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Accurate Energy Consumption for Comparison of Climate Change Impact of Thermal and Electric Vehicles

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Abstract: Performing a climate impact assessment of vehicles is essential for comparing different powertrain options during an entire vehicle life. Life Cycle Assessment (LCA) is used to estimate these effects over a vehicle's lifecycle, including manufacturing, usage, and end-of-life phases. LCA comprises several indicators, such as the Global Warming Potential (GWP). Generally, LCA or GWP studies use manufacturer-reported standard cycle data to estimate the energy consumption of vehicles. In this article, we develop diesel, gasoline, and electric vehicle simulation tools using the Energetic Macroscopic Representation formalism to evaluate that practice. These simulations are validated with actual, measured driving cycles. The simulations are then used to compare the calculated GWP from real, measured driving cycles relative to standard driving cycles used as industry benchmarks. The results show that standard driving cycles consistently underestimate the benefit of switching from fossil fueled vehicles to electric vehicles. Finally, a sensitivity analysis of the battery life duration is included in this work. It shows that the replacement or second life of batteries is also a key parameter in the GWP advantages of electric vehicles.

Keywords: Electric vehicle, Conventional vehicle, Life cycle assessment, Global warming potential, Vehicle simulation

Highlights

- Global Warming Potential of European conventional and electric small cars are compared
- Benefits of EVs are larger in real driving cycles instead of standard ones
- Sensitivity analysis is done for EV battery life duration
- Battery second life increases the benefits of the electric vehicles up to 43%

1. Introduction

Electric Vehicles (EVs) are a promising solution to reduce greenhouse gas (GHG) emissions in the transportation sector [1]. Unfortunately, the production of the batteries that they require has a significant ecological impact [2]. For a fair comparison between thermal and electric vehicles, a Life Cycle Assessment (LCA) approach is needed. LCA enables the computation of several footprint indicators of a product [3][4]. The climate change indicator, also called Global Warming Potential (GWP), is related to GHG emissions during the entire lifecycle of the product, which is the focus of this paper. Several phases are considered in vehicle LCA. The manufacturing phase deals with the extraction of any materials, the manufacture of the complete vehicle and the related energy used in creating or delivering the product. The usage phase considers GHG from driving the vehicle, including the extraction of primary energy sources, conversion to the vehicle energy (e.g., gasoline or electricity), distribution of this energy and emissions when moving. The energy consumption of the vehicle is thus the key point for this phase. The end-of-life phase considers the GHGs due to recycling operations and waste management.

For a considered vehicle, the GHG of the manufacturing and end-of-life phases are constant as we consider a fixed number of components (e.g., filters, tyers, etc.) changed during the life of the vehicle. Thus, the sizing of the battery is an essential point of the EV assessment [5]. For EVs, battery replacement is an important concern [6]. When this occurs, the GHG footprint of the vehicle is significantly increased. In addition, there is increasing research and development on the reuse of the vehicle battery for a second life [7] [8]. In this case, the GHG footprint of battery production is shared with another application. As the GHG of the battery is a significant contributor to the overall climate change indicator for EVs, a sensitivity analysis of the battery life should be included in the LCA.

The usage phase GHG emissions strongly depend on the amount and type of travel realized by the vehicle. Moreover, for EVs, the method of electricity production also has a strong impact [3]. When estimating the energy consumption of electric vehicles, constant consumption factors are often used for modeling simplicity. Examples include 12.7 kWh/100km for a Volkswagen e-golf in Europe [6] or 20.6 kWh/100 km for a Nissan Leaf in Europe [9]. Other studies use consumption factors from different manufacturers or regulatory entities within these limits [10]-[14]. These constant factors are derived from standard driving cycles to compute the energy consumption of both thermal and electrical vehicles [15][16]. Standard driving cycles are used throughout the vehicle development process, from the vehicle design to its certification. Evaluation of a vehicle's energy consumption and pollutant emissions also uses these standard cycles. There are numerous standard driving cycles that aim to represent the driving habits of different kinds of vehicles (e.g., cars, buses, etc.) and for different countries or regions [17][18].

But these driving cycles are not always representative of actual driving or energy use [19] and correction factors are sometimes considered [20]. A recent study demonstrates that standard driving cycles underestimate the energy consumption of thermal vehicles and overestimate those of EVs [21]. This suggests that most assessments of the energy/carbon footprint of vehicle operations may be consistently biased in favor of thermal vehicles. A fair comparison of GHG footprints of both types of vehicles requires realistic driving cycles. Some past work has focused on energy consumption measured on the road [22][23]. This is logical and justifiable, but such results cannot be easily applied to other vehicles and strongly depend on driving conditions (e.g., traffic) [24][25].

The objective of this paper is to provide a fair comparison of the GWP of three vehicles (diesel, gasoline and electric) by using real measured driving cycles and to compare these results to traditional constant consumption factors. In Europe, most vehicle sales at the beginning of the 2010s were diesel. However, in recent years, the diesel car market share has fallen and has been progressively replaced by gasoline, while the EV market is rapidly developing [26]. In this work, three actual vehicles are considered, from the same small-car segment and the same manufacturer for a fair comparison. The studied electric vehicle has been designed from the studied diesel vehicle which leads to an easier and more relevant comparison. In the years up to 2020, the small car vehicle segment has been around 20% of the sales in the European market [27]. Within that segment, 80% of the thermal cars have a 5-speed manual gearbox.

