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Analysing the potential of a simulation-based method for the assessment of CO_2 savings from eco-innovative technologies in light-duty vehicles[1]

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ABSTRACT

Mandatory targets are set in Europe for Carbon Dioxide (CO_2) emissions of light-duty vehicles. EU law recognises the potential of certain innovative technologies to contribute to reducing CO_2 emissions. Vehicle systems and innovations are becoming increasingly complex, and the accurate quantification of their benefits increasingly difficult. The study investigates the potential of the CO_2MPAS simulator to serve this purpose. Two innovative technologies were studied, Light-emitting diode (LED) lighting systems, efficient alternators (EA), and their combination. The model was validated on detailed test results from eight vehicles. A total of 452 passenger cars, for which test data were available, were subsequently simulated using CO_2MPAS simulator. The mean simulated CO_2 savings was 0.91gCO_2/km (LED lights), 0.98 gCO_2/km (EA), and 1.78 gCO_2/km (combined). Results show that simulated CO_2 savings were comparable to those calculated using the existing standardised method. For gasoline and diesel vehicles respectively, the difference in CO_2 savings between simulated and existing method was 2.8% and 0.14% in the LED lights case, and 0.6% and 0.67% in the alternator case. In the combined case, the difference was calculated to be 1.7% and 0.34%. Similar approaches could be used in the future for accurately capturing the benefits of more complex technologies.

1. Introduction

According to United Nations, 2019 was the third consecutive year when global greenhouse gasses (GHG) emissions continued growing up to a record of 52.4 gigatons of Carbon Dioxide (CO_2) equivalent, including land-use change emissions. From these, emissions from fossil fuel and carbonates also reached a new record: 38.0 gigaton of CO_2 [1]. The transport sector is the second contributor to these CO_2 emissions representing the 26%, after the *Energy industries* sector with 30% of CO_2 emissions [2]. Passenger cars, road freight and aviation are the main contributors to GHG emissions in transport sector, where passengers cars represent the 81% of total energy use by the transport sector [2]. Worldwide, several States have set in place policy frameworks to address the increase of CO_2 emissions in this sector: United States [3], Japan [4], Canada [5] or Australia [6] among others. According to the European Environmental Agency [7], CO_2 emissions represented around 87% of the total GHG emissions in the European Union (EU) in 2018. European Union's regulation (EU) 2019/631 sets targets for the average CO_2 emissions of new passenger cars. In December 2019, the *European Green Deal* was published, setting out new growth strategies to deal with climate and environmental-related challenges in the EU [8]. It calls for a transition to net-zero greenhouse gas emissions by 2050 [9]. Zero- and Low-emission vehicles need to contribute to the mobility system's decarbonisation [10].

The European Commission monitors compliance with the CO_2 targets through the reporting by Member States of the official CO_2 emission values declared for individual vehicles during vehicle type

[1] The views expressed in this paper are purely those of the authors and shall not be considered as an official position of the European Commission under any circumstance.

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approval (TA). The test procedure followed during TA does not capture all CO_2-reducing effects of innovative technologies. Regulation (EU) 2019/631 provides for the possibility to recognise these technologies as eco-innovations (EIs). Manufacturers and suppliers may apply for the approval of innovative technologies that contribute to CO_2 emissions reduction in off-cycle conditions [11]. The Commission assesses the applications and the applicant's testing methodology for determining the CO_2 savings from the innovative technology. Where the application is approved, the Commission formally adopts a relevant quantification methodology. The vehicle manufacturer that wishes to benefit from the CO_2 savings will have to apply to a type-approval authority for the certification of the savings using the quantification methodology. The detailed procedures are set out in Commission Implementing Regulations (EU) No 725/2011 and (EU) No 427/2014, where the total contribution of those technologies to reducing the average specific emissions of a manufacturer may be up to 7 gCO_2/km. The CO_2 emissions savings from eco-innovations must be demonstrated independently from the homologation cycle with verified data. The calculation of the eco-innovation's CO_2 savings is based on the general principles defined in the Technical Guidelines [12], creating a frame methodology hereinafter referred to as EI methodology. There are several EI approved under Worldwide harmonised Light-duty vehicles Test Procedure (WLTP) in the European Union. Some of them are Light-emitting diode (LED) lighting, efficient alternator, among others. Before 2021, technologies were approved under the New European Driving Cycle (NEDC) [13]. Methods to evaluate CO_2 savings from EIs can be implemented for specific technologies, but on a broader basis, the simplified evaluation becomes more and more challenging because the electrification degree, and the interaction among technologies, increases [14–16]. A potential solution to facilitate the development of the EI methodology could be the use of methods primarily based on simulation techniques to assess the CO_2 emission savings from innovative technologies in view of the Commission approval.

Currently, no approved EI methodologies are fully based on simulation methods. Literature studies apply computing tools to simulate the prediction of future vehicle's fuel consumption [17], GHG emissions depending on acceleration/deceleration rates [18], or CO_2-reductant impact of thermal components [19]. Several studies have simulated vehicle's fleet total CO_2 emissions [20–23], innovative designs of alternators and LED lamps in vehicles can be found in Refs. [24–29], as well as simulation of battery properties [30,31] and ultra-capacitors [32]. Also, simulation methods are being applied to calculate the energy mix used in electric vehicles [33–35], as well as energy management strategies [36]. In Ref. [37], the authors simulated well-to-wheels CO_2 emissions of electric vehicles under NEDC, where the difference between simulated and measured electric consumption was lower than 1.9%, showing the potential of a simulation-based approach to estimate CO_2 emissions. Hangiu et al. [38] simulated the performance of an efficient alternator (EA) to calculate the state of charge and torque behaviour in hybrid vehicles, and in Ref. [39] different hybrid architectures are compared using simulated EA performance, without evaluating the corresponding CO_2 emissions. To the authors' knowledge, no studies were conducted specifically on the simulation of CO_2 savings due to more efficient vehicle's external light-emitting diodes (LED) lights, nor due to a combination of LED and EA in conventional ICE vehicles.

Commercial tools are widely used in R&D for simulation purposes [23,40]. This study aims to simulate innovative technologies with computational tools and analyse the capacity of the CO_2MPAS light-duty vehicle simulator, already introduced in EU's vehicle CO_2 emissions certification by Regulations (EU) 2017/1152 and (EU) 2017/1153 [41]. Previous study showcases the accuracy of the tool [42]. The proposed method uses CO_2MPAS to evaluate the CO_2 savings from eco-innovative technologies under WLTP conditions [43]. Simulation results are compared to the CO_2 emissions savings obtained with the established Technical Guidelines.

The reason for electing LED lights and efficient alternator is twofold. First, because of the well understanding of their performance (so possible deviations of the new method can be easily recognised). Second, because of their high market penetration compared to other technologies (Table 1). The technology identified as an “efficient alternator” is the most frequent eco-innovation, formed by 12-V alternators from several manufacturers (no 48-V generators were reported). The EEA database does not specify the alternators' efficiency or the type of LED lights packages (consumption or number of lamps), but only the number of vehicles fitted with such eco-innovations.

2. Methodology

According to EU regulation, the EI assessment is based on the analysis of the CO_2 emissions of a baseline vehicle (vehicle B) and an eco-innovation vehicle (vehicle E) under both type-approval (TA) and modified conditions (MC). The former represents the WLTC homologation test conditions. The latter are conditions modified from TA to more closely representing the real-world operation of the innovative technology. The methodology for our study assumes that vehicle B is not equipped with any EI technology and vehicle E is, but the definition of vehicles B and E depends on the type of technology. Technologies shall reach the minimum threshold (MT) of 0.5 gCO_2/km of savings under Worldwide harmonised Light-duty vehicles Test Cycles (WLTC) to be considered eco-innovations. The combined CO_2 savings from more than one technology may be less than the sum of the individual savings from each technology considered separately because the functioning of the one has an effect on the other, also referred to as ‘interaction’ [12].

