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Comparing and Parameterizing the Electrical Energy Consumption Models in SUMO

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Abstract: This paper examined the performances of the current four battery models in SUMO. The possibility of expanding the model parameterization was also investigated and the corresponding extension was carried out for PHEMlight. Accordingly, the models can be compared more fairly. Three scenarios were used, namely the Worldwide harmonized Light vehicles Test Cycle, a constant high-speed highway scenario and an area scenario with a relatively complex traffic situation. The results show that all models can address recuperation and propulsion, and deliver the similar result at very low acceleration. The models based on average vehicle data generally tend to deliver higher battery consumption than the models with individual vehicle type-specific parameterization, especially PHEMlight5, while HBEFA4 only has one electric vehicle class and is therefore not sensitive to various vehicle characteristics. Moreover, the model by Kurczveil and López (EVM) seems to tend to have the lowest consumption of all models.

Keywords: Battery Model, Parameterization of PHEMlight

1 Introduction

The popularity of electric vehicles (EVs) has increased rapidly worldwide. This is reflected in the global annual sales of plug-in electric passenger cars, which have increased rapidly over the past decade: from 1 million vehicles in 2015, to 5 million vehicles in 2018, and over 10 million vehicles in 2022. This has led to more than 26 million electric cars on the roads in 2022, representing a 60 percents uptake from 2021 [1]. This change is driven by national policies, such as subsidies for the purchase of EVs, plans to phase out fuel vehicles and the improved quality and accessibility of the charging infrastructure, the increasing range of EVs, lower battery costs, and the increasing awareness of environmental protection. Plug-in electric vehicles generally include battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). With the improvement on battery technology, the EV market has been shifting towards pure BEVs, with the global ratio between BEVs and HEVs changed from 56:44 in 2012 to 71:29 in 2021 [2]. This rapidly growing trend is expected to continue.

Given the rapid growth of EVs, there is a strong need to enhance EV-related facilities, such as charging infrastructure planning and deployment, and to further understand the potential effects of EVs on the environment and the energy sector for policy development and decision making. The project SekQuaSens[3] of the German Aerospace Center (DLR) addresses this issue and develops a concept to aggregate data via networked sensors to reap the benefits of coupling transportation, heating and energy supply in a district [3]. The presence and absence of BEVs are also taken into account. Various vehicular emission and energy models have been developed that can help with this. Currently, four types of emission and energy models are integrated into the traffic simulation tool SUMO. Questions have been raised about how well these models reflect real-world battery usage, which model would be suitable for which conditions, and what possible differences there would be when using these models. Moreover, not all of these models can be easily parameterized currently, which makes model comparison difficult. The aim of this work is therefore to address the above-mentioned issues and to explore the extent to which these models can be adequately compared with similar parameter settings.

2 The electrical energy consumption models in SUMO

All emission and energy consumption models in SUMO can be used to calculate electric energy consumption and have been presented in various publications, e.g. in [4], [5], [6], [7], [8]. Each model is briefly introduced below.

2.1 HBEFA

It is the first emission model integrated into SUMO. This model is based on the HBEFA (Handbook for Emission Factors for Road Traffic), which is a database containing the specific emission values for the most common vehicle types corresponding to the European emission standard. The respective contributions have been made by research institutes across Europe. Moreover, the Passenger Car and Heavy Duty Emission Model (PHEM) [9], a model for calculating instantaneous vehicle emissions, processed the collected data to determine the so-called “basic emission factors” for the ”operating warm” emission factors of regulated pollutants, CO_2 and energy consumption. Accordingly, these basic emission factors have been further corrected for different influences, e.g. vehicle age, ambient temperature, energy efficiency and fuel quality. Following the regular update every two to six years, there are 3 versions, HBEFA2, HBEFA3, HBEFA4, in SUMO, while HBEFA3 is the current default emission class in SUMO. From HBEFA4 onwards, electric vehicles (BEVs and HEVs) are taken into consideration.

All versions of HBEFA are able to calculate fuel consumption and emissions according to the respective vehicle categories. Taking into account the amount of data available and the representativeness of the emissions, five emissions: CO_2, CO, NO_x, HC and PMx can be calculated in SUMO. According to the collected data per vehicle category, a polynomial curve fitting was performed to determine the respective coefficient of each term. For some vehicle categories, the fitting results are not good for every emission type due to e.g. an insufficient amount of data or an unclear relationship between data and emissions/energy consumption. Thus, the information about the fitting errors and the fleet shares in HBEFA4 is also listed in [10] for reference. It should also be noted that the non-exhaust PMx for both fuel and electric vehicles is only considered and calculated in HBEFA4. Thus, a combination of different vehicle categories from different model versions could lead to inconsistent PMx results. No license is required for using this model.

2.2 PHEMlight

PHEMlight is a derivate of PHEM. This model has been developed by the Graz University of Technology (TU Graz) and the FVT mbH, and integrated into SUMO in cooperation with the DLR as part of the European project COLOMBO (Cooperative Self-Organizing System for low Carbon Mobility at low Penetration Rates) with the grant agreement no.318622 [5]. In comparison to PHEM, the model complexity of PHEMlight has been reduced to allow better coupling with microscopic traffic simulation tools. There are currently two versions available, PHEMlight and PHEMlight5, which take into account both fuel and electric vehicles. The emissions and fuel consumption considered are the same as in HBEFA.

Instead of curve fitting with the collected data in HBEFA, PHEMlight calculates the energy consumption based on the vehicle data, e.g. maximum power, driving resistances, losses in drive train, gear ratio, and the driving cycle, related to vehicle speed and road gradient, according to the selected vehicle categories. Auxiliary consumption for managing the systems within a vehicle, e.g. air conditioning, heater and electronic devices, is separately considered as the product of the specified auxiliary factor, maximum power and travel duration. The required engine power and energy consumption are derived from this. Accordingly, the respective emissions are determined using the prepared look-up table that describes the relationship between engine power and emission production. All vehicle-related data is an average of the measurements collected for each vehicle category and defined in a data file (*.veh). This means that all vehicles in the same category have the same vehicle specific data, even if in reality they may differ in terms of weight, loading, maximum power etc. During a simulation, SUMO directly reads the relevant *.veh files according to the defined PHEMlight emission classes. Users can modify the *.veh file if vehicle data other than the defaults should be used. However, this will become unmanageable when several vehicle types with e.g. different weights and maximum powers need to be considered for the same vehicle emission class. SUