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Article

Exploring the Impact of Vehicle Lightweighting in Terms of Energy Consumption: Analysis and Simulation on Real Driving Cycle

Giulia Sandrini *, Daniel Chindamo, Marco Gadola, Andrea Candela and Paolo Magri

Department of Mechanical and Industrial Engineering, University of Brescia, I-25123 Brescia, Italy

* Correspondence: giulia.sandrini@unibs.it

Abstract: Today, reducing vehicle energy consumption is a crucial topic. For electric vehicles, reducing energy consumption is essential to address some of the most critical issues associated with this type of vehicle, such as the limited range of electric powertrains and the long battery recharging times. To lower the environmental impact during the vehicle's use phase and reduce energy consumption, vehicle mass reduction (lightweighting) is an effective strategy. The objective of this work is to analyze the vehicle parameters that influence lightweighting outcomes on a real driving cycle, representative of the home-to-work travel in the northern Italy. In particular, a previous work carried out on standard driving cycles is repeated, in order to observe whether it is possible to draw the same conclusions regarding the variability of the lightweighting outcome. This study was conducted using two opposite vehicle models, a compact car and an N1 vehicle, simulated through a well-established vehicle simulation tool for energy consumption estimation. The study reveals that even for the real driving cycle, as for the WLTC and US06 standards, the parameters that most influence the outcome of the lightening are rolling resistance, the characteristics of the battery pack, the aerodynamic coefficients and the efficiency of the transmission. Finally, the standard cycle that best fits with the real one considered in this study is the Artemis Urban Cycle.

Keywords: vehicle lightweighting; automotive; energy consumption; consumption analysis; Fuel Reduction Value (FRV); Energy Reduction Value (ERV); real driving cycle; real data

1. Introduction

The issue of reducing consumption has become highly significant today, both for internal combustion vehicles and electric vehicles. Fuel efficiency is especially crucial for internal combustion engines due to the concerns about emissions and the strict regulations surrounding them [1–3]. On the other hand, for electric vehicles, minimizing energy consumption is key to addressing some of their most pressing challenges, particularly the limited driving range and the long battery recharging times [4].

A useful technique to reduce the impacts in the use phase and the fuel or energy consumption of vehicles [5,6] is to reduce the mass of the vehicle [7–12]. This process is commonly referred to as “vehicle lightweighting” in the automotive field.

The vehicle lightweighting can be achieved in different ways: through material substitution and design and construction changes, using lighter materials, while maintaining the required strength characteristics [5,9,13–17]; and minimizing the size of the battery pack adopting alternative/hybrid powertrains [18–20], ad hoc regenerative braking logics and range management logics [21–23], and/or improve battery efficiency, for example by changing their chemistry [21,24] or studying alternative battery cooling systems [25,26].

Numerous scientific studies, such as [7,27–30], present the outcomes of the vehicle lightweighting using the Fuel Reduction Value (FRV), which is measured in L/(100 km · 100 kg). In the context of internal combustion vehicles, the FRV index stands for the liters of gasoline or diesel saved every 100 km, resulting from a 100 kg reduction in vehicle mass.

However, when referring to electric vehicles, consumption is no longer referred to fuel consumption, but to the variation of energy stored in the battery pack. If the study is then conducted using the FRV index, as in the case of [30], the latter index will represent the equivalent liters per 100 km and per 100 kg of lightweighting. An alternative is to analyze the lightweighting outcome on the basis of the Energy Reduction Value (ERV) index, expressed in kWh/(100 km · 100 kg), which corresponds to the energy savings every 100 km, every 100 kg of mass reduction. Studies [31–33] use ERV coefficient, and, in particular, [33] considers FRV index for the internal combustion vehicles and the ERV index for electric vehicles.

Scientific papers [28,29] show how the FRV coefficient changes based on the vehicle class considered, therefore depending on the size/volume of the vehicle considered. However, they do not identify the specific vehicle parameters responsible for this variation, in this way it might seem that this change is simply due to the variation in the vehicle weight. In contrast, the focus of [32] is the research and analysis of the vehicle parameters that influence the lightweighting results of electric vehicles, thus considering the ERV index.

However, the study [32] was conducted on standardized driving cycles, in particular on the WLTC and on the US06 cycles, finally comparing the outcome of the vehicle lightweighting obtained on different standard driving cycles and showing how this outcome varies according to the cycle considered. What is missing from the work presented in [32] is the analysis of the parameters that influence the lightweighting result based on a real-world driving cycle.

Non-legislative driving cycles are widely used in research focused on energy efficiency and pollution assessment. They have been utilized in studies covering topics from performance prediction to vehicle design [34]. In fact, vehicle emissions are influenced by driving cycles, which are primarily determined by traffic conditions [35]. Given the possible strong variability of local traffic, or from city to city, for the same geographical area, the standardized driving cycles often cannot be representative of all cases [34].

This paper is therefore focusing on the use of a real-world driving cycle to estimate the impact of the vehicle lightweighting, considering the north of Italy as the reference working area, specifically the province of Brescia, in Lombardy region. In this regard, the outcome of the lightweighting has been evaluated on a real-world cycle acquired on board the vehicle equipped with a GPS antenna, on a representative home-to-work journey, from a town in the province of Brescia, crossing the city center, up to the north of the municipality of Brescia.

Finally, the results obtained using the real-world driving cycle were compared with those coming from different standard cycles, to try and establish which standard driving cycle is the more representative of the chosen case (northern Italy, Lombardy region, home-to-work journey from the province to the municipality of Brescia) [36].

In this work, it has been found that in order to achieve an accurate calculation of the ERV index it is crucial to correctly define the rolling resistance coefficient, the aerodynamics coefficients, the battery pack parameters, and transmission efficiency for both the real-world driving cycle and the standardized driving cycles, while the inertia contribution can be considered negligible. Finally, it has been also found that the standardized driving cycle that best fits the real-world scenario is the Artemis Urban Cycle.

This paper is organized as follows:

- Section 2 outlines the adopted methodology, detailing the reference vehicles used in this study, the reference real driving cycle, the simulation tool utilized, the vehicle parameters under investigation, and a brief description of the simulations conducted;
- Section 3 presents the results of the study, and the considerations derived from them;
- Section 4 discusses and organizes the results presented in Section 3;
- Section 5 provides concluding remarks, summarizes the most relevant information from Section 4, and proposes future works.

2. Materials and Methods

The aim of this study is to assess the vehicle parameters that affect the outcomes of lightweighting, considering vehicle categories M and N1 [37]. To conduct this analysis, several simulations with variable vehicle mass were performed using the last version of the model described in [38] to estimate energy consumption across a real driving cycle, representative of the geographical context considered: northern Italy, Lombardy region, province of Brescia.

2.1. Reference Vehicles

For this work, the same reference vehicles as in study [32] were considered, i.e. two opposite vehicle types: a utility compact car (segment B) of M category, and a light commercial vehicle of N1 category. Where the B segment vehicle is the consolidated “CompactCar” model from VI-CarRealTime (VI-Grade), but without endothermic engine and with the electric driveline of the “Fiat 500e Hatchback 42 kWh” instead [39,40], a popular car in Italy and Europe, characterized by an 87 kW electric motor, a single reduction transmission ratio of 9.6, and a 42 kWh battery pack. On the other side, the N1 category vehicle is the same one used in [38] for the validation of the tool during simulations of low performance vehicles, but with a total transmission ratio of 6.22.

For the two vehicle models (compact car of M category and N1 vehicle), Table 1 reports the model parameters used for the purpose of this study.

Table 1. Model parameters used for the purpose of this study, for the compact car (M category) and for the N1 category vehicle [32].

Analyzed Parameters	Compact Car Value	N1 Value
Transmission efficiency	1	0.9409
$A_f \cdot C_x *$	1.034 m ²	2.1 m ²
Vertical aerodynamic coefficient	-0.026 m ²	0
Rolling friction coefficient	0.01	0.015
Total gear ratio	9.6	6.22
Front wheel radius	0.2987 m	0.35 m
Rear wheel radius	0.3005 m	0.35 m
Moment of inertia of each wheel	0.882 kg m ²	1.09 kg m ²
Moment of inertia of the motor	0.02 kg m ²	0.086 kg m ²
Moment of inertia of the transmission	0.0001 kg m ²	0.01 kg m ²
Battery capacity	42 kWh (105 Ah)	120 Ah
Number of battery cells in series	96	108
Number of battery cells in parallel	2	1
Nominal battery pack voltage	400.0 V	356.1 V
Internal resistance of the battery pack	0.086 Ω	0.097 Ω

* Frontal area (Af) multiplied by longitudinal aerodynamic coefficients (drag, Cx).

It was chosen to simulate the two vehicle models without regenerative braking, to avoid the results to be influenced by a regenerative braking logic with different behaviors depending on the vehicle considered.

2.2. Driving Cycle

For this study, a real-world driving cycle was considered, representing a home-to-work journey for all the people who live in northern Italy, commuting from the province and crossing the city to reach their workplace.

For the driving cycle acquisitions, a GPS antenna connected to a MoTeC ADL2 [41] data acquisition system was used. The GPS receiver is a LOCOSYS - LS23036 [42], with an update rate of up to 10 Hz and a position accuracy of 2.5 meters. Figure 1 shows the installation position of the GPS receiver and the location in the vehicle of the data acquisition system.



