15	6.09	6.12	5.88	6.03	5.97	6.00
25	7.45	7.60	7.52	7.45	7.33	7.48	7.41	7.33	7.20	7.36	7.30	7.21	7.07	7.24	7.19	7.09	6.95	7.12	7.09	6.98
26	6.83	6.90	6.94	7.03	6.70	6.77	6.82	6.91	6.58	6.64	6.71	6.78	6.45	6.52	6.59	6.66	6.33	6.40	6.47	6.54
27	5.76	5.87	5.96	6.25	5.64	5.75	5.85	6.14	5.52	5.63	5.74	6.03	5.40	5.51	5.63	5.92	5.28	5.39	5.51	5.81
28	6.64	6.78	6.67	6.65	6.51	6.63	6.55	6.54	6.38	6.48	6.42	6.43	6.26	6.36	6.30	6.31	6.14	6.23	6.17	6.20
29	8.43	8.56	8.51	8.30	8.28	8.42	8.38	8.17	8.13	8.28	8.25	8.04	7.98	8.15	8.13	7.91	7.83	8.02	8.01	7.78
30	8.51	8.63	8.59	8.32	8.35	8.49	8.46	8.18	8.19	8.35	8.33	8.05	8.04	8.22	8.20	7.92	7.89	8.09	8.08	7.79
31	6.58	6.71	6.52	6.52	6.46	6.58	6.40	6.41	6.34	6.46	6.29	6.30	6.23	6.34	6.18	6.18	6.11	6.23	6.07	6.07
32	7.46	7.52	7.28	7.18	7.31	7.39	7.16	7.05	7.17	7.26	7.04	6.93	7.04	7.14	6.92	6.81	6.91	7.02	6.80	6.68

Table SI5.1.3. Fuel consumption of reference and PMR mass-configurations [l/100km] (GT D-class case studies)

	***Fuel consumption (FC)* [l/100km] (GT A/B-class)**																			
	Reference mass-configuration				**SE mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
1	5.08	5.14	5.22	5.58	4.93	4.99	5.06	5.43	4.77	4.83	4.91	5.29	4.60	4.68	4.76	5.14	4.43	4.52	4.61	5.00
2	4.92	5.07	5.10	5.29	4.76	4.92	4.96	5.16	4.60	4.77	4.81	5.03	4.45	4.62	4.67	4.90	4.30	4.47	4.52	4.77
3	5.56	5.70	5.72	5.82	5.38	5.54	5.55	5.67	5.20	5.37	5.39	5.51	5.02	5.19	5.22	5.36	4.85	5.02	5.05	5.21
4	6.44	6.55	6.55	6.62	6.22	6.34	6.34	6.44	6.01	6.13	6.13	6.25	5.79	5.91	5.93	6.07	5.57	5.70	5.72	5.88
5	4.71	4.75	4.89	5.32	4.58	4.63	4.77	5.21	4.46	4.52	4.65	5.11	4.33	4.40	4.54	5.00	4.21	4.28	4.44	4.89
6	4.73	4.82	4.89	5.30	4.58	4.68	4.76	5.18	4.44	4.55	4.63	5.06	4.30	4.41	4.51	4.93	4.16	4.28	4.38	4.81
7	4.94	5.02	5.14	5.53	4.79	4.88	5.01	5.40	4.65	4.74	4.88	5.27	4.49	4.60	4.74	5.13	4.34	4.46	4.61	5.00
8	5.83	5.95	6.07	6.34	5.63	5.76	5.88	6.17	5.44	5.57	5.69	6.01	5.25	5.39	5.51	5.84	5.05	5.20	5.32	5.67
9	5.03	5.20	5.25	5.47	4.87	5.05	5.11	5.35	4.72	4.89	4.96	5.22	4.56	4.74	4.82	5.09	4.41	4.59	4.68	4.96
10	5.01	5.18	5.23	5.47	4.85	5.03	5.08	5.34	4.70	4.87	4.94	5.21	4.55	4.72	4.79	5.08	4.39	4.57	4.65	4.95

Table SI5.1.4. Fuel consumption of reference and SE mass-configurations [l/100km] (GT A/B-class case studies)

	***Fuel consumption (FC)* [l/100km] (GT C-class)**																			
	Reference mass-configuration				**SE mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
11	6.16	6.31	6.32	6.70	5.95	6.10	6.11	6.50	5.74	5.89	5.90	6.31	5.53	5.69	5.71	6.12	5.32	5.49	5.53	5.93
12	6.43	6.51	6.49	6.91	6.21	6.30	6.28	6.70	5.99	6.09	6.07	6.50	5.78	5.88	5.87	6.31	5.56	5.68	5.67	6.11
13	5.38	5.52	5.57	5.79	5.21	5.35	5.41	5.64	5.03	5.19	5.24	5.49	4.86	5.02	5.08	5.34	4.69	4.85	4.92	5.19
14	6.55	6.61	6.59	6.69	6.32	6.40	6.38	6.49	6.09	6.20	6.17	6.30	5.87	5.99	5.96	6.11	5.65	5.77	5.75	5.92
15	6.60	6.70	6.65	6.75	6.37	6.50	6.44	6.55	6.14	6.29	6.23	6.35	5.91	6.07	6.02	6.16	5.69	5.86	5.82	5.96
16	6.05	6.16	6.18	6.55	5.84	5.96	5.98	6.36	5.63	5.76	5.77	6.17	5.43	5.57	5.59	5.98	5.22	5.37	5.40	5.80
17	6.48	6.62	6.62	6.98	6.26	6.41	6.41	6.78	6.04	6.19	6.19	6.57	5.81	5.96	5.97	6.36	5.57	5.72	5.75	6.15
18	5.43	5.56	5.67	5.95	5.25	5.39	5.50	5.80	5.07	5.22	5.32	5.64	4.90	5.05	5.16	5.49	4.72	4.88	5.00	5.33
19	5.48	5.59	5.72	6.02	5.30	5.42	5.55	5.86	5.13	5.25	5.37	5.71	4.96	5.09	5.22	5.55	4.78	4.92	5.06	5.40
20	6.45	6.57	6.60	6.80	6.22	6.35	6.38	6.61	5.98	6.13	6.17	6.41	5.76	5.91	5.95	6.22	5.53	5.70	5.74	6.03
21	6.46	6.57	6.60	6.79	6.23	6.35	6.39	6.59	6.00	6.13	6.17	6.40	5.78	5.91	5.96	6.21	5.56	5.69	5.74	6.02

Table SI5.1.5. Fuel consumption of reference and SE mass-configurations [l/100km] (GT C-class case studies)

	***Fuel consumption (FC)* [l/100km] (GT D-class)**																			
	Reference mass-configuration				**SE mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
22	6.51	6.67	6.58	6.63	6.27	6.44	6.36	6.41	6.03	6.20	6.14	6.20	5.79	5.97	5.91	5.99	5.55	5.75	5.69	5.78
23	7.90	7.89	7.65	7.41	7.56	7.59	7.36	7.17	7.21	7.30	7.08	6.92	6.90	7.02	6.80	6.68	6.59	6.73	6.53	6.44
24	6.37	6.52	6.43	6.47	6.14	6.30	6.21	6.26	5.90	6.07	6.00	6.06	5.68	5.85	5.79	5.86	5.45	5.63	5.57	5.66
25	7.45	7.60	7.52	7.45	7.17	7.33	7.26	7.21	6.89	7.06	6.99	6.97	6.62	6.80	6.73	6.73	6.35	6.53	6.48	6.49
26	6.83	6.90	6.94	7.03	6.57	6.66	6.71	6.81	6.31	6.41	6.48	6.59	6.06	6.18	6.25	6.38	5.80	5.94	6.02	6.17
27	5.76	5.87	5.96	6.25	5.56	5.68	5.78	6.08	5.37	5.49	5.59	5.90	5.18	5.31	5.42	5.73	4.99	5.12	5.25	5.56
28	6.64	6.78	6.67	6.65	6.40	6.53	6.45	6.46	6.17	6.29	6.23	6.27	5.95	6.07	6.03	6.09	5.73	5.85	5.82	5.90
29	8.43	8.56	8.51	8.30	8.09	8.25	8.20	8.06	7.75	7.93	7.89	7.81	7.43	7.62	7.58	7.56	7.11	7.32	7.28	7.32
30	8.51	8.63	8.59	8.32	8.17	8.31	8.27	8.07	7.83	7.99	7.94	7.82	7.50	7.68	7.64	7.57	7.17	7.37	7.33	7.33
31	6.58	6.71	6.52	6.52	6.34	6.47	6.29	6.32	6.09	6.24	6.07	6.12	5.86	6.01	5.85	5.92	5.63	5.78	5.64	5.72
32	7.46	7.52	7.28	7.18	7.16	7.25	7.02	6.94	6.86	6.97	6.75	6.70	6.58	6.71	6.50	6.47	6.30	6.45	6.25	6.25

Table SI5.1.6. Fuel consumption of reference and SE mass-configurations [l/100km] (GT D-class case studies)

	***Fuel consumption (FC)* [l/100km] (DT A/B-class)**																			
	Reference mass-configuration				**PMR mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
1	4.76	4.87	4.80	4.94	4.66	4.78	4.71	4.86	4.56	4.68	4.62	4.77	4.46	4.59	4.54	4.69	4.36	4.49	4.46	4.61
2	3.60	3.71	3.72	3.82	3.52	3.64	3.65	3.77	3.44	3.57	3.58	3.71	3.36	3.50	3.50	3.65	3.28	3.42	3.43	3.59
3	4.44	4.53	4.48	4.69	4.34	4.44	4.39	4.60	4.24	4.35	4.31	4.52	4.14	4.26	4.22	4.43	4.04	4.17	4.14	4.35
4	3.64	3.77	3.77	3.95	3.57	3.70	3.71	3.90	3.50	3.63	3.64	3.84	3.43	3.56	3.58	3.79	3.36	3.49	3.51	3.73
5	3.64	3.79	3.81	3.95	3.57	3.71	3.74	3.89	3.50	3.64	3.66	3.83	3.43	3.57	3.59	3.77	3.36	3.49	3.52	3.71
6	3.74	3.87	3.89	4.08	3.66	3.79	3.82	4.01	3.58	3.71	3.75	3.95	3.51	3.63	3.68	3.89	3.44	3.56	3.61	3.83
7	3.93	4.05	3.99	4.23	3.85	3.97	3.92	4.16	3.76	3.88	3.85	4.10	3.68	3.80	3.78	4.04	3.61	3.72	3.71	3.97
8	3.93	4.06	4.04	4.33	3.85	3.98	3.97	4.27	3.77	3.90	3.90	4.20	3.69	3.82	3.83	4.14	3.61	3.74	3.76	4.08
9	3.62	3.77	3.79	3.99	3.55	3.70	3.72	3.93	3.48	3.63	3.65	3.86	3.40	3.56	3.58	3.80	3.33	3.49	3.52	3.73
10	3.72	3.87	3.87	4.12	3.65	3.80	3.80	4.05	3.57	3.73	3.73	3.99	3.50	3.66	3.66	3.92	3.42	3.59	3.59	3.85

Table SI5.1.7. Fuel consumption of reference and PMR mass-configurations [l/100km] (DT A/B-class case studies)

	***Fuel consumption (FC)* [l/100km] (DT C-class)**																			
	Reference mass-configuration				**PMR mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
11	4.88	5.00	4.92	5.05	4.77	4.90	4.83	4.96	4.67	4.80	4.74	4.87	4.56	4.70	4.65	4.78	4.46	4.60	4.56	4.70
12	5.32	5.45	5.36	5.41	5.21	5.35	5.26	5.31	5.09	5.24	5.16	5.21	4.98	5.14	5.07	5.12	4.87	5.04	4.98	5.03
13	5.14	5.29	5.24	5.34	5.03	5.18	5.14	5.25	4.93	5.08	5.05	5.16	4.82	4.98	4.96	5.07	4.72	4.88	4.86	4.98
14	4.13	4.27	4.24	4.43	4.04	4.19	4.16	4.35	3.95	4.10	4.08	4.27	3.86	4.02	4.00	4.19	3.78	3.94	3.92	4.12
15	4.40	4.52	4.48	4.56	4.30	4.44	4.39	4.48	4.20	4.35	4.31	4.40	4.11	4.26	4.22	4.33	4.02	4.17	4.14	4.25
16	4.98	5.16	5.02	5.07	4.87	5.06	4.92	4.98	4.76	4.96	4.82	4.89	4.66	4.86	4.72	4.80	4.55	4.76	4.62	4.71
17	4.74	4.84	4.73	4.86	4.64	4.74	4.64	4.77	4.53	4.65	4.55	4.68	4.43	4.55	4.46	4.60	4.33	4.45	4.38	4.51
18	4.84	4.95	4.88	4.98	4.73	4.84	4.79	4.90	4.63	4.74	4.70	4.81	4.52	4.64	4.61	4.73	4.42	4.55	4.51	4.64
19	5.29	5.45	5.35	5.39	5.18	5.33	5.25	5.29	5.06	5.22	5.14	5.19	4.94	5.11	5.05	5.09	4.83	5.01	4.95	5.00
20	4.50	4.63	4.52	4.70	4.40	4.54	4.44	4.62	4.30	4.44	4.35	4.54	4.21	4.35	4.27	4.46	4.12	4.26	4.19	4.38
21	4.58	4.70	4.62	4.76	4.48	4.60	4.52	4.67	4.37	4.50	4.42	4.59	4.27	4.41	4.34	4.51	4.17	4.31	4.25	4.42
22	5.16	5.31	5.16	5.25	5.04	5.20	5.05	5.15	4.92	5.10	4.95	5.05	4.81	4.99	4.84	4.96	4.69	4.89	4.73	4.86

Table SI5.1.8. Fuel consumption of reference and PMR mass-configurations [l/100km] (DT C-class case studies)