2.1. General approach for the CO_2 savings calculation

The benefits of an eco-innovative technology are calculated as the difference of CO_2 emissions between the baseline and the innovative vehicle under TA and MC conditions. The technology's emissions can be measured from component or vehicle test. In the second case, the terms “vehicle B″ and “vehicle E″ are used. The baseline vehicle shall not be fitted with the innovative technology but is identical to the eco-innovation vehicle in all other aspects [11]. In addition, when the technology is active under TA conditions, CO_2 savings must be subtracted to the ones under MC to avoid double-counting, as per Equation (1).

$$C_{CO_2} = \sum_{i=1,2,..} (B_{MC,i} - E_{MC,i}) \cdot UF_{MC,i} - (B_{TA} - E_{TA}) \cdot UF_{TA} \; [gCO_2/km] \quad (1)$$

Where C_{CO_2} are the savings from the EI technology, $B_{MC,i}$ and $E_{MC,i}$ are the CO_2 emissions of the vehicles B and E under modified conditions i, B_{TA} and E_{TA} are the CO_2 emissions under type-approval conditions [gCO_2/km], $UF_{MC,i}$ [−] and UF_{TA} [−] are the usage factors for modified and type-approval conditions *i*, respectively. *i* stands for the different modified conditions if existing. If type-approval conditions are perfectly defined with the parameters used to calculate B_{TA} and E_{TA}, UF_{TA} shall be 1. When modified conditions represent real-world appropriately, UF_{MC} shall be 1 [11].

Table 1
Penetration of eco-innovations in EU28 passenger cars. EEA final database, 2018 [44].

Vehicles	Number of vehicles	Share among all EEA vehicles	Share among vehicles with EI
All new passenger cars[a]	15 273 273	100%	–
With one or more EI	840 688	5.50%	100%
With only EA	575 612	3.77%	68.47%
With only LED lighting	187 607	1.23%	22.32%
With LED and EA	27 493	0.18%	3.270%
With LED and EA and other EI	103	0.0007%	0.013%
With one or multiple EI (excluding LED and EA)	124	0.0008%	0.015%

[a] New registrations during 2018.

2.2. Description of the selected test cases

In this study, we have considered three different case studies:

- case study 1, vehicle E has exterior LED lights, and a standard alternator,
- case study 2, vehicle E has exterior halogen (HL) lights, and an efficient alternator,
- case study 3, vehicle E has exterior LED lights and an efficient alternator.

Vehicle B has halogen lights and a standard alternator in all case studies, and its other components are identical to the eco-innovation vehicle. Exterior lights electric consumption from halogen and LED light (P_{HL}, P_{LED}), and standard and efficient alternator efficiency (η_A, η_E) are thus the main parameters that differ from vehicle B to E. Other parameters are total vehicle's electric consumption in TA and real-world (RW) operation (i.e., P_{TA} and P_{RW}, respectively). The values of P_{HL}, η_A, P_{RW} and P_{TA} (expressed as their difference in the simulation function, "delta load") are taken as in Table 4.

Considering exterior LED lights, since the technology is turned off during type-approval and the savings are not even partially covered by the standard test cycle B_{TA} is equal to E_{TA}. On the other hand, the alternator is active also under type-approval. Therefore, its CO_2 savings are partially covered by the cycle, and B_{TA} is not equal to E_{TA}. The lighting system and the type of alternator of each test case are summarised in Table 2.

2.3. CO_2 savings from eco-innovations according to the regulated method

The regulated method allows for the use of reference values [45,46], which represent average EU conditions. When the reference values are taken from the Technical Guidelines, using them does not require any justification. Examples of reference values are Willans' factors [l/Wh], CO_2 conversion factors [gCO_2/l], average vehicle electric power consumption [W] or average baseline alternator efficiency. Equation (1) uses simplified mathematical formulae outlined in Table 19 (Annex). Since these electrical technologies are only affecting the vehicle CO_2 emissions due to its electrical consumption, the terms of Eq. (1) are further simplified. Equation (1) is expressed as follows, where e denotes CO_2 emissions due to electric consumption.

$$C_{CO_2} = (Be_{MC} - Ee_{MC}) - (Be_{TA} - Ee_{TA})\ [gCO_2/km] \tag{2}$$

The definition of terms of Equation (2) depending on the test case can be found in the Annex.

For the technologies investigated the equations can be expressed as follows, Equation (3) for LED case (where $P_{RW(LED)} = P_{RW} - P_{HL} + P_{LED}$, see Table 7), Equation (4) for EA case, and Equation (5) for the combination case. Table 4 lists the default values used in the equations.

$$C_{CO_2} = \frac{V_{Pe} \cdot CF}{\eta_A \cdot v}\left(P_{RW} - P_{RW(LED)}\right)\ [gCO_2/km] \tag{3}$$

$$C_{CO_2} = \frac{V_{Pe} \cdot CF}{v}\left[\left(\frac{P_{RW}}{\eta_A} - \frac{P_{RW}}{\eta_E}\right) - \left(\frac{P_{TA}}{\eta_A} - \frac{P_{TA}}{\eta_E}\right)\right]\ [gCO_2/km] \tag{4}$$

$$C_{CO_2} = \frac{V_{Pe} \cdot CF}{v} \cdot \left[\left(\frac{P_{RW}}{\eta_A} - \frac{P_{RW(LED)}}{\eta_E}\right) - \left(\frac{P_{TA}}{\eta_A} - \frac{P_{TA}}{\eta_E}\right)\right]\ [gCO_2/km] \tag{5}$$

2.4. CO_2 savings from eco-innovations according to the simulated method

2.4.1. CO_2MPAS workflow and CO_2 emissions

An alternative method is examined for calculating the CO_2 savings. This alternative method employs the CO_2MPAS simulator (henceforward "simulated method"). Test data and vehicle characteristics are used for calibrating specific model sub-components such as the engine fuel consumption model, the gear-shifting model in case of automatic transmission vehicle, and the electric system model. Then, CO_2MPAS can be used to predict the CO_2 emissions that correspond either to a specific test protocol or to real-world trip, by adjusting the input and the model variables that correspond to the test. More information about the model operation and calibration can be found in Ref. [42].

In the present study, WLTP High configuration test results are used for the calibration of the model. The High configuration

Table 2
Configurations for baseline and eco-innovation vehicle under TA and MC, for the three different test cases.

	Case study 1 LED lighting		Case study 2 Efficient alternator		Case study 3 LED lighting + Efficient alternator		
	Lights	Power [W]	Alternator	Power [W]	Alternator	Lights	Power [W]
B_{TA}	HL (off)	P_{TA}	Baseline	P_{TA}	Baseline	HL (off)	P_{TA}
E_{TA}	LED (off)	P_{TA}	Efficient	P_{TA}	Efficient	LED (off)	P_{TA}
B_{MC}	HL (on)	P_{RW}	Baseline	P_{RW}	Baseline	HL (on)	P_{RW}
E_{MC}	LED (on)	$P_{RW(LED)}$	Efficient	P_{RW}	Efficient	LED (on)	$P_{RW(LED)}$

corresponds to the vehicle model version with the highest cycle energy consumption. In Fig. 1, a simplified flowchart of the electric system model is presented. If the vehicle to simulate does not have the eco-innovation installed, the value of CO_2 emissions simulated is the term B_{TA} from Equation (1). If the vehicle has the eco-innovation installed, the simulated value corresponds to term E_{TA}. The initial input data and model parameters are modified to represent the type of vehicle and condition (hereinafter referred to as "adjusted data") to simulate the other terms of CO_2 emissions from Equation (1) (i.e., B_{MC}, E_{MC}, and E_{TA} or B_{TA}). The adjusted data is formed by the modified input data and is represented in Fig. 1 in red boxes. In further detail:

- **Calibration data:** The calibration of the electric model uses the electrics module, battery capacity, battery nominal voltage, battery and alternator current time-series, average alternator efficiency, and nominal alternator voltage, as input parameters. The alternator and battery currents are measured over a test cycle, while the service battery capacity, and the service battery nominal voltage are scalar values provided by the user. The "service battery loads" are calculated by the tool.
- **Service Battery operation:** CO_2MPAS identifies various operating conditions of the vehicle service-battery charging system, namely "charging statuses" (discharging, charging, engine-stop operation, and brake energy recuperation).). The vehicle electric-load is defined in as negative power.
- **Alternator operation:** The alternator model's calibration is done using a gradient boost regressor to identify the way the alternator operates. By doing so, the model identifies various alternator operating conditions by analysing alternator currents, the engine on/off signal, the service battery state of charge (SOC) and the charging statuses signal mentioned previously. In the prediction phase, the alternator currents and the SOC are calculated with an iterative procedure in each time step using the calibrated alternator and battery charging statuses model according to the input alternator efficiency, motive power, acceleration, and battery load.

To have comparable results in the simulation, CO_2MPAS first applies the Rechargeable Electric Energy Storage System (REESS) charge balance (RCB) correction according to Appendix 2 to Sub-Annex 6 to Annex XXI of 2017/1151/EU.