Figure 1. Location (a) of the GPS receiver (red circle), installed on the vehicle hood via magnetic connection, and (b) of the MoTeC ADL2 data acquisition unit, on the passenger mat, inside a protective box.

The vehicle used is a Suzuki Jimny, light duty vehicle model (N1) from 2021. The vehicle weight is 1065 kg (empty weight), it is powered by petrol with a nominal engine power of 102 CV (75 kW). It is equipped with a 4WD 5-gears transmission and with reduced gears. The measurements were carried out with the gearbox in standard mode (reduced gear and 4WD disengaged).

With this vehicle, equipped with the MoTeC ADL2/GPS data acquisition system, several driving cycles including speed profile, altitude profile, and other information were acquired. Among all of them, the most representative driving cycle was chosen (see Figure 2), excluding cycles characterized by extraordinary events that rarely occur, for example heavy rain, strong wind, stops at petrol stations, emergency braking with activation of the ABS system, roadworks, etc.

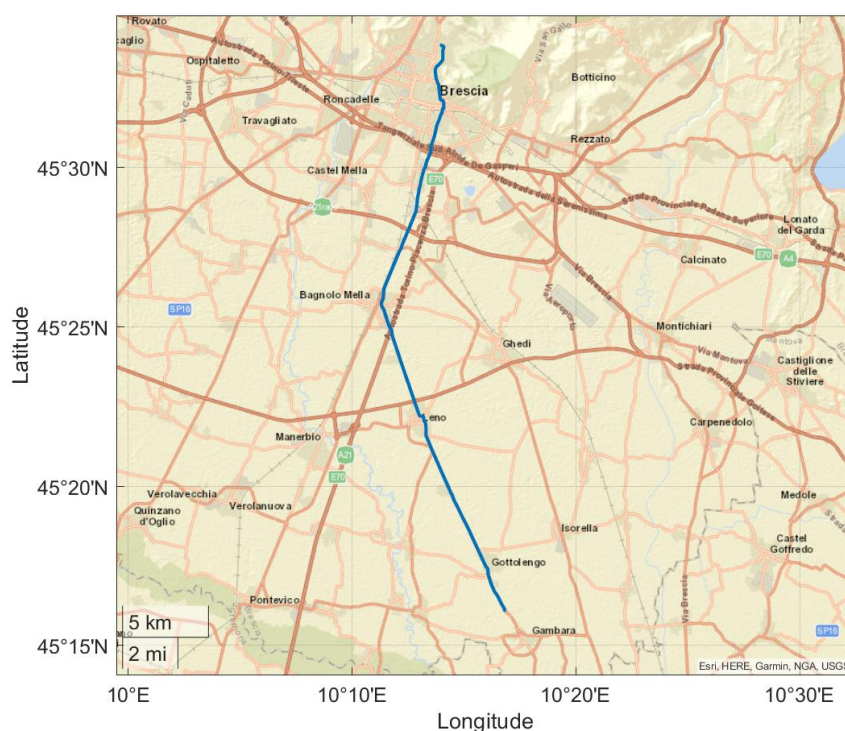


Figure 2. Home-to-work commute real-world reference driving cycle.

The chosen reference real-world driving cycle was acquired from 8:15 to 9:15 am, starting from the province of Brescia, from a place located between the towns of Gambara and Gottolengo, and arriving at the engineering faculty of the University of Brescia. This route includes the crossing the

Brescia city center during the time of the day with highest level of traffic. The acquired speed profile, reported in Figure 3, is characterized by many phases at zero speed, a maximum speed of 100.5 km/h and an average speed of 36.1 km/h.

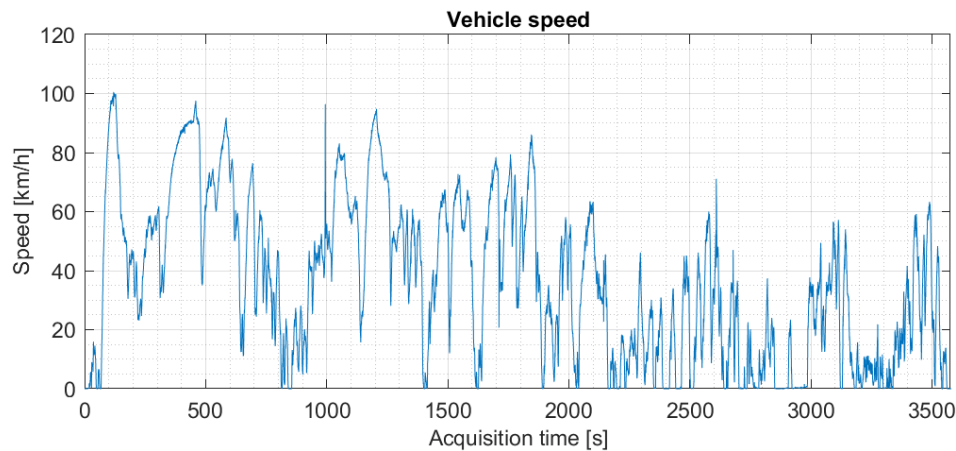


Figure 3. Acquired speed profile of the reference real driving cycle.

The reference real-world driving cycle is a mixed cycle, urban and extra-urban, and in this journey approximately 40 minutes are spent at speeds below 50 km/h, approximately 18 minutes are spent at speeds between 50 and 90 km/h, while only about 1 minute is spent at speeds above 90 km/h. For more information see also Figure 4.

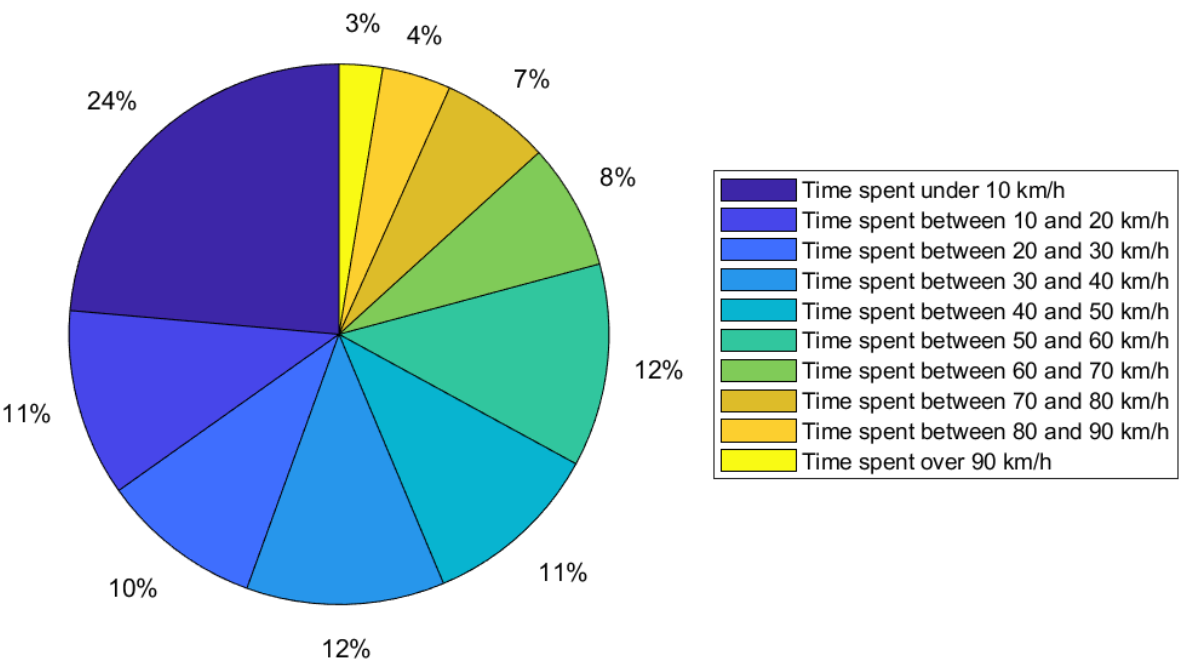


Figure 4. Time spent at different vehicle speed range, as a percentage of total travel time (about 59.67 minutes).

GPS systems are known to provide accurate longitude and latitude data, while they typically provide imprecise altimetric information. For this reason, it was decided to use a software available on the web, “GPS Visualizer” [43], to obtain a more precise altimetric profile of the real cycle acquired. This tool allows to obtain altimetric data starting from latitude and longitude data, using different DEMs (Digital Elevation Models) sources. In particular, it is possible to set “GPS Visualizer” so that it automatically uses the best source among various DEMs. The altimetry profile obtained is reported in Figure 5 and compared to the profile acquired directly with the GPS on board the vehicle.