An accurate simulation is developed to estimate the energy consumption of the three vehicles for any driving cycle. After experimental validation of the simulation, real driving cycles are used as the input for later analysis. This method makes it possible to have identical driving cycles in the different vehicles as well as a comparison with standardized test cycles. The GWP of the different vehicles is then computed and the battery replacement or reuse is also considered. The diesel and electric vehicle simulation has been developed for a prior economic comparison of both cars [21]. This simulation is now extended to a gasoline car, and GWP indicators of the usage phase are implemented. Finally, the GWP of the three life phases of the vehicles is computed to show the effect of improved resolution on usage phase energy use and emissions.

Section 2 presents the methodology. Section 3 develops the simulation of the vehicles and the validation by experimental results. The Global Warming Potential of the different cars is compared in Section 4. Section 5 discusses the limitations and advances of the proposed method.

2. Methodology

Three vehicles of the same segment are studied for a fair comparison: the Renault Clio (gasoline and diesel) and the Renault Zoe (electric vehicle). An accurate simulation is then developed to estimate their GHG emissions in the usage phase using real on-road driving cycles. Then their GWPs are computed for their entire life cycle.

2.1 Studied Vehicles

The chosen vehicles (Figure 1) are the Renault Zoé for the electric vehicle [28] and Renault Clio for thermal cars (i.e., diesel and gasoline) [29]. All three vehicles are in the small-car segment, also called B-segment in Europe. The EV has a mass of 1480 kg including a Li-ion NMC battery of 41 kWh. The mass of the diesel and gasoline vehicles are respectively 1130 kg and 1080 kg. Due to the battery, the EV has a higher mass than the conventional ones.

Figure 1: Studied vehicles: Renault Zoé Q90 41 kWh 2016 and Renault Clio III 1.5 dci 90 hp -2015 (diesel car).

All three vehicles are composed of an energy source (the battery for the EV and the fuel tank for the thermal vehicles), an energy transformer (electric motor for the EV and Internal Combustion Engine for the conventional cars), a gearbox, wheels, mechanical brakes and a chassis. For the EV, the gearbox is composed of a simple gear connected to the differential. For model validation reasons, the gearbox is a 5-gear manual gearbox connected to the differential for the thermal vehicles as used in most European vehicles. However, the method can be extended to newer gearbox technologies when measurements are available. While the simulation of other gearbox designs is possible, the lack of on-road validation of the simulation would limit the validity of the analysis in this work.

2.2 Accurate energy consumption

The general strategy in this research is first to develop accurate simulation models of each of the three vehicles, which are validated with experimental testing. Next, the simulations can be used to compute the energy consumption of the three vehicles using identical realistic driving cycles. There are several reasons for this strategy. First, it is impossible to have precisely the same on-road driving conditions for each of the three vehicles. Even when traveling the same route with the same driver, the traffic, weather, and streetlight conditions will vary. These differences lead to bias in comparisons of energy consumption. Moreover, as the simulation is rapid, different driving cycles can be compared without the time and cost needed to prepare the car (e.g., charging for the EV), drive, and recover the data.

The simulation is organized using Energetic Macroscopic Representation (EMR) [30]. EMR is a graphical formalism used to organize the models of energy conversion systems and their controls. EMR has been widely used to study the energy consumption of various electric and hybrid vehicles [31]-[33]. It enables a common framework for the simulation of the studied electric, diesel and gasoline vehicles.

2.3 Computation of the Global Warming Potential

The vehicle GWP computation is decomposed into three phases (Figure 2). The manufacturing phase is related to 3 subsystems: the battery, the powertrain and the glider (i.e., the body and non-drive components). The glider is assumed

to be the same for all vehicles, as the Renault Zoe is built based on existing thermal vehicles, which is common for first-generation EVs. Indeed Renault Zoe has been designed as an electric version of the Renault Clio. The usage phase has the vehicle energy consumption as an input for a considered driving cycle. The energy consumption is computed from simulation combined with measured driving cycles, as explained above. For the end-of-life phase, the three initial subsystems are considered.

