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Article

Lightweight Design Solutions in the Automotive Field: Environmental Modelling Based on Fuel Reduction Value Applied to Diesel Turbocharged Vehicles

Massimo Delogu *, Francesco Del Pero and Marco Pierini

Department of Industrial Engineering, University of Florence, Florence 50139, Italy; francesco.delpero@unifi.it (F.D.P.); marco.pierini@unifi.it (M.P.)

* Correspondence: massimo.delogu@unifi.it; Tel.: +39-055-275-8733

Abstract: A tailored model for the assessment of environmental benefits achievable by "light-weighting" 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 mass reduction. The work is composed of 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/100 km × 100 kg, respectively, for mass reduction only and powertrain adaptation (secondary effects). The implementation of FRVs within the environmental modelling represents the added value of the research and makes the model a valuable tool for application to real case studies of automotive lightweight LCA.

Keywords: automotive, fuel consumption; Fuel Reduction Value (FRV); Life Cycle Assessment (LCA); light-weighting; vehicle system dynamics

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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 greenhouse gas (GHG) emissions, and around 20% of these emissions are caused 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 two 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 [6–11]. For an Internal Combustion Engine (ICE) car, use stage is responsible for a relevant quota of total Life Cycle (LC) impact (e.g., 85% in terms of Global Warming Potential (GWP)); the latter is mainly due to Fuel Consumption (FC), which strongly depends on vehicle mass [12–19].

"Light-weighting" is unanimously recognized as one of the key measures in order to lower car use stage FC and environmental burden [20–24]; on the other hand, the adoption of novel materials and innovative technologies often shifts the impacts to other LC stages (e.g., production and End-of-Life (EoL)) [25,26]. In this regard, plastics, composites, aluminium, high-strength steel and magnesium and sandwich materials are expected to play a leading role in the future. Aluminium, high-strength steel and composites can be used both in structural (i.e., frame or seat structure) and functional (i.e., steering or transmission) parts where strength is the key requirement; on the other

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hand, for interior parts, plastic will remain the predominant element and it will also become more important in the future, due to its favourable cost-weight ratio. On the other hand, even though light-weighting allows lowering use stage impact by reduction of FC, it usually involves negative effects on production and EoL stages [27–31]. Indeed, lightweight materials are usually more energy-intensive and involve higher CO_2 emissions prior to operation 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 [12,32–35]. Therefore, a balance of benefits and disadvantages involved with 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 actual benefits.

The Life Cycle Assessment (LCA) methodology is the most indicated approach for performing the environmental assessment of lightweight solutions. Many LCA studies already exist in the transportation sector [36–40] and interest is continuously growing, particularly in the automotive field [12,37,41–46].

Considering the automotive lightweight LCA context, literature provides several examples of comparative studies based on Fuel Reduction Value (FRV) coefficient [2,38,47–49]. The FRV adopted by current LCAs is comprised within the range 0.02–1.00 L/100 km × 100 kg; this estimation derives from other works [14,50–57] hat model mass-induced FC taking into account 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 values of FRV are influenced by technical features of case studies without being really representative of entire vehicle classes or engine technologies. Furthermore, the existing works determine the FRV basing on standardized driving cycles [58–60]: the American researches generally refer to the Federal Test Procedure driving cycles [61] while the European ones to the NEDC [62]. Consequently, the reference cycle changes passing from one study to another, thus involving a relevant limitation in terms of comparability for the FRV value. Additionally, the adoption of a single cycle as basis for calculation strongly limits the reliability of results as no further driving styles are taken into account.

The proposed work is an extension of [50] and it refines an environmental model able to treat the use stage within the automotive lightweight LCA context in applications to Diesel Turbocharged (DT) vehicles; the aim is supporting LCA practitioners to evaluate the environmental benefits achievable by light-weighting in 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 based on the most globally widespread driving cycles;
- The analysis is extended to both Primary Mass Reduction only (PMR) and Secondary Effects (SE); in the case of SE, a valid criterion for their application is refined.

2. Materials and Methods

The construction of the model consists of three main stages. In the first stage, FC is calculated for various mass-configurations of a certain number of vehicle case studies; calculation is performed through simulation modelling of car dynamics. The second stage evaluates the mass-induced FC starting from the output of the first one; based on values of FC obtained for 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 LCIA impacts. The following paragraphs describe in detail the three stages.

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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. The model estimates torque at wheels needed in order to follow the speed profile of driving cycle by simulating all components of vehicle drivetrain. The automotive network is 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 complete model is shown in Figure 1.

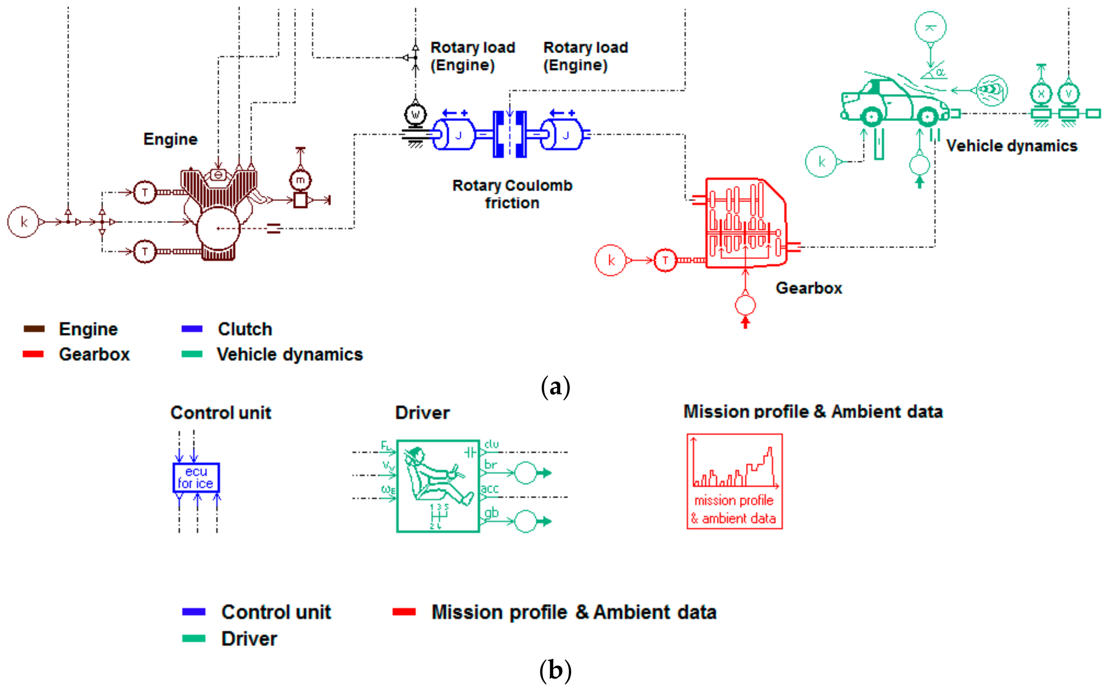

Figure 1. Use stage simulation model: drive train section (**a**); and control logic section (**b**).

The driving cycles assumed as reference for simulation are the following: Federal Test Procedure 72 (FTP72) [63], Japan 08 (JC08) [64], New European Driving Cycle (NEDC) [63] and World Light Test Cycle (WLTC) [58]. The first three cycles are the reference for current type approval test, respectively, in the U.S., Japan and Europe, while WLTC will substitute the NEDC in the coming years. The modelling is applied to a large number of DT vehicle case studies representative of different classes within the 2015 European car market, thus allowing the consideration of a certain variability of technical features within each class. The number of case studies (see Table 1) per vehicle class depends exclusively on the availability in literature of data needed for the setting of simulation model.

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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): Mass-induced FC is determined as the consumption saving achievable through car mass reduction only and it is calculated by equation 1:

$$FC_{use\_sav\_PMR} = FRV_{PMR} \times mass_{sav} \quad (1)$$

where FRV_{PMR} = Fuel Reduction Value in the case of Primary Mass Reduction (L/100 km·100 kg); $FC_{use\_sav\_PMR}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in the case of Primary Mass Reduction (L/100 km); and $mass_{sav}$ = saved mass thanks to light-weighting (kg).

The FRV coefficient is estimated based on values of FC obtained in Stage 1. For each of the vehicle case studies, consumption is calculated for the following five mass-configurations: reference and 5%, 10%, 15%, and 20% lightweight. Starting from values of FC, the FRV is determined as the slope of regression line of consumption in function of mass. As the target is evaluating the effect of mass only, FC of lightweight configurations is estimated through the same simulation model, in which the only change is vehicle weight, and all others remain unaltered.

Secondary Effects (SE): Mass-induced FC is determined as the consumption saving achievable through car mass reduction with further interventions in the vehicle. It is calculated through equation 2:

$$FC_{use\_sav\_SE} = FRV_{SE} \times mass_{sav} \quad (2)$$

where FRV_{SE} = Fuel Reduction Value in the case of Secondary Effects (L/100 km × 100 kg); $FC_{use\_sav\_SE}$ = amount of Fuel Consumption saved during operation thanks to light-weighting in the case of Secondary Effects (L/100 km); and $mass_{sav}$ = saved mass thanks to light-weighting (kg).

SE 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". 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 expressions are reported below (equations 3, 4, 5):

$$BMEP_{max} = \frac{T_{max} \times 4\pi}{V} \quad (3)$$

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$$SBR = \frac{stroke}{bore} \quad (4)$$

$$MPS = \frac{stroke \times rpm}{30} \quad (5)$$

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); and 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 sub-stages that compose 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 WTT and TTW processes is conceived. In the construction of the plan, TTW process is completely modelled by an analytical parameterization of inputs/output flows while WTT process is taken from the GaBi6 process database (section "Energy conversion-Fuel production-Refinery products") without any modification. For this reason, hereinafter, the only TTW process is described in detail in terms of input/output flows and equations that model input/output flows. Table 2 shows TTW inputs/output flows and a qualitative description of them.

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 light-weighting (FC_{use_sav})	*Diesel—Refinery products* (kg)
OUTPUT	Amount of biogenic CO_2 emission saved during operation thanks to light-weighting ($CO_{2BIO\_use\_sav}$)	*Carbon dioxide (biotic)—Inorganic emissions to air* (g)
	Amount of fossil CO_2 emission saved during operation thanks to light-weighting ($CO_{2FOS\_use\_sav}$)	*Carbon dioxide (fossil)—Inorganic emissions to air* (g)
	Amount of SO_2 emission saved during operation thanks to light-weighting ($SO_{2\_use\_sav}$)	*Sulphur dioxide—Inorganic emissions to air* (kg)

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

The environmental model is customizable 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 case study;
- 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 Section 3.2;
- ρ_{fuel}, $mileage_{use}$, $ppm_{sulphur}$, and $share\ CO_{2BIO}$ are taken from the GaBi6 process database depending on fuel type of the specific case study;
- $FC_{veh\ 100km}$, $mass_{saved}$, $mileage_{use}$, $share_{mw}$, $share_{ru}$, and $share_{ur}$ depend on the specific case study.

Table 3. Environmental model: Basic equations of TTW process.