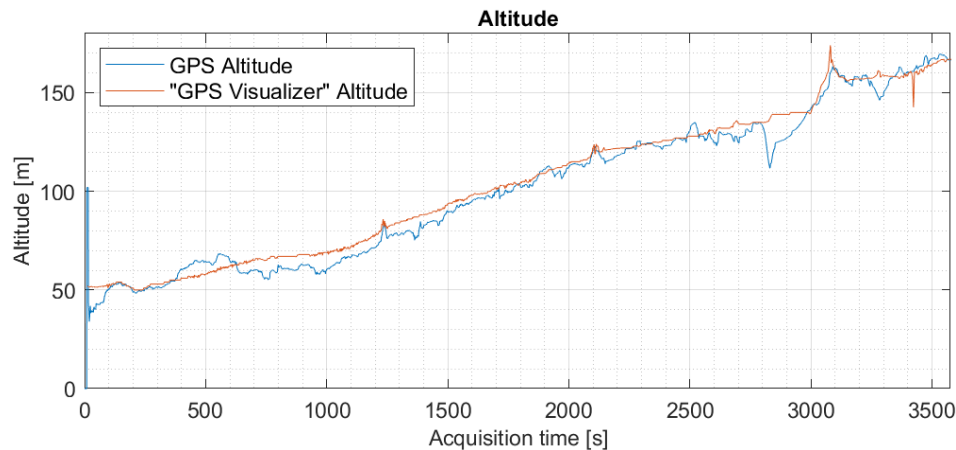


Figure 5. Altimetry profile obtained through “GPS Visualizer” [43] tool using GPS latitude and longitude vs. altimetry profile directly acquired from GPS on board the vehicle.

The effects of lightweighting on real driving cycle, for both reference vehicles, were compared with the following standard driving cycles:

- WLTC (Worldwide Harmonized Light-Duty Vehicles Test Cycle), class 3b, described in the WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure) procedure [44];
- SFTP-US06, described in the “EPA Supplemental Federal Test Procedure” (SFTP) [45];
- FTP75 (EPA Federal Test Procedure) [46];
- HWFET (EPA Highway Fuel Economy Cycle);
- Japanese JC08 Emission Test Cycle [47], with a first additional phase equal to the phase corresponding to the last 172 seconds of the standard JC08 cycle itself;
- Artemis, Urban, Rural Road, and Motorway (130) Cycle [48].

2.3. Simulation Tool

For the simulation, the last version of TEST (Target-speed EV Simulation Tool) model [38] was used. This is a vehicle longitudinal dynamics simulation tool that enables the simulation of both the mechanical and electrical behaviors of fully electric or hybrid electric vehicles. The model is presented in [38] (for more information, see also [49,50]), and the latest version also includes the integration described in [18,19,22,32].

2.4. Parameters of the Vehicle (and of Its Model) Which Can Affect the Lightweighting Results

In this study, the variability of the outcome given by the lightweighting was analyzed as a function of the variation of the same parameters considered in [32], the following:

- Battery pack parameters (nominal voltage, capacity, and internal resistance);
- Aerodynamic parameters;
- Transmission efficiency;
- Rolling resistance, in particular changing the rolling friction coefficient;
- Moments of inertia of the electric motor, of the rotating parts of the transmission, and of the wheels;
- Total transmission ratio (including wheel ratio given by the wheel radius);

Finally, the driving cycle considered is also a fundamental parameter to take into account, therefore the results obtained considering the real-world driving cycle were compared with those obtained on different standardized driving cycles.

2.5. Set of Simulations

In this study, “set of simulation” (or “simulation set”) means the collection of simulations, conducted for the same driving cycle and for the same vehicle model, differentiated only by the mass of the vehicle. In particular, for the compact car models, simulations were carried out starting from

700 kg, up to 2500 kg, for every 50 kg of variation in vehicle weight. For the N1 vehicle, always every 50 kg, but from 700 kg up to 3500 kg, which corresponds to the maximum permitted weight for light commercial vehicles. 700 kg for a commercial vehicle is unrealistic, but the simulations were pushed up to this value for easier comparison with the results of the compact car.

A first set of simulations for each reference vehicle model (compact car and N1) was obtained by providing the real-world speed profile acquired via GPS as input to the TEST model and, for each single simulation, by varying the mass of the vehicle under examination. Then, these sets of simulations were initially repeated by setting all the inertia contributions of the two vehicle models to zero.

Further sets of simulations, always on the real driving cycle, instead concern the compact car, in which one or more parameters have been modified, imposing them equal to those of the reference N1 category vehicle. The modified parameters for each simulation set are as follows:

- Battery pack parameters (nominal voltage, capacity, and internal resistance);
- Aerodynamics;
- Transmission efficiency;
- Rolling friction coefficient;
- Moments of inertia (of motor, transmission, and wheels);
- All the previous parameters simultaneously;
- Motor reduction ratio, transmission ratio and wheel radii;
- All of the above parameters simultaneously.

Finally, for this work, the simulation sets obtained for study [32] were considered, in particular relating to the compact car and N1 models, without regenerative braking, on the standard cycles reported at the end of section “2.2. Driving Cycle”. These simulations were finally compared with those obtained on the real driving cycle covered by this study.

3. Results

This section presents the results of the simulation sets conducted, with consequent considerations.

3.1. Consumption Analysis

Figure 6 shows the results of the simulation sets obtained for the compact car and N1 vehicle models, with and without inertia contributions. In particular, the results are reported in terms of average energy consumption over the real-world cycle as a function of vehicle weight.

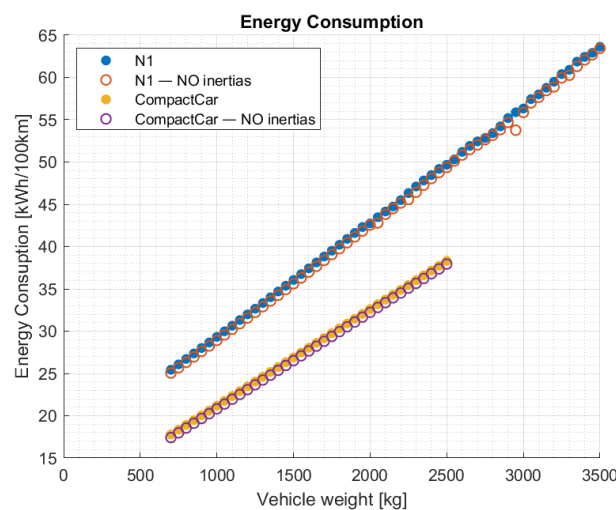


Figure 6. Average energy consumption on the reference real driving cycle, as a function of vehicle weight, for the N1 category vehicle model (“N1”) and for the same model, but with zero inertia contributions (“N1 — NO inertias”); for the compact car model (“CompactCar”) and for the same model, but with zero inertia contributions (“CompactCar — NO inertias”).

From Figure 6, the inertia can be considered negligible, as obtained for study [32] for the WLTC and US06 standard driving cycles.

In Figure 6, it is also possible to see that there is an error for the consumption result for the simulation on the N1 model without inertia contribution, with the vehicle weight equal to 2950 kg. In fact, this consumption value is not aligned with the other data trend.

In particular, this problem is due to the fact that the vehicle, for high weights, has difficulty following the speed target, in the area of 994 seconds elapsed from the start of the simulation, due to the excessively high acceleration. In this regard, Figure 7 shows a comparison between the target speed and the vehicle speed during the simulation, for a vehicle weight of 2950 kg, and without inertia contributions. In fact, as can be observed in Figure 8, the high acceleration of that stretch leads to a high torque request, which cannot be satisfied by the vehicle under examination. A torque limit of 10 000 Nm was implemented in the model used for the simulations, in order to allow it to travel the imposed speed profiles without incurring limitations; but this limitation still occurs in the case in question (weight equal to 2950 kg), leading to a calculation error: a positive peak is noted in the voltage of the battery pack, a negative peak in the pack current (which therefore corresponds to the current absorbed by the battery pack itself), these two variables lead to a negative peak in the power of the batteries (which corresponds to the power absorbed by the pack), all resulting in the battery SOC (State of Charge) trend as reported in Figure 9 (see in particular the increase of SOC in the area around 1000 seconds). However, the resolution of this tool calculation error is not of vital importance for the study in question, since what is important is the trend of the average consumption over the real driving cycle as the weight of the vehicle varies and not the individual consumption relative to each weight considered.

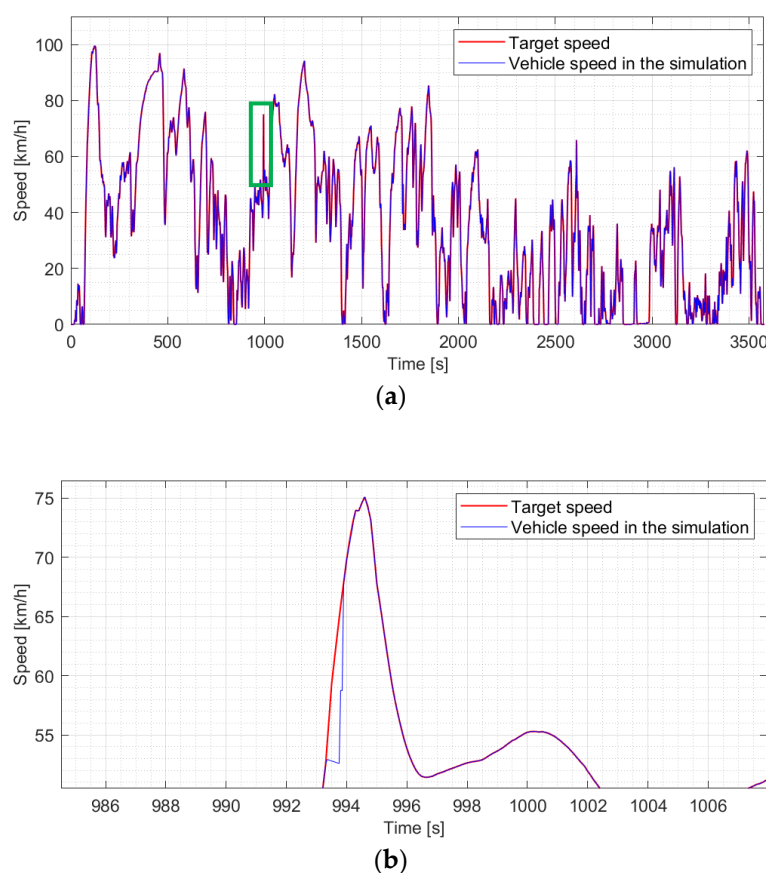


Figure 7. Target speed and vehicle speed in the simulation vs. time elapsed since the beginning of the simulation itself, for the N1 vehicle without moments of inertia and with a weight of 2950 kg: (a) for the entire simulation; (b) an enlargement relative to the green box in Figure 1(a).