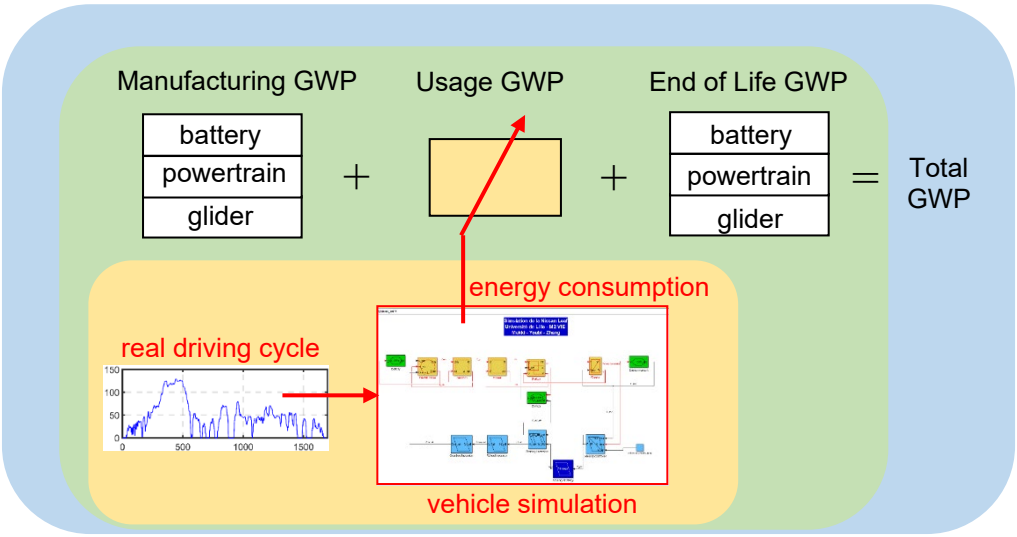

Figure 2: Improved global warming potential computation with more accurate usage phase, through detailed simulation and real driving cycles.

3. Energy consumption of the studied vehicles

3.1 Model of the electric vehicle

The EMR of the EV is presented from left to right (Figure 3). The battery is a green oval and describes the battery voltage u_{bat} as a function of the current i_{ed} and the Open Circuit Voltage (OCV), which depends on the battery State of Charge (SoC).

$$u_{bat} = OCV(SoC) - R_{bat} i_{bat} \quad (1)$$

The battery is connected to the electric drive, represented by a multi-physical element (orange circle). The drive is composed of an inverter and an electric motor. It transforms the electricity into mechanical energy on the rotating shaft of the motor. The drive equation gives the current i_{ed} as a function of u_{bat}, the motor torque T_m and the gearbox speed Ω_{wh}.

$$i_{ed} = \frac{T_m \Omega_{gb}}{u_{bat}} \quad (2)$$

Next, the gearbox is represented by a mono-physical conversion element (orange square) which converts the motor torque T_m to the gearbox torque T_{gb} and the wheel speed Ω_{wh} to the gearbox speed Ω_{gb} through the gearbox ratio k_{gb}.

$$\begin{cases} T_{gb} = k_{gb} T_m \\ \Omega_{gb} = k_{gb} \Omega_{wh} \end{cases} \quad (3)$$

The wheels are represented by an equivalent wheel with the radius R_{wh}, which converts the gearbox torque to the wheel force F_{wh} and the vehicle velocity v_v to the wheel speed (orange square).

$$\begin{cases} F_{wh} = \frac{T_{gb}}{R_{wh}} \\ \Omega_{wh} = \frac{v_v}{R_{wh}} \end{cases} \quad (4)$$

The total force F_{tot} applied to the vehicle is the sum of the wheel force F_{wh} and the mechanical brake force F_{br}. This equation is represented by a coupling element (double orange squares).

$$F_{tot} = F_{wh} + F_{br} \tag{5}$$

The chassis of the vehicle is an energy accumulation element (crossed orange rectangle) because its mass accumulates energy during accelerations and restores this energy during decelerations. In this element, the vehicle velocity v_v depends on the total force F_{tot}, the resistive force F_{res} and the mass of the vehicle M_v.

$$v_v = \frac{1}{M_v} \int F_{tot} - F_{res} \tag{6}$$

This chassis is connected to the road (green oval). The resistive force is a function of the rolling resistance F_{roll}, aerodynamic resistance F_{aero} and the slope resistance F_{slope}.

$$F_{res} = F_{roll} + F_{aero} + F_{slope} \tag{7}$$

The inversion-based control of the vehicle is systematically deduced from the EMR. First, the accumulation element of the chassis is indirectly inverted using a control loop of the vehicle velocity (crossed light blue parallelogram). The total force reference F_{tot_ref} depends on the measured resistive force F_{res_mes}, a controller $C(x)$, a reference velocity v_{v_ref} which comes from the driving cycle profile and the measure of the vehicle velocity v_{v_mes}.

$$F_{tot\_ref} = F_{res\_mes} + C\big((v_{v\_ref} - v_{v\_mes})\big) \tag{8}$$

The other EMR blocks are directly inverted. The inversion of the coupling element gives a distribution element (double light blue parallelogram) which splits the total force into the brake and wheel forces, F_{br_ref} and F_{wh_ref}, using a braking input k_{br} given by the braking strategy.

$$\begin{cases} F_{wh\_ref} = k_{br} F_{tot\_ref} \\ F_{br\_ref} = (1 - k_{br}) F_{tot\_ref} \end{cases} \tag{9}$$

The inversion of the wheel is the direct inversion of equation (4):

$$T_{gb\_ref} = R_{wh} F_{wh\_ref} \tag{10}$$

The reference torque applied to the motor T_{m_ref} depends on the gearbox reference torque and the gearbox ratio.