2.4.2. Targeted vehicle sample

Four diesel and four gasoline vehicles were used for an initial plausibility check. The tests of the eight vehicles were carried out in the Vehicle Emission Laboratory (VELA) of the JRC (Joint Research Centre) [47–49]. Measured in house, these datasets provided a detailed and comprehensive basis for verifying the approach. All vehicles were tested according to regulated conditions, including vehicle preconditioning and soak time. The technical characteristics of the vehicles are listed in Table 3. Having access to detailed experimental data allowed the comparison of the simulation outputs to the measured references, including the experimentally measured CO_2 emissions. In this way, we could assess the models' accuracy to reproduce the CO_2 emissions of the baseline case (i.e., B_{TA}), in which we based the next steps.

2.4.3. Extended vehicle sample

To test the applicability of the method on a fleet level, we used data from the DICE database, containing official vehicle type-approval tests. According to 2017/1152/EU and 2017/1153/EU, such data are collected by the JRC for validation and quality control purposes. The study used a sample of 452 vehicles with a range of engine capacities with representativeness in all displacement categories. Sampled vehicles have an average alternator efficiency of 67%, which is the default values set by the technical guidelines and the most frequent value seen in the full dataset (Fig. 2). A CO_2-emissions simulation was performed for each vehicle, simulated as vehicle B and E under different conditions: B_{TA}, E_{TA}, B_{MC}, and E_{MC}, i.e., 2416 simulations performed.

It is important to have good agreement of the simulated baseline CO_2 value with its correspondent *official target value*. The difference for these 452 vehicles between the target CO_2 emissions and the simulated ones had a mean of −4.5%, and standard deviation of 3.7%. The standard deviation is small, proving consistency and exhibiting the absence of outliers. The bias of the simulation values was expected and is attributed to the regulatory provisions forcing officially declared values to be at least 1% higher than the test results. In reality the average difference between WLTP tested values and officially declared ones for the sample was estimate to be 5% [50], indicating that the true bias of the model is likely to be of the order of 0.5%.

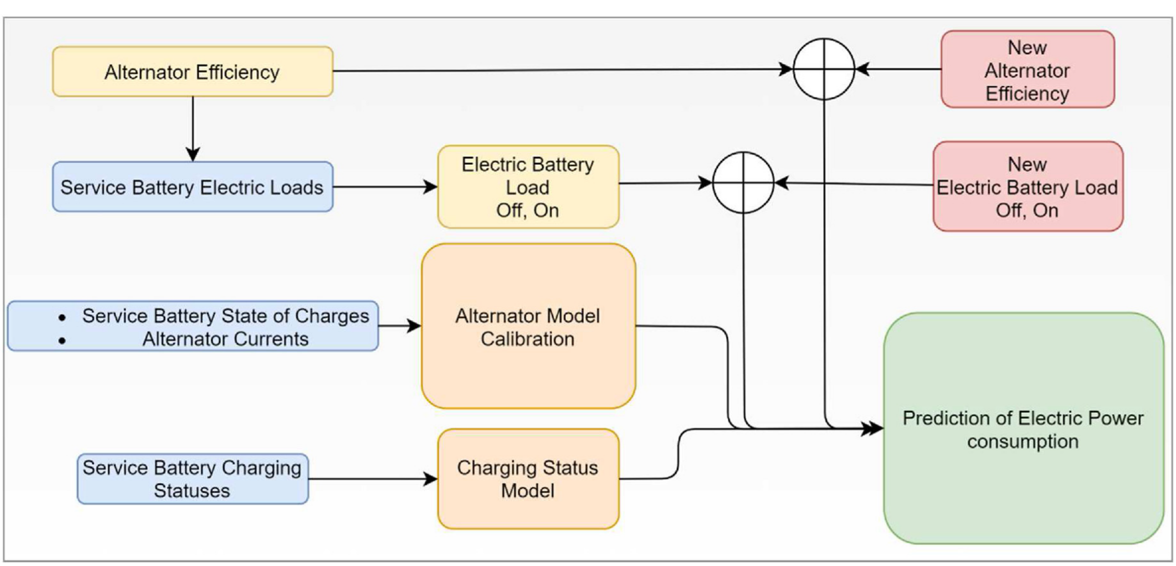


Fig. 1. CO_2MPAS Electric system model workflow.

Table 3
Baseline values of electrical loads and alternator efficiency for each vehicle.

Vehicle ID	Fuel Type	Displacement [cc]	Displacement cluster	P_{MAX} [kW]	load off, on [kW]	η_A [−]
1	Turbo Gasoline	875	cc=<1200	63	−0.071, −0.195	0.67
2	Turbo Gasoline	1199	cc=<1200	94	−0.187, −0.187	0.67
3	Turbo Gasoline	1798	$1600 < cc \leq 2000$	125	−0.295, −0.354	0.67
4	Gasoline	3498	$cc > 2000$	225	−0.32, −0.375	0.67
5	Turbo Diesel	1956	$1600 < cc \leq 2000$	104	−0.262, −0.263	0.67
6	Turbo Diesel	1995	$1600 < cc \leq 2000$	120	−0.094, −0.260	0.67
7	Turbo Diesel	2000	$1600 < cc \leq 2000$	140	−0.189, −0.287	0.67
8	Turbo Diesel	2143	$cc > 2000$	125	−0.276, −0.290	0.67

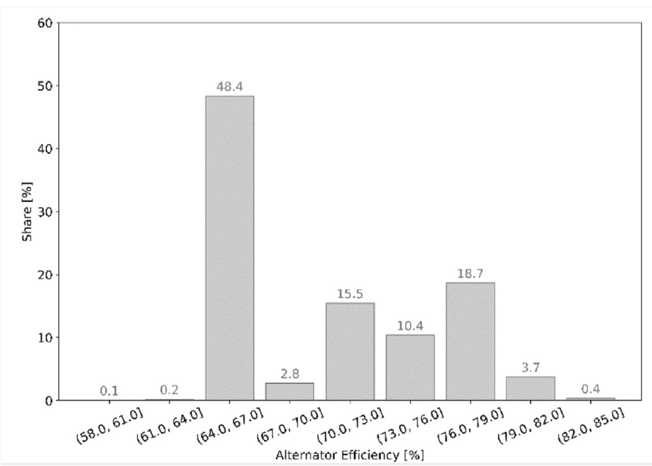


Fig. 2. Share of vehicles of the whole DICE database divided in clusters of their alternator efficiency [%].

2.5. Numerical values used in the selected test cases

In the regulated method, P_{TA}, P_{RW}, V_{Pe}, and CF are fixed average EU values taken from the Technical Guidelines, as well as the cycle speed. These values are listed in Table 4 and Table 7.

From the P_{TA} and P_{RW} values in Ref. [12], the electric power difference in type-approval and real-world conditions is assumed to be 400 W [11]. To calculate P_{RW} in the simulation, we implement an increment of 400 W in the type-approval electric consumption for each vehicle. CO_2MPAS simulation of the electric consumption has two negative values: “engine off” and “engine on”, so the difference of −400 W is applied in both terms.

The vehicle's total electric consumption depends on the lighting system consumption, meaning that the installation of LED reduces the P_{RW}. The European average vehicle uses halogen headlamps [51]. EU average consumption of halogen lights is 64.7 W, see Table 5. For the calculation of the lighting system consumption, the share of use of each lamp in an average trip must be considered. Considering all the lights package, a realistic average value of P_{LED} is 16.8 W and respectively, see Table 6. Therefore, the calculation of the vehicle electric consumption with exterior LED lights results in 702.1 W (as per $P_{RW(LED)} = P_{RW} - P_{HL} + P_{LED}$, see Table 7), being the electric power between type-approval and real-world conditions used in the simulations of 352.1 W when LED light are active (i.e., in real-world driving).

The value of η_E comes from DICE database, and it is based on the distribution of officially declared data, as shown in Fig. 2.

We see that the vehicle cluster with 64−67% of alternator efficiency is formed by 48.4% of vehicles in the database, followed by the cluster with 76−79% representing 18.7% of the vehicles. The arithmetic mean of the latter group was considered as a threshold for improved alternator efficiency ($\eta_E = 77\%$). When comparing this value to η_A from the Technical Guidelines, we obtain an efficiency improvement of 10% which was used as an input parameter in the simulated method. A summary is provided in Table 7.