			TTW equations	
INPUT	FC_{use_sav}		$FC_{use\_sav} = \frac{FRV \times mass_{sav} \times mileage_{use}}{10000} \times \rho_{fuel}$	(6)
OUTPUT	$CO_{2BIO\_use\_sav}$		$CO_{2BIO\_use\_sav} = CO_{2BIO\_veh\_km} \times mileage_{use} \times \frac{FC_{use\_sav}}{FC_{use\_veh}}$	(7)
		Where:	$CO_{2BIO\_veh\_km} = CO_{2\_veh\_km} \times share\ CO_{2BIO}$	(8)
			$CO_{2\_veh\_km} = share_{mw} \times CO_{2\_veh\_km\_mw} + share_{ru} \times CO_{2\_veh\_km\_ru} + share_{ur} \times CO_{2\_veh\_km\_ur}$	(9)
			$FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} \times mileage_{use} \times \rho_{fuel}$	(10)
	$CO_{2FOS\_use\_sav}$		$CO_{2FOS\_use\_sav} = CO_{2FOS\_veh\_km} \times mileage_{use} \times \frac{FC_{use\_sav}}{FC_{use\_veh}}$	(11)
		Where:	$CO_{2FOS\_veh\_km} = CO_{2\_veh\_km} \times (1 - share\ CO_{2BIO})$	(12)
	$SO_{2\_use\_sav}$		$SO_{2\_use\_sav} = SO_{2\_veh\_km} \times mileage_{use} \times \frac{FC_{use\_sav}}{FC_{use\_veh}}$	(13)
		Where:	$SO_{2\_veh\_km} = \frac{ppm_{sulphur}}{1000000} \times 2 \times \frac{FC_{veh\_100km}}{100} \times \rho_{fuel}$	(14)
			$FC_{use\_veh} = \frac{FC_{veh\_100km}}{100} \times mileage_{use} \times \rho_{fuel}$	(15)

Legend:
FRV = Fuel Reduction Value (l/100 km × 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/100 km);
$CO_{2FOS\_veh\_km}$ = 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);

3. Results, Interpretation and Discussion

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

3.1. Simulation Modelling

Fuel Reduction Value: analysis of results. Table 4 reports the FRV for all case studies. Data are presented for both PMR (FRV_{PMR}) and SE (FRV_{SE}). Within each of them, five values are reported: four values calculated with respect to driving cycles assumed as reference for the study (FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, and FRV_{WLTC}); and one value calculated as the arithmetic mean of FRV_{FTP72}, FRV_{JC08}, FRV_{NEDC}, and FRV_{WLTC} ($FRV_{MeanCycles}$).

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

- PMR: FRV_{FTP72_PMR}, FRV_{JC08_PMR}, FRV_{NEDC_PMR}, FRV_{WLTC_PMR}, and $FRV_{MeanCycles\_PMR}$; and
- 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/100 km × 100 kg).

		FRV **(L/100 km × 100 kg)**									
		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

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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.