$$T_{m\_ref} = \frac{T_{gb\_ref}}{k_{gb}} \tag{11}$$

Finally, the braking strategy distributes the forces between the wheel and the brakes (dark blue parallelogram). As the electric motor is reversible, energy can be recovered during braking phases in an EV. The energy recovery depends on several constraints, such as the maximal battery current and SoC. When the vehicle is in the braking phase, the total force applied to the car is negative. In this configuration, the braking coefficient k_{br} is set to 60 % and can be limited if the battery current reaches its charging limitation or the battery is full (SoC >99 %). When the vehicle is not in the braking phase, the braking coefficient is set to 1.

$$\begin{cases} k_{br} = 0.6 \; when \; F_{tot\_ref} < 0 \\ k_{br} = 1 \; when \; F_{tot\_ref} \geq 0 \end{cases} \tag{12}$$

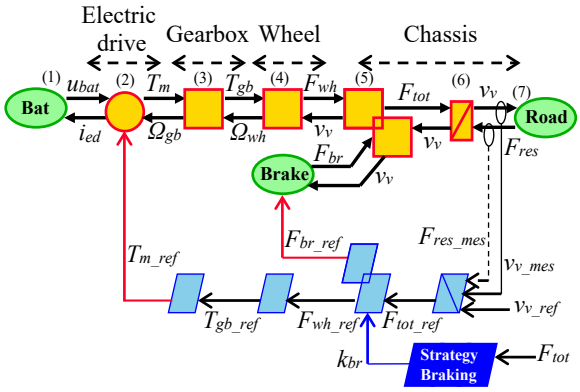

Figure 3: EMR of the electric vehicle

3.2 Model of the thermal vehicles

The EMR of the thermal vehicles is represented in figure 4. The two cars have the same representation. The only difference is the fuel used by the vehicles. The Internal Combustion Engine (ICE) is the energy source of the thermal vehicles (left green oval). The consumption of diesel and gasoline vehicles is calculated using a consumption map for each car. These maps are a function of the motor torque and speed. It is assumed an ideal control of the ICE:

$$T_{ice} = T_{ice\_ref} \tag{10}$$

The ICE is connected to the manual gearbox of the vehicle (orange square). The equation of the gearbox is the same as the EV (3). In this vehicle, the gearbox ratio can take five different values. These values are selected in the strategy as a function of the vehicle velocity.

The manual gearbox is connected to the wheels (orange square). The wheel equation is given by (4). The wheel is coupled with the brakes (double orange squares) (5) and the chassis of the vehicle (crossed orange rectangle) (6). The chassis is connected to the road (right green oval) (7).

The control of the vehicle is deduced (light blue parts) directly from the EMR of the vehicle. In these cars, the brakes are only mechanical. So, when the total force F_{tot_ref} is positive, the wheel force F_{wh_ref} is equal to the total force F_{tot_ref} and the brake force F_{br_ref} is equal to 0. And when the total power is negative, the wheel force is null and the brake force is similar to the total force.

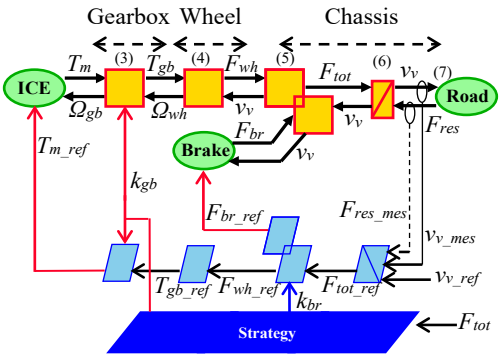

Figure 4: EMR of the thermal vehicles

3.3 Validation of the diesel vehicle

After the achievement of the simulation tools of the vehicles above, they are validated by comparison with real measurements from the cars during on-road driving. For each car, the velocity is measured with a GPS (Global Positioning System) device and the energy consumption is read on the Can Bus of the cars through an OBD (On-Board Diagnostic) reader. In this article, only the validation for the diesel vehicle is presented. The validation of the electric vehicle is similar and detailed in [34].

The velocity profile is introduced in the simulation tool and the consumption is calculated for each test and compared with the measured consumption (Fig. 5). For the real trip, the measured fuel consumption is 4.88 l/100 km. The fuel consumption calculated by the simulation is 4.91 l/100 km. That leads to an error of about 1%.

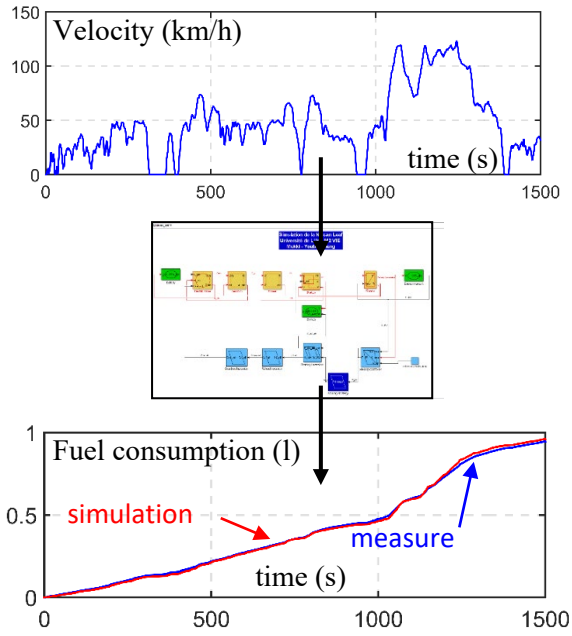

Figure 5: Validation approach of the diesel vehicle

After the validation of the different vehicle simulation tools, they can be used to calculate the energy consumption and then the GHG emissions for each vehicle for different driving cycles.