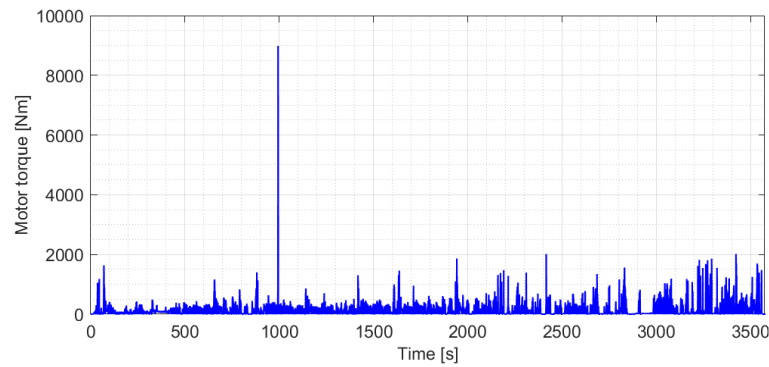


Figure 8. Motor torque vs. time elapsed since the beginning of the simulation, for the N1 vehicle without moments of inertia and with a weight of 2950 kg.

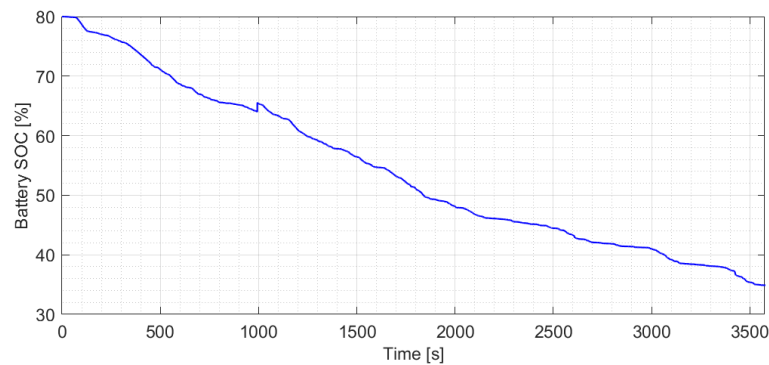


Figure 9. Battery SOC (State of Charge) vs. time elapsed since the beginning of the simulation, for the N1 vehicle without moments of inertia and with a weight of 2950 kg.

Figure 10 shows the average energy consumption for the sets of simulations for the compact car and N1 models, compared with those of compact car model with some N1 parameters, relating the battery pack, the aerodynamic, the trasmission efficiency, the rolling resistance, and all the above features simultaneously.

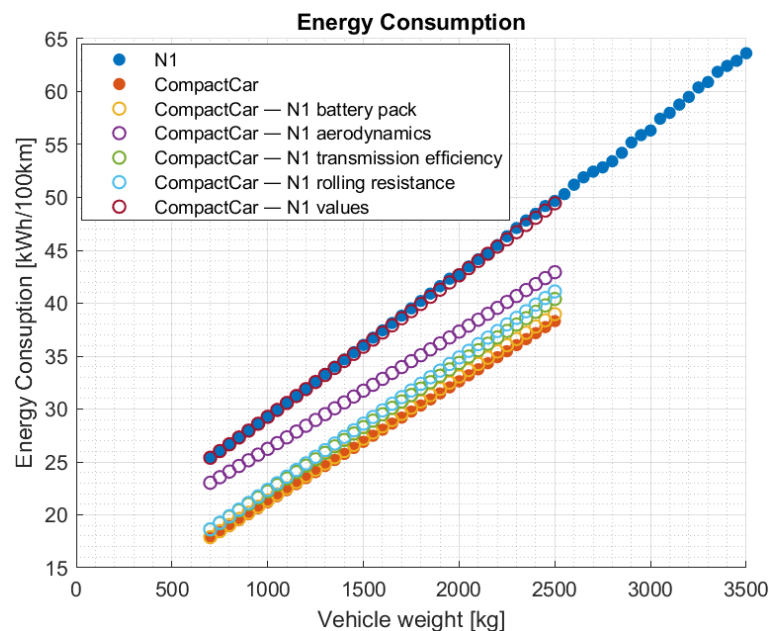


Figure 10. Average energy consumption on the reference real driving cycle, as a function of vehicle weight, for the following vehicle models: N1 vehicle ("N1"), compact car ("CompactCar"); compact car with the N1 battery pack on board ("CompactCar - N1 battery pack"); compact car with the aerodynamic coefficients of the N1 vehicle ("CompactCar - N1 aerodynamics"); compact car with the transmission efficiency of the N1 vehicle ("CompactCar - N1 transmission efficiency"); compact car with the rolling resistance of the N1 vehicle ("CompactCar - N1 rolling resistance"); and compact car with all N1 values ("CompactCar - N1 values").

the transmission efficiency equal to that of the N1 vehicle ("CompactCar — N1 transmission efficiency"); compact car with the rolling resistance coefficient equal to that of the N1 vehicle ("CompactCar — N1 rolling resistance"); and, finally, compact car with all the parameters previously mentioned equal to those of N1 vehicle ("CompactCar — N1 values").

From Figure 10 it is possible to see that the contribution that has the greatest impact on consumption is aerodynamics, followed in the following order by rolling resistance, transmission efficiency, and battery pack. In particular, the last contribution can be considered negligible. Once again, the same considerations were obtained which are also valid for the standard driving cycles [32].

Furthermore, even for the real driving cycle, as for the standards, the modification of the rolling resistance coefficient involves a greater variation in the slope of the average cycle consumption curve as a function of the vehicle weight, while the modification of the aerodynamics, as we will see better below, involves a less influential variation to this slope.

In the graph shown in Figure 10, the curve corresponding to the compact car with battery pack, aerodynamics, transmission efficiency, and rolling resistance parameters identical to those of the N1 vehicle closely aligns with the curve of the N1 class vehicle, for low vehicle weights, while for higher weights, torque limitations begin to intervene which cause the driving cycle to deviate slightly from the target in some small areas, with a consequent slight drop in consumption. This is because inertia, as previously defined, is negligible, and the total transmission ratios (and wheel radii) do not influence the regenerative braking recovery, which is absent (for more details see [32]). In this case, the transmission ratios only affect the contribution of inertia (see Figures 11 and 12). In particular, this is visible in Figure 11, for low vehicle weights, for higher weights the average consumption with different transmission ratios differs. Most likely due to the difficulty of the heavy vehicle to faithfully follow the imposed real driving cycle, which is "dirtier" than a standard one and characterized by phases of greater acceleration.

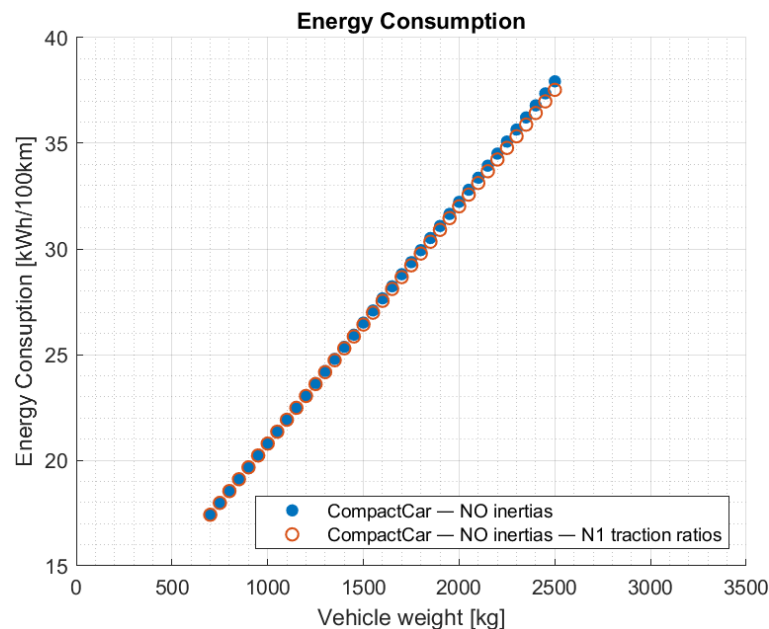


Figure 11. Average energy consumption on the reference real driving cycle, according to the vehicle weight, for the following vehicle models: compact car without inertia ("CompactCar — NO inertias"); compact car with transmission ratios (and wheel radii) equal to those of the N1 vehicle and without inertia ("CompactCar — NO inertias — N1 traction ratios").