	***Fuel consumption (FC)* [l/100km] (DT D-class)**																			
	Reference mass-configuration				**PMR mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
23	5.16	5.30	5.13	5.11	5.03	5.18	5.02	5.01	4.89	5.07	4.91	4.90	4.77	4.95	4.81	4.80	4.65	4.84	4.70	4.70
24	5.73	5.78	5.57	5.47	5.56	5.65	5.45	5.34	5.40	5.51	5.33	5.21	5.26	5.39	5.22	5.11	5.11	5.26	5.11	5.00
25	5.77	5.83	5.66	5.52	5.60	5.69	5.54	5.40	5.43	5.56	5.42	5.29	5.29	5.44	5.30	5.18	5.16	5.31	5.19	5.06
26	6.25	6.24	6.04	5.95	6.08	6.11	5.92	5.83	5.90	5.98	5.80	5.70	5.73	5.85	5.69	5.58	5.56	5.73	5.57	5.46
27	4.66	4.80	4.73	4.85	4.54	4.69	4.63	4.76	4.43	4.59	4.53	4.66	4.32	4.48	4.43	4.57	4.21	4.37	4.32	4.47
28	5.33	5.51	5.39	5.47	5.20	5.39	5.26	5.36	5.07	5.26	5.14	5.24	4.94	5.14	5.03	5.13	4.81	5.01	4.91	5.01
29	5.45	5.61	5.47	5.53	5.31	5.48	5.35	5.41	5.17	5.35	5.24	5.28	5.04	5.22	5.12	5.17	4.90	5.10	5.00	5.06
30	4.76	4.89	4.83	4.92	4.65	4.78	4.73	4.83	4.54	4.67	4.62	4.73	4.42	4.57	4.52	4.64	4.31	4.46	4.42	4.54
31	5.44	5.55	5.40	5.39	5.29	5.43	5.29	5.28	5.14	5.30	5.17	5.17	5.01	5.18	5.06	5.07	4.88	5.06	4.94	4.96
32	5.92	6.00	5.82	5.68	5.75	5.86	5.70	5.55	5.59	5.72	5.57	5.42	5.45	5.60	5.45	5.31	5.30	5.47	5.33	5.19

Table SI5.1.9. Fuel consumption of reference and PMR mass-configurations [l/100km] (DT D-class case studies)

	***Fuel consumption (FC)* [l/100km] (DT A/B-class)**																			
	Reference mass-configuration				**SE mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
1	4.76	4.87	4.80	4.94	4.59	4.71	4.64	4.79	4.42	4.55	4.48	4.65	4.25	4.38	4.33	4.50	4.08	4.22	4.18	4.36
2	3.60	3.71	3.72	3.82	3.48	3.60	3.62	3.75	3.37	3.49	3.52	3.68	3.26	3.38	3.42	3.61	3.15	3.27	3.32	3.53
3	4.44	4.53	4.48	4.69	4.27	4.38	4.33	4.56	4.10	4.22	4.18	4.44	3.95	4.06	4.03	4.31	3.79	3.90	3.88	4.18
4	3.64	3.77	3.77	3.95	3.52	3.66	3.67	3.85	3.40	3.54	3.56	3.75	3.29	3.43	3.46	3.65	3.17	3.32	3.35	3.55
5	3.64	3.79	3.81	3.95	3.52	3.67	3.70	3.86	3.40	3.55	3.59	3.78	3.29	3.44	3.48	3.69	3.17	3.32	3.38	3.61
6	3.74	3.87	3.89	4.08	3.61	3.74	3.78	3.97	3.49	3.62	3.67	3.86	3.37	3.50	3.56	3.76	3.25	3.38	3.44	3.66
7	3.93	4.05	3.99	4.23	3.79	3.92	3.87	4.11	3.66	3.78	3.76	3.99	3.53	3.66	3.64	3.87	3.40	3.53	3.53	3.75
8	3.93	4.06	4.04	4.33	3.79	3.93	3.92	4.21	3.65	3.79	3.80	4.09	3.52	3.67	3.68	3.97	3.39	3.54	3.57	3.85
9	3.62	3.77	3.79	3.99	3.51	3.66	3.68	3.91	3.40	3.55	3.57	3.83	3.29	3.44	3.47	3.74	3.18	3.33	3.38	3.66
10	3.72	3.87	3.87	4.12	3.60	3.76	3.76	4.03	3.49	3.65	3.66	3.94	3.38	3.53	3.55	3.84	3.26	3.42	3.44	3.75

Table SI5.1.10. Fuel consumption of reference and SE mass-configurations [l/100km] (DT A/B-class case studies)

	***Fuel consumption (FC)* [l/100km] (DT C-class)**																			
	Reference mass-configuration				**SE mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
11	4.88	5.00	4.92	5.05	4.71	4.84	4.77	4.91	4.53	4.67	4.62	4.77	4.38	4.52	4.48	4.65	4.22	4.37	4.34	4.52
12	5.32	5.45	5.36	5.41	5.14	5.28	5.19	5.25	4.95	5.10	5.03	5.09	4.77	4.92	4.86	4.95	4.59	4.75	4.70	4.81
13	5.14	5.29	5.24	5.34	4.96	5.11	5.07	5.18	4.78	4.93	4.90	5.03	4.60	4.76	4.73	4.88	4.41	4.58	4.56	4.73
14	4.13	4.27	4.24	4.43	3.98	4.13	4.11	4.31	3.84	3.99	3.98	4.19	3.70	3.85	3.85	4.08	3.57	3.71	3.71	3.96
15	4.40	4.52	4.48	4.56	4.25	4.38	4.35	4.44	4.10	4.24	4.21	4.33	3.95	4.09	4.08	4.21	3.80	3.95	3.95	4.09
16	4.98	5.16	5.02	5.07	4.80	4.99	4.86	4.94	4.62	4.83	4.70	4.81	4.45	4.66	4.54	4.67	4.28	4.49	4.38	4.54
17	4.74	4.84	4.73	4.86	4.54	4.65	4.56	4.70	4.33	4.47	4.39	4.54	4.17	4.32	4.25	4.40	4.02	4.16	4.11	4.27
18	4.84	4.95	4.88	4.98	4.65	4.77	4.72	4.84	4.47	4.59	4.56	4.69	4.31	4.44	4.41	4.56	4.15	4.30	4.27	4.43
19	5.29	5.45	5.35	5.39	5.10	5.26	5.17	5.23	4.91	5.08	4.99	5.06	4.72	4.89	4.82	4.92	4.53	4.71	4.65	4.77
20	4.50	4.63	4.52	4.70	4.33	4.47	4.38	4.57	4.17	4.32	4.23	4.44	4.00	4.16	4.09	4.31	3.84	4.01	3.95	4.18
21	4.58	4.70	4.62	4.76	4.42	4.55	4.48	4.64	4.27	4.40	4.34	4.52	4.10	4.24	4.19	4.40	3.94	4.09	4.05	4.28
22	5.16	5.31	5.16	5.25	4.97	5.13	4.99	5.10	4.77	4.96	4.82	4.96	4.59	4.78	4.67	4.82	4.41	4.61	4.51	4.68

Table SI5.1.11. Fuel consumption of reference and SE mass-configurations [l/100km] (DT C-class case studies)

	***Fuel consumption (FC)* [l/100km] (DT D-class)**																			
	Reference mass-configuration				**SE mass-configurations**															
					5%				**10%**				**15%**				**20%**			
Case study	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
23	5.16	5.30	5.13	5.11	4.95	5.11	4.95	4.96	4.74	4.92	4.77	4.80	4.54	4.74	4.60	4.65	4.35	4.55	4.42	4.50
24	5.73	5.78	5.57	5.47	5.48	5.57	5.37	5.29	5.23	5.36	5.18	5.10	5.02	5.16	5.00	4.94	4.81	4.97	4.82	4.79
25	5.77	5.83	5.66	5.52	5.52	5.61	5.46	5.34	5.26	5.40	5.26	5.15	5.04	5.20	5.07	5.00	4.83	4.99	4.87	4.84
26	6.25	6.24	6.04	5.95	5.96	6.01	5.83	5.74	5.67	5.78	5.62	5.53	5.41	5.56	5.41	5.33	5.15	5.34	5.20	5.13
27	4.66	4.80	4.73	4.85	4.48	4.63	4.57	4.71	4.31	4.45	4.40	4.57	4.13	4.28	4.24	4.43	3.96	4.10	4.07	4.29
28	5.33	5.51	5.39	5.47	5.12	5.31	5.19	5.30	4.92	5.10	5.00	5.14	4.73	4.91	4.82	4.98	4.54	4.71	4.63	4.82
29	5.45	5.61	5.47	5.53	5.22	5.40	5.28	5.35	5.00	5.19	5.09	5.18	4.79	4.99	4.89	5.01	4.58	4.78	4.70	4.84
30	4.76	4.89	4.83	4.92	4.58	4.72	4.66	4.78	4.39	4.54	4.50	4.64	4.22	4.36	4.33	4.50	4.04	4.19	4.17	4.36
31	5.44	5.55	5.40	5.39	5.24	5.37	5.24	5.28	5.03	5.19	5.08	5.17	4.82	4.99	4.89	4.98	4.61	4.80	4.71	4.79
32	5.92	6.00	5.82	5.68	5.67	5.78	5.62	5.49	5.43	5.56	5.43	5.30	5.21	5.36	5.23	5.15	4.98	5.15	5.04	5.00

Table SI5.1.12. Fuel consumption of reference and SE mass-configurations [l/100km] (DT D-class case studies)

SI appendix – Chapter 6

SI 6.1. Fuel Consumption

		Fuel consumption (FC) [l/100km] - Analysis per vehicle class and driving cycle																			
		A/B-class					**C-class**					**D-class**					**All classes**				
		Minimum	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**
GT	**FTP72**	4.71	6.44	1.73	5.22	0.55	5.38	6.60	1.22	6.13	0.48	5.76	8.51	2.75	7.13	0.89	4.71	8.51	3.80	6.19	1.02
	JC08	4.75	6.55	1.80	5.34	0.56	5.52	6.70	1.19	6.25	0.47	5.87	8.63	2.76	7.24	0.87	4.75	8.63	3.88	6.30	1.01
	NEDC	4.89	6.55	1.66	5.41	0.54	5.57	6.65	1.08	6.27	0.42	5.96	8.59	2.63	7.15	0.85	4.89	8.59	3.69	6.30	0.94
	WLTC	5.29	6.62	1.33	5.68	0.46	5.79	6.98	1.19	6.54	0.42	6.25	8.32	2.07	7.11	0.71	5.29	8.32	3.03	6.47	0.79
DT	**FTP72**	3.60	4.76	1.16	3.90	0.39	4.13	5.32	1.20	4.83	0.38	4.66	6.25	1.59	5.45	0.50	4.71	8.51	3.80	6.19	1.02
	JC08	3.71	4.87	1.16	4.03	0.38	4.27	5.45	1.18	4.96	0.38	4.80	6.24	1.44	5.55	0.46	4.75	8.63	3.88	6.30	1.01
	NEDC	3.72	4.80	1.08	4.02	0.35	4.24	5.36	1.12	4.88	0.36	4.73	6.04	1.31	5.40	0.41	4.89	8.59	3.69	6.30	0.94
	WLTC	3.82	4.94	1.12	4.21	0.36	4.43	5.41	0.98	4.98	0.33	4.85	5.95	1.10	5.39	0.34	5.29	8.32	3.03	6.47	0.79

Table SI6.1.1. Fuel consumption of reference configuration [l/100km]: analysis per vehicle class and driving cycle in terms of minimum and maximum, size of range max-min, arithmetic mean and standard deviation

		Fuel consumption S&S system (FC$_{S\&S}$) **[l/100km] (GT case studies n°9, 17, 28)**																			
		Reference mass-configuration				**PMR mass-configurations**															
						5%				**10%**				**15%**				**20%**			
Class	**Case study**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**9**	4.85	4.74	5.02	5.37	4.77	4.66	4.94	5.29	4.68	4.57	4.85	5.21	4.59	4.48	4.77	5.13	4.51	4.40	4.69	5.05
C	**17**	6.29	6.10	6.36	6.86	6.17	5.99	6.26	6.75	6.06	5.89	6.16	6.64	5.95	5.79	6.06	6.54	5.84	5.68	5.97	6.44
D	**28**	6.43	6.23	6.40	6.52	6.30	6.08	6.27	6.41	6.18	5.94	6.15	6.30	6.05	5.81	6.02	6.19	5.93	5.68	5.90	6.07

Table SI6.1.2. Fuel consumption of reference and PMR mass-configurations with S&S system [l/100km] (GT case studies n°9, 17, 28)

		Fuel consumption S&S system (FC$_{S\&S}$) **[l/100km] (GT case studies n°9, 17, 28)**																			
		Reference mass-configuration				**SE mass-configurations**															
						5%				**10%**				**15%**				**20%**			
Class	**Case study**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**9**	4.85	4.74	5.02	5.37	4.70	4.60	4.88	5.24	4.55	4.45	4.74	5.12	4.40	4.30	4.60	4.99	4.25	4.16	4.46	4.86
C	**17**	6.29	6.10	6.36	6.86	6.07	5.89	6.15	6.66	5.85	5.69	5.94	6.45	5.62	5.46	5.72	6.24	5.39	5.23	5.50	6.03
D	**28**	6.43	6.23	6.40	6.52	6.20	5.99	6.19	6.34	5.97	5.76	5.97	6.15	5.75	5.55	5.77	5.96	5.53	5.33	5.56	5.78

Table SI6.1.3. Fuel consumption of reference and SE mass-configurations with S&S system [l/100km] (GT case studies n°9, 17, 28)