3. Results

3.1. Accuracy of electric system simulation

As a first step a validation of the electric system simulation was performed. The distribution of the electric load identified by CO_2MPAS in the DICE sample ranges from 0 to −1 kW. The shape of distributions and basic statistics are presented in Fig. 3. In Fig. 4, the electric load (when engine on and off) is plotted versus the vehicle engine displacement and linear regression lines are fitted. The linear regression was performed every 200 cc (i.e., considering as a point the whole cluster formed by [1000−1200) cc, [1200−1400) cc, [1400−1600), and similar continuation until 7000 cc) due to the non-equally distributed shares of vehicles in the range of engine displacement. The electric load shows a tendency to increase (in absolute terms) as the engine displacement increases. More details about the linear regression lines are presented in Table 8.

The final battery SOC depends on the power consumption, for this reason, it differs in the type-approval test cases and the real-world driving cases. Fig. 5 shows the dependency of the SOC on the electric power in the LED lights case, where the only parameter modified from the initial input values is the electric power consumption (electric loads). Fig. 5 compares SOC in different types of vehicles and conditions, with several data series for LED lights case:

- B_{TA} Calibrated: SOC derived from the calibration of the initial data (declared values and experimentally measured).
- B_{TA} Prediction: SOC derived from the simulation result using the declared values and the calibrated models as input. The declared

Table 4
Default values for the calculation of the CO_2 emissions of diesel and gasoline vehicles. Regulated method.

Parameter	Diesel	Gasoline
Effective power consumption ‘Willans factor’, V_{Pe} [l/Wh]	$2.2 \cdot 10^{-4}$	$2.64 \cdot 10^{-4}$
Conversion factor, CF [gCO_2/l]	2640	2330
Mean driving speed of WLTP, v [km/h]	46.5	46.5

Table 5
Weighted average electric consumption halogen lighting system [12].

Type of lighting	Usage factor (UF)	Halogen lights [W] ($P_{HL,i}$)	$P_{HL,i}$ UF [W]
Low beam headlamp	0,33	137	45,21
High beam headlamp	0,03	150	4,50
Front position	0,36	12	4,32
Fog – front	0,01	124	1,24
Turn signal – front	0,15	13	1,95
Turn signal – side	0,15	3	0,45
Fog – rear	0,01	26	0,26
Turn signal – rear	0,15	13	1,95
License plate	0,36	12	4,32
Reversing	0,01	52	0,52
Total [W], $\Sigma P_{HL,i}$*UF =			**64,7**

Table 6
Weighted average electric consumption exterior LED lighting system.

Type of lighting	**Usage factor (UF)** [12]	LED lights [W] ($P_{LED,i}$)[a]	$P_{LED,i}$ UF
Low beam headlamp	0,33	40	13,2
High beam headlamp	0,03	40	1,2
Front position	0,36	2	0,72
Fog – front	0,01	25	0,25
Turn signal – front	0,15	2,5	0,375
Turn signal – side	0,15	0,5	0,075
Fog – rear	0,01	3	0,03
Turn signal – rear	0,15	1,5	0,225
License plate	0,36	2	0,72
Reversing	0,01	4	0,04
Total [W], $\Sigma P_{LED,i}$[a]UF =			**16,8**

[a] [feedback received from manufacturers].

Table 7
Parameters values for the study cases.

Parameter	Symbol	Value	Unit
Vehicle's power under TA [12]	P_{TA}	350	[W]
Vehicle's power in real-world with halogen lighting [12]	P_{RW}	750	[W]
Difference in electric load with halogen lights	$\Delta load_{HL}$	400	[W]
Halogen lights electric consumption [12]	P_{HL}	64.7	[W]
LED lights electric consumption	P_{LED}	16.8	[W]
Difference in electric load with LED lighting	$\Delta load_{LED}$	352.1	[W]
Real-world electric consumption with LED lighting	$P_{RW(LED)}$	702.1	[W]
Baseline alternator efficiency [12]	η_A	0.67	[–]
Efficient alternator efficiency	η_E	0.77	[–]
Difference in alternator efficiency	$\Delta\eta$	0.1	[–]

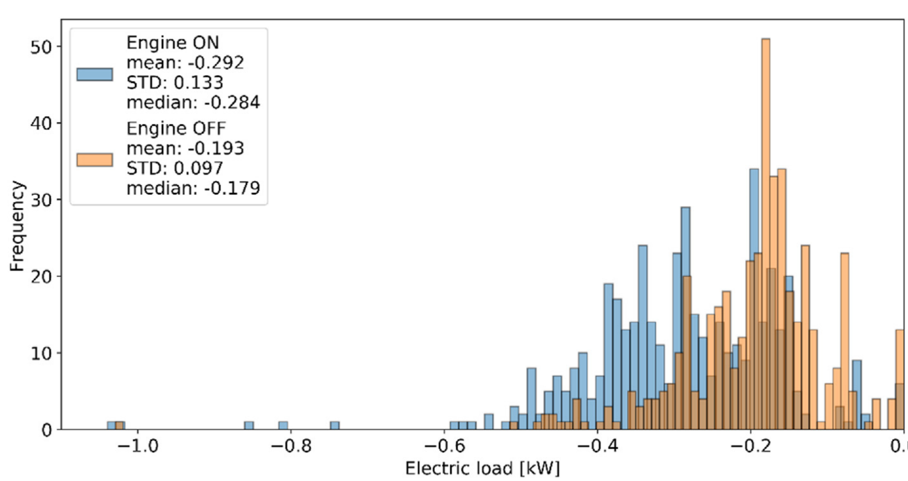


Fig. 3. Service battery electric load estimated from the test data retrieved for WLTC (base case).

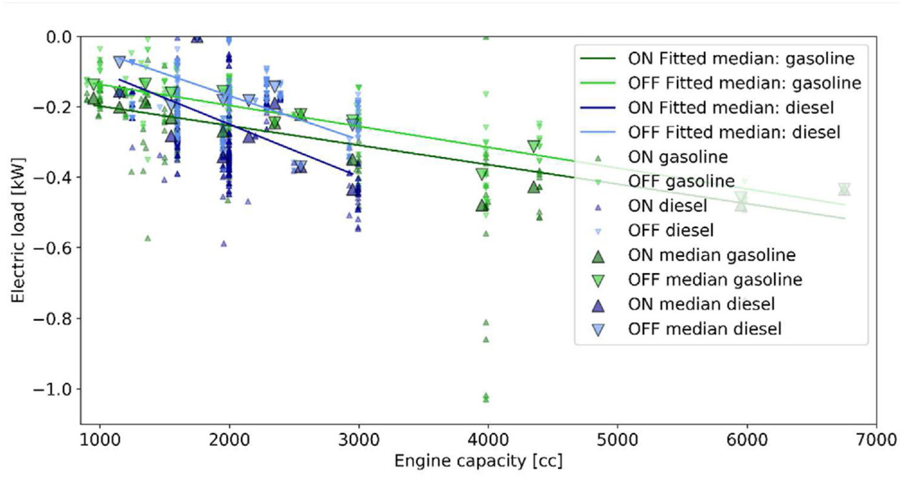


Fig. 4. Service battery electric load estimated [kW] versus vehicle engine displacement (cc).

Table 8
Coefficients and coefficient of determination of the linear fitting of the battery electric load versus engine displacement.

Fuel type		Diesel		Gasoline	
Engine load		off	on	off	on
$y = a + b \cdot x$	A	0.014	0.007	−0.07	−0.14
	B	−9.5e-05	−13. e−05	−5.9e-05	−5.5e-05
	$\mathbf{R^2}$	0.37	0.4	0.91	0.8

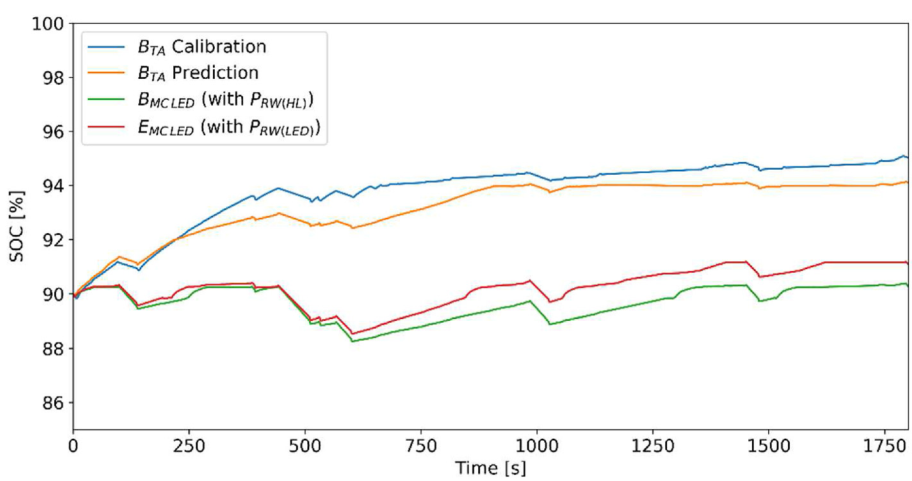


Fig. 5. Experimental and simulated service battery state of charge for different simulation cases, LED test case. (Note that in LED tes case, signals B correspond to halogen lights.)

data is used for the simulation of *CO_2 emission in baseline vehicle under type-approval* (B_{TA}).