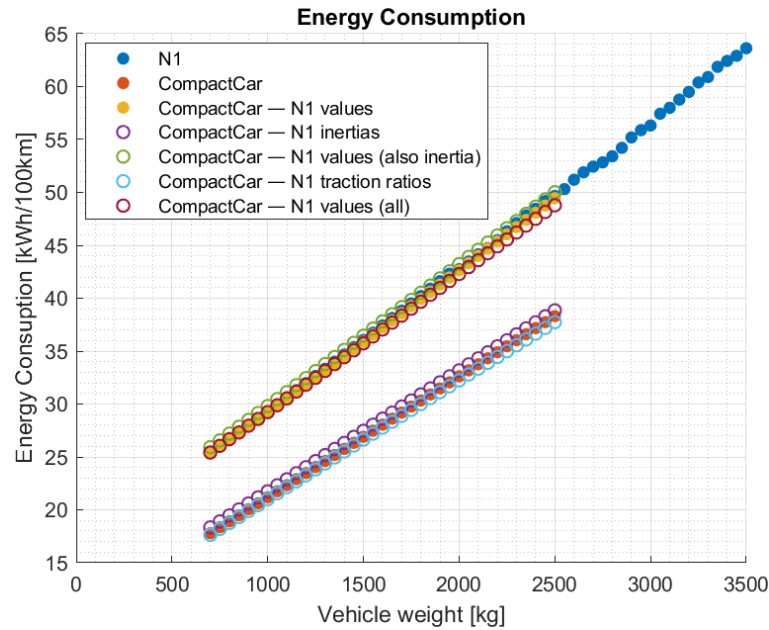


Figure 12. Average energy consumption on the reference real driving cycle, as a function of vehicle weight, for the following vehicle models: vehicle of category N1 (“N1”), compact car (“CompactCar”); compact car with the battery pack of the N1 vehicle on board, with the aerodynamic coefficients, the efficiency of the transmission, and with the rolling resistance coefficient of the N1 vehicle (“CompactCar — N1 values”); compact car with the same moments of inertia as vehicle N1 (“CompactCar — N1 inertias”); compact car with the battery pack, aerodynamics, transmission efficiency, rolling resistance, and moments of inertia of the N1 vehicle (“CompactCar — N1 values (also inertia)”); compact car with the transmission ratios and wheel radii of the N1 vehicle (“CompactCar — N1 traction ratios”); and, finally, compact car with all the previously mentioned parameters equal to those of the N1 vehicle, i.e., the parameters relating to the battery pack, aerodynamics, transmission efficiency, rolling resistance, moments of inertia, transmission ratios, and wheel radii (“CompactCar — N1 values (all)”).

Unless there are limitations for high vehicle weights, the considerations obtained in this section are the same as those obtained for the WLTC (class 3b) and US06 standard cycles in study [32].

3.2. Polynomial Interpolation and ERV Index

In this section, we will examine the polynomial functions that best represent the curves previously shown in Section 3.1. Specifically, first, second, and third-degree polynomial functions were analyzed to approximate the selected curve, with the parameters obtained using MATLAB’s “polyfit” function. The function used for polynomial interpolation is presented in Equation (1) of [32], and below in Equation (1).

$$y = c_3 \cdot x^3 + c_2 \cdot x^2 + c_1 \cdot x + c_0 \quad (1)$$

Here, y represents the average energy consumption in kWh/100 km, for the curve analyzed, and x refers to the vehicle weight (in 100 kg). The coefficients c_3 , c_2 , c_1 , and c_0 are the polynomial coefficients determined by the MATLAB “polyfit” function.

Figure 13 shows the curves, relating, respectively, to the N1 vehicle and the compact car, obtained by means of the polynomial functions.

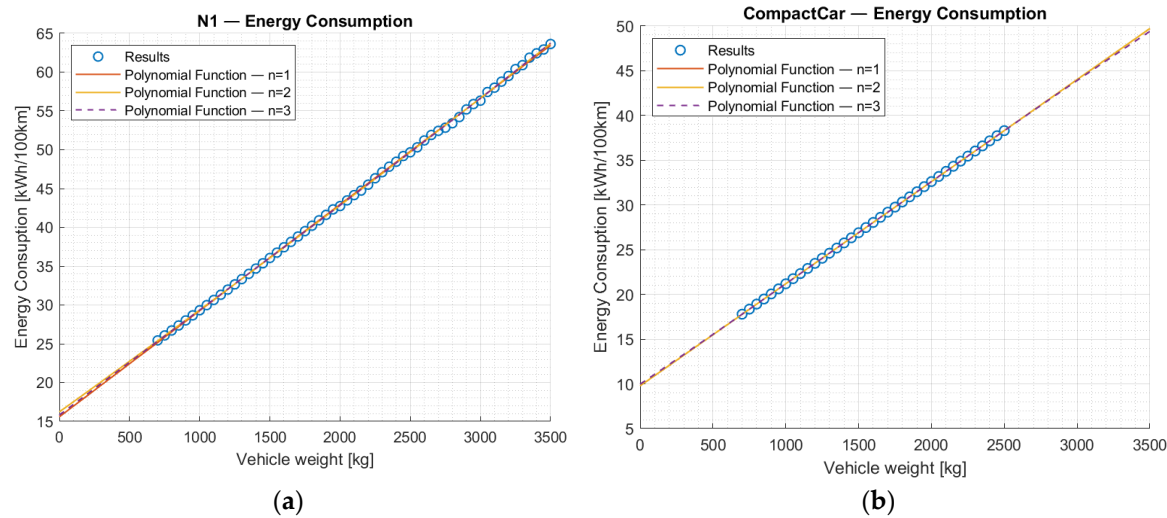


Figure 13. Average energy consumption on reference real driving cycle, as a function of the vehicle weight. Curves relating to the results were obtained by means of simulations (“Results”), and curves were obtained thanks to the polynomial approximation of the first (“n = 1”), second (“n = 2”), and third degree (“n = 3”) for (a) the N1 vehicle; and (b) the compact car.

As can be observed in Figure 13, all three polynomial functions (first, second and third degree) approximate the represented curves very well. For their description it is therefore sufficient to approximate with the first-degree polynomial, for greater simplicity. The same result was also observed in all other simulations conducted (with altered parameters).

Table 2 presents the values of the polynomial coefficients that approximate the consumption–weight curves, with the coefficients obtained using MATLAB’s “polyfit” function. Only the coefficients for the first-degree polynomials are reported, as the second- and third-degree polynomials have negligible c_2 and c_3 coefficients, which are several orders of magnitude smaller than the other two coefficients (c_0 and c_1). In fact, as shown in Figure 13, the curve under consideration can be approximated with sufficient accuracy using only a first-degree polynomial, and the same situation applies to the polynomials corresponding to the curves from all the previous simulations conducted.

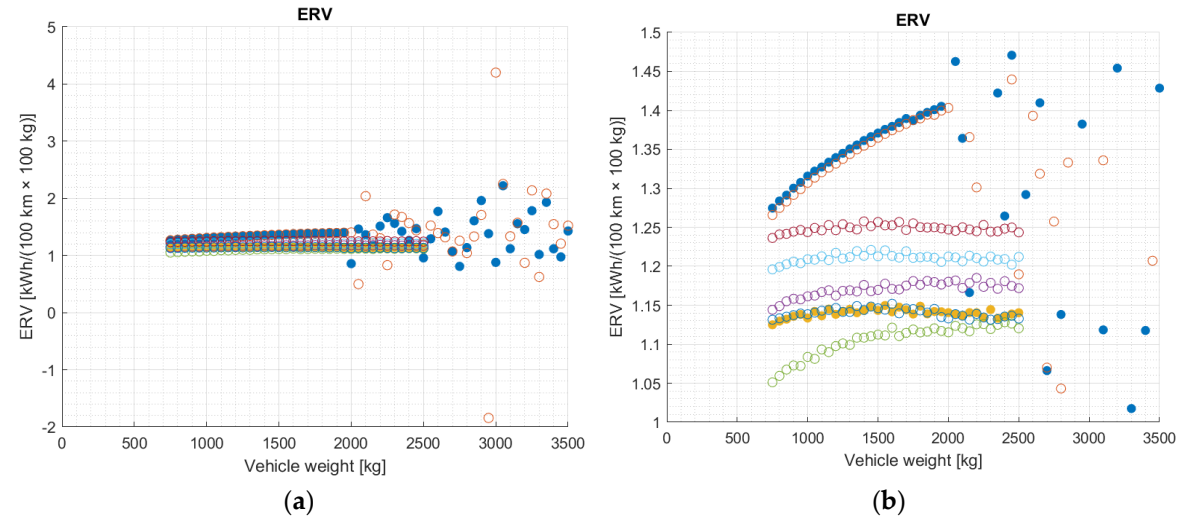
Table 2. Coefficients of the polynomial functions that approximate the consumption curves, as a function of the vehicle weight, obtained by means of simulations on the various vehicle models.