3.4 Comparison of the energy consumption using a standard driving cycle (WLTC)

In this part, the simulation results and the data from the manufacturers are compared on the basis of the energy consumption of the vehicles and the GWP in the usage phase, also called Well-to-Wheel emissions. The standard driving cycle is the World Light vehicles Test Cycle (WLTC) class 3, adopted in Europe in 2017 (Fig. 6). This driving cycle is now the standard used to estimate the pollutant emissions and energy consumption of the vehicles on roads in Europe.

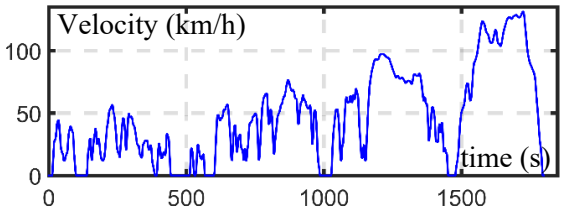

Figure 6: Velocity of the WLTC driving cycle

The WLTC driving cycle is used with the vehicle simulations developed above and compared to manufacturer-reported energy efficiency (Table 1). The fuel efficiency data are referred to as "reported values" in the remainder of this article. For the thermal vehicles, the data are taken from [35]. Notably, this method suggests that the reported fuel consumption is underestimated by about 10 %. Using the reported value, which is commonly done in studies of vehicle GWP, would reduce the calculated climate impact of conventional thermal vehicles. For the EV, the reported value is taken from [35] and [36]. It appears to overestimate the consumption of the vehicle by about 17%. Thus, the energy and GWP of the EV may be regularly overestimated when using the reported values for energy efficiency. These calculations imply that the GWP of these vehicles may be consistently misestimated in favor of thermal vehicles, affecting a wide variety of conclusions and vehicle regulation decisions. It also highlights the importance of accurate energy consumption inputs for improved accuracy in GWP studies. Right now, standard driving cycles are generally used even if they are not representative [19].

Table 1: Evaluation of the consumption and emission due to the WLTC driving cycles for the different vehicles

Vehicles	Gasoline Vehicle	Diesel Vehicle	Electric Vehicle
Simulated energy consumption	4.8 L/ 100km	4.6 L/ 100km	17.1 kWh/ 100km
Reported energy consumption	4.3 L/ 100km	4.1 L/ 100km	20.1 kWh/ 100km

4. Global warming potential of the different vehicles

In this section, the inventory of the GWP for the manufacturing and end-of-life phases of the vehicles is integrated with the impact of the use phase, estimated with varying driving cycles. Finally, the effect of battery second life is discussed.

4.1 Global warming potential inventory of the studied vehicles

While the manufacturing and end-of-life phases of the vehicle lifecycle are not the focus of this work, they are included in order to show how usage phase misestimation affects overall GWP. The GWP inventory of the manufacturing and end-of-life of the various vehicle components is given in Tables 2 and 3. All vehicles use the same glider, as the studied electric vehicle design is derived from the conventional ones. The inventory of conventional vehicles is based on [37]. A reduction coefficient of 0.83 is applied to convert from a medium-size vehicle into a small-size vehicle. This coefficient is based on the methodology used to study different vehicle segments [5]. The Electric Vehicle inventory comes from prior work during the PANDA project [34], including a detailed GWP estimation of the battery.

The 41 kWh NMC battery of the electric car is a Lithium Ion battery with a Nickel Manganese Cobalt anode and a graphite cathode. All battery parts are produced in Asia and assembled in France. As the battery's end-of-life is uncertain, it is assumed that the battery has been split into several parts which are disposed, recycled or re-purposed. Recycling has been realized by hydrometallurgical processes. The glider and powertrains of the vehicles are produced in Europe. The final assembly and dismantling of the vehicle are also realized in Europe.

Table 2: GWP inventory of the manufacturing of the studied vehicles (kg CO_2eq)

Components	Gasoline Vehicle	Diesel Vehicle	Electric Vehicle
Battery	0	0	4650
Powertrain	591	661	356
Glider	3900	3900	3900

Table 3: GWP inventory of the end-of-life of the studied vehicles (kg CO_2eq)

Components	Gasoline Vehicle	Diesel Vehicle	Electric Vehicle
Battery	0	0	634
Powertrain	41	46	25
Glider	271	271	271

The considered electricity mix is 449 g CO_2eq/kWh. This value is based on the average European electricity mix and includes charging and distribution losses [34]. The GHG emissions of fuel production and usage are based on the average value given by the Joint Research Center of the European Commission [38]. These GHG emissions include emissions from the three most important gases emitted by fuel combustion: CO_2, CO, CH_4 and NO_2. The lifetime mileage for the different vehicles is set to 150 000 km, a typical value used in such studies [3]. The initial assumption for battery life is that the battery could be used for this distance and its life cycle is ended with the end of life of the vehicle. This assumption is investigated further at the end of this paper.

