Lightweight design solutions in the automotive field: environmental modelling based on Fuel Reduction Value applied to diesel turbocharged vehicles

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Abstract

A tailored model for the assessment of environmental benefits achievable by light-weighting design solutions in the automotive field is presented. The model is based on the Fuel Reduction Value (FRV) coefficient which expresses the Fuel Consumption (FC) saving involved by a 100 kg vehicle mass reduction. The work is composed by two main sections: simulation and environmental modelling. Simulation modelling performs an in-depth calculation of weight-induced FC whose outcome is the FRV evaluated for a wide range of Diesel Turbocharged (DT) vehicle case studies. Environmental modelling converts fuel saving to impact reduction basing on the FRVs obtained by simulations. Results show that for the considered case studies FRV is within the range 0.115-0.143 and 0.142-0.388 l/100km*100kg respectively for mass reduction only and powertrain adaptations (secondary effects). The implementation of FRVs within the environmental modelling represents the added value of the research and makes the model a valuaflexible and tailorable tool for application to realany automotive DT case studies of automotive lightweight LCAy.

Keywords

Automotive, Fuel consumption, Fuel Reduction Value (FRV), Life Cycle Assessment (LCA), Light-weighting, Vehicle system dynamics.

1. Introduction

Global society strongly depends on transportation and the development trends forecast a substantial growth in this sector over the coming decades [1]. Considering the European Union, transportation industry represents the second largest contributor to anthropogenic gGreenhHouse gGas (GHG) emissions and around 20% of these emissions are causgenerated by road transports [2]. In this context light-duty vehicles account for approximately 10% of total energy use and GHG emissions [3], [4]. Considering that the number of cars is expected to increase from roughly 700 million to 2 billion over the period 2000-2050 [5], a dramatic increase in gasoline and diesel demand with implications on energy security, climate change and urban air quality appears to be very likely ([6], [7], [8], [9], [1], [10], [811], [912], [103], [114], [15], [16], [17], [18]). FIt is known that for an Internal Combustion Engine (ICE) car the use stage is responsible forof a relevant quota of total Life Cycle (LC) impact (e.g. 85% in terms of Global Warming Potential, (GWP)); the latter and it is mainly due to Fuel Consumption (FC) which in turn strongly depends on vehicle mass ([129], [1320], [1421], [1522], [1623], [1724], [1825], [1926]).
Light-weighting through the adoption of novel materials and innovative technologies is unanimously recognized as one of the key measures in order to lower the car use stage FC and environmental burdenpressure ([207], [218], [229], [2330], [2431]);, although, on the other hand, the adoption of novel materials and innovative technologies oftenthe risk to shifts the impacts to other LC stages (e.g. production and End-of-Life, (EoL) [2532], [2633], [34], [35], [36],) could be very high ([37], [38], [39], [40], [41], [19], [42]). In this regard plastics, composites, aluminum, high-strength steel and, magnesium and sandwich materials and sandwichare key materials are expected to play a leadingn increasingly important role in the future. Aluminum, high-strength steel and composites can be used both in structural (i.e. frame or seat structure) and functional (i.e. steering, transmission) parts where strength is the key requirement; on the other hand for interior parts plastic will remain the predominant element and it will become also more important in the next future, due to its favorable cost-weight ratio. On the other hand, despite light-weighting allows lowering use stage impact by reduction of use stage FC, it usually involves negative effects on production and End-of-Life (EoL) stages [2734], [2835], [2936], [307], [318]. Indeed lightweight materials are usually more energy-intensive and involve higher CO_2 emissions prior to operationuse stage if compared with conventional steel. At the same time, recycling of composites is still not a well-established practice, contrary to what happens for metals [329], [3340], [3441], [129], [3542]. Therefore, a balance of benefits and disadvantages involved by light-weighting during the whole vehicle LC is needed; this allows quantifying the driving distance for which the reduced use stage FC compensates production and EoL emissions thus involving an actual LC benefits.
TIn this regardAt this purpose, the Life Cycle Assessment (LCA) methodology iresults the most indicated approach forto performing the environmental assessment and balance the eco-profile of lightweight solutions during their whole LC. Many LCA studies already exist in the transportation sector ([3643], [3744], [3845], [46], [47], [48], [349], [450],

[51]) and the interest is continuously growing, particularly in the automotive field ([3744], [129], [4152], [4253], [4354], [4455], [4556], [57], [58], [59], [4660]).

Considering use stage within the automotive lightweight LCA context, literature provides several examples of comparative studies based on Fuel Reduction Value (FRV) coefficient ([2], [3845], [4761], [4862], [4963]). The FRV adopted by current LCAs is comprised within the range between 0.02- and 1.00 [l/100km*100kg]; this estimationsuch a range derives from other works (([1421], [5064], [65], [66], [67], [5168], [5269], [5370], [5471], [72], [5573], [5674], [5775]) that treat with analytical modelling of mass-induced FC takby investigating into accountthe theoretical background and underlying physical correlations. From the review of this typology of studies, some considerations emerge. The researches are based on simulation modelling of a very restricted number of specific car models; therefore the resulting values of FRVs obtainedFRVs are influenced bydepend on technical features of the considered case studies without being really representative of the entire entire vehicle classes or engine technologiesy they belong to. Furthermore the existing works determine the FRV basing on standardized a reference driving cycles ([5876], [5977], [6078];) that 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 [6179] while the European ones to the NEDC [6280]). Consequently the adopted reference cycles changes passing from one study to anthe other, thus involving a relevant limitation in terms of comparability for theof FRV value. Additionally to this, the adoption of a single cycle as basis for calculation strongly limits theinvolves a relevant limitation in terms of reliability of results as no further driving stylepattern is taken into accountevaluated.