		***Fuel consumption S&S system ($FC_{S\&S}$)* [l/100km] (DT case studies n°7, 21, 31)**																			
		Reference mass-configuration				**PMR mass-configurations**															
						5%				**10%**				**15%**				**20%**			
Class	**Case study**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**7**	3.83	3.75	3.85	4.16	3.75	3.66	3.78	4.09	3.66	3.58	3.71	4.03	3.58	3.50	3.64	3.97	3.51	3.42	3.57	3.90
C	**21**	4.47	4.37	4.47	4.68	4.37	4.27	4.37	4.60	4.26	4.17	4.27	4.51	4.16	4.08	4.18	4.43	4.06	3.98	4.09	4.35
D	**31**	5.32	5.17	5.23	5.30	5.17	5.04	5.11	5.19	5.01	4.92	4.99	5.08	4.88	4.80	4.88	4.98	4.75	4.68	4.77	4.87

Table SI6.1.4. Fuel consumption of reference and PMR mass-configurations with S&S system [l/100km] (DT case studies n°7, 21, 31)

		***Fuel consumption S&S system ($FC_{S\&S}$)* [l/100km] (DT case studies n°7, 21, 31)**																			
		Reference mass-configuration				**SE mass-configurations**															
						5%				**10%**				**15%**				**20%**			
Class	**Case study**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**7**	3.83	3.75	3.85	4.16	3.69	3.62	3.74	4.04	3.56	3.49	3.62	3.92	3.43	3.37	3.51	3.80	3.30	3.25	3.40	3.68
C	**21**	4.47	4.37	4.47	4.68	4.32	4.22	4.33	4.56	4.16	4.08	4.19	4.45	4.00	3.93	4.05	4.32	3.84	3.78	3.91	4.20
D	**31**	5.32	5.17	5.23	5.30	5.11	4.99	5.07	5.19	4.90	4.82	4.91	5.08	4.70	4.63	4.73	4.90	4.49	4.44	4.54	4.71

Table SI6.1.5. Fuel consumption of reference and SE mass-configurations with S&S system [l/100km] (DT case studies n°7, 21, 31)

			***Fuel consumption (FC)* [l/100km] – Sensitivity analysis based on *Coulomb friction coefficient f* (GT case studies n°9, 17, 28)**															
			Reference mass-configuration				**PMR mass-configurations**											
							5%				**10%**				**15%**			**20%**
Class	**Case study**	***f***	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**9**	0.007	4.80	4.97	5.02	5.22	4.72	4.89	4.95	5.15	4.65	4.81	4.88	5.08	4.57	4.74	4.80	5.01
		0.013	5.25	5.42	5.49	5.73	5.15	5.33	5.39	5.64	5.06	5.23	5.29	5.55	4.96	5.14	5.20	5.47
C	**17**	0.007	6.21	6.34	6.36	6.68	6.11	6.25	6.28	6.59	6.01	6.15	6.20	6.49	5.91	6.06	6.11	6.40
		0.013	6.77	6.91	6.92	7.29	6.64	6.79	6.80	7.17	6.52	6.67	6.68	7.05	6.39	6.55	6.57	6.93
D	**28**	0.007	6.33	6.46	6.36	6.32	6.22	6.34	6.25	6.22	6.10	6.21	6.14	6.12	5.99	6.09	6.03	6.01
		0.013	6.95	7.09	6.99	6.99	6.81	6.94	6.85	6.86	6.67	6.78	6.71	6.74	6.53	6.64	6.57	6.62

			20%			
Class	**Case study**	***f***	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**9**	0.007	4.50	4.66	4.73	4.95
		0.013	4.87	5.05	5.10	5.38
C	**17**	0.007	5.81	5.98	6.03	6.31
		0.013	6.27	6.44	6.45	6.82
D	**28**	0.007	5.88	5.97	5.92	5.90
		0.013	6.39	6.50	6.43	6.49

Table SI6.1.6. Sensitivity analysis based on *Coulomb friction coefficient f* - Fuel consumption of reference and PMR mass-configuration for *f* = 0.007 and *f* = 0.010 [l/100km] (GT case studies n°9, 17, 28)

			***Fuel consumption (FC)* [l/100km] – Sensitivity analysis based on *Coulomb friction coefficient f* (GT case studies n°9, 17, 28)**																			
			Reference mass-configuration				**SE mass-configurations**															
							5%				**10%**				**15%**				**20%**			
Class	**Case study**	***f***	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**9**	0.007	4.80	4.97	5.02	5.22	4.66	4.83	4.89	5.10	4.51	4.69	4.76	4.99	4.37	4.55	4.63	4.87	4.23	4.41	4.49	4.76
		0.013	5.25	5.42	5.49	5.73	5.09	5.26	5.33	5.59	4.92	5.10	5.18	5.45	4.76	4.94	5.03	5.31	4.60	4.78	4.87	5.18
C	**17**	0.007	6.21	6.34	6.36	6.68	6.00	6.14	6.16	6.49	5.79	5.94	5.96	6.30	5.57	5.72	5.74	6.10	5.35	5.50	5.53	5.90
		0.013	6.77	6.91	6.92	7.29	6.53	6.68	6.69	7.07	6.30	6.45	6.47	6.85	6.05	6.20	6.23	6.63	5.80	5.95	5.99	6.40
D	**28**	0.007	6.33	6.46	6.36	6.32	6.11	6.24	6.16	6.15	5.89	6.02	5.95	5.98	5.73	5.87	5.81	5.82	5.56	5.71	5.67	5.66
		0.013	6.95	7.09	6.99	6.99	6.70	6.83	6.75	6.79	6.44	6.57	6.51	6.58	6.21	6.34	6.29	6.38	5.98	6.11	6.07	6.18

Table SI6.1.7. Sensitivity analysis based on *Coulomb friction coefficient f* - Fuel consumption of reference and SE mass-configuration for *f* = 0.007 and *f* = 0.010 [l/100km] (GT case studies n°9, 17, 28)

			***Fuel consumption (FC)* [l/100km] – Sensitivity analysis based on *Coulomb friction coefficient f* (DT case studies n°7, 21, 31)**																			
			Reference mass-configuration				**PMR mass-configurations**															
							5%				**10%**				**15%**				**20%**			
Class	**Case study**	***f***	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**7**	0.007	3.72	3.85	3.78	4.03	3.65	3.77	3.72	3.97	3.57	3.70	3.66	3.91	3.50	3.62	3.60	3.86	3.43	3.55	3.54	3.80
		0.013	4.14	4.25	4.21	4.43	4.05	4.16	4.13	4.36	3.96	4.07	4.05	4.29	3.87	3.98	3.97	4.22	3.78	3.90	3.89	4.15
C	**21**	0.007	4.33	4.46	4.38	4.51	4.24	4.37	4.29	4.43	4.15	4.29	4.21	4.36	4.06	4.20	4.13	4.29	3.97	4.11	4.05	4.21
		0.013	4.83	4.94	4.87	5.01	4.72	4.83	4.77	4.92	4.60	4.73	4.68	4.82	4.49	4.62	4.57	4.73	4.38	4.51	4.45	4.63
D	**31**	0.007	5.15	5.28	5.12	5.10	5.02	5.16	5.01	5.00	4.88	5.04	4.91	4.90	4.76	4.94	4.81	4.81	4.65	4.83	4.71	4.72
		0.013	5.74	5.85	5.71	5.69	5.58	5.71	5.58	5.57	5.42	5.57	5.44	5.45	5.27	5.43	5.31	5.33	5.12	5.30	5.18	5.22

Table SI6.1.8. Sensitivity analysis based on *Coulomb friction coefficient f* - Fuel consumption of reference and PMR mass-configuration for *f* = 0.007 and *f* = 0.010 [l/100km] (DT case studies n°7, 21, 31)

			***Fuel consumption (FC)* [l/100km] – Sensitivity analysis based on *Coulomb friction coefficient f* (DT case studies n°7, 21, 31)**																			
			Reference mass-configuration				**SE mass-configurations**															
							5%				**10%**				**15%**				**20%**			
Class	**Case study**	***f***	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**	**FTP72**	**JC08**	**NEDC**	**WLTC**
A/B	**7**	0.007	3.72	3.85	3.78	4.03	3.60	3.72	3.67	3.92	3.47	3.60	3.56	3.81	3.35	3.48	3.46	3.70	3.23	3.37	3.36	3.59
		0.013	4.14	4.25	4.21	4.43	3.99	4.11	4.08	4.30	3.85	3.97	3.95	4.17	3.71	3.83	3.83	4.04	3.57	3.70	3.71	3.90
C	**21**	0.007	4.33	4.46	4.38	4.51	4.19	4.32	4.25	4.40	4.04	4.18	4.12	4.29	3.90	4.04	3.99	4.18	3.75	3.90	3.85	4.07
		0.013	4.83	4.94	4.87	5.01	4.66	4.78	4.71	4.88	4.49	4.62	4.56	4.75	4.31	4.45	4.40	4.62	4.14	4.29	4.24	4.49
D	**31**	0.007	5.15	5.28	5.12	5.10	4.96	5.11	4.97	5.00	4.77	4.94	4.83	4.90	4.58	4.76	4.65	4.72	4.38	4.57	4.48	4.55
		0.013	5.74	5.85	5.71	5.69	5.52	5.65	5.53	5.57	5.29	5.45	5.35	5.44	5.07	5.24	5.15	5.24	4.84	5.02	4.95	5.04

Table SI6.1.9. Sensitivity analysis based on *Coulomb friction coefficient f* - Fuel consumption of reference and SE mass-configuration for *f* = 0.007 and *f* = 0.010 [l/100km] (DT case studies n°7, 21, 31)

SI 6.2. Fuel Reduction Value

		Fuel Reduction Value (*FRV*) [l/100km*100kg] - Analysis per vehicle class and driving cycle (GT)																			
		A/B-class					**C-class**					**D-class**					**All classes**				
		Minimum	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**
PMR	**FTP72**	0.166	0.203	0.037	0.187	0.012	0.175	0.189	0.014	0.181	0.004	0.180	0.237	0.057	0.195	0.019	0.166	0.237	0.071	0.188	0.014
	JC08	0.171	0.184	0.013	0.176	0.004	0.163	0.181	0.018	0.173	0.005	0.173	0.203	0.030	0.188	0.009	0.163	0.203	0.040	0.179	0.009
	NEDC	0.162	0.176	0.014	0.169	0.005	0.161	0.171	0.010	0.166	0.004	0.159	0.191	0.032	0.175	0.009	0.159	0.191	0.032	0.170	0.007
	WLTC	0.161	0.174	0.013	0.168	0.005	0.163	0.181	0.018	0.170	0.005	0.166	0.187	0.021	0.178	0.007	0.161	0.187	0.026	0.172	0.007
	Mean cycles	0.167	0.181	0.015	0.175	0.005	0.167	0.177	0.010	0.173	0.003	0.172	0.203	0.031	0.184	0.009	0.167	0.203	0.037	0.177	0.008
SE	**FTP72**	0.274	0.407	0.133	0.322	0.037	0.298	0.389	0.091	0.351	0.034	0.290	0.477	0.187	0.392	0.062	0.274	0.477	0.203	0.356	0.054
	JC08	0.259	0.393	0.134	0.309	0.038	0.287	0.369	0.082	0.337	0.031	0.283	0.441	0.158	0.373	0.049	0.259	0.441	0.182	0.341	0.047
	NEDC	0.252	0.389	0.137	0.299	0.041	0.282	0.365	0.083	0.331	0.032	0.270	0.441	0.171	0.360	0.053	0.252	0.441	0.189	0.331	0.049
	WLTC	0.233	0.346	0.113	0.276	0.031	0.265	0.342	0.077	0.310	0.028	0.262	0.354	0.092	0.321	0.031	0.233	0.354	0.121	0.303	0.035
	Mean cycles	0.255	0.384	0.129	0.301	0.037	0.283	0.362	0.079	0.332	0.031	0.276	0.425	0.148	0.362	0.048	0.255	0.425	0.170	0.333	0.045

Table SI6.2.1. Fuel Reduction Value (*FRV*) [l/100km*100kg]: analysis per vehicle class and driving cycle in terms of minimum and maximum, size of range max-min, arithmetic mean and standard deviation (GT)

		***Fuel Reduction Value* (*FRV*) [l/100km*100kg] - Analysis per vehicle class and driving cycle (DT)**																			
		A/B-class					**C-class**					**D-class**					**All classes**				
		Minimum	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**	**Minimum**	**Maximum**	**Size of range max-min**	**Arithmetic mean**	**Standard deviation**
PMR	**FTP72**	0.145	0.174	0.029	0.154	0.011	0.154	0.180	0.026	0.169	0.008	0.156	0.243	0.087	0.196	0.029	0.145	0.243	0.098	0.173	0.024
	JC08	0.140	0.165	0.025	0.151	0.007	0.146	0.170	0.024	0.159	0.006	0.149	0.189	0.040	0.172	0.013	0.140	0.189	0.049	0.160	0.012
	NEDC	0.129	0.148	0.019	0.139	0.007	0.140	0.163	0.023	0.150	0.007	0.143	0.172	0.029	0.160	0.010	0.129	0.172	0.043	0.150	0.011
	WLTC	0.115	0.148	0.033	0.125	0.012	0.133	0.152	0.019	0.141	0.006	0.131	0.175	0.044	0.156	0.015	0.115	0.175	0.060	0.141	0.017
	Mean cycles	0.136	0.158	0.022	0.142	0.008	0.145	0.163	0.019	0.155	0.006	0.145	0.192	0.047	0.171	0.016	0.136	0.192	0.056	0.156	0.016
SE	**FTP72**	0.217	0.295	0.078	0.250	0.024	0.245	0.294	0.049	0.276	0.016	0.243	0.388	0.145	0.305	0.045	0.217	0.388	0.171	0.277	0.036
	JC08	0.212	0.284	0.072	0.244	0.021	0.246	0.283	0.037	0.264	0.013	0.246	0.320	0.074	0.280	0.024	0.212	0.320	0.108	0.262	0.024
	NEDC	0.194	0.270	0.076	0.225	0.023	0.231	0.270	0.039	0.248	0.014	0.232	0.300	0.068	0.262	0.022	0.194	0.300	0.106	0.245	0.024
	WLTC	0.142	0.253	0.111	0.203	0.033	0.196	0.243	0.047	0.220	0.015	0.197	0.292	0.095	0.231	0.028	0.142	0.292	0.150	0.218	0.028
	Mean cycles	0.191	0.276	0.084	0.230	0.024	0.233	0.271	0.039	0.252	0.014	0.230	0.325	0.096	0.269	0.029	0.191	0.325	0.134	0.251	0.027