4.2 Global Warming Potential of the studied vehicles on extra-urban driving cycles

The global warming potential of the three vehicles is detailed for a real, measured extra-urban driving cycle (Figure 7). These cycles have been selected to be representative of real trips realized in Europe. The GWP of the usage phase is computed from the simulations of the three cars. For all vehicles, the usage phase is decomposed into two parts: the emission during the driving phase (also called tank-to-wheel, TTW) and the emissions due to the production of the energy (also called well-to-tank, WTT). The simulation of the different vehicles leads to an emission of 36 g CO_2eq/ km, 32 g CO_2eq/km and 79 g CO_2eq/km for the well-to-tank of the gasoline, diesel and electric vehicles. For the tank-to-wheel, the real extra-urban driving cycle leads to the emission of 187 g CO_2eq/km and 156 g CO_2eq/km for gasoline and diesel cars. Of course, there is no direct CO_2 emission from EVs during driving.

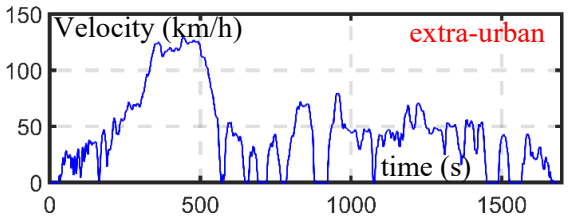

Figure 7: Real extra-urban driving cycle

The total GWP can thus be computed, including all phases. The EV has a climate impact of 140 gCO_2eq/km. The diesel has an impact of 198 gCO_2eq/km and the gasoline vehicle is 219 gCO_2eq/km. As expected, the electric car has the lowest use phase GWP of the three vehicles despite the relatively high impact of the battery manufacturing and end-of-life.

The GWP is also computed for the WLTC, the standard extra-urban driving cycle used in Europe. Between 2017 and 2021, automaker figures are estimated using a WLTC driving cycle and calculated for the NEDC cycle (which was the standard cycle until 2017) using a corrective factor. However, we prefer to compute them by simulation to ensure that all calculations use the same process, which leads to similar figures as those reported by automakers. A lifecycle GWP comparison is then carried out for the three vehicles (Fig. 8). For all vehicles, the estimated GWP is reduced by using the WLTC instead of the real extra-urban driving cycles by 7% for the two conventional vehicles and 1% for the electric vehicle. Thus, once again, the standard driving cycles favor the thermal vehicles in comparison with the real driving cycles.

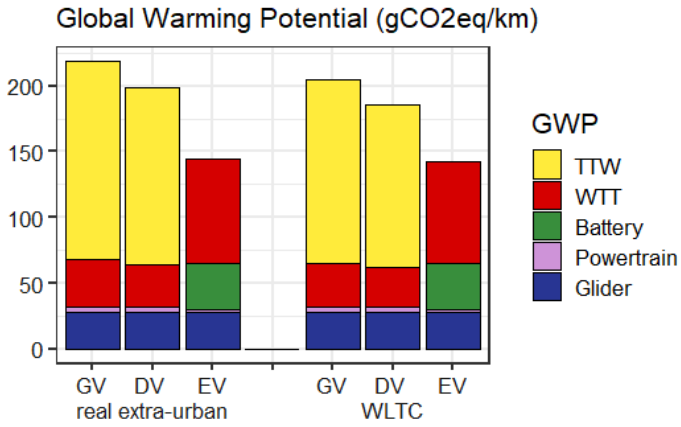

Figure 8: GWP of the gasoline (GV), diesel (DV) and electric (EV) vehicles for a real extra-urban driving cycle and WLTC.

It has been demonstrated that the NEDC leads to lower estimates of energy consumption and pollutant emission than the WLTC for the usage phase [19]. As some studies still use NEDC as a driving cycle, the benefits of transitioning from conventional to electric vehicles would be further underestimated in terms of GWP.

4.3 Impact of different driving cycles on the Global Warming Potential

In order to demonstrate that the effects described above are consistent, this section compares the GWP from different driving cycles, between gasoline and electric vehicles. The gasoline vehicle is selected because it is the highest CO_2 emitter. The results of the diesel vehicle will thus be between the gasoline and electric vehicles. We introduce two additional real, measured driving cycles. These driving cycles represent urban and highway road conditions which can be found in Europe. We compare them with equivalent standard driving cycles (Figure 9). The two upper driving cycles are real ones measured with the electric vehicle. The two bottom driving cycles are the JC08, the Japanese standard driving cycle and the HWFET, an American highway standard driving cycle.