The proposed work is an extension of [5064] and it refines an environmental model able to treat with the use stage within the automotive lightweight LCA context in applicationss to Diesel Turbocharged (DT) vehicles; t. he aim is supporting LCA practitioners to evaluate the environmental benefits achievable by light-weighting in real case studies. The aim of the model is supporting LCA practitioners to estimate the environmental benefits achievable by light-weighting in application to real case studiesis aimed estimating the potentiality of lightweighting to lower the environmental impact since the early design phase and it is proposed as tool for LCA practitioners in application to real case studies.Starting from the amount of mass reduction, the model estimates the avoided impacts through the Fuel Reduction Value (FRV) coefficient which is determined by a simplified calculation procedure based on vehicle technical features. Such a procedure derives from an in-depth simulation modelling of car weight-induced FC which tries to fill the gaps of existing literature:

- FRV is estimated for a large number of vehicle case studies belonging to A/B, C and D classes; within each class a wide range of car technical features is taken into account;
- vehicle case studies are representative of 2015 European car market;
- FRV is evaluated basing on the most globally widespread driving cycles;
- the analysis is extended to both Primary Mass Reduction only (PMR) and Secondary Effects (SE); in case of SE a valid criterion for their application is refined.

The benefits advantage obtained throughachieved by mass reduction isare quantified in terms of avoided impacts bythrough an environmental modelling based on the FRV coefficient; this latter is determined through an in depth calculation of weight induced FC which struggles to overcome the points of criticism thatwhich affect current LCA practices.

2. Materials and method

The construction of the model consistsis articulated into of three main stages. In tThe first stage envisages the calculation of FC is calculated for various mass-configurations of a certain number of vehicle case studies; c. The calculation is performed through a car system dynamics simulation modelling of car dynamics. The output of the stage is constituted exclusively by vehicle FC. The second stage evaluates the mass-induced FC starting from the output of the first one; basing on values of FC obtained foreof the different mass-configurations, mass-induced FC is determined through the relation between consumption and mass. The third stage consists in the conception of a tailored LCA model which implements mass-induced FC calculated in stage 2 and provides as an output the LCIA impacts. Following paragraphs describeillustrate in detail the three stages.

2.1. Calculation of use stage FC

The calculation of use stage FC is performed through an AMESim simulation model. Below the modelling is described in terms of model composition, driving cycles and range of vehicle case studies.extension of the analysis. The model estimates torque at wheels needed in order to follow the speed profile of the considered driving cycle by simulating all vehicle drivetrain components of vehicle drivetrain. The automotive network is subdivided into two sections: drive train

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(sub-models: engine, clutch, gearbox and vehicle dynamics) and control logic (sub-models: mission profile and ambient data, driver and control unit). The complete model is shown in Figure 1.

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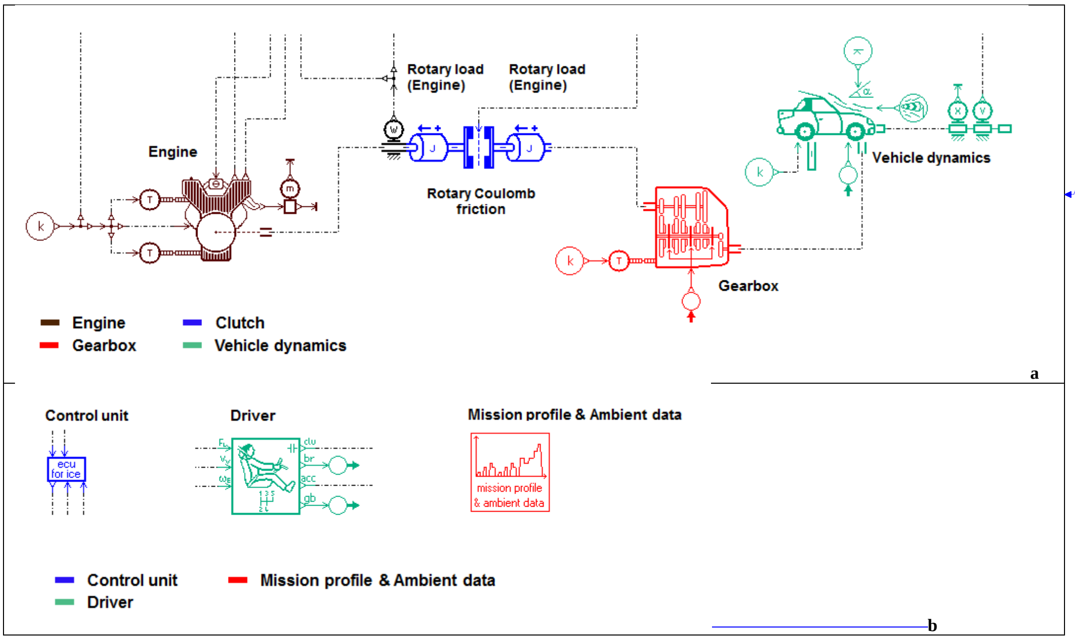

Figure 1. Use stage simulation model: drive train section (a) and control logic section (b)