Table SI6.2.2. Fuel Reduction Value (*FRV*) [l/100km*100kg]: analysis per vehicle class and driving cycle in terms of minimum and maximum, size of range max-min, arithmetic mean and standard deviation (DT)

		***Fuel Reduction Value S&S ($FRV_{S\&S}$)* [l/100km*100kg] (GT)**							
		PMR				**SE**			
Class	**Case study**	**FTP72 ($FRV_{S\&S\_FTP75\_PMR}$)**	**JC08 ($FRV_{S\&S\_JC08\_PMR}$)**	**NEDC ($FRV_{S\&S\_NEDC\_PMR}$)**	**WLTC ($FRV_{S\&S\_WLTC\_PMR}$)**	**FTP72 ($FRV_{S\&S\_FTP75\_SE}$)**	**JC08 ($FRV_{S\&S\_JC08\_SE}$)**	**NEDC ($FRV_{S\&S\_NEDC\_SE}$)**	**WLTC ($FRV_{S\&S\_WLTC\_SE}$)**
A/B	**9**	0.177	0.180	0.172	0.161	0.313	0.302	0.287	0.260
C	**17**	0.183	0.168	0.161	0.170	0.369	0.355	0.352	0.339
D	**28**	0.185	0.203	0.187	0.168	0.333	0.332	0.310	0.276

Table SI6.2.3. Fuel Reduction Value S&S ($FRV_{S\&S}$) of GT case studies n°9, 17, 28 [l/100km*100kg]

		***Fuel Reduction Value S&S ($FRV_{S\&S}$)* [l/100km*100kg] (DT)**							
		PMR				**SE**			
Class	**Case study**	**FTP72 ($FRV_{S\&S\_FTP75\_PMR}$)**	**JC08 ($FRV_{S\&S\_JC08\_PMR}$)**	**NEDC ($FRV_{S\&S\_NEDC\_PMR}$)**	**WLTC ($FRV_{S\&S\_WLTC\_PMR}$)**	**FTP72 ($FRV_{S\&S\_FTP75\_SE}$)**	**JC08 ($FRV_{S\&S\_JC08\_SE}$)**	**NEDC ($FRV_{S\&S\_NEDC\_SE}$)**	**WLTC ($FRV_{S\&S\_WLTC\_SE}$)**
A/B	**7**	0.150	0.153	0.130	0.120	0.243	0.231	0.209	0.223
C	**21**	0.166	0.157	0.153	0.137	0.256	0.237	0.230	0.194
D	**31**	0.197	0.170	0.160	0.148	0.288	0.255	0.239	0.206

Table SI6.2.4. Fuel Reduction Value S&S ($FRV_{S\&S}$) of DT case studies n°7, 21, 31 [l/100km*100kg]

			Sensitivity analysis based on *Coulomb friction coefficient f* (GT case studies)							
			***Fuel Reduction Value (FRV)* [l/100km*100kg]**							
			PMR				**SE**			
Class	**Case study**	***f***	**FTP72 (FRV_{FTP72_PMR})**	**JC08 (FRV_{JC08_PMR})**	**NEDC (FRV_{NEDC_PMR})**	**WLTC (FRV_{WLTC_PMR})**	**FTP72 (FRV_{FTP72_SE})**	**JC08 (FRV_{JC08_SE})**	**NEDC (FRV_{NEDC_SE})**	**WLTC (FRV_{WLTC_SE})**
A/B	**9**	0.007	0.155	0.160	0.151	0.139	0.294	0.291	0.272	0.237
		0.013	0.197	0.193	0.198	0.182	0.338	0.330	0.316	0.286
C	**17**	0.007	0.161	0.149	0.137	0.153	0.352	0.345	0.343	0.321
		0.013	0.202	0.191	0.189	0.194	0.395	0.391	0.381	0.363
D	**28**	0.007	0.168	0.181	0.164	0.154	0.285	0.278	0.255	0.258
		0.013	0.207	0.217	0.205	0.183	0.361	0.363	0.341	0.299

Table SI6.2.5. Sensitivity analysis based on *Coulomb friction coefficient* (GT): Fuel Reduction Value (FRV) of GT case studies n°9, 17, 28 [l/100km*100kg]

			Sensitivity analysis based on *Coulomb friction coefficient f* (DT case studies)							
			***Fuel Reduction Value (FRV)* [l/100km*100kg]**							
			PMR				**SE**			
Class	**Case study**	***f***	**FTP72 (FRV_{FTP72_PMR})**	**JC08 (FRV_{JC08_PMR})**	**NEDC (FRV_{NEDC_PMR})**	**WLTC (FRV_{WLTC_PMR})**	**FTP72 (FRV_{FTP72_SE})**	**JC08 (FRV_{JC08_SE})**	**NEDC (FRV_{NEDC_SE})**	**WLTC (FRV_{WLTC_SE})**
A/B	**7**	0.007	0.136	0.140	0.111	0.105	0.228	0.224	0.194	0.204
		0.013	0.166	0.165	0.147	0.133	0.264	0.255	0.232	0.248
C	**21**	0.007	0.146	0.143	0.135	0.119	0.237	0.230	0.215	0.178
		0.013	0.184	0.173	0.168	0.154	0.280	0.264	0.254	0.214
D	**31**	0.007	0.177	0.156	0.141	0.134	0.269	0.246	0.222	0.190
		0.013	0.217	0.191	0.184	0.167	0.314	0.288	0.267	0.229

Table SI6.2.6. Sensitivity analysis based on *Coulomb friction coefficient* (DT): Fuel Reduction Value (FRV) of DT case studies n°7, 21, 31 [l/100km*100kg]

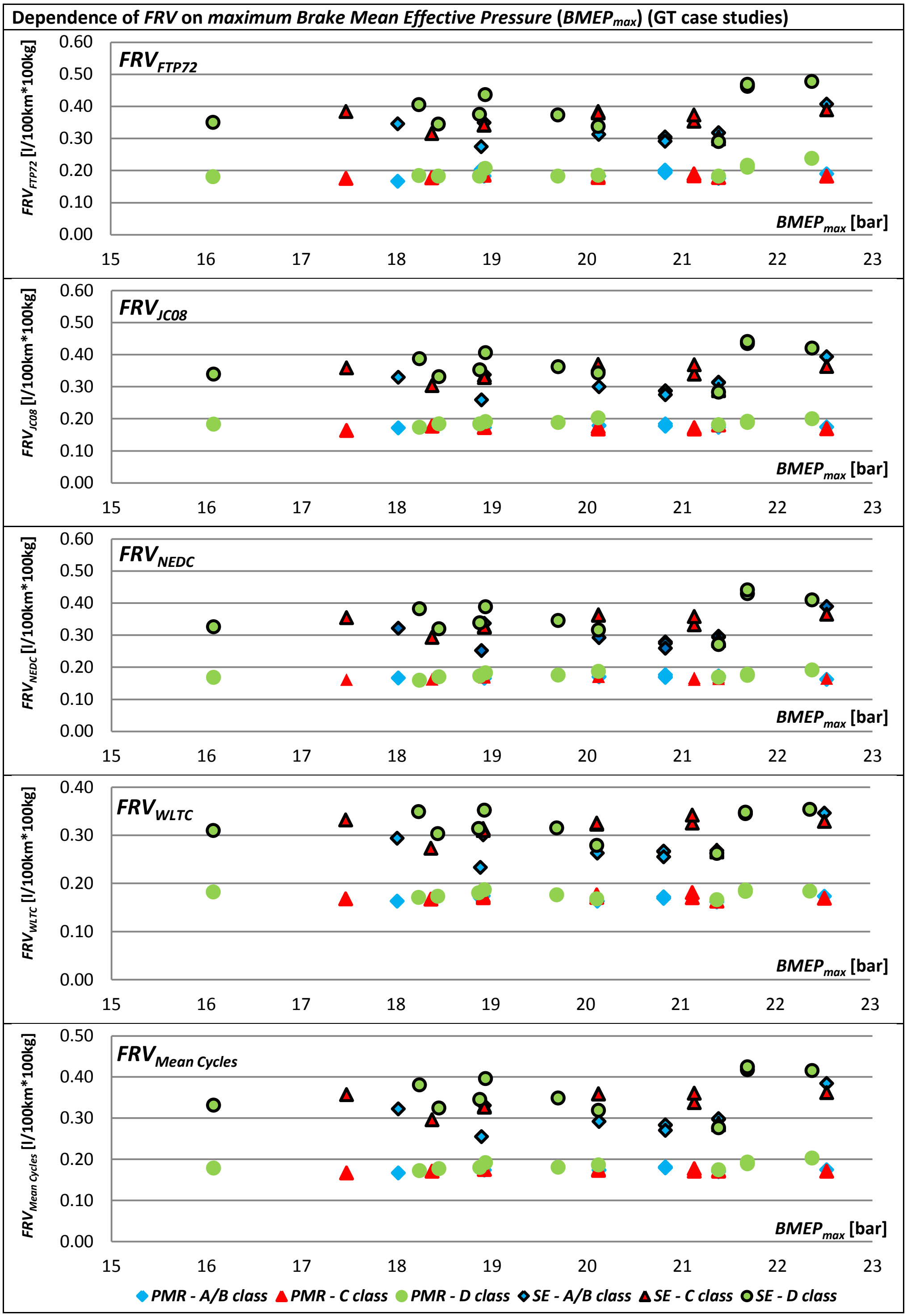
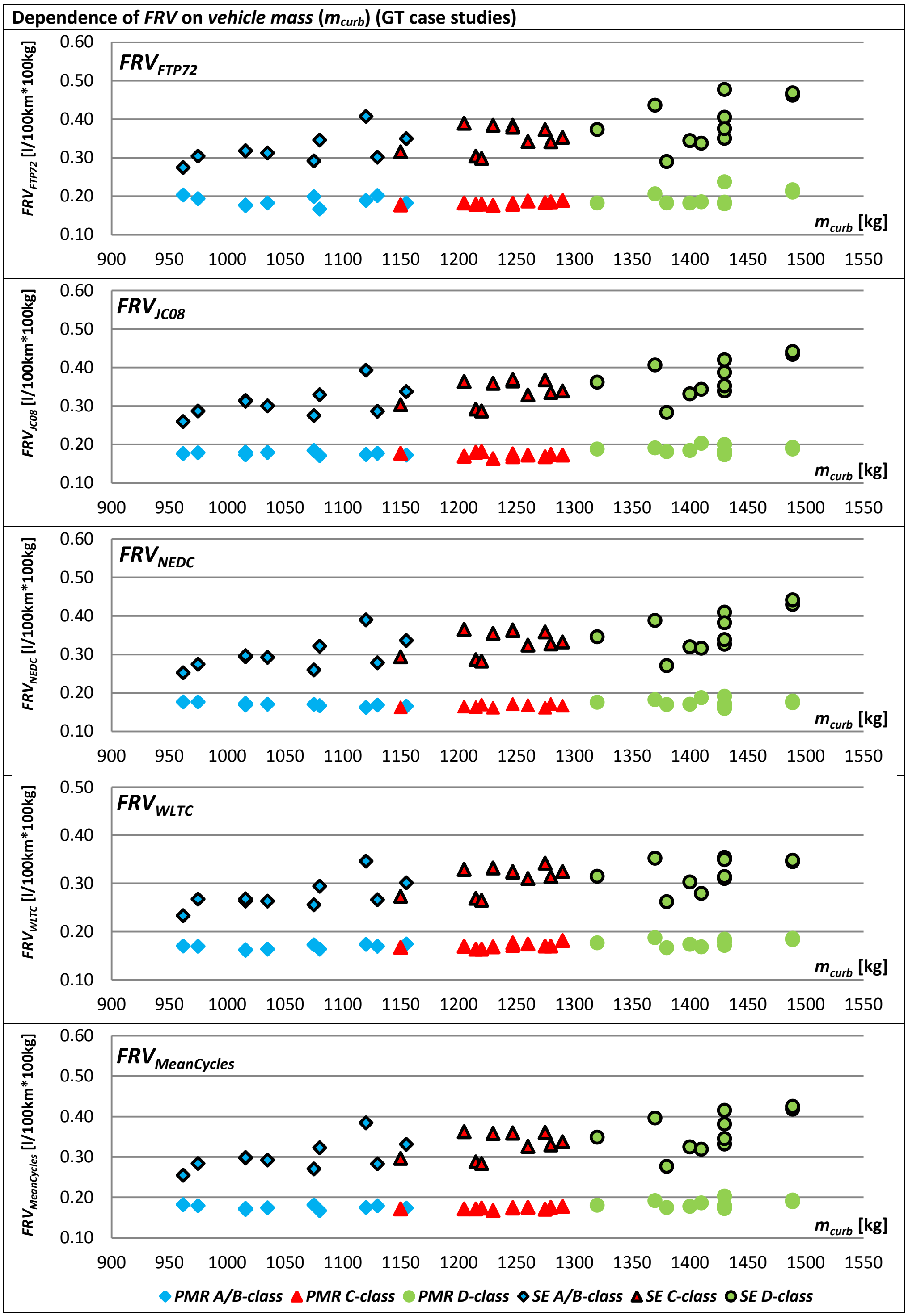