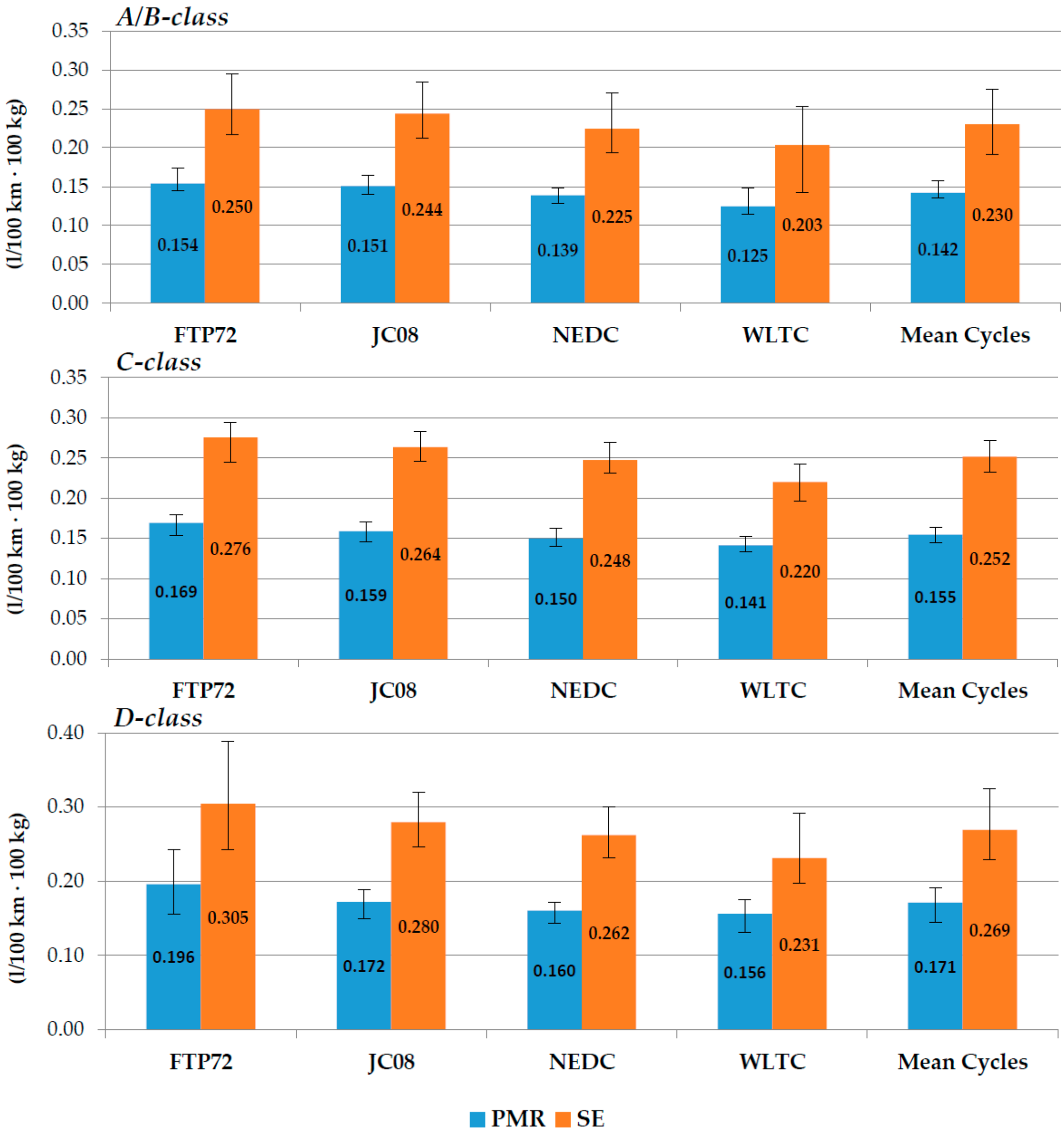

Figure 2. Arithmetic mean of FRV over case studies per driving cycle (L/100 km × 100 kg).

Dependence of FRV on vehicle technical features. This paragraph aims to establish if any correlation between the values of FRV and the main vehicle technical features exists. The 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_{PMR} and FRV_{SE} in function of $BMEP_{max}$, m_{veh}, P_{max} and P/M. Figure 3 reports regression lines and corresponding coefficient of determination for $FRV_{MeanCycles}$.