The driving cycles assumed as reference for simulation ~~modelling~~ are the following: Federal Test Procedure 72 (FTP72) [63~~81~~], Japan 08 (JC08) [64~~82~~], New European Driving Cycle (NEDC) [63~~81~~] and World Light Test Cycle (WLTC) [58~~76~~]. The first three cycles~~y~~ are the reference for current type approval test ~~approval~~ respectively in~~of~~ the U.S., Japan and Europe while WLTC will substitute the NEDC in the coming years. T~~In order to determine results really representative of the considered classes, t~~he modelling is applied to a large~~certain~~ number of DT vehicle case studies~~s~~ ~~belonging to A/B, C and D classes~~ representative of~~from~~ different classes within the 2015 European car market, thus allowing~~; this allows estimating the FRV by a range, thus~~ to consider~~ing~~ a certain variability of ~~vehicle~~ technical features within each class. The number of case studies (see Table 1) ~~within~~ per vehicle~~each~~ class depends exclusively on the availability in literature of data needed for the setting of simulation model.

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Tabella formattata

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Table 1. Reference mass-configuration – Variable model parameters: car models chosen as reference

Reference mass-configuration - Variable model parameters - Reference car models					
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*		

2.2. Evaluation of mass-induced FC reduction

The evaluation of mass-induced FC is performed through the FRV coefficient. The procedure for calculating the FRV is described below separately between the cases of Primary Mass Reduction (PMR) and Secondary Effects (SE).

Primary Mass Reduction (PMR). M~~The m~~ass-induced FC is determined as the consumption saving achievable through car mass reduction only and it is calculated by~~through~~ the following relation:

$$FC_{use\_sav\_PMR} = FRV_{PMR} * mass_{sav} \qquad \text{Eq. 1}$$

Where FRV_{PMR} = Fuel Reduction Value in case of Primary Mass Reduction [l/100km*100kg]; $FC_{use\_sav\_PMR}$ = amount of Fuel Consumption saved during operation thanks to lightweighting in case of Primary Mass Reduction [l/100km]; $mass_{sav}$ = saved mass thanks to lightweighting [kg].

The FRV coefficient is estimated basing on values of FC obtained in stage 1. For each one of ~~the considered~~ vehicle case studies, consumption is calculated for the following five mass-configurations: reference ~~mass~~ and ~~lightweighting of~~ 5%, 10%, 15%, ~~and~~ 20% lightweight~~respectively~~. Starting from values of FC, the FRV is determined as the slope of regression line of consumption in function of mass. As ~~in case of PMR~~ the target is evaluating the effect of mass~~mass~~ only, FC of lightweight configurations is estimated through the same simulation model in which~~where~~ the only ~~parameter that~~ change~~s~~ is vehicle weight, all the others remaining unaltered.

Secondary Effects (SE). M~~The m~~ass-induced FC is determined as the consumption saving achievable through car mass reduction with ~~implementation of~~ further interventions at the vehicle ~~to the vehicle~~. It is calculated through the following relation:

$$FC_{use\_sav\_SE} = FRV_{SE} * mass_{sav} \qquad \text{Eq. 2}$$

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

SE~~econdary Effects~~ are applied to lightweight configurations only and they consist in resizing vehicle powertrain in order that mass reduction is exclusively used for lowering FC while performance and technological levels remain unaltered. For performance level the chosen criterion is the “80-120 km/h elasticity in the upper gear ratio”. On the other hand technological level is represented by parameters Maximum Brake Mean Effective Pressure ($BMEP_{max}$), Stroke-to-Bore ratio (SBR) and Mean Piston Speed (MPS), whose analytical expression is reported below:

$$BMEP_{max} = \frac{T_{max} * 4\pi}{V} \qquad \text{Eq. 3}$$

$$SBR = \frac{stroke}{bore} \qquad \text{Eq. 4}$$

$$MPS = \frac{stroke * rpm}{30} \qquad \text{Eq. 5}$$

Where $BMEP_{max}$ = maximum Brake Mean Effective Pressure [bar]; T_{max} = maximum engine torque [Nm]; V = engine displacement [l]; SBR = Stroke-to-Bore ratio [null]; $stroke$ = engine stroke [m]; $bore$ = engine bore [m]; MPS = Mean Piston Speed [m/s]; rpm = engine speed [rpm].

2.3. Environmental modelling

The third stage consists in the conception of a tailored LCA model able to convert mass reduction to avoided use stage environmental impacts. The model takes into account both ~~the~~ sub-stages that compose ~~the~~ use stage: Well-To-Tank -

WTT (fuel transformation processes upstream to fuel consumption) and Tank-To-Wheel - TTW (FC for car driving). In order to include both quota, a GaBi6 plan composed by ~~the~~ WTT and TTW processes is conceived. In the construction of the plan ~~the~~ TTW process is~~has been~~ completely modelled by an analytical parameterization of inputs/output flows while ~~the~~ WTT process is~~has been~~ taken from the GaBi6 process database (section "Energy conversion-Fuel production-Refinery products") without any modification. For this reason hereinafter~~in the following~~ the only TTW process is described in detail in terms of input/output flows and equations that model input/~~and~~ output flows. Table 2 shows TTW i~~The i~~nputs/~~and~~ output flows ~~of TTW process are reported in Table 2~~ and~~:~~ ~~for each flow~~ a qualitative description ~~and the reference from GaBi6 database~~ of them~~are reported~~.

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Table 2. Environmental model: inputs/outputs and related GaBi6 flows of TTW process

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

The equations that model input/output flows of TTW process are reported in Table 3.