- $B_{MC.(LED\ CASE)}$: SOC derived from the simulation result using the adjusted data for the baseline vehicle (with halogen lights), i.e., adding 400 W to the declared data.
- $E_{MC.(LED\ CASE)}$: SOC derived from the simulation result using the adjusted data for the eco-innovation vehicle (with LED lights), i.e., adding 352.1 W to the declared data (i.e., 400 [W] − P_{HL} + P_{LED}) (see Table 7).

There is no need to include the case of an eco-innovation vehicle under type-approval because E_{TA} are equivalent to B_{TA} (lights are deactivated during TA, see section 2.2).

From the Fig. 5 we can see the good agreement of the calibrated and predicted signal for B_{TA}, proving the accuracy of the prediction over the calibration in the electric system model under type-approval. This good agreement provides confidence for the prediction of other cases. In the LED lights case, the baseline vehicle under TA is charging the battery during the driving. In the other hand, introducing the extra electric consumption (P_{RW} in B_{MC} and $P_{RW(LED)}$ in E_{MC}, both in LED case), the SOC oscillates close to its initial value (i.e., a range from 88% to 91%).

The distribution of the ΔSOC error between calibration and prediction (cases "B_{TA} Calibration" and "B_{TA} Prediction") is shown in Fig. 6. The ΔSOC is defined as the initial battery state of charge minus the state of charge at the end of the trip, and its error as *ΔSOC predicted [%] − ΔSOC calibrated [%]*, where the *predicted* data is the simulation result, and the *calibrated* ΔSOC is calculated from the

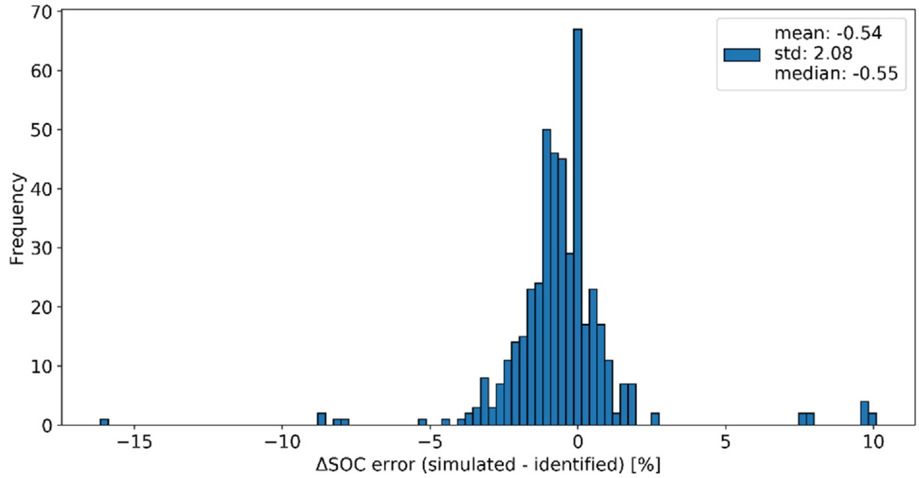


Fig. 6. ΔSOC [%] error distribution between the simulated and calibrated ("identified") service battery state of change signal.

declared data (DICE data). The ΔSOC error distribution is almost symmetrical, and its mean is −0.54% with a standard deviation of 2.08%, which confirms the good agreement of the individual case from Fig. 5 for all the simulated vehicles from the DICE database.

After checking the difference between calibrated and predicted data, ΔSOC from baseline vehicle in type-approval (B_{TA} Prediction) is compared to ΔSOC from $B_{MC.\ LED}$ and $E_{MC.\ LED}$ in Fig. 7. We see that the use of LED lights ($E_{MC.LED}$ series) results to a lower difference in ΔSOC (i.e., series line closer to the diagonal). The real-world driving introduces a difference in ΔSOC of 14.43% in case of halogen lights and 12.39% in case of LED lights in during trip with the WLTP test profile.

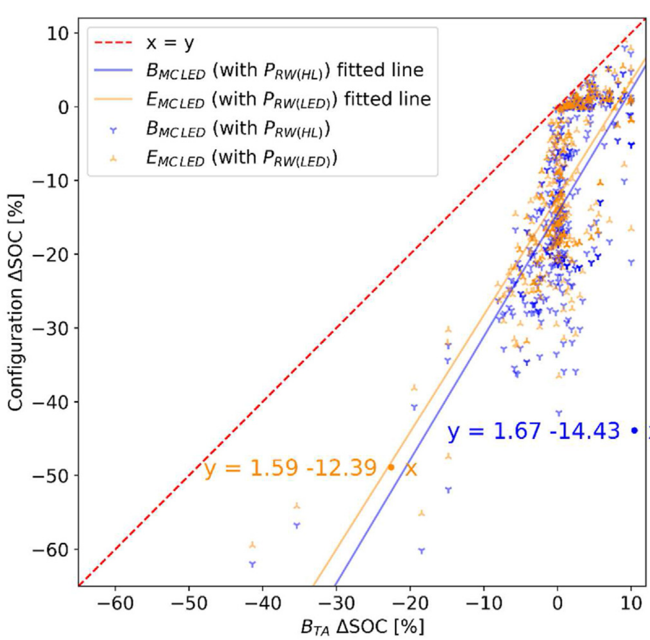


Fig. 7. LED test case comparison of ΔSOC between vehicles B and E in real-world driving (with extra electric load): $B_{MC.\ LED}$ (with P_{RW}, halogen lights) and $E_{MC.\ LED}$ (with $P_{RW(LED)}$, LED lights), over B_{TA} (with P_{TA}, no lights).

3.2. Results of the targeted sample

A controlled sample of vehicles was simulated to obtain the CO_2 emissions and savings for each type of vehicle and driving condition. For each vehicle of the sample, the CO_2 emissions (B_{TA}, E_{TA}, $B_{MC,}$ and E_{MC}) were simulated. As for the regulated method, CO_2 saving were calculated by Equations (3)–(5), depending on the case study.

The results show that simulated savings are in line with the regulated methodology (i.e., deviations of 0.006 in gasoline and 0.039 gCO_2/km in diesel vehicles). Nevertheless, CO_2 savings of LED have higher deviation from the theoretical ones i.e., 0.423 in gasoline and 0.457 gCO_2/km in diesel vehicles. Seen in perspective this is a rather limited deviation compared to the total CO_2 emissions of the vehicles and well within the uncertainty range of both the WLTP test and the simulations. Very low deviations of 0.014 and 0.101 gCO_2/km in gasoline and diesel vehicles occurred for the combination of the two technologies. The electric power consumption (i.e., the LED case) has the largest influence in the difference between methods.

3.3. Results of the extended sample

In the DICE sample we compared the CO_2 savings mean of the simulated values with the regulated method value. The summary of the simulated method results of the extended study can be seen in Fig. 8.

The distribution of CO_2 savings for the LED case has a distinctive peak, while there are some instances with lower values. Similarly, the distribution is bimodal in the EA case, having one major peak and one with lower CO_2 saving value. The combination case is again bimodal, presenting two distinctive peaks as a sum of the smaller peaks from the individual technologies. Table 10 provides the descriptive statistics. The mean savings calculated for the LED case is 0.91 gCO_2/km. For the EA, it is calculated to be slightly higher, reaching 0.98 gCO_2/km (see further details in Annex). Combining the two eco-innovation technologies, the mean saving calculated is 1.78 gCO_2/km.