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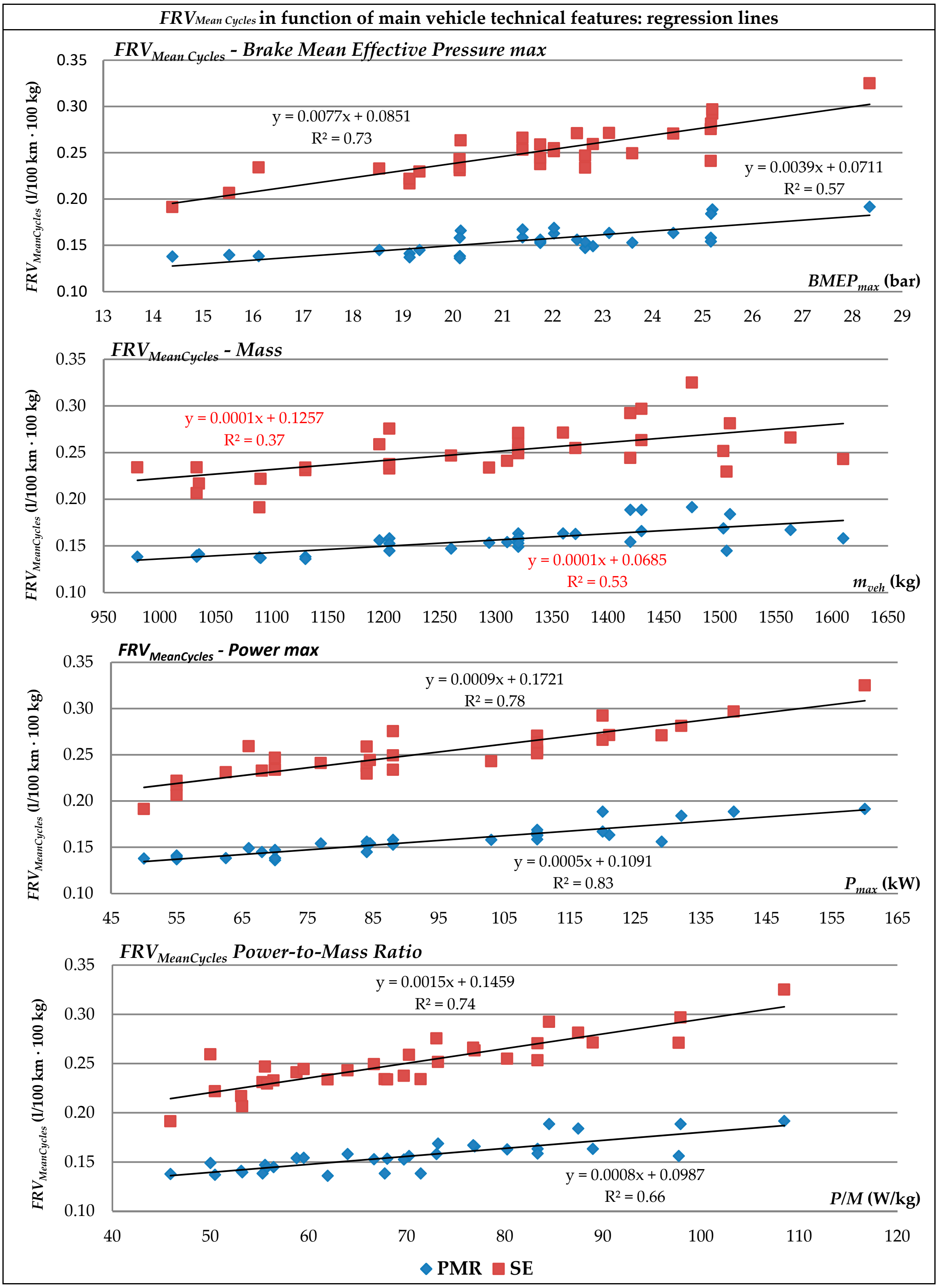

Figure 3. $FRV_{MeanCycles}$ of all case studies in function of maximum Brake Mean Effective Pressure ($BMEP_{max}$), vehicle mass (m_{veh}), maximum Power (P_{max}) and Power-to-Mass Ratio (P/M) with regression lines and corresponding coefficient of determination (R^2).

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

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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 show that, for both PMR and SE, a significant correlation between FRV and vehicle technical features exists. R^2 varies 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 Section 2.3) are customizable for the specific application. In particular, the possibility of setting the FRV allows performing the quantification of impact reduction taking into account technical features of the specific case study; therefore, impacts saving is determined more accurately with respect to comparative studies that assume a value for the FRV fixed a priori. Based on the entirety of FRVs obtained for the various case studies, a criterion able to deduce a value customized for any generic application is defined; therefore, simulation and environmental modelling are merged and the output of the first one represents the input for the second one. The chosen approach struggles to take into account the variability of FRV with respect to the main vehicle technical features. Based on values of R^2 reported in Table 5, 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 any generic vehicle case study.