Table 3. Environmental model: basic equations of TTW process

		TTW equations
INPUT	FC_{use_sav}	$FC_{use\_sav} = \frac{FRV * mass_{sav} * mileage_{use}}{10000} * \rho_{fuel}$ *Eq. 6*
OUTPUT	$CO_{2BIO\_use\_sav}$	$CO_{2BIO\_use\_sav} = CO_{2BIO\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav}}{FC_{use\_veh}}$ *Eq. 7* Where: $CO_{2BIO\_veh\_km} = CO_{2\_veh\ km} * share\ CO_{2BIO}$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$CO_{2FOS\_use\_sav}$	$CO_{2FOS\_use\_sav} = CO_{2FOS\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav}}{FC_{use\_veh}}$ *Eq. 8* Where: $CO_{2FOS\_veh\_km} = CO_{2\_veh\_km} * (1 - share\ CO_{2BIO})$ $CO_{2\_veh\_km} = share_{mw} * CO_{2\_veh\_km\_mw} + share_{ru} * CO_{2\_veh\_km\_ru} + share_{ur} * CO_{2\_veh\_km\_ur}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$
	$SO_{2\_use\_sav}$	$SO_{2\_use\_sav} = SO_{2\_veh\_km} * mileage_{use} * \frac{FC_{use\_sav}}{FC_{use\_veh}}$ *Eq. 9* Where: $SO_{2\_veh\_km} = \frac{ppm_{sulphur}}{1000000} * 2 * \frac{FC_{veh\_100km}}{100} * \rho_{fuel}$ $FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} * mileage_{use} * \rho_{fuel}$

Legend~~a~~:
FRV = Fuel Reduction Value [l/100km*100kg];
$mass_{sav}$ = saved mass thanks to lightweighting [kg];
$mileage_{use}$ = total mileage during operation [km];
ρ_{fuel} = fuel density [kg/l];
$CO_{2BIO\_veh\_km}$ = per-kilometre biogenic CO_2 emission of reference vehicle [g/km];
FC_{use_veh} = amount of Fuel Consumption during operation of reference vehicle [g/km];
$CO_{2\_veh\_km}$ = per-kilometre CO_2 emission of reference vehicle [g/km];
$share\ CO_{2BIO}$ = share of biogenic C in fuel;
$share_{mw}$ $share_{ru}$ $share_{ur}$ = share of total mileage respectively for motorway, rural and urban route;
$CO_{2\_veh\_km\_mw}$, $CO_{2\_veh\_km\_ru}$, $CO_{2\_veh\_km\_ur}$ = per-kilometre CO_2 emission of reference vehicle respectively for motorway, rural and urban route [g/km];
FC_{veh_100km} = per-100kilometre Fuel Consumption of reference vehicle [l/100km];
$CO_{2FOS\_veh\_km}$ = per-kilometre fossil CO_2 emission of reference vehicle [g/km];
$SO_{2\_veh\_km}$ = per-kilometre SO_2 emission of reference vehicle [kg/km];
ppm_{suphur} = sulphur content in fuel [ppm];

The environmental model is customiz~~tailor~~able for the specific case study through the setting of the following parameters:

- $CO_{2\_veh\_km}$ and $SO_{2\_veh\_km}$ are taken from the GaBi6 process database (section "Transport-Road-Passenger car") depending on emission standard, engine size and technology of the specific~~considered~~ case study~~vehicle~~;
- *FRV* is an output of stage 2 "Evaluation of mass-induced FC reduction" and it is chosen depending on the specific case study through the criteria identified in paragraph 3.2~~4.1.~~;
- ρ_{fuel}, $mileage_{use}$, $ppm_{sulphur}$, $share\ CO_{2BIO}$ are taken from the GaBi6 process database depending on fuel type of the specific case study~~considered vehicle~~;
- $FC_{veh\ 100km}$, $mass_{saved}$, $mileage_{use}$, $share_{mw}$, $share_{ru}$, $share_{ur}$ depend on the specific case study~~application~~.

3. Results, interpretation and discussion

Results, interpretation and discussion are presented subdivided into two main sections: simulation and environmental modelling.

3.1. Simulation modelling

Fuel Reduction Value: analysis of results. Table 4 reports the FRV~~s~~ for all~~ the considered~~ case studies. Data are presented for both PMR (FRV_{PMR}) and SE (FRV_{SE}). W~~ and w~~ithin each one of them five values are reported:

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- four values calculated with respect to 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 for the 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}, $FRV_{MeanCycles\_SE}$.

Table 4. Fuel Reduction Value for the considered case studies [l/100km*100kg]

		FRV [l/100km*100kg]									
		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

Figure 2~~Figure 2~~ reports the arithmetic mean of FRV within the class per driving cycle: the black bars identify the maximum range of variation around the mean.