The consistency of the simulation results was later monitored by the calculation of the normalised standard deviation. When the consistency is confirmed, we compare the divergence of the simulation results from the regulated method's results. Simulation

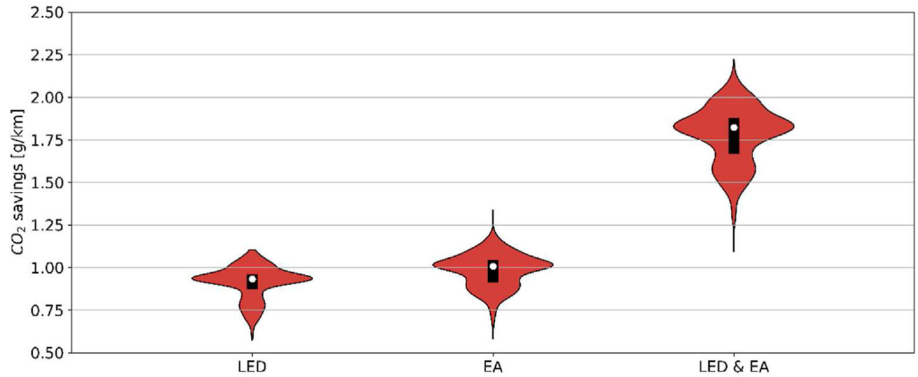


Fig. 8. Distribution of the CO_2 savings from LED, EA and combination of LED and EA (considering electric interaction). The white dots refer to the median values, while the thick black line corresponds to the range of the first to the third quartile.

Table 9
CO_2 savings comparison of LED, EA and combination of both in the control sample.

CO_2 savings	Reg. method [gCO_2/km]	Simulation [gCO_2/km]
Ext. LED lighting		
Gasoline	0.945	1.368
Diesel	0.893	1.350
Efficient Alternator		
Gasoline	1.026	1.032
Diesel	0.968	0.929
Ext. LED lighting & Efficient Alternator		
Gasoline	1.848	1.834
Diesel	1.745	1.644

Table 10
Overall simulated results of the CO_2 savings [gCO_2/km] in the DICE sample for the LED, EA and their combination.

CO_2 saving [gCO_2/km]	LED	EA	LED and EA
Mean	0.91	0.98	1.78
Std	0.10	0.10	0.17
Median	0.93	1.00	1.82

results are divided into groups with different engine capacities. Each group has a different sample size, therefore the CO_2 savings shown in the upcoming tables are the mean of all the vehicles inside the group with same engine displacement range. Also, the mean, percentiles 25th, 50th and 75th of each cluster, as well as the CO_2 savings from the regulated method are displayed to easily compare both methods.

3.3.1. LED lighting CO_2 savings

As seen in Table 11 and Table 12, the simulated CO_2 savings mean was 0.972 gCO_2/km in gasoline and 0.892 gCO_2/km in diesel cars. According to the EEA average emission values (i.e., 123.4 and 121.5 gCO_2/km) [52], LED lighting reduces CO_2 emissions by 0.79% and 0.73% in gasoline and diesel cars respectively. The calculation of CO_2 savings by the regulated method are 0.945 and 0.893 gCO_2/km in gasoline and diesel vehicles (0.77% and 0.73% savings respective to EEA average). The overall normalised standard deviation of 9.4% and 13.32%, for gasoline and diesel respectively, is driven by the results in the highest displacement cluster (Tables 11 and 12). The limited variance of the results suggests high confidence in the simulated results.

The simulation deviation from the regulated method is shown in Tables 11 and 12, where for both types of fuel the difference is negligible: 0.027 gCO_2/km in gasoline (2.86%), and 0.001 gCO_2/km in diesel cars (−0.14%). As seen in the tables below, the divergence between methods grows when the engine displacement is lower (i.e., smaller cars). Fig. 9a and Fig. 9b illustrate the results.

For the gasoline vehicles (Fig. 9a), all percentiles, including the 50th, are close to the regulated method for each cluster. For diesel vehicles (Fig. 9b), there is less diversity. The CO_2 savings in the cluster $1200 < cc \leq 1600$ do not diverge, and most of the values simulated are close to the regulated method.

3.3.2. Efficient alternator CO_2 savings

The CO_2 savings due to an efficient alternator are presented in Table 13 and Table 14. The mean simulated CO_2 savings (Sim_Cco2) were 1.032 and 0.961 gCO_2/km in gasoline and diesel cars respectively. Assuming the EEA average emissions of 123.4 and 121.5 gCO_2/km [52], the results translate to 0.77%, and 0.73% reduction respectively. The savings calculated by regulated method (Reg_C_{CO2}) are 1.026 (gasoline) and 0.968 gCO_2/km (diesel) translating to reductions of 0.83%, and 0.79% (see Table 17). The statistical values are coherent for the engine displacement clusters lower than 2000 cc. Overall, the normalised standard deviation is low: 10.63% (gasoline) and 8.79% (diesel), respectively (see Tables 13 and 14).

The differences can be considered negligible for both types of fuel in terms of grams of CO_2: 0.006 gCO_2/km (0.58%) in gasoline cars, and 0.007 gCO_2/km in diesel cars (0.72%). Fig. 10a and Fig. 10b illustrate the results. For both fuel types, the majority of engine displacement cluster distribution looks similar, replicating a

Table 11
CO_2 emission savings from simulated and regulated method due to LED lights, gasoline vehicles.

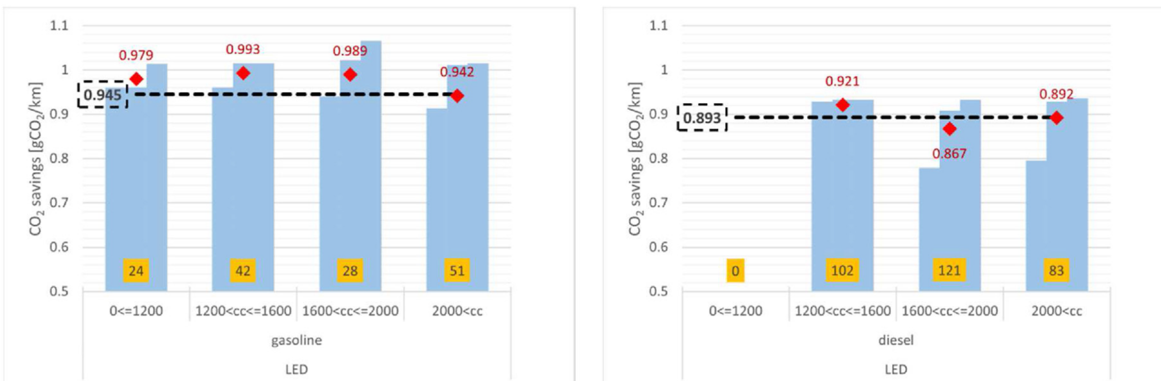
Gasoline	No. vehicles	Sim_C_{CO2} [gCO_2/km][a]	Normalised std [%]**	Reg_C_{CO2} [gCO_2/km]	(S_C_{CO2} - R_C_{CO2})/R_C_{CO2} [%]
cc=<1200	24	0.979	2.99	0.945	+3.63
$1200 < cc \leq 1600$	42	0.993	3.58	0.945	+5.05
$1600 < cc \leq 2000$	28	0.989	9.59	0.945	+4.68
2000 < cc	51	0.942	13.56	0.945	−0.34
Total:	145	0.972	9.40	0.945	+2.86

[a] Mean. **Result of: std [gCO_2/km]·100/S_C_{CO2} [gCO_2/km].

Table 12
CO_2 emission savings from simulated and regulated method due to LED lights, diesel vehicles.

Diesel	No. vehicles	S_C_{CO2} [gCO_2/km][a]	Normalised std [%]**	R_C_{CO2} [gCO_2/km]	(S_C_{CO2} - R_C_{CO2})/R_C_{CO2} [%]
cc=<1200	0***	–	–	0.893	–
1200 < cc ≤ 1600	102	0.921	4.69	0.893	+3.14
1600 < cc ≤ 2000	121	0.867	10.93	0.893	−2.91
2000 < cc	83	0.892	20.99	0.893	−0.15
Total:	306	0.892	13.32	0.893	−0.14

[a] Mean. **Result of: std [gCO_2/km]·100/S_C_{CO2} [gCO_2/km]. ***No data available.



(a) (b)

Fig. 9. CO_2 savings for LED lights in gasoline (a), and diesel vehicles (b). For each range of engine capacities (in cc): mean is red diamond; percentiles 25th, 50th, 75th are shown as blue bars; number of vehicles is seen in a yellow box at the bottom of the 50% percentile bar. Regulated CO_2 savings are plotted as the dashed line and box.

Table 13
CO_2 emission savings from simulated and regulated method due to an efficient alternator, gasoline vehicles.