Figure SI6.2.7.. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of $BMEP_{max}$ (GT)



Dependence of *FRV* on *vehicle mass* (m_{curb}) (GT case studies)

Figure SI6.2.8. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of m_{curb} (GT)

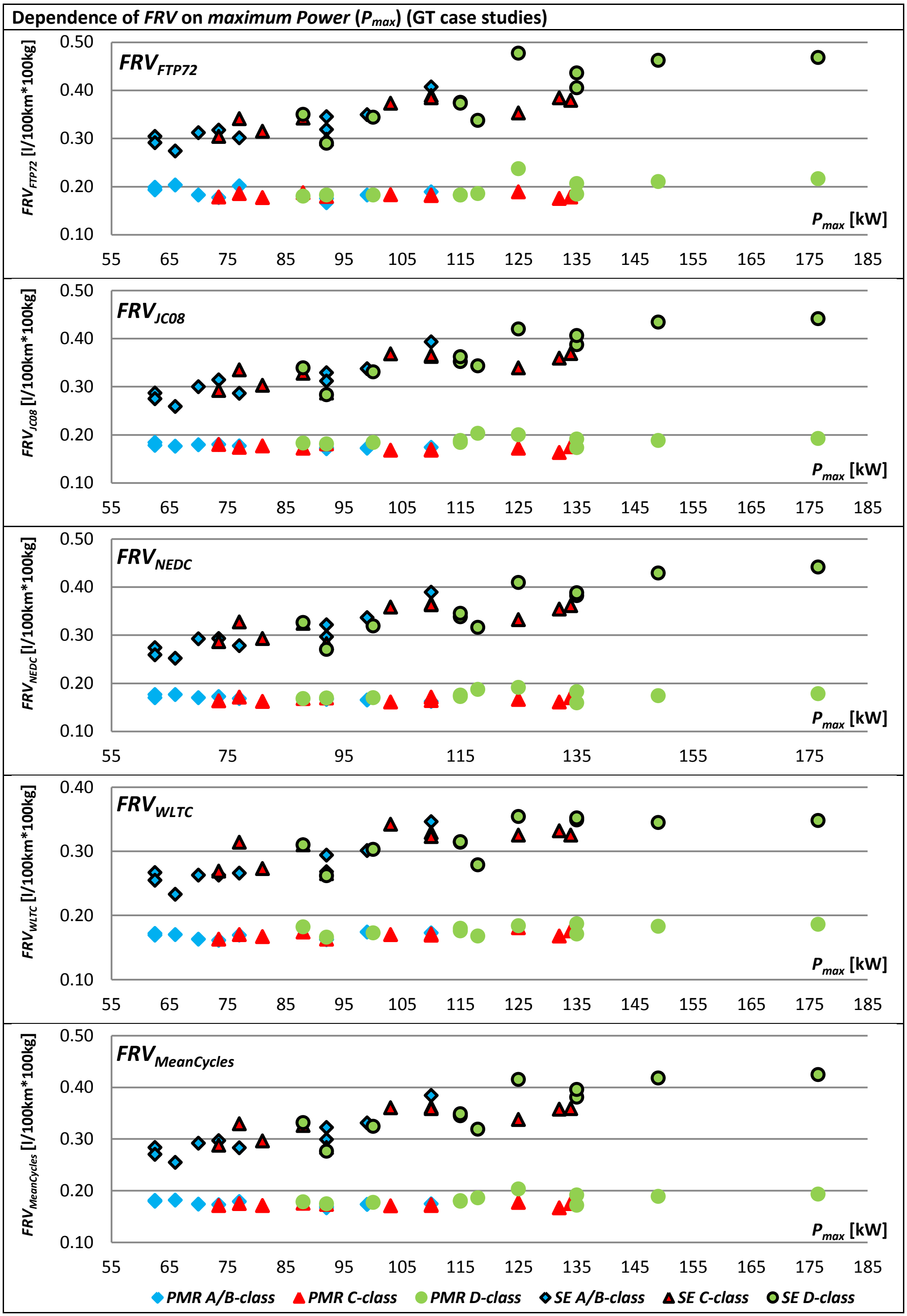


Figure SI6.2.9. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of m_{curb} (GT)

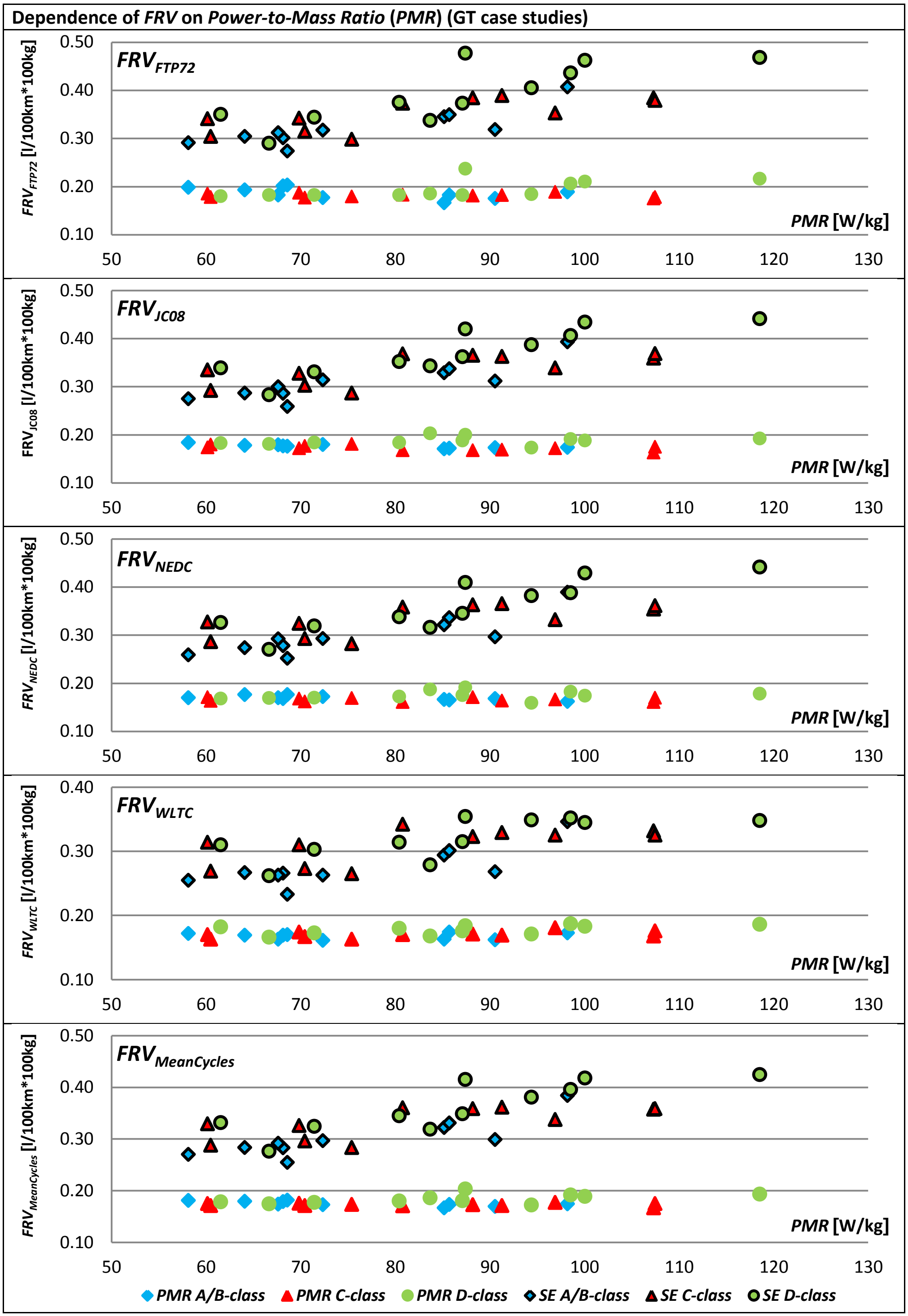


Figure 6.2.10. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of *PMR* (GT)

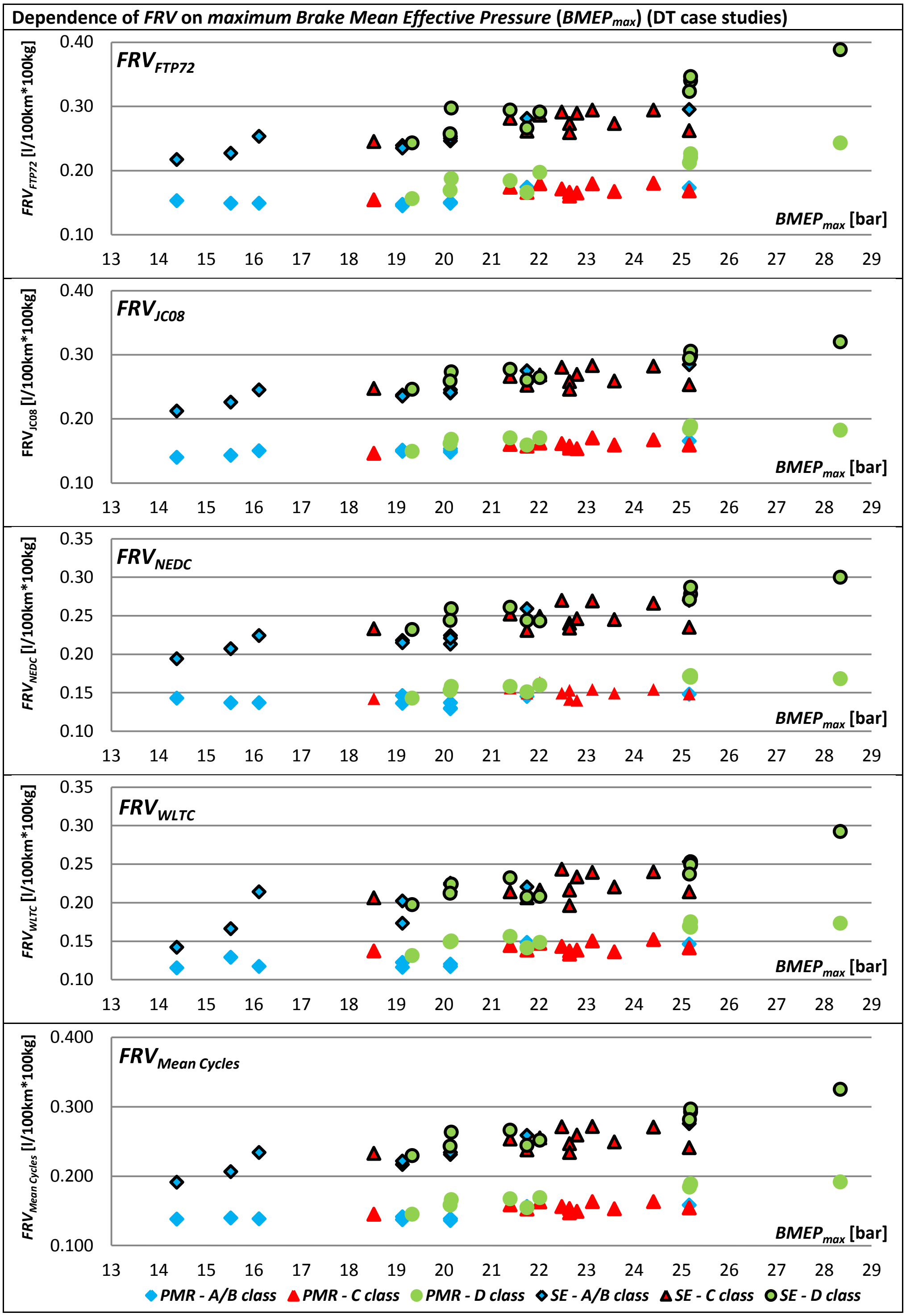


Figure 6.2.11. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of $BMEP_{max}$ (DT)