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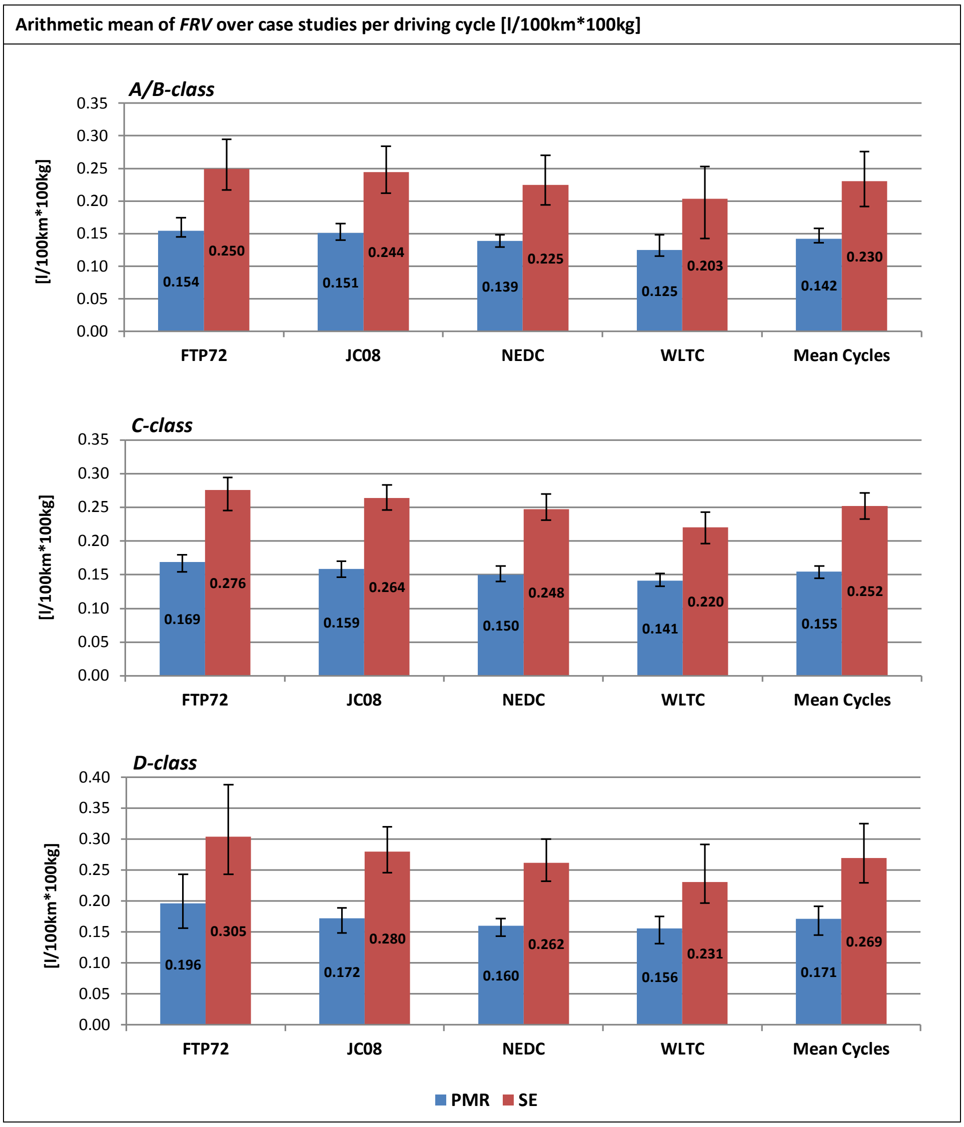

Figure 2. Arithmetic mean of FRV over case studies per driving cycle [l/100km*100kg]

Dependence of FRV on vehicle technical features. This sub-paragraph is aimed to establish if any correlation between the values of FRV and the main vehicle technical features exists. The~~ investigated~~ parameters taken into account are *maximum Brake Mean Effective Pressure* ($BMEP_{max}$), *vehicle mass* (m_{veh}), *maximum Power* (P_{max}) and *Power-to-Mass Ratio* (*P/M*). The existence of any correlation is investigated through the analysis of regression lines of $FRV_{MeanCycles\_PMR}$ and $FRV_{MeanCycles\_SE}$~~ respectively~~ in function of $BMEP_{max}$, m_{veh}, P_{max} and *P/M*~~ w~~; Figure 3 reports~~ith~~ regression lines and corresponding coefficient of determination~~ R^2 (Figure 3).~~ for $FRV_{MeanCycles}$~~.~~