Gasoline	No. vehicles	Sim_C_{CO2} [gCO_2/km][a]	Norm. std [%]**	Reg_C_{CO2} [gCO_2/km]	(Sim_C_{CO2} - Reg_C_{CO2})/Reg_C_{CO2} [%]
cc=<1200	24	1.046	4.75	1.026	+1.95
1200 < cc ≤ 1600	42	1.067	6.92	1.026	+4.00
1600 < cc ≤ 2000	28	1.061	7.60	1.026	+3.41
2000 < cc	51	0.981	14.85	1.026	−4.39
Total:	145	1.032	10.63	1.026	+0.58

[a] Mean. **Result of: std [gCO2/km]·100/S_CCO2 [gCO2/km].

Table 14
CO_2 emission savings from simulated and regulated method due to an efficient alternator, diesel vehicles.

Diesel	No. vehicles	Sim_C_{CO2} [gCO_2/km][a]	Norm. std [%]**	Reg_C_{CO2} [gCO_2/km]	(Sim_C_{CO2} - Reg_C_{CO2})/Reg_C_{CO2} [%]
cc=<1200	0***	–	–	–	–
1200 < cc ≤ 1600	102	0.983	7.56	0.968	+1.55
1600 < cc ≤ 2000	121	0.943	8.52	0.968	−2.58
2000 < cc	83	0.962	10.03	0.968	−0.62
Total:	306	0.961	8.79	0.968	−0.72

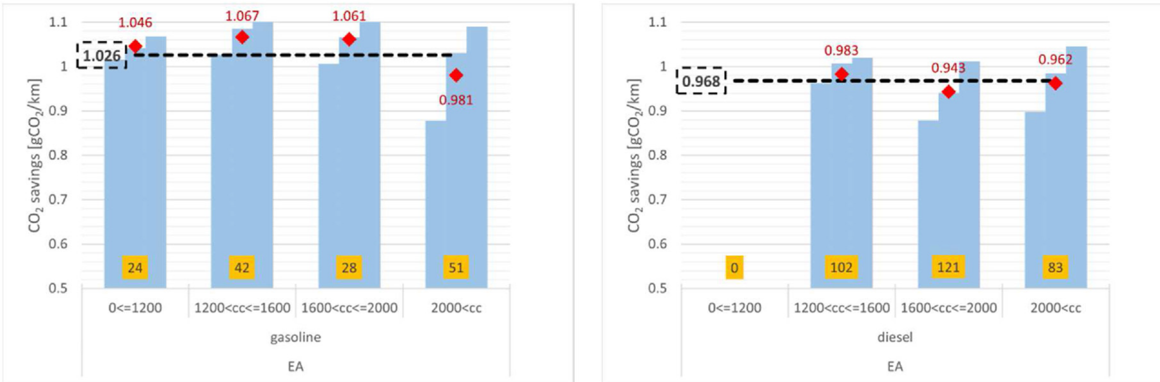
[a] Mean. **Result of: std [gCO_2/km]·100/S_C_{CO2} [gCO_2/km]. ***No data available.

normal distribution, with the mean values being very close to the regulated method.

Comparing CO_2 savings of the different engines capacities in both fuels, larger engines (cc < 2000) lead to closer results to the regulated method's CO_2 savings (dashed line) in diesel vehicles, but not in gasoline vehicles, where the closest cluster to the regulated method values are the vehicles with engines of *cc > 1200*.

3.3.3. Combined CO_2 savings

The simulated combined CO_2 savings mean was 1.879 gCO_2/km in gasoline and 1.739 gCO_2/km in diesel cars corresponding to reductions of 1.5% and 1.4% considering the EEA average emissions. CO_2 savings by the regulated method (Reg_C_{CO2}) are 1.848 gCO_2/km in gasoline and 1.745 gCO_2/km in diesel vehicles corresponding to improvements of about 1.5% (see Table 17). The standard deviations were 9.38% and 9.31%, respectively (see Table 15 and Table 16). For both types of fuel, the difference can be considered negligible: 0.031 gCO_2/km in gasoline cars (1.68%), and 0.06 gCO_2/km in diesel cars (0.34%). A visual of the comparison between methods can be seen in Fig. 11a for gasoline, and in Fig. 11b for diesel cars. The mean values for both gasoline and diesels are in good agreement with the regulated method, and in most cases the CO_2 saving values are placed in a narrow range.



(a) (b)

Fig. 10. CO_2 savings for efficient alternator in gasoline (a), and diesel vehicles (b). For each range of engine capacities (in cc): mean is red diamond; percentiles 25th, 50th, 75th are shown as blue bars; number of vehicles is seen in a yellow box at the bottom of the 50th percentile bar. Regulated CO_2 savings are plotted as the dashed line and box.

Table 15
CO_2 emission savings from simulated and regulated method due to LED lights and efficient alternator, gasoline vehicles.

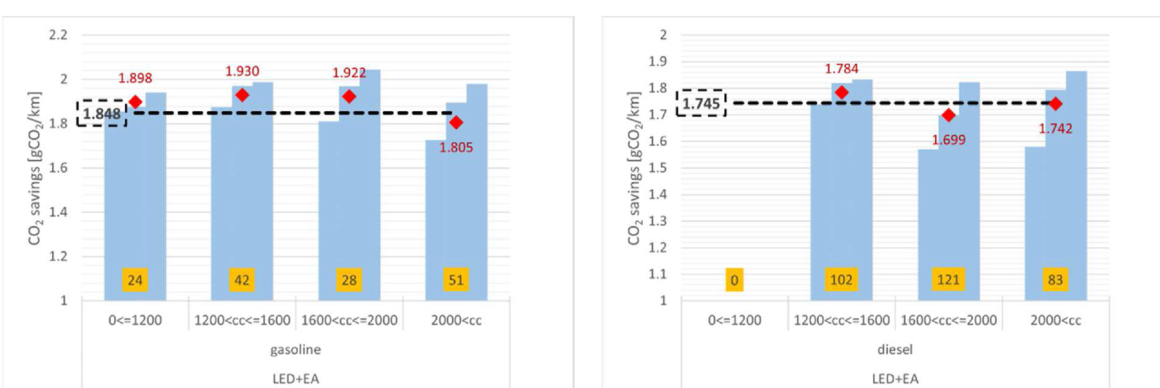
Gasoline	No. vehicles	Sim_C_{CO2} [gCO_2/km][a]	Norm std [%]**	Reg_C_{CO2} [gCO_2/km]	(Sim_C_{CO2} - Reg_C_{CO2})/Reg_C_{CO2} [%]
cc=<1200	24	1.898	3.67	1.848	+2.71
1200 < cc ≤ 1600	42	1.930	5.35	1.848	+4.44
1600 < cc ≤ 2000	28	1.922	7.68	1.848	+4.00
2000 < cc	51	1.805	13.33	1.848	−2.33
Total:	145	1.879	9.38	1.848	+1.68

[a] Mean. **Result of: std [gCO_2/km]·100/S_C_{CO2} [gCO_2/km].

Table 16
CO_2 emission savings from simulated and regulated method due to LED lights and efficient alternator, diesel vehicles.

Diesel	No. vehicles	S_C_{CO2} [gCO_2/km][a]	Normalised std [%]**	R_C_{CO2} [gCO_2/km]	(S_C_{CO2} - R_C_{CO2})/R_C_{CO2} [%]
cc=<1200	0***	–	–	–	–
1200 < cc ≤ 1600	102	1.784	5.05	1.745	+2.23
1600 < cc ≤ 2000	121	1.699	8.54	1.745	−2.64
2000 < cc	83	1.742	13.08	1.745	−0.17
Total:	306	1.739	9.31	1.745	−0.34

[a] Mean. **Result of: std [gCO_2/km]·100/S_C_{CO2} [gCO_2/km]. ***No data available.



(a) (b)

Fig. 11. CO_2 savings for LED lights and efficient alternator in gasoline (a), and diesel vehicles (b). For each range of engine capacities (in cc): mean is red diamond; percentiles 25th, 50th, 75th are shown as blue bars; number of vehicles is seen in a yellow box at the bottom of the 50th percentile bar. Regulated CO_2 savings are plotted as the dashed line and box.

Table 17
Average EU vehicle's specific CO_2 emissions in NEDC, and simulated CO_2 savings due to innovative technologies.