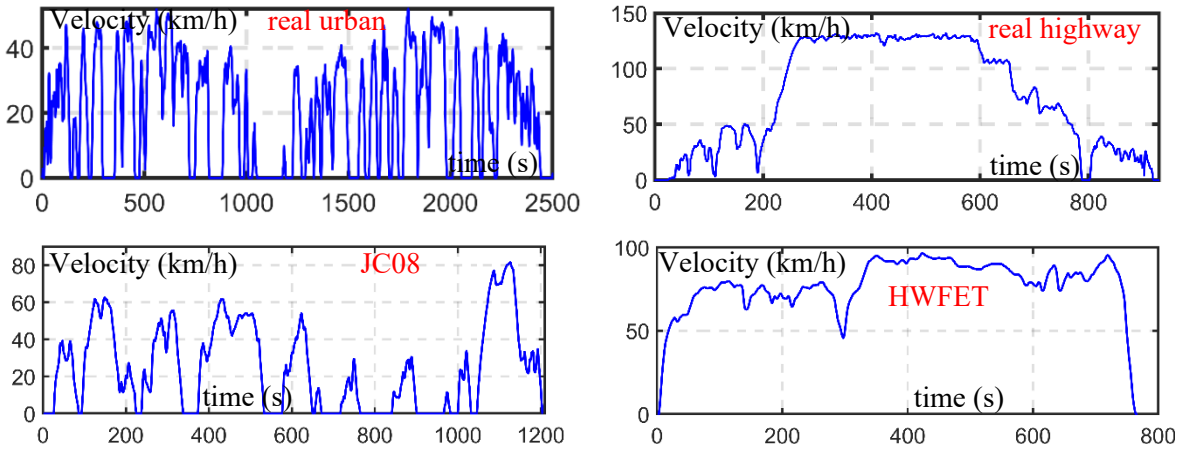

Figure 9: Four additional driving cycles used in this analysis

For each velocity profile, the Global Warming Potential of the usage phase is calculated using the vehicle simulation tools (Table 4).

Table 4: GWP for the gasoline and electric vehicles for the different cycles (g CO_2eq/km)

Driving cycles	Real urban	JC08	Real highway	HWFET
Gasoline Vehicle	223	191	202	125
Electric Vehicle	64	57	103	68

The difference in the GWP between gasoline and electric vehicles (g CO_2eq/km for the gasoline vehicle minus g CO_2eq/km for the electric vehicle) for the six considered driving cycles is presented in Figure 10. The GWP difference is about 83 g CO_2eq/km for the extra-urban driving cycle, with higher emissions per km for urban driving and lower emissions per km on highways. In all cases, the EV has a lower climate impact per km, but the advantage of EVs is consistently underestimated when standard driving cycles are used. Relative to the real extra-urban driving cycle, using the standard WLTC driving cycle reduces the benefits of switching to EV by 16% (from 83 g CO_2eq/km to 70 g CO_2eq/km). For the JC08 driving cycle, the benefits of switching to EV are reduced by 23% (from 134 g CO_2eq/km to 109 g CO_2eq/km) relative to the real urban driving cycle. And for highways, the standard HWFET cycle underestimates the emissions advantage of EVs by 57% (from 74 g CO_2eq/km to 32 g CO_2eq/km). Moreover, the GWP for the two vehicles has also been calculated from the reported consumption data given in Table 1. The GWP difference, in this case, is 7 g CO_2eq/km. Once again, these comparisons show the importance of considering real driving cycles when estimating GWP potential of vehicles instead of the common practice in the literature of using manufacturers' reported data. As

explained above, the difference between the diesel and electric vehicle are lower as the gasoline vehicle has more GWP in the usage phase than the diesel vehicle.

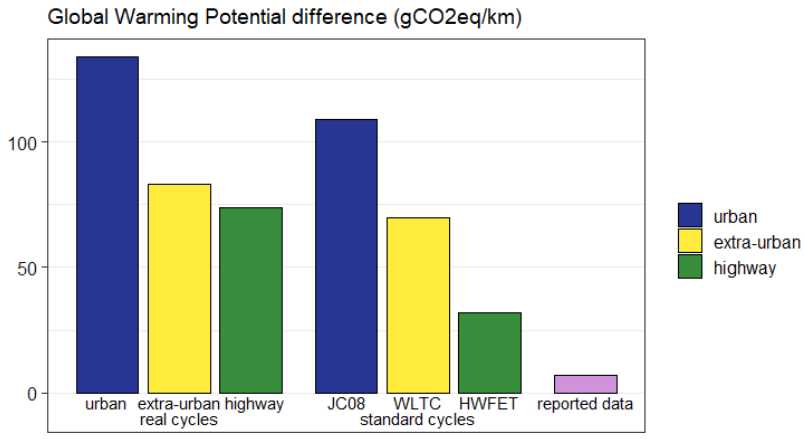

Figure 10: GWP difference between the gasoline and electric vehicles as a function of the driving cycle