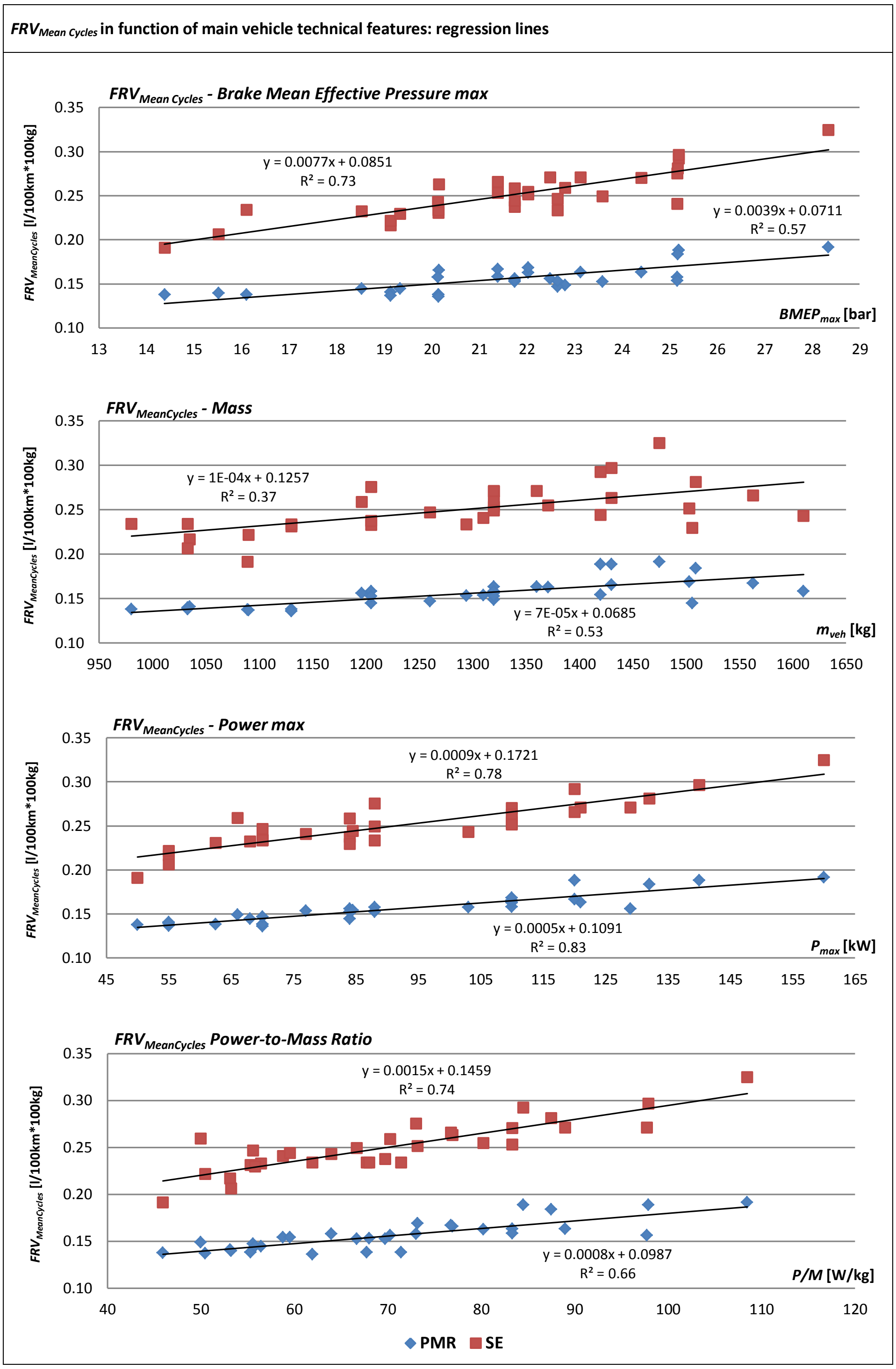

Figure 3. $FRV_{MeanCycles}$ of all case studies in function of maximum Brake Mean Effective Pressure ($BMEP_{max}$), vehicle mass (m_{veh}), maximum Power (P_{max}) and Power-to-Mass Ratio (P/M) with regression lines and corresponding coefficient of determination R^2

Table 5 quantifies the effectiveness of the correlation between FRV and vehicle parameters by reporting R^2 of regression lines for FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, FRV_{WLTC} and $FRV_{MeanCycles}$.

Table 5. Coefficient of determination R^2 of regression lines of FRV in function of vehicle technical features

	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
Maximum Brake Mean Effective Pressure ($BMEP_{max}$)	0.55	0.68	0.61	0.71	0.40	0.69	0.57	0.67	0.57	0.73
Vehicle mass (m_{veh})	0.45	0.36	0.46	0.41	0.53	0.43	0.59	0.21	0.53	0.37
Maximum Power (P_{max})	0.79	0.78	0.78	0.80	0.74	0.82	0.78	0.55	0.83	0.78
Power-to-Mass Ratio (PMR)	0.65	0.72	0.66	0.73	0.56	0.75	0.58	0.57	0.66	0.74

The values of R^2 in Table 5 showevidence that for both PMR and SE a significant correlation between FRV and vehicle technical features exists. The values of R^2 variesy 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_{veh} (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*.

3.2. Environmental modelling

The environmental modelling converts mass saving to impact reduction through the implementation of the FRV coefficient within the basic equations of TTW process; the added value is represented by the fact that parameters which characterize TTW process (see paragraph 2.3.) are customizable foron the specific application. 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; t. hereforeSo that impacts saving achievable through lightweighting isis determined more accurately with respect to comparative studies that assume as reference a value for theof FRV fixed a priori. In order to customize the environmental model described in paragraph 2.3. in such a way it represents a valid reference for LCA practitioners in application to real case studies, Based on the entirety of FRVs obtained for the various case studies, a criterion able to deduce a value of FRV customizedtailored for any genericany generic application starting from the entirety of FRVs referring to the various case studies is definneeded; therefore. By so doing simulation and environmental modelling are merged and the output of the first one represents the input forof the second one. The chosen approach struggles to take into account the variability of FRV with respect to the main vehicle technical features. Previous paragraph analyzes the correlation between FRV and maximum Brake Mean Effective Pressure ($BMEP_{max}$), vehicle mass (m_{veh}), maximum Power (P_{max}) and Power-to-Mass Ratio (*P/M*) by identifying regression lines and corresponding coefficients of determination R^2. Basing on values of R^2 reported in Table 5, it has been shown that it can be stated that for both PMR 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 quantifying the FRV for any generic application is the same for both PMR and SE:

- PMR: 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 3).
- 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 3).

Table 6 summarizes the chosen approach in order to quantify the FRV for application to any generic vehicle case study.