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

FRV (L/100 km·100 kg)	
PMR	SE
$FRV_{PMR} = 0.0005 \times P_{max} + 0.1091$	$FRV_{SE} = 0.0009 \times P_{max} + 0.1721$

Notes: P_{max} in (kW).

With respect to basic equations of TTW process (see Table 3), the following observations are made:

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- The amount of FC saved during operation (FC_{use_sav}) has a leading role in the economy of the overall plan. On the one hand, FC_{use_sav} fixes the amount of fuel whose avoided production is assessed by WTT process. On the other hand, FC_{use_sav} determines the amount of TTW air emissions saved during operation (see Equations (7)–(15));
- FC_{use_sav} scales linearly with the saved mass on the basis of the FRV coefficient;
- The amount of air emissions saved during operation ($CO_{2BIO\_use\_sav}$, $CO_{2FOS\_use\_sav}$, and SO_{2use_sav}) scales linearly with the amount of FC saved during operation (FC_{use_sav});
- 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 only influences 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 kilometre,s 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]. 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]).
- Lightweight solution: Polypropylene composite reinforced with 35% glass fibre, PPGF35 (scenario N 5 [39]).

The functional unit for the study is the distribution of the appropriate air intake flow to the individual cylinders of a 1300 cc 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), and photochemical ozone creation potential (POCP). As reference vehicle for the modelling of use stage, a specific compact car is 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
Emission stage	EURO 6
Mixed consumption (L/100 km)	3.6
CO_2 emissions (g/km)	94
SO_2 emissions (g/km)	6.42×10^{-4}
Use stage (km)	150,000

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 Section 3.2 (equation for FRV_{PMR} in Table 6) and it amounts to 0.144 L/100 km × 100 kg.

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 impacts. The highest 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

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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).

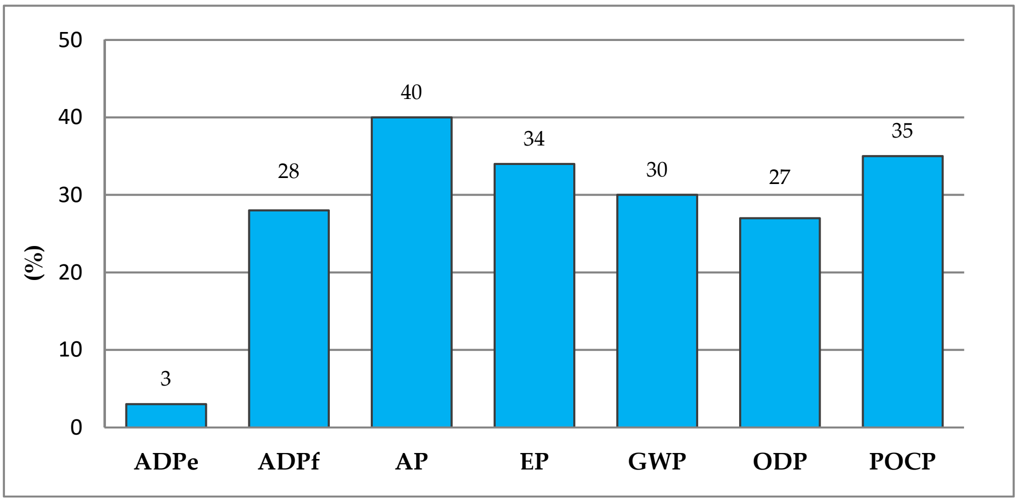

Figure 4. LCA results for polypropylene composite AIM (PPGF35 AIM) expressed as percentage of polyamide composite AIM (PAGF30 AIM)