Vehicle Model	Model description	c_1	c_0
		$\left[\frac{\text{kWh}}{100\text{km} \cdot 100\text{kg}}\right]$	$\left[\frac{\text{kWh}}{100\text{km}}\right]$
N1	N1 model	1.368	15.592
N1— NO inertias	N1 model without inertia contributions	1.365	15.201
CompactCar	Compact car model	1.141	9.782
CompactCar— NO inertias	Compact car model without inertia contributions	1.141	9.406
CompactCar— N1 battery pack	Compact car model with the N1 battery pack on board	1.172	9.633
CompactCar— N1 aerodynamics	Compact car model with the aerodynamic coefficients of the N1 vehicle	1.109	15.149
CompactCar— N1 transmission efficiency	Compact car model with the transmission efficiency equal to that of the N1 vehicle	1.211	10.110
CompactCar— N1 rolling resistance	Compact car model with the rolling resistance coefficient equal to that of the N1 vehicle	1.250	9.875

CompactCar— N1 values	Compact car model compact car with all the above-mentioned parameters equal to those of the N1 vehicle	1.339	15.862
CompactCar— N1 inertias	Compact car model with the same moments of inertia as vehicle N1	1.141	10.345
CompactCar— N1 values (also inertia)	Compact car model compact car with all the above-mentioned parameters (also moments of inertia) equal to those of the N1 vehicle	1.342	16.385
CompactCar— N1 traction ratios	Compact car model with the transmission ratios and wheel radii of the N1 vehicle	1.119	9.832
CompactCar— N1 inertias and traction ratios	Compact car model with the moments of inertia, the transmission ratios and wheel radii of the N1 vehicle	1.118	10.031
CompactCar— N1 values (all)	Compact car model compact car with all the above-mentioned parameters equal to those of the N1 vehicle, including moments of inertia, traction ratios, and wheel radii	1.303	16.209

As mentioned in the introduction section, the FRV index is often referenced in the literature when calculating the energy savings associated with vehicle lightweighting. For electric vehicles, however, it is more appropriate to calculate an equivalent index, the ERV index, which corresponds to the c_1 coefficient of the first-degree polynomial, presented in Table 2 for each simulated vehicle model.

Figure 14 reports the ERV index, calculated for each pair of average consumptions on the reference real driving cycle, for consecutive weights; for further information refer to Equation (2) of [32].



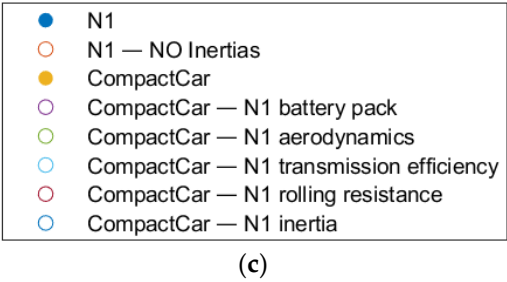


Figure 14. ERV index, calculated for the reference real driving cycle and calculated between a simulation performed at a given vehicle weight and the simulation with the vehicle weight immediately lower than that under examination (considering the set of simulations performed), as a function of the vehicle weight, for the following vehicle models: N1 category vehicle (“N1”); N1 vehicle with zero inertia (“N1 — NO Inertias”); compact car (“CompactCar”); compact car with the N1 battery pack on board (“CompactCar — N1 battery pack”); compact car with the aerodynamic coefficients of the N1 vehicle (“CompactCar — N1 aerodynamics”); compact car with transmission efficiency equal to that of the N1 vehicle (“CompactCar — N1 transmission efficiency”); compact car with the N1 vehicle rolling resistance coefficient (“CompactCar — N1 rolling resistance”); and, finally, compact car with moments of inertia equal to those of the N1 vehicle (“CompactCar — N1 inertia”). In particular, in (a) the graph with all the ERV index calculated; in (b) the graph with the y-axis limited between 1 and 1.5 kWh/(100km·100kg); in (c) the legend valid for both graphs.

From Figure 14(a) it can be seen that the technique consisting in obtaining the ERV index point by point is not effective for high vehicle weights. This is due to the limitations that arise when the vehicle is not equipped with sufficient performance in order to follow the acceleration targets. This phenomenon was not observed in [32] for the WLTC and US06 standardized cycles, in fact, the standard driving cycles are usually characterized by low accelerations, which are not very realistic. The real driving cycles, unlike the standardized ones, are therefore able to cause a crisis in the simulation tools, thus resulting more difficult to manage.

For low vehicle weights, Figure 14(b) shows some aspects already previously identified, namely that, for example, inertia has little influence on consumption variation and is therefore negligible in the context of this study, which focuses on evaluating the impact of vehicle lightweighting. Moreover, for the same vehicle model, the ERV index increases as the vehicle weight increases. This indicates that heavier vehicles benefit more from lightweighting for the same weight reduction. Additionally, it is possible to observe which parameters (when equal to those of a higher-class vehicle, such as class N1 in this case) raise the ERV index and which lower it. For example, it can be observed that rolling resistance has a major influence on the ERV index, i.e. on the slope of the average energy consumption curve as a function of weight.

To estimate the reduction in average consumption over real driving cycles following the vehicle lightweighting, it is therefore more appropriate to obtain the ERV index as the c_1 coefficient of the first-degree polynomial function that approximates the average consumption curve identified by means of simulations.

Now, for each compact car weight, starting from the same vehicle but with an additional 300 kg of weight, the ERV index obtained from the polynomial function is used to determine the average consumption on the reference driving cycle. Furthermore, multiple ERV indices are assumed, reported in Table 2, obtained by assuming errors in the construction of the model, in particular by mistakenly setting one or more parameters equal to those of the N1 category vehicle. The result of these tests is reported in Figure 15.

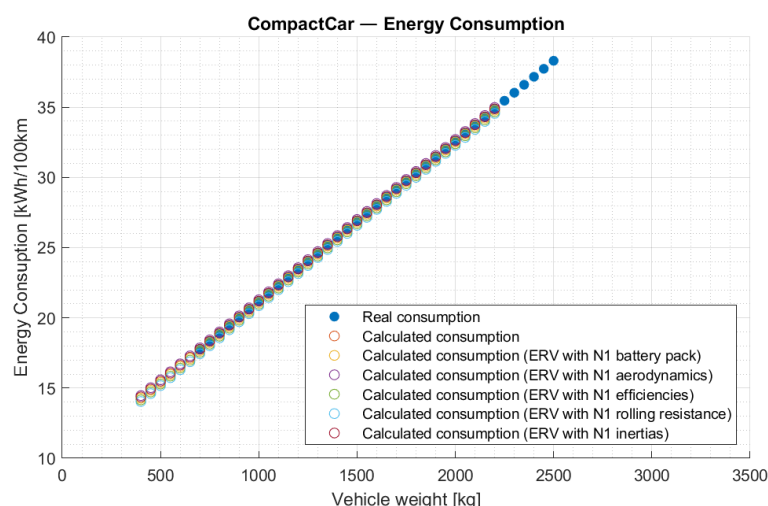


Figure 15. Average energy consumption on the reference real driving cycle, as a function of vehicle weight, for the compact car, obtained through simulations with the TEST model (“Real consumption”), and considering the ERV obtained through polynomial interpolation, for the following vehicle models (lightweighting by 300 kg): CompactCar (“Calculated consumption”); CompactCar with the vehicle battery pack N1 on board (“Calculated consumption (ERV with N1 battery pack)”); CompactCar with the aerodynamic coefficients of vehicle N1 (“Calculated consumption (ERV with the N1 aerodynamics)”); CompactCar with the transmission efficiency equal to that of the N1 vehicle (“Calculated consumption (ERV with N1 efficiencies)”); CompactCar with the vehicle rolling resistance coefficient of N1 (“Calculated consumption (ERV with N1 rolling resistance)”); and, finally, CompactCar with moments of inertia of vehicle N1 (“Calculated consumption (ERV with N1 inertias)”).

Figure 15 shows that an incorrect definition of the model does not cause significant errors in the evaluation of a 300 kg weight reduction, as long as the vehicle’s actual consumption in the given real driving cycle is known, as obtained in [32] for the WLTP and US06 standard cycles. This approach reveals a contrasting situation compared to evaluating lightweighting based on the consumption curve obtained through vehicle model simulations. In the latter case, as shown in Figure 10, an incorrect assessment of the vehicle model parameters, in particular relating the aerodynamics, can cause a non-negligible error. In fact, increasing the aerodynamic resistance coefficient, as seen in Figure 10, raises the consumption curve, but it has little effect on the slope of the curve itself.

Therefore, if the consumption data for the reference cycle is available and we want to assess the results of a hypothetical lightweighting, it is more convenient to use the constant ERV index approach (polynomial interpolation) for more realistic conclusions. The same consideration has also been deduced for the standard driving cycles analyzed in [32].

3.3. Comparison Between the Reference Real-World Driving Cycle and Standard Cycles

In this section, the consumption curves obtained for the real reference driving cycle is compared with the curves obtained for different standardized cycles [32]. This with the ultimate aim of evaluating which standard driving cycle can be most representative of the real case under examination, and which of these can therefore be useful for estimating the impact of vehicle lightweighting for the case of northern Italy.

Figure 16 shows the average energy consumption obtained from various sets of simulations across the reference real driving cycle and different regulated cycles [32]. Specifically, each point on the graph represents the average energy consumption on the analyzed cycle, determined by running a simulation with the TEST model on the respective cycle, with a pre-set weight (as indicated on the x-axis of the graph).