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Table 6. Input for environmental modelling: criterion for quantifying the FRV of any generic vehicle case study

FRV [l/100km*100kg]	
PMR	**SE**
$FRV_{PMR} = 0.0005 * P_{max} + 0.1091$ ~~$FRV_{PMR} = 0.0009 * P_{max} + 0.1721$~~	$FRV_{SE} = 0.0009 * P_{max} + 0.1721$ ~~$FRV_{SE} = 0.0005 * P_{max} + 0.1091$~~

Notes: P_{max} in [kW]

With respect to basic equations of TTW process (see Table 3) 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 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 impact is calculated~~. On the other hand FC_{use_sav} determines the amount of TTW air emissions saved during operation~~ on the basis of which the saving in TTW impact is calculated~~ (see Eq. 7, 8, 9);
- 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 too with the saved mass, also the saved emissions behaves the same way~~;
- 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 while the limited emissions depend exclusively on the number of travelled kilometers as they are treated by exhaust gas treatment system.

3.3. Application to real case study

This section deals with the application of simulation and environmental modelling to a real LCA case study. The chosen application is taken from a comparative lightweight LCA for an automotive component [39]~~(Delogu et al., 2015)~~. The assessment is aimed to assess two solutions for an Air Intake Manifold (AIM) which differ in construction material:

- Reference solution: polyamide reinforced with 30% of glass fibre, PAGF30 (scenario n°1 in [39]~~Delogu et al., 2015~~);
- Lightweight solution: polypropylene composite reinforced with 35% of glass fibre, PPGF35 (scenario n°5 [39]~~in Delogu et al., 2015~~).

The functional unit for the study is the distribution of the appropriate air intake flow to the individual cylinders of a 1300cc DT engine in order to ensure the correct combustion process of the fuel. The PAGF30 AIM mass is about 1.9 kg opposite to 1.6 kg of PPGF35 AIM; therefore the lightweight solution allows a 18% mass reduction. For the impact assessment, the following impact categories are adopted: abiotic depletion potential elements (ADPe), abiotic depletion potential fossil (ADPf), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP) ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP). As reference vehicle~~car~~ for the modelling of use stage, a specific compact car is~~has been~~ selected: Table 7 shows its main technical data.

Table 7. Technical data of reference car model for use stage

FIAT Panda 1.3. MJT (model year 2016)	
Curb mass [kg]	1045
Propulsion	Diesel Turbocharged
Engine displacement [cc]	1248
Maximum power [kW]	70

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Emission stage	EURO 6
Mixed consumption [l/100km]	3.6
CO_2 emissions [g/km]	94
SO_2 emissions [g/km]	~~Vedere da GaBi~~$6.42*10^{-4}$
Use stage [km]	150000

~~**Table 7.** Technical data of reference car model for use stage~~

Considering that weight reduction represents a negligible share of total car mass, for the modelling of use stage it is assumed to take into account only the case of PMR; FRV is determined through the criterion defined in paragraph 3.2. (equation for FRV_{PMR} in Table 6) and it amounts to 0.144 l/100km*100kg.

Figure 4 reports total LC impact of lightweight solution expressed as percentage of the one of reference solution. Results show that lightweight solution involves a notable reduction of the AIM LC ~~potential environmental~~ impacts. The highest ~~impact~~ reduction (40%) regards AP, while for ADPe the benefit is negligible (3%); the other categories present reductions that range between 27 and 35%.

Figures 5 and 6 report contribution analysis by LC stage of potential environment impact respectively for polyamide and polypropylene composite AIM. Data show that the change of construction material causes a notable growth of use stage quota for the majority of impact categories (15 – 20%), totally to the detriment of production. This fact can be explainable through the minor energy intensity of polypropylene composite production processes despite the lower mass. EoL quotas present a moderate increase (maximum increase is 6% for EP).

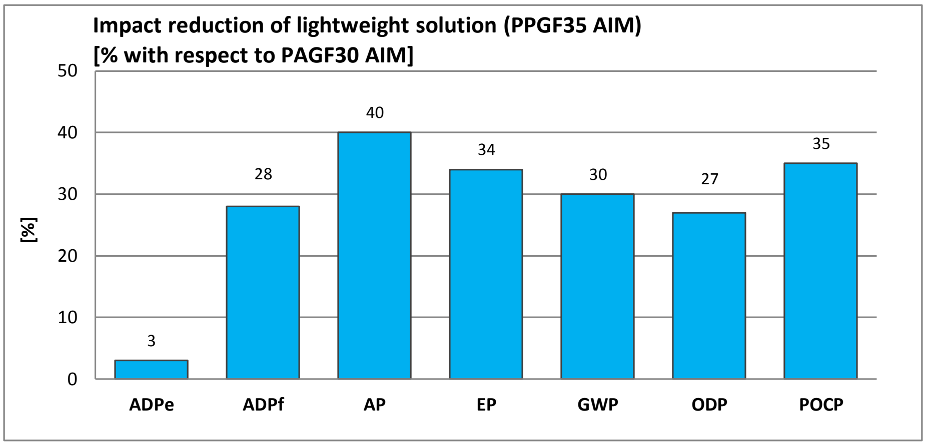

Figure 4. LCA results for polypropylene composite AIM expressed as percentage of polyamide composite AIM