4.4 Impact of the battery lifetime and second life

We have also investigated the effect of the battery usage/replacement on the difference in climate change impact between gasoline and electric vehicles, using the real extra-urban driving cycle (Fig. 11). In the results above, the battery is assumed to be at the end of its life at the same time as the end of the vehicle's life. This case corresponds to a GWP difference of 83 g CO_2eq/km between gasoline and electric vehicles. Two other scenarios are considered for the battery life duration. First, a second life of the battery is assumed, for example in a stationary application [8]. The GWP of the battery is thus split between the vehicle use and the secondary use. For simplification, an equivalent usage time is considered for the vehicle and the secondary services (i.e., a coefficient of 0.5 is applied to the battery manufacturing and end-of-life contribution). In this case, the GWP benefit of the EV is increased by 22% (from 83 g CO_2eq/km to 101 g CO_2eq/km). Second, we consider a case where two batteries are required during the vehicle's lifetime. This case corresponds to rapid aging during the usage phase (e.g. frequent ultra-fast charging). In this second case, the GWP benefit of an EV is reduced by 43% (from 83 g CO_2eq/km to 45 g CO_2eq/km). Once again, the difference between the diesel and electric vehicles are lower as the gasoline vehicle has the largest GWP in the usage phase.

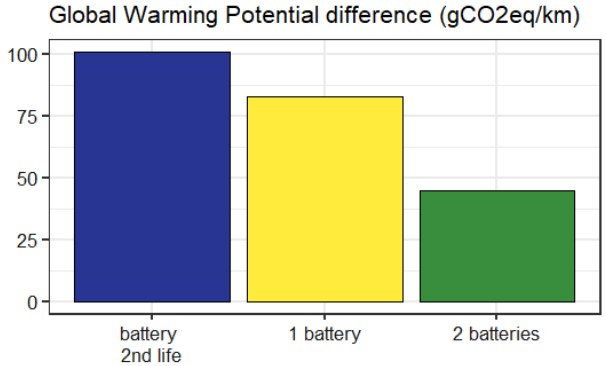

Figure 11: GWP difference between gasoline and electric vehicles as a function of the battery usage for the real extra-urban driving cycle

5. Conclusion

This work offers a comparison of climate change impacts of different driving cycles for conventional and electric vehicles in Europe. In order to have accurate values of the GHG emissions during the usage phase, vehicle simulation tools have been developed and connected to GWP studies. These simulation tools were validated by comparison with measurements from real vehicles and used to illustrate the systematic biases of traditional standard driving cycles.

We applied the same driving cycles for each vehicle in order to have a fair comparison of the climate effects of vehicle operation. However, the experimental basis of this work means that it is limited in scope. The driving cycles in this study do not cover all possible trips and driving conditions such as traffic, driving behavior, or weather conditions. In addition, this work proposes only one comparison between two B-segment vehicles with manual gearboxes which are the main mechanical transmissions in conventional vehicles. Further experimentation and analysis are necessary to explore all the options available on the market: other segments (sedan, SUV), other propulsion (hybrids) or different gearboxes (automated, Dual clutch Transmission). However, we propose that the results above give sufficient information to have fair comparisons between the studied vehicles and to illustrate an important bias in existing studies.

The results show a lower GWP for EVs, relative to thermal vehicles, in the case of the current European electricity mix. Furthermore, this work highlights the importance of considering real driving cycles instead of relying on traditional standard cycles and the manufacturer-reported data that comes from data sheets. Standard driving cycles underestimate the benefits of EVs in terms of GWP. As EVs are more commonly used on urban roads, we consider that real driving cycles are more representative for the EV. In this case, standard driving cycles reduce the potential GWP benefits of EVs by 50% relative to real urban driving cycles. Consequently, the scope of GWP or LCA studies should mention the type of driving cycles used and consider which driving assumptions are most appropriate.

Finally, the analysis of battery life opens further discussions. The analysis in this paper focuses on the NMC battery which represents around 80 % of the batteries present in vehicles [1]. The consideration of the secondary use of the battery leads to a reduction of the GWP of the EV. Such a practice would further increase the benefits of EVs in terms of GWP. This discussion can be improved with better knowledge and data about the lifetime of a battery for an electric vehicle in both vehicle usage and secondary life usage. Battery technology also has an important GWP impact due to both recycling and reuse [39][40]. Other chemistries used in EVs, like LFP which has a longer lifetime than NMC [41], can be studied in the future.

This work only considers electric and thermal vehicles. Hybrid vehicles such as hybrids electric vehicles and fuel cell electric vehicles are not considered. For these vehicles, intermediary results on the GWP can be expected [5]. However, these kinds of vehicles can have different designs (series, parallel) and different levels of hybridization (micro to full hybrid) [42]. Furthermore, energy management and the driving cycle also have an impact on GWP potential [43]. Due to the high number of parameters, it is much more complex to give accurate figures for these vehicles.

This work does not include a detailed analysis of the manufacturing and end-of-life phases of the vehicles. In fact, the manufacturing of the engine of conventional vehicles is more complex over time and the use of resources is more relevant. For EVs, battery sizes are still increasing and the battery recycling processes are still mostly unknown. While these details are being investigated by other researchers, these limitations have an impact on the results. These gaps will be studied in future work.

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