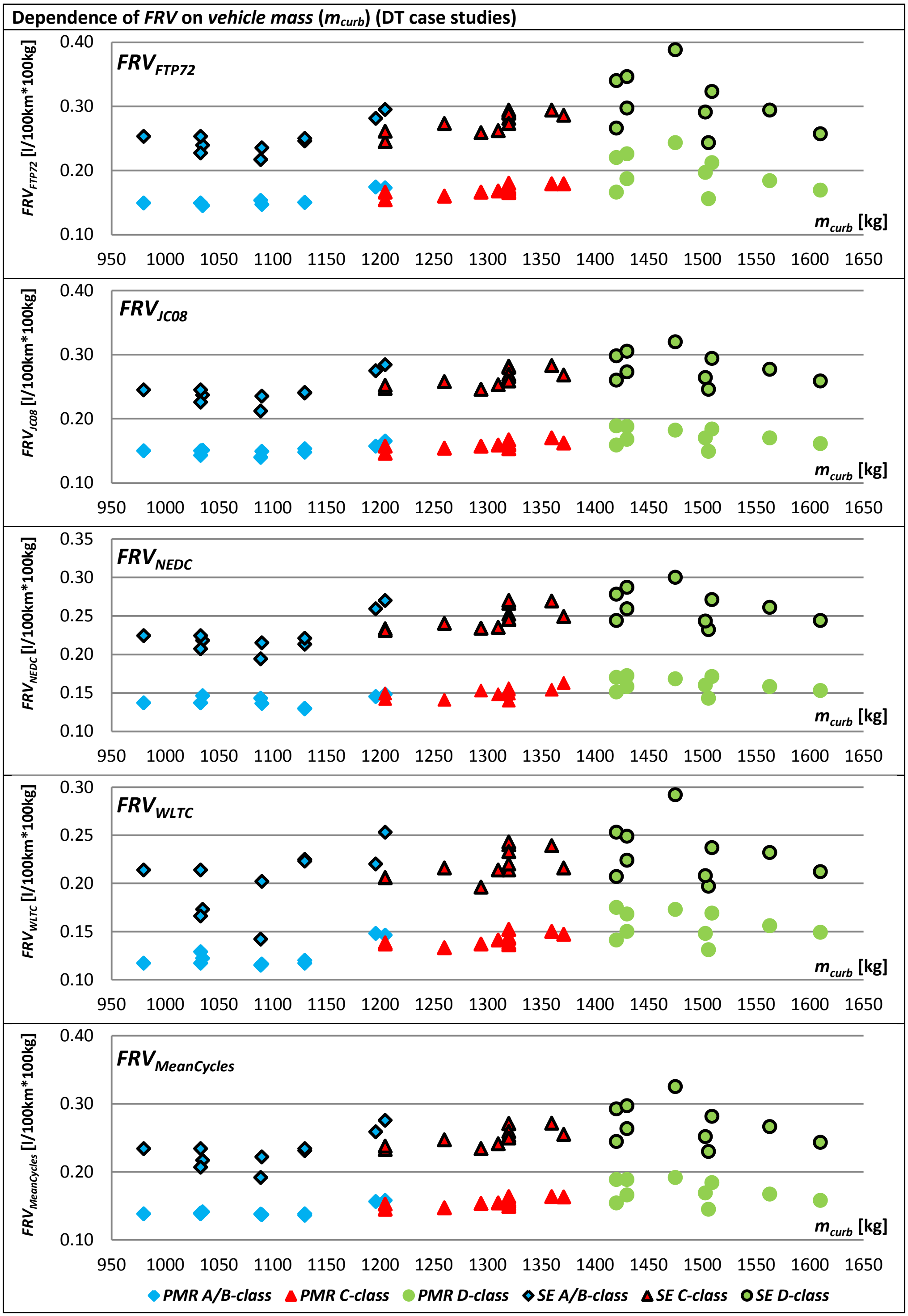


Figure 6.2.12. *FRV*$_{FTP72}$, *FRV*$_{JC08}$, *FRV*$_{NEDC}$, *FRV*$_{WLTC}$ and *FRV*$_{MeanCycles}$ in function of m_{curb} (DT)

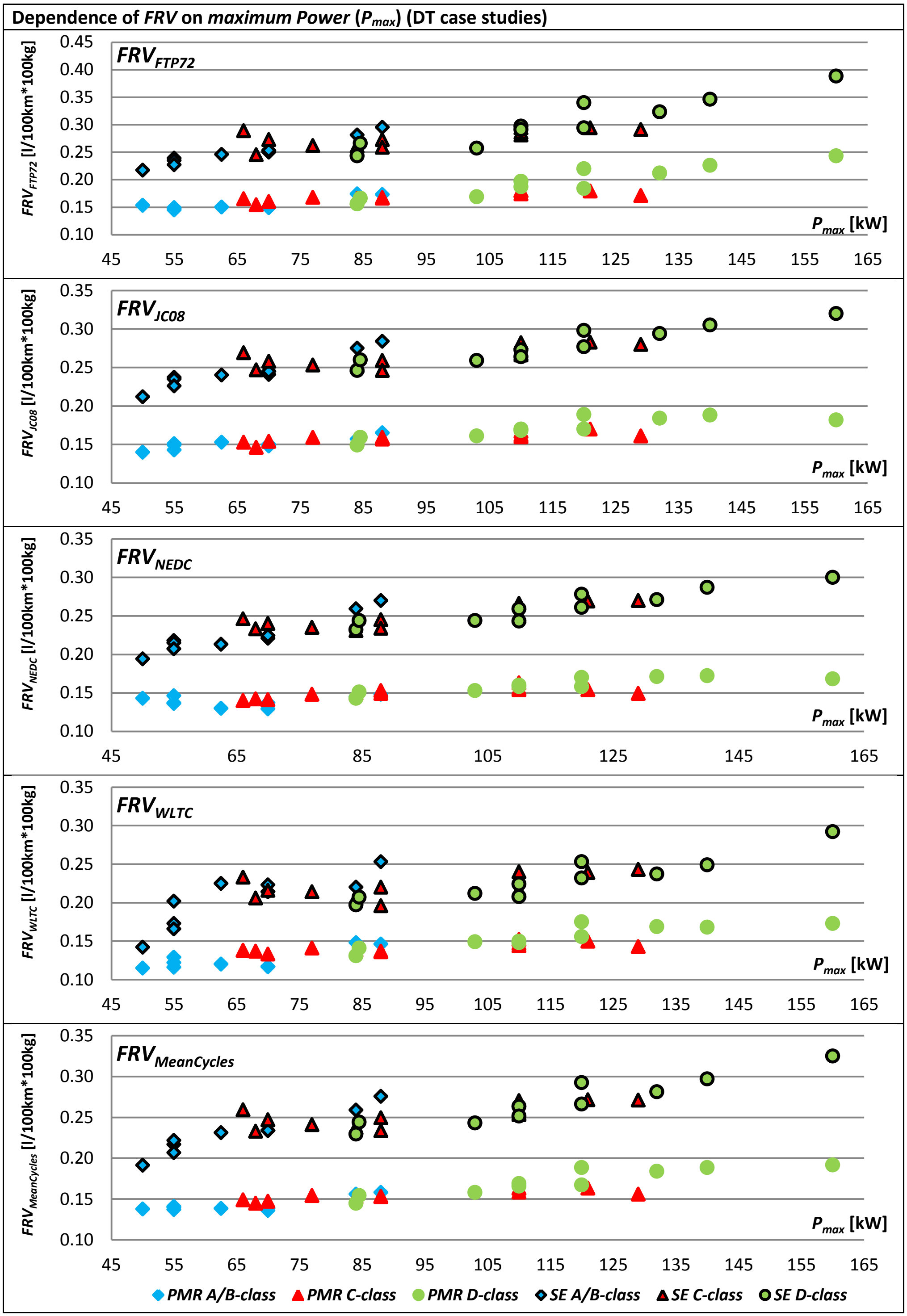


Figure 6.2.13. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of *maximum Power* (P_{max}) (DT)

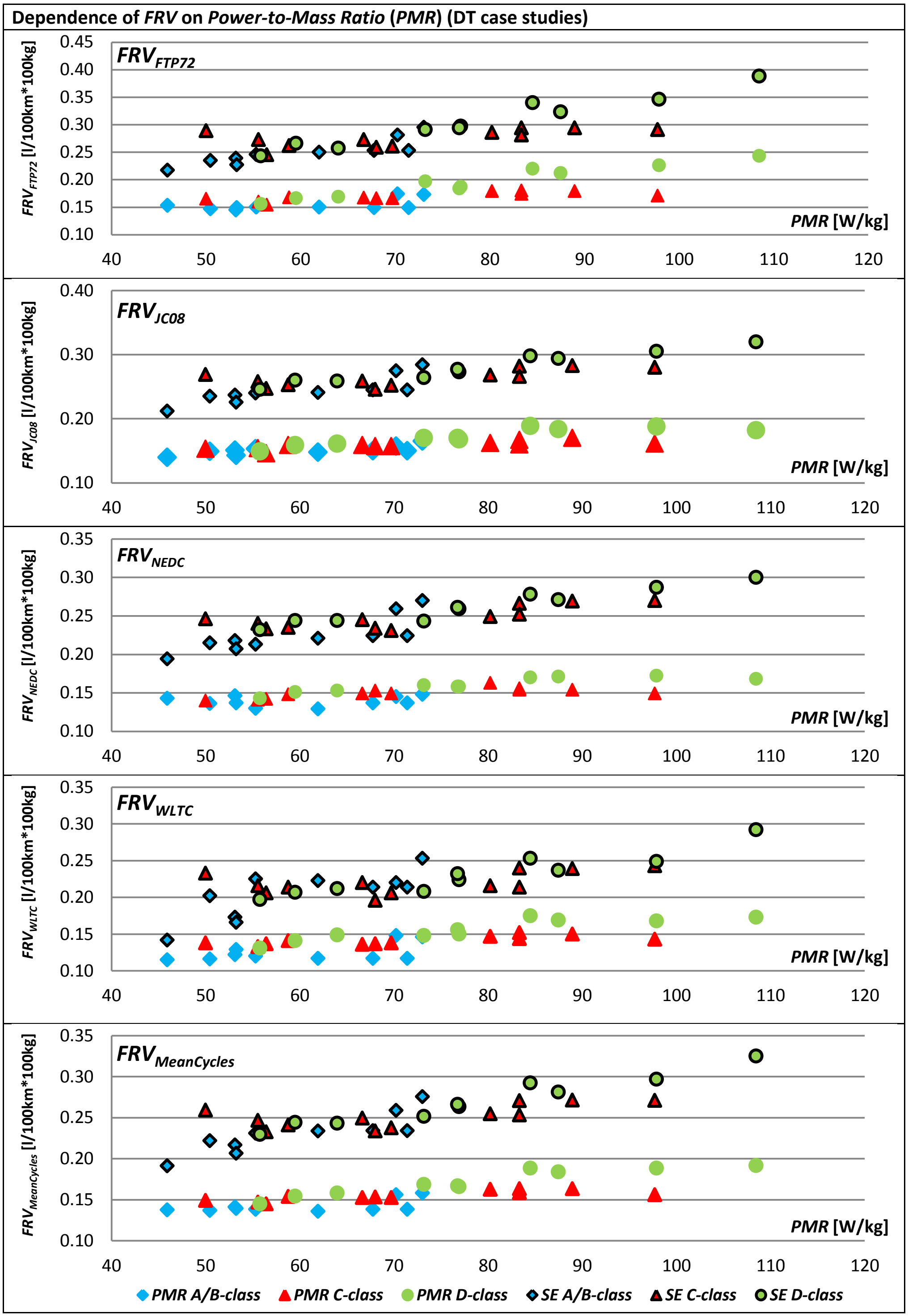
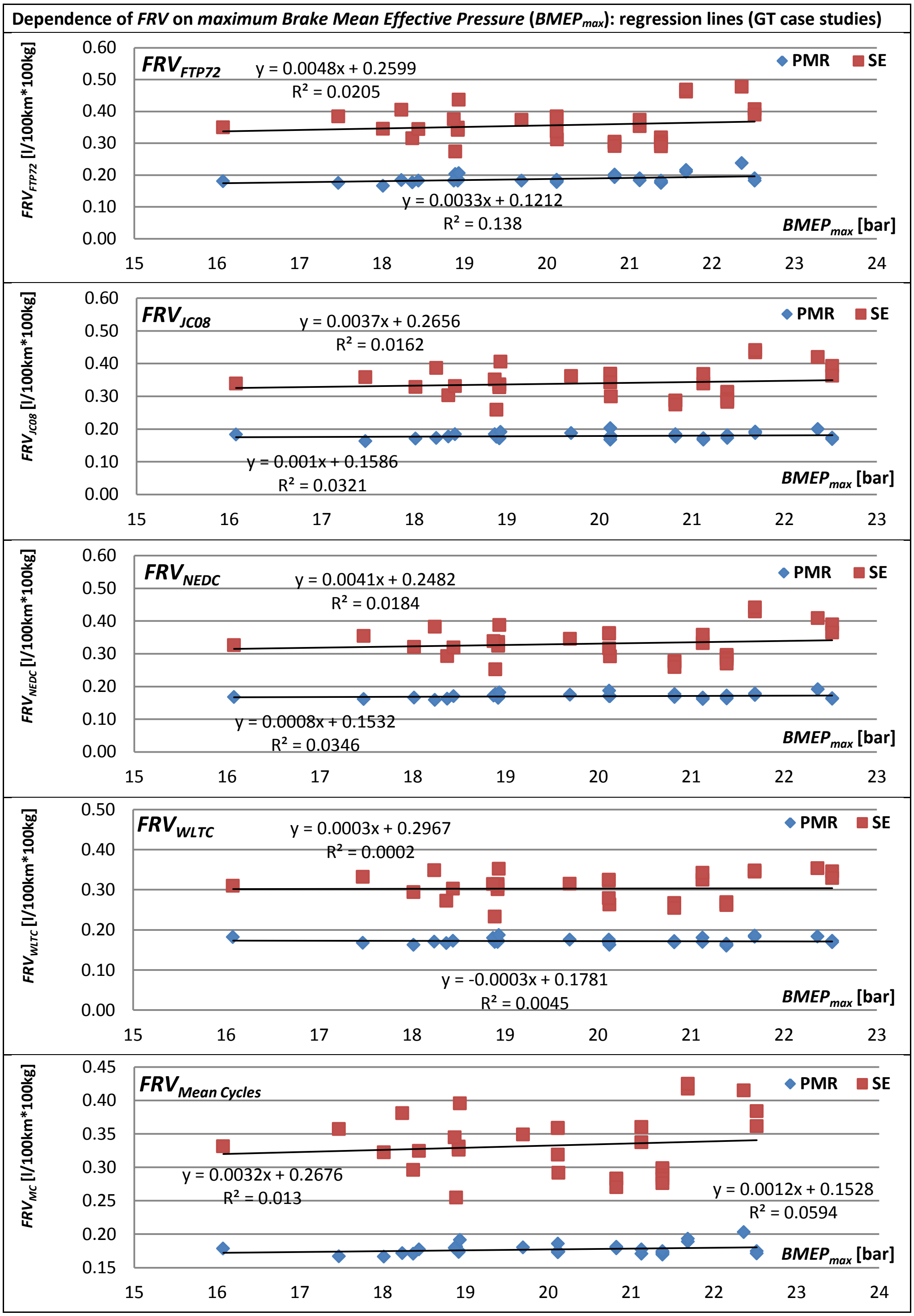


Figure 6.2.14. *FRV$_{FTP72}$*, *FRV$_{JC08}$*, *FRV$_{NEDC}$*, *FRV$_{WLTC}$* and *FRV$_{MeanCycles}$* in function of *Power-to-Mass Ratio* (*PMR*) (DT)