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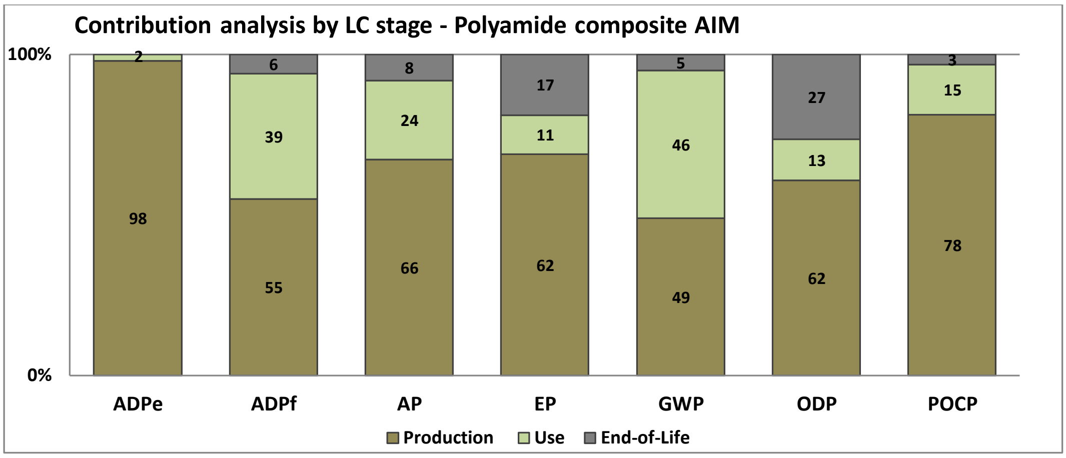

Figure 5. Contribution analysis by LC stage for polyamide composite AIM

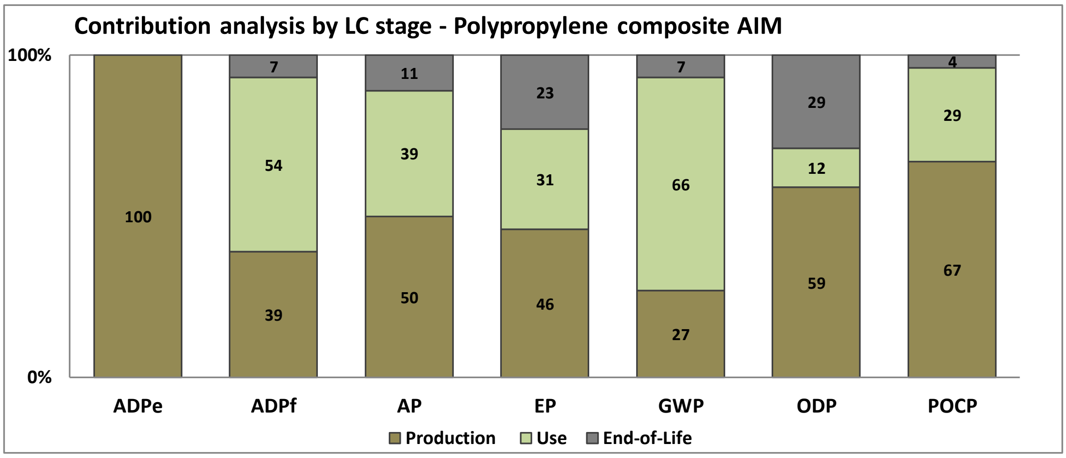

Figure 6. Contribution analysis by LC stage for polypropylene composite AIM

4. Conclusions

The work refines a tool for the assessment of environmental benefits achievable by lightweight design solutions in the automotive field. The tool is obtained through the integration of~~ an use stage~~ a simulation and environmental modelling ~~that implements a FRV-based approach with an environmental modelling~~ in LCA perspective and it is based on t~~.~~ ~~T~~he estimation of FC reduction achievable by light-weighting by means of~~is performed basing on~~ the FRV coefficient. The FRV is determined through a simulation modelling of entire vehicle drivetrain; this allows taking into account all car energy expenditures and evaluating the effect that each drivetrain component has on FC and, consequently, on FRV. As input for the modelling, data of 32 DT vehicle case studies~~vehicle models~~ taken from 2015 European car market are~~have been~~ gathered and elaborated; the~~d. The characterization of FRV for a~~ wide range of~~ vehicle~~ case studies enables examining as much as possible in detail each specific application, thus obtaining more accurate results with respect to current FRV-based approaches~~existing studies~~~~FRV-based approach literature~~. The calculation is based on~~performed taking into account not only the NEDC but also other three~~ four standardized driving cycles, allowing both comparison with existing studies and evaluation of use stage basing on various driving styles~~scenarios of route and driving behavior~~. For the estimation of~~ environmental~~ impacts reduction~~ achievable by lightweighting~~, a model based on the FRV and customiz~~tailor~~able for any generic application is refined; this is done~~. The potentiality to lower FC through mass reduction is estimated~~ by taking into account the value of FRV~~ (output of simulation modelling) that is~~ closest to the specific application in terms of vehicle class, size and technical features. The~~is~~ remarkable modularity of

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the model allowspermits to obtaine more accurate results with respect to literature. Particularly, in the comparative LCA perspective, a balancinge between the opposite effects that the adoption of light-weighting design solutions involves on component LC stages (higher energy-intensity/emissions during production and reduced FC during operation) is possible; in this regard. Furthermore, the possibility to set LC mileage within the environmental modelling allows to determineidentifying the break-even mileage for the effective environmental convenience of innovative lightweight solutions with respect to the reference ones. At this regard, the model is able to perform assessments both in case lightweighting does not involve car re-design and in case re-design is applied to the vehicle.

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