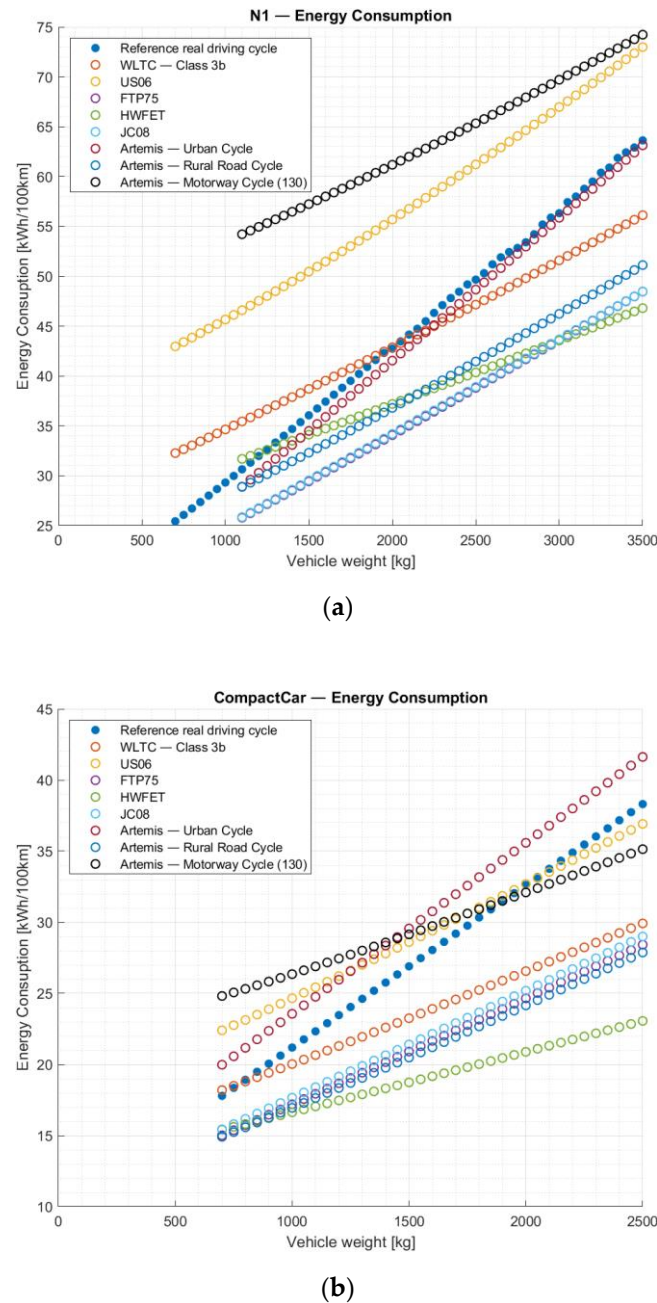


Figure 16. Average energy consumption, for (a) the N1 category vehicle and (b) compact car, on the reference real driving cycle and on the following standard driving cycles: WLTC (class 3b); US06; FTP75; HWFET; JC08; Artemis Urban Cycles; Artemis Rural Road Cycle; Artemis Motorway Cycle (130) [32].

From Figure 16(a) it can be observed that for light commercial vehicles (category N1), the standard driving cycle that best represents the real case object of this study is the Artemis Urban Cycle. It should be remembered that the real driving cycle considered is representative of home-work trips, from the province of Brescia, crossing the city of Brescia, in the Lombardy region, in northern Italy.

For the compact vehicle, however, there is no standardized driving cycle that accurately approximates the real reference driving cycle. However, it can be noted that the slope of the consumption curve calculated on the real cycle is quite close to the slope of the curve obtained for the Artemis Urban Cycle. It follows that this last cycle can be useful for estimating the outcome of the lightweighting also for compact cars, provided that only the ERV index is considered.

The closeness of the ERV indices relating to the Artemis Urban Cycle speed profile with the indices obtained on the real driving cycle, for both vehicles, can also be observed in Table 3 (for N1 category vehicle) and in Table 4 (for compact car), remembering that the ERV index corresponds to the c_1 coefficient of the first-degree polynomial function.

Table 3. Coefficients of the polynomial functions (first-degree) which approximate the consumption curves as a function of the vehicle weight obtained by means of simulations on the N1 category vehicle model, on the reference real driving cycle and on the following standard driving cycles: WLTC (class 3b); US06; FTP75; HWFET; JC08; Artemis Urban Cycles; Artemis Rural Road Cycle; Artemis Motorway Cycle (130) [32].

Driving Cycle	$\frac{c_1}{\left[\frac{\text{kWh}}{100 \text{ km} \cdot 100 \text{ kg}}\right]}$	$\frac{c_0}{\left[\frac{\text{kWh}}{100 \text{ km}}\right]}$
Reference real driving cycle	1.368	15.592
WLTC – Class 3b	0.852	25.995
US06	1.077	34.562
FTP75	0.946	15.229
HWFET	0.630	24.647
JC08	0.944	15.362
Artemis – Urban Cycle	1.426	13.082
Artemis – Rural Road Cycle	0.929	18.344
Artemis – Motorway Cycle (130)	0.835	44.654

Table 4. Coefficients of the polynomial functions (first-degree) which approximate the consumption curves as a function of the vehicle weight obtained by means of simulations on the compact car model, on the reference real driving cycle and on the following standard driving cycles: WLTC (class 3b); US06; FTP75; HWFET; JC08; Artemis Urban Cycles; Artemis Rural Road Cycle; Artemis Motorway Cycle (130) [32].

Driving Cycle	$\frac{c_1}{\left[\frac{\text{kWh}}{100 \text{ km} \cdot 100 \text{ kg}}\right]}$	$\frac{c_0}{\left[\frac{\text{kWh}}{100 \text{ km}}\right]}$
Reference real driving cycle	1.141	9.782
WLTC – Class 3b	0.654	13.488
US06	0.809	16.549
FTP75	0.746	9.742
HWFET	0.426	12.370
JC08	0.754	10.114
Artemis – Urban Cycle	1.203	11.528
Artemis – Rural Road Cycle	0.723	9.709
Artemis – Motorway Cycle (130)	0.482	21.253

Finally, from Figure 16, it is also possible to observe how, as the weight of the vehicle varies, a standard driving cycle can underestimate or overestimate energy consumption. For example, for the N1 category vehicle, on the considered home-work travel, the WLTC driving cycle will underestimate real consumption if the weight of the vehicle is less than approximately 2100 kg, vice versa, for higher weights, it will overestimate them.

4. Discussion

In this paper, the outcome of vehicle lightweighting on a real-world driving cycle was analyzed, with a focus on identifying which vehicle model parameters have the greatest influence on the results and, consequently, which parameters must be estimated more accurately for a proper analysis. In

particular, one objective is to compare the results obtained on the real-world cycle with those obtained in [32] using the WLTC (class 3b) and US06 standard driving cycles.

As seen in [32] for the two standard cycles, also for the real cycle the contribution of the moments of inertia on energy consumption can be considered negligible, for both N1 category vehicle and compact car. Instead, the aspect that has the greatest impact on higher consumption is the increase in aerodynamic resistance, followed by rolling resistance, while the aspect that least affects consumption is the battery pack, followed by the efficiency of the transmission.

In particular, the increase in aerodynamic drag has a significant impact on the absolute value of the average vehicle consumption on the real cycle; however, it does not lead to a notable change in the slope of the consumption curve, as observed in [32] for the two normed cycles.

Finally, to estimate the vehicle consumption accurately and therefore to effectively evaluate the outcome of the lightweighting, it may be sufficient to correctly set the vehicle model parameters relating to the battery pack, aerodynamics, transmission efficiency and rolling resistance, as stated in [32]. While as regards the functions that approximate the consumption curves identified through simulations, it is enough to consider the first-degree polynomial functions for a good level of precision.

The ERV index, useful to analyzed the lightweighting results for electric vehicles, expressed in kWh/(100 km · 100 kg), increases as the vehicle weight rises for the same vehicle model. This implies that heavier vehicles benefit more from lightweighting for the same amount of weight reduction. The vehicle parameters that most influence the ERV index are the transmission efficiency and those relating to the battery pack. Aerodynamics, on the other hand, has little influence since it modifies consumption in a non-negligible way, but not the slope of the average consumption curve as a function of vehicle weight. This therefore applies to the reference real-world driving cycle considered in this study, as seen in [32] for the WLTC (class 3b) and US06 standard cycles.

Figure 17 summarizes the ERV indices obtained on the reference real-world driving cycle, for the different vehicle models.