Dependence of *FRV* on *maximum Brake Mean Effective Pressure* (*$BMEP_{max}$*): regression lines (GT case studies)

Figure 6.2.15. *FRV_{FTP72}*, *FRV_{JC08}*, *FRV_{NEDC}*, *FRV_{WLTC}* and *$FRV_{MeanCycles}$* in function of *$BMEP_{max}$* with regression lines (GT)

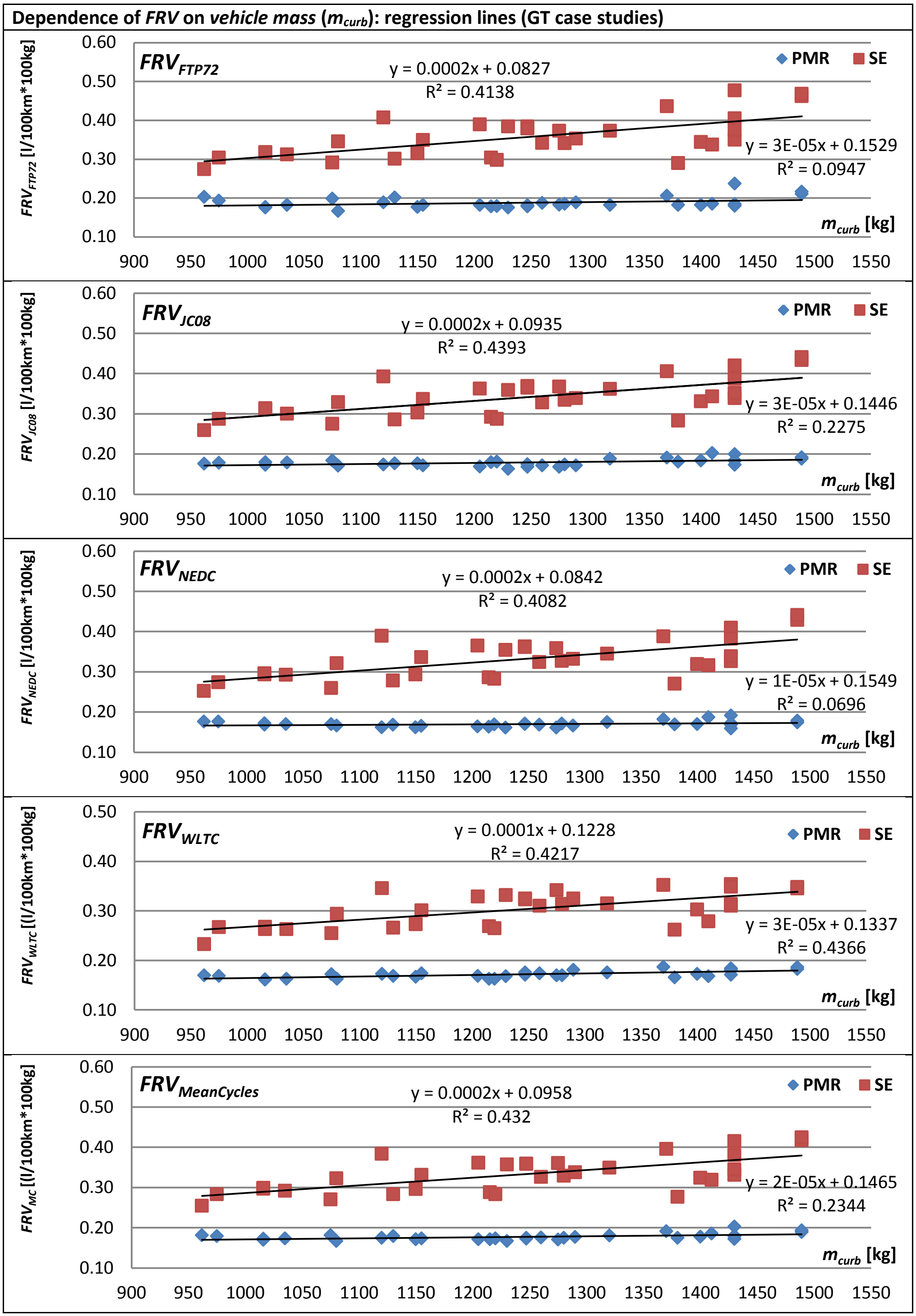


Figure 6.2.16. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of m_{curb} with regression lines (GT)

Dependence of *FRV* on *maximum Power* (P_{max}): regression lines (GT case studies)

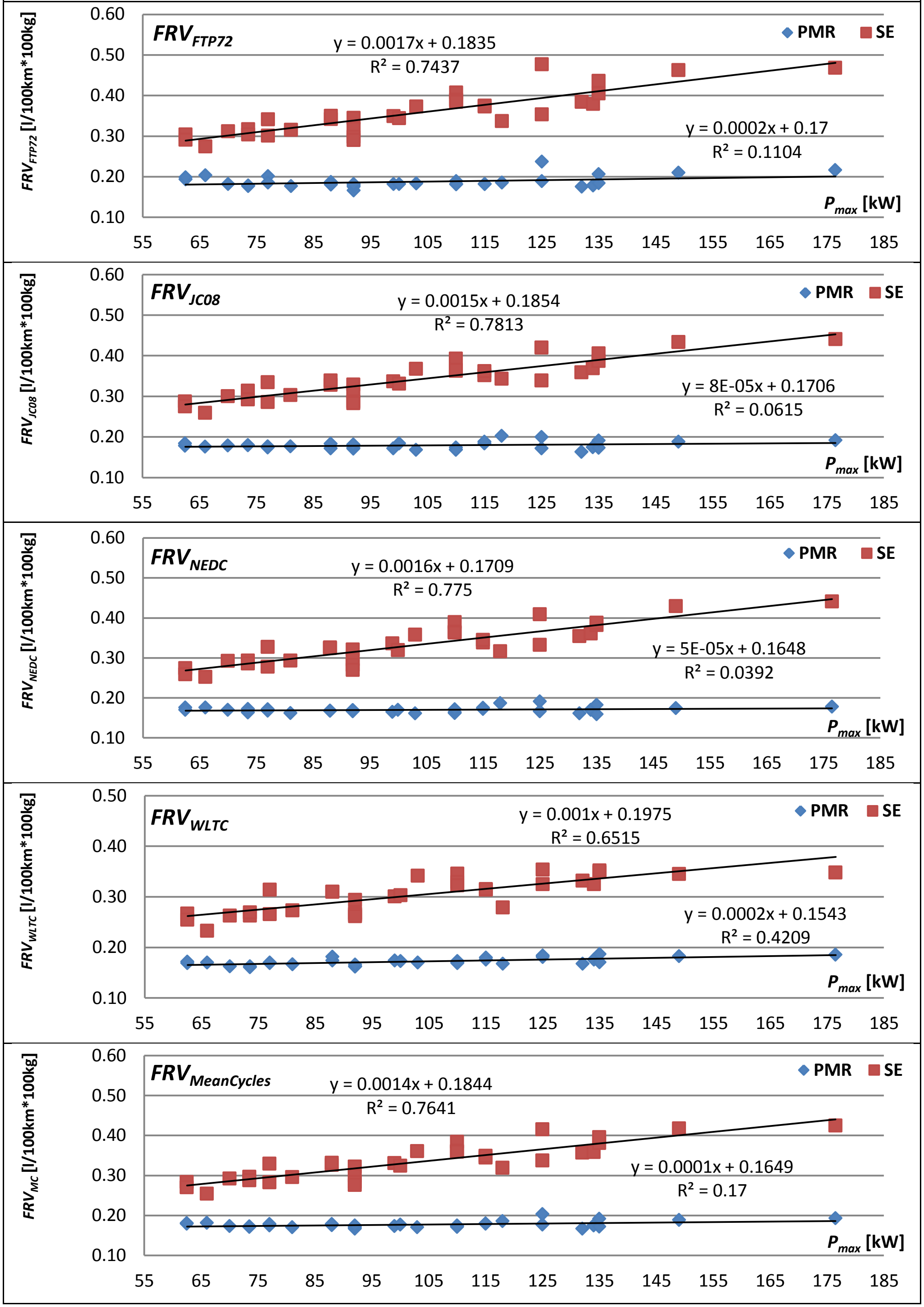


Figure 6.2.17. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of P_{max} with regression lines (GT)

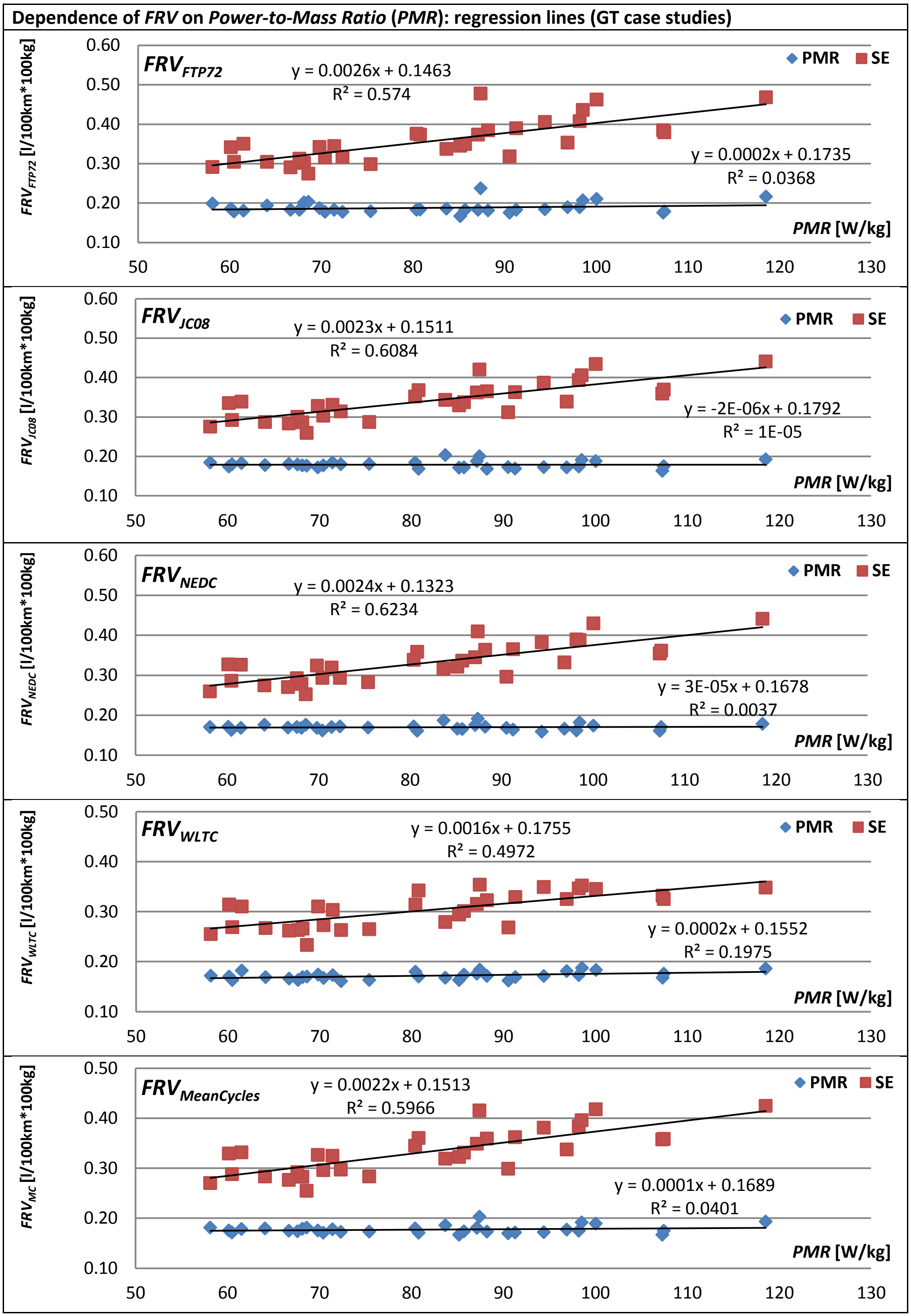


Figure 6.2.18. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of *PMR* with regression lines (GT)