Specific vehicle emissions		LED lights savings		EA savings		Combined savings	
[gCO_2/km] [44]		**gCO_2**/km	**%**	**gCO_2**/km	**%**	**gCO_2**/km	**%**
Simulated method, Sim_C_{CO2}							
Gasoline	123.4	0.972	0.79	1.032	0.84	1.879	1.52
Diesel	121.5	0.893	0.73	0.961	0.79	1.739	1.43
Regulated method, Reg_C_{CO2}							
Gasoline	123.4	0.945	0.77	1.026	0.83	1.848	1.50
Diesel	121.5	0.893	0.73	0.968	0.79	1.745	1.43

In summary, the CO_2 savings (%) are presented in Table 17. We observe both methods give comparable results with the regulated method being marginally more conservative than the simulated one.

3.4. Impact on EU average emissions[a]

An effort to quantify how much actual CO_2 can be saved thanks to the installation of eco-innovations is shown in Table 18. The combined savings are from vehicles with both EI installed, which are fewer than vehicles with one EI, as mentioned in the Introduction. The top part of Table 18 shows the absolute impact of CO_2 savings in an average new passenger car of 2018. The calculation considers the gasoline and diesel annual mileages (12 700 km and 17 000 km, respectively), set out in the Technical Guidelines. The bottom part of Table 18 shows the absolute CO_2 savings at EU28 fleet level of new registered cars in 2018. This calculation considers the number of diesel and gasoline cars with EI reported in EEA database during 2018. Diesel savings (15.1–16.3 kg) appear to be around 3 kg more that gasolines (12.3–13.1 kg) in the individual technologies, mostly due to their higher average annual milage. In the vehicles with the two technologies, the divergence in the savings is higher (23.8 kg for gasolines, 29.5 kg in diesels). To put some perspective to the numbers and the importance of these savings, according to Eurostat, these savings are comparable to the annual $kgCO_2$ emitted due to textiles, clothes and related products per person during 2019 [53]. The fleet of new registered cars in 2018 saved around 11 thousand tonnes (i.e. the summation of lower part of the table). This is the same amount of CO_2 that 1641 people emit during one year considering all their activities and purchases (as well as industrial process of them) [53].

In 2018, the average eco-innovation's specific CO_2 savings reported in EEA database under NEDC were 1.4, 1.1 and 2.6 gCO_2/km for LED, EA and the combination of both, respectively [44], see Table 29 in the Annex. Same average values were reported under NEDC in 2019 in the provisional data of EEA's database [44] (more details in the section 7.4 of the Annex). The specific emissions in 2019 were higher than in 2018 despite more new registered cars included CO_2-reductant technologies [52]: in 2018, the new registered cars were 15 273 273, from which 820 174 (5.4%) had some EI installed; and in 2019, new car registrations were 15 499 771, from which 1 747 028 (11.3%) had some EI installed.

Table 18
Impact of simulated CO_2 savings at EU-wide fleet level, for new registered passenger cars in 2018.

	LED lights savings	EA savings	Combined savings
$kgCO_2$ saved per average car in 2018[a]			
Gasoline	12.3	13.1	23.8
Diesel	15.1	16.3	29.5
$kgCO_2$ saved per all 2018 fleet of new registered cars with EI[b]			
Gasoline	1 383 642	4507 317	391 974
Diesel	1 029 962	3404 557	294 259

[a] Calculated as: S_C_{CO2} [gCO_2/km] in Table 17 multiplied per EU average mileage from Ref. [12].
[b] Calculated as: gCO_2/km saved per vehicle in 2018 (top part of the table) multiplied per vehicles with EI registered in 2018 [44].

4. Conclusions

A first attempt to simulate eco-innovative technologies under the EU regulatory scheme using simulation software has been successfully carried out. Understanding the applicability of simulations to eco-innovations would be of great interest, especially for complex, innovative technologies, and functions. The study explored the equivalence of the simulated method by comparing it to the regulated method, for the calculation of CO_2 savings due to LED lights, efficient alternator, and their combination, in gasoline and diesel vehicles. Results show that simulation performs with high accuracy: differences between methods are minimal in the six scenarios (i.e., three cases studied in gasoline and diesel vehicles), i.e., from 0.006 to 0.06 gCO_2/km. In an attempt to investigate potential parameters influencing the CO_2 savings, the simulated sample was divided in different engine displacement clusters. As seen in our results, no pattern can be concluded from the influence of the engine displacements, which confirms the approach of the regulated method, where no influence of engine displacement is foreseen. Further analysis will focus on understanding the engine displacement's influence and other vehicle characteristics on the CO_2 savings. Future work should go towards monitoring the behaviour of the simulated method in more-complex electrical technologies. Apart from comfort systems, electric technologies that could interact with the ones analysed in this study are 48 V motor-generator with a 48V/12V DC/DC converter. Other effects of their installation must be considered in these specific cases, such as the extra-mass that affects the total specific CO_2 emissions. Apart from electric technologies, there are other type of eco-innovations that would require additional research along the lines presented in the paper, including vehicles' test and simulations, analysing the potential interaction between electrical and other systems.

Authors contributions

The authors, **Susana Gil-Sayas (SGS)**, **Dimitrios Komnos (DK)**, **Chiara Lodi (CL)**, **Davide Currò (DC)**, Simone Serra **(SS)**, **Alberto Broatch (AB)**, **and Georgios Fontaras (GF)** contributed to the paper as follows:

Study conceptualisation: **GF**, **SGS**; data collection, curation, and analysis: **SGS**, **DK**; model simulations: **DK**; analysis and interpretation of results: **SGS**, **DK**, **CL**, **DC**; manuscript preparation: **SGS**, **DK**, **CL**; revision and comments: **SS**, **CL**, **AB**, **GF**; research coordination: **GF**, **AB**. All authors reviewed the results and approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.123238.

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6. Nomenclature

Abbreviations

B: Baseline vehicle
CO_2: Carbon Dioxide
CO_2 e: Carbon Dioxide equivalent
CID: Commission Implementing Decision
E: Eco-innovation vehicle
EA: Efficient alternator
EC: European Commission
EEA: European Environmental Agency
EI: Eco-innovation
EU: European Union in 2018 (EU28)
GHG: Greenhouse gases
HL: Halogen lights
LED: Light Emitting Diode
MC: Modified conditions
MT: Minimum threshold
NEDC: New European Driving Cycle
REESS: Rechargeable Electric Energy Storage System
RCB: REESS charge balance
TA: Type-approval
TG: Technical guidelines for EI
WLTP: Worldwide Harmonised Light Vehicles Test Procedure

Symbols

$B_{MC,i}$: Specific CO_2 emissions of B vehicle under modified conditions i [gCO_2/km]
Be_{MC}: Specific CO_2 emissions of B_{MC} due to electric consumption [gCO_2/km]
B_{TA}: Specific CO_2 emissions of B vehicle under type-approval conditions [gCO_2/km]
Be_{TA}: Specific CO_2 emissions of B_{TA} due to electric consumption [gCO_2/km]
CO_2: Carbon dioxide
C_{CO2}: CO_2 savings [gCO_2/km]
CF: Conversion factor [gCO_2/l]
$E_{MC,i}$: Specific CO_2 emissions of E vehicle under modified conditions i [gCO_2/km]
Ee_{MC}: Specific CO_2 emissions of E_{MC} due to electric consumption [gCO_2/km]
E_{TA}: Specific CO_2 emissions of E vehicle under type-approval conditions [gCO_2/km]
Ee_{TA}: Specific CO_2 emissions of E_{TA} due to electric consumption [gCO_2/km]
i: index for the different modified conditions
P_{HL}: Power consumption of halogen lighting [W]
P_{LED}: Power consumption of LED lighting [W]
P_{MAX}: Maximum engine power [kW]
P_{RW}: Vehicle's power in real-world (with HL) [W]
P_{TA}: Vehicle's power under TA [W]
$P_{RW(LED)}$: $P_{RW} - P_{HL} + P_{LED}$ [W]
R_C_{CO2}: Specific CO_2 savings from regulated method [gCO_2/km]
S_C_{CO2}: Specific CO_2 savings from simulated method [gCO_2/km]
$UF_{MC,i}$: Usage factor for type-approval conditions [−]
UF_{TA}: Usage factor for the modified conditions i [−]
v: Mean driving speed of WLTP [km/h]
Vpe: Effective power consumption 'Willans factor' [l/Wh]
η_A: Efficiency of alternator [−] in the baseline vehicle
η_E: Efficiency of alternator [−] in the eco-innovation vehicle
std: Standard deviation [gCO_2/km]