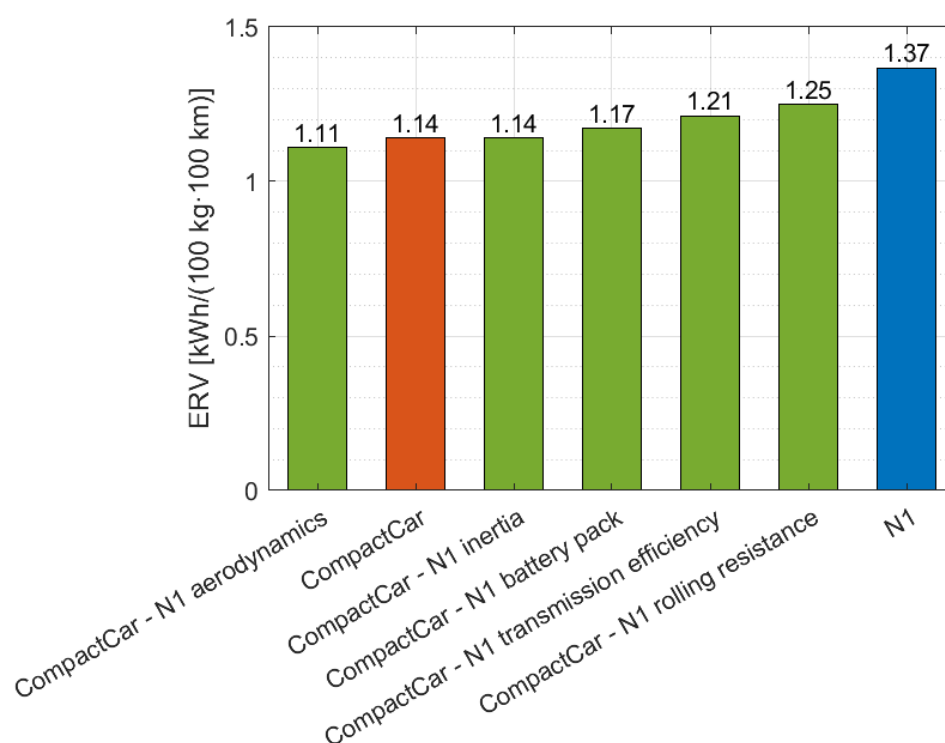


Figure 17. ERV index, obtained from the “polyfit” MATLAB function, on the reference real driving cycle, for the N1 vehicle, for the compact car, and for the compact car with the following parameters, aspects, and components of the N1 vehicle: aerodynamics; moments of inertia; battery pack; transmission efficiency; and rolling resistance.

Then, the results obtained on the real-world driving cycle, in terms of consumption as the vehicle weight varies, were compared with the results obtained in [32] for different standard driving cycles: WLTC (class 3b); US06; FTP75; HWFET; JC08; and Artemis Urban, Rural Road, and Motorway Cycle.

From this comparison it has been found that, for light commercial vehicles (N1 category), the standard driving cycle that best fits the home-to-work journey in reference geographic area considered is the Artemis Urban Cycle. In fact, the curve of the average consumption on the cycle as a function of the vehicle weight matches well between the real-world cycle and the Artemis Urban Cycle.

This standardized cycle can be considered useful for estimating the lightweighting result also for compact cars. In fact, although in this case the consumption curve obtained on the real cycle does not match that of the Artemis Urban Cycle, the slope of this curve (which corresponds approximately to a straight line) is about the same. The reference real-world driving cycle and the Artemis Urban Cycle therefore have in common the ERV index referred to compact vehicles.

Finally, Figure 18 summarizes the outcome of the vehicle lightweighting for different driving cycles, presenting the ERV indices obtained for the various cycles for both the N1 category vehicle and the compact car. From this figure it is possible to see that, for the case study of this paper, the most representative standard driving cycle for both the vehicles is the Artemis Urban Cycle, in fact this cycle has ERV indices very similar to those calculated for the real driving cycle.

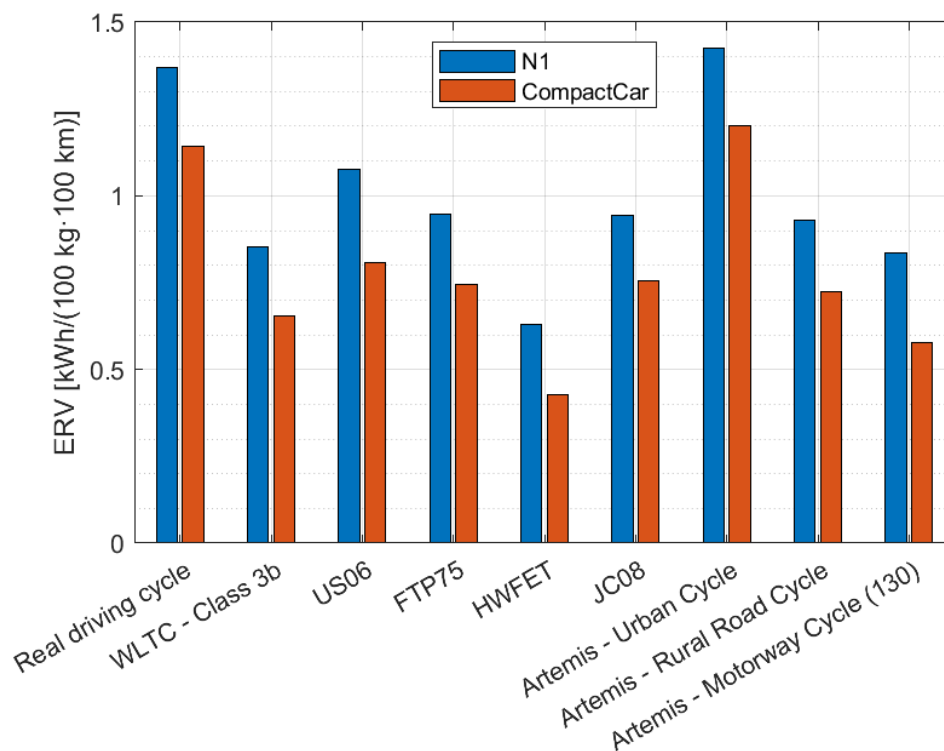


Figure 18. ERV index, obtained from the “polyfit” MATLAB function, for different standard driving cycles, for the N1 vehicle and for the compact car [32].

5. Conclusions

In this study, the research conducted in [32] was replicated using a real-world driving cycle, recorded via GPS on a vehicle to represent typical home-to-work commutes in northern Italy, specifically around the city and province of Brescia in Lombardy.

In fuel efficiency literature, the Fuel Reduction Value (FRV) index, expressed in L/(100 km · 100 kg), is commonly used to estimate fuel savings from vehicle lightweighting. For electric vehicles, however, an equivalent index—the Energy Reduction Value (ERV)—expressed in kWh/(100 km · 100 kg), is more appropriate, as it directly measures energy savings without converting them to fuel-equivalent liters.

The actual ERV for a given vehicle model generally increases with vehicle weight, meaning that heavier vehicles gain greater benefits from the same level of weight reduction. However, assuming a constant ERV across weight variations is a reasonable approximation within the same vehicle model. This holds especially true for the specific real-world driving cycle examined, where consumption patterns for both N1-category vehicles and compact cars, as weight varies, are well approximated by linear relationships (i.e., first-degree polynomial functions).

In this study, it was observed that for an accurate calculation of the ERV index—even for the selected real-world driving cycle, and consistent with standardized cycles such as the WLTC (class 3b) and US06 cycles analyzed in [32]—it is crucial to accurately define parameters such as rolling resistance coefficient, aerodynamics, battery pack characteristics, and transmission efficiency, while the impact of inertia can be considered negligible.

The results obtained on the real-world driving cycle, in terms of average energy consumption as a function of vehicle weight and ERV index, were then compared with those from several standardized cycles: WLTC (class 3b), US06, FTP75, HWFET, JC08, and the Artemis Urban, Rural Road, and Motorway cycles [32]. Among these, the Artemis Urban Cycle was identified as most representative of home-to-work travel from the province of Brescia to the city center. Specifically, for N1-category vehicles, the average consumption on the real cycle closely aligns with the Artemis cycle across all vehicle weights. For compact cars, this alignment holds true only with respect to the ERV index, which, when the base vehicle’s consumption is known, serves as a valuable indicator for assessing potential lightweighting outcomes.

Future work will focus on building a comprehensive vehicle database across various classes, enabling precise estimation of the parameters that most influence lightweighting outcomes, following the approach outlined here and in [32]. This database would ideally include the ERV index for each vehicle across a set of standardized cycles and, where possible, multiple real-world cycles that represent distinct regions or types of journeys. Additionally, the goal would be to identify the standardized cycle that best corresponds to each real-world cycle.

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Nomenclature

Abbreviation	Description
Af	Frontal area of the vehicle
c_3, c_2, c_1, c_0	Coefficients of the y polynomial
Cx	Longitudinal aerodynamic coefficient (drag)
DEM	Digital Elevation Model
EPA	U.S. Environmental Protection Agency
ERV	Energy Reduction Value
EV	Electric Vehicle
FRV	Fuel Reduction Value
FTP75	Standard driving cycle (FTP75) described in the EPA Federal Test Procedure (FTP)

GPS	Global Position System
HWFET	EPA Highway Fuel Economy Cycle
JC08	Japanese Emission Test Cycle
SFTP	EPA Supplemental Federal Test Procedure
SFTP-US06	Standard driving cycle (US06) described in the EPA Supplemental Federal Test Procedure (SFTP)
TEST	Target-speed EV Simulation Tool
WLTC	Worldwide Harmonized Light-Duty Vehicles Test Cycle
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure
x	Vehicle weight (expressed in 100 kg)
y	Polynomial interpolation function, energy consumption expressed in kWh/(100 km)

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