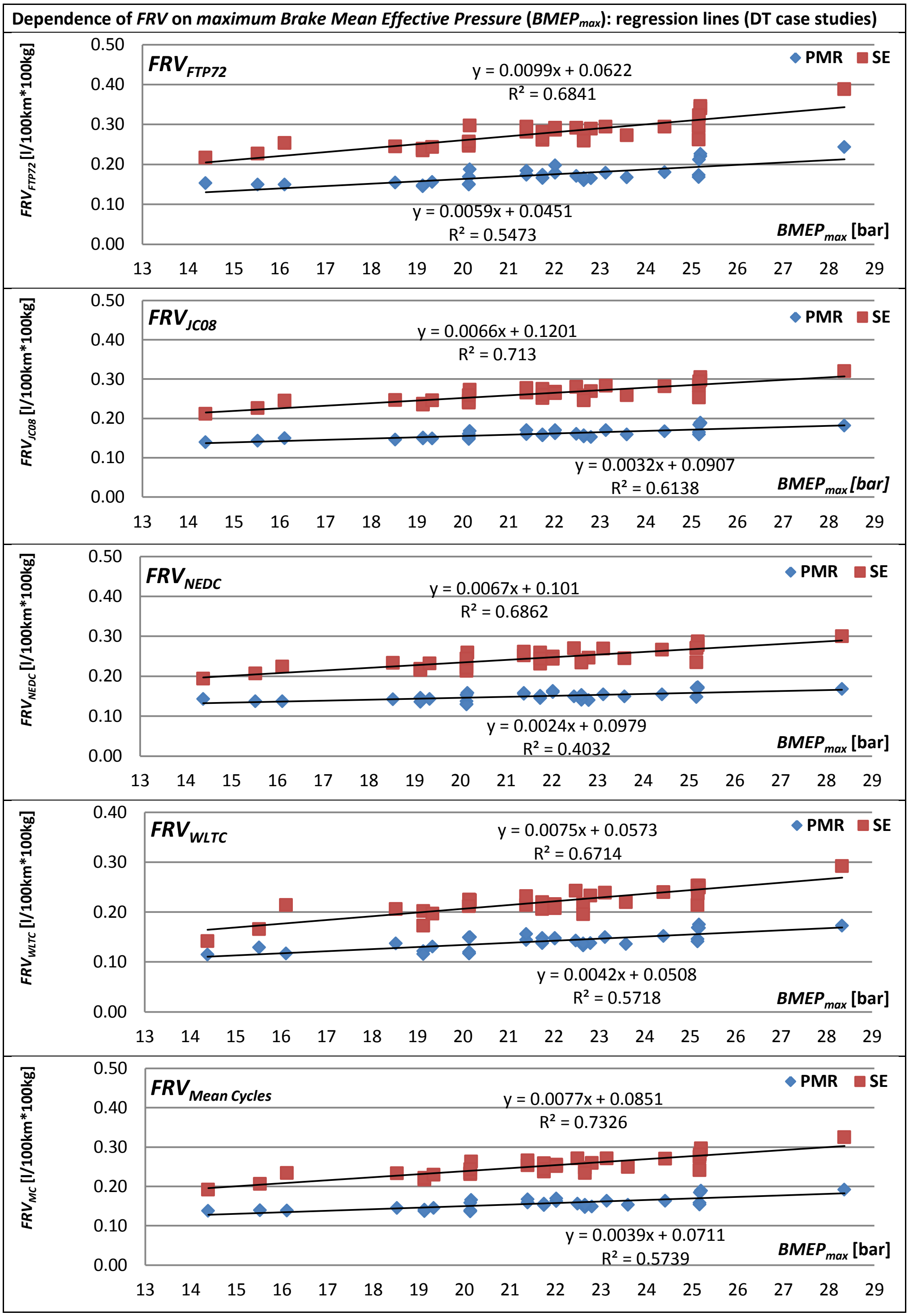


Figure 6.2.19. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of $BMEP_{max}$ with regression lines (DT)

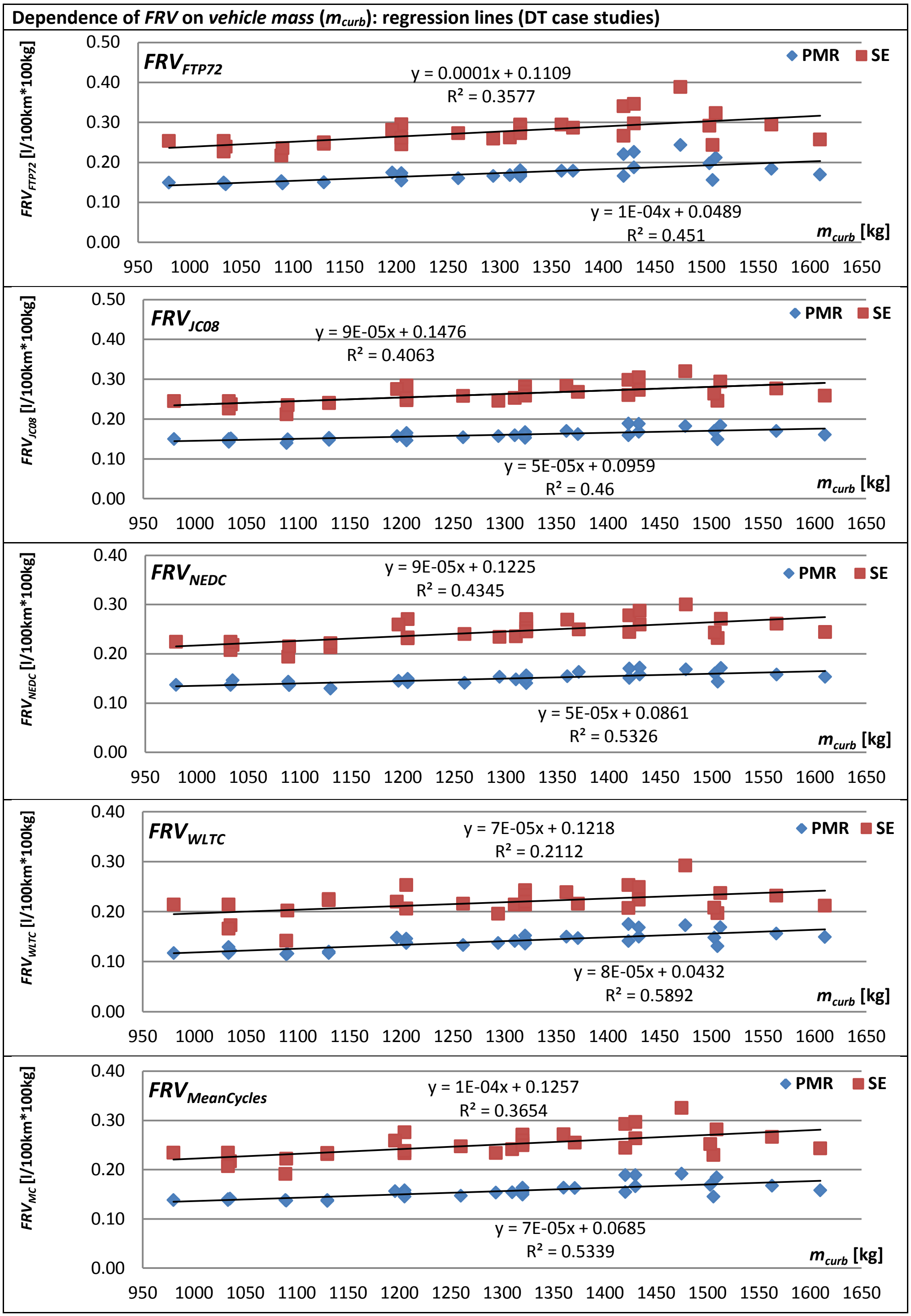


Figure 6.2.20. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of m_{curb} with regression lines (DT)

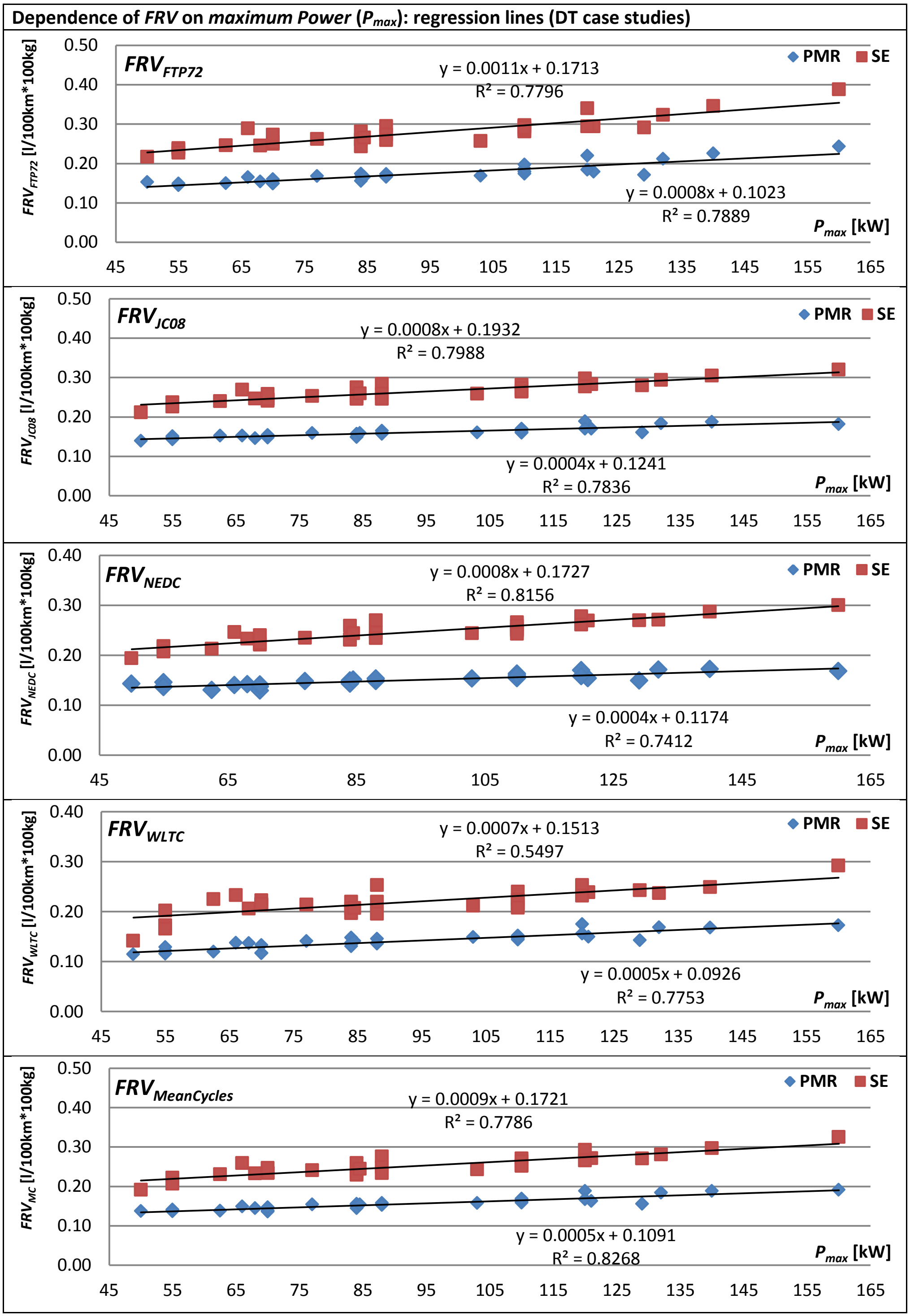


Figure 6.2.21. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of P_{max} with regression lines (DT)

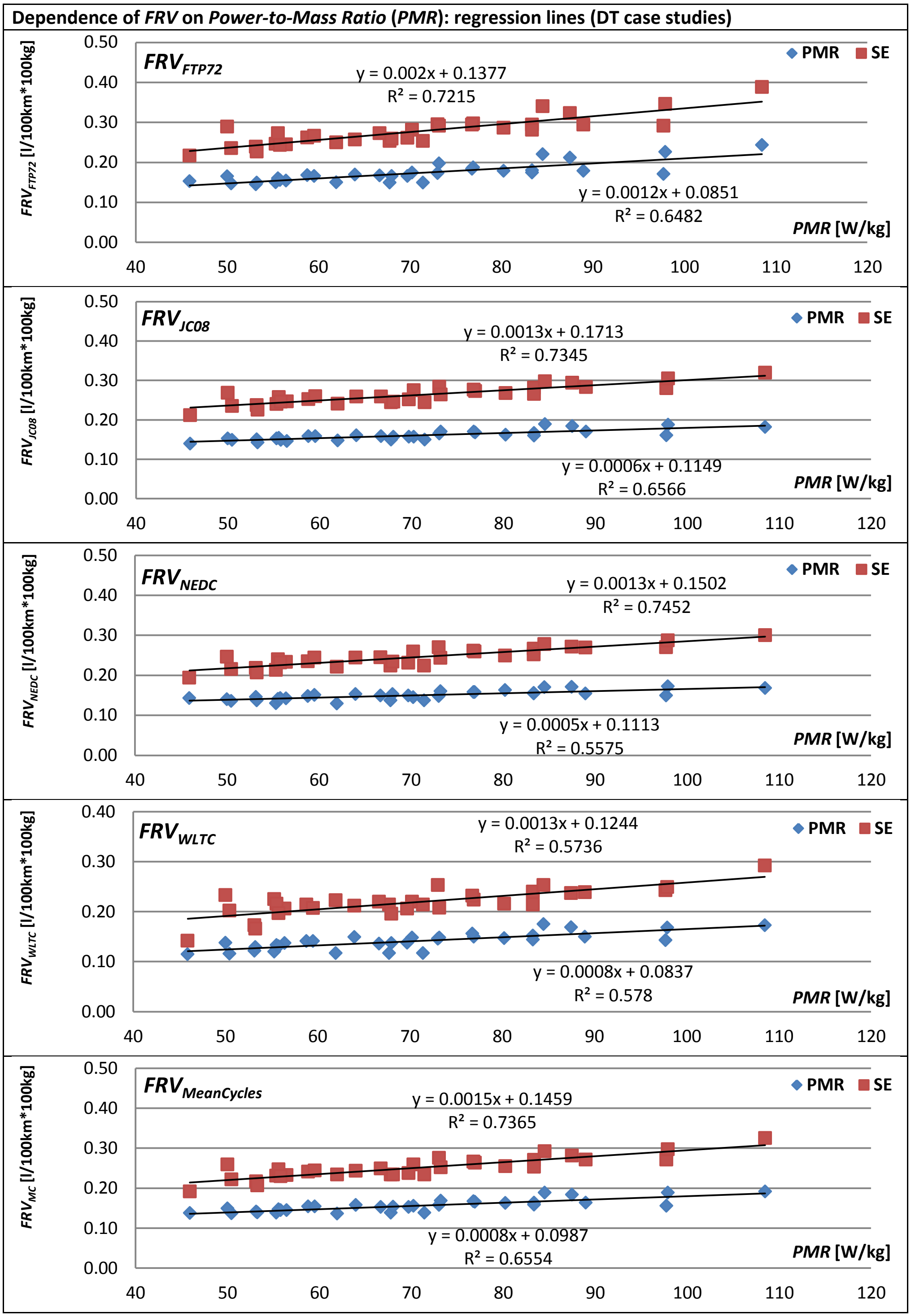


Figure 6.2.22. FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$ in function of *PMR* with regression lines (DT)