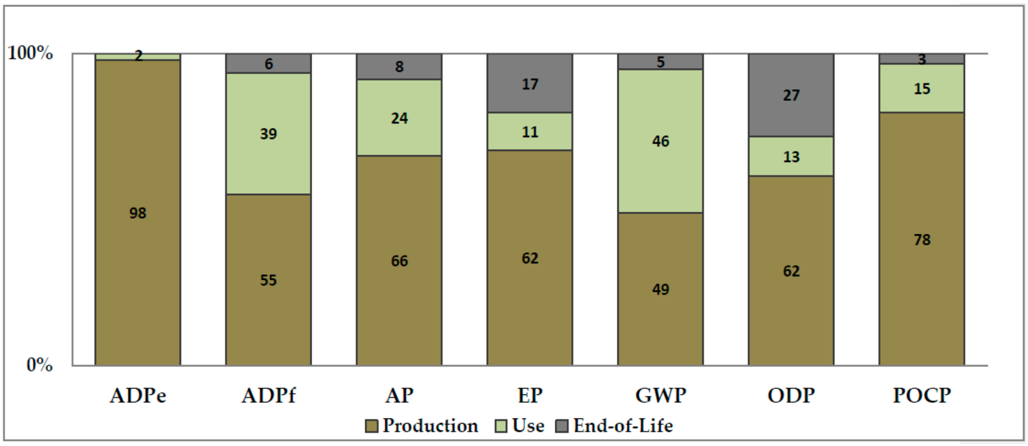

Figure 5. Contribution analysis by LC stage for polyamide composite AIM.

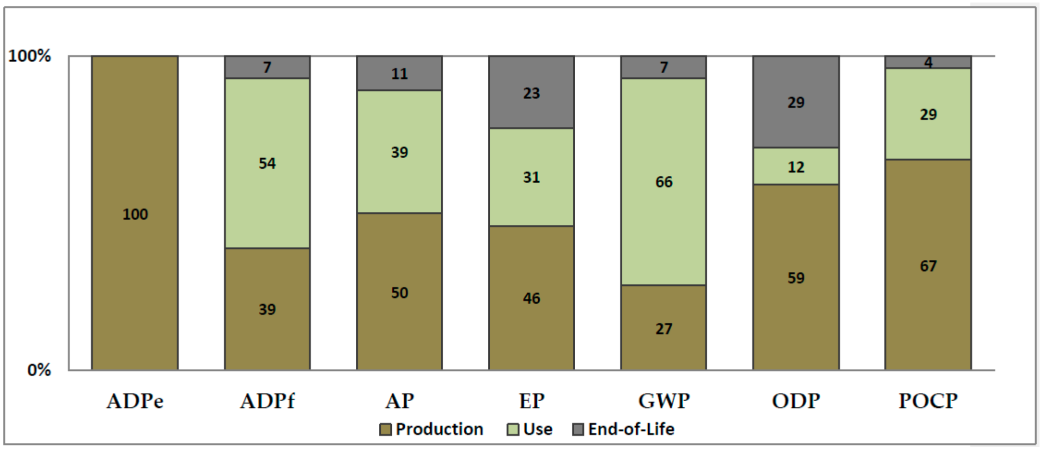

Figure 6. Contribution analysis by LC stage for polypropylene composite AIM.

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4. Conclusions

This 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 a simulation and environmental modelling in LCA perspective and it is based on the estimation of FC reduction achievable by "light-weighting" by means of 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 taken from 2015 European car market are gathered and elaborated; the wide range of 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. The calculation is based on four standardized driving cycles, allowing both comparison with existing studies and evaluation of use stage basing on various driving styles. For the estimation of impacts reduction, a model based on the FRV and customizable for any generic application is refined; this is done by taking into account the value of FRV closest to the specific application in terms of vehicle class, size and technical features. The remarkable modularity of the model allows balancing the opposite effects that light-weighting involves on LC stages (higher energy-intensity/emissions during production and reduced FC during operation); in this regard, the possibility to set LC mileage within the environmental modelling allows determining the break-even mileage for the effective environmental convenience of innovative solutions with respect to reference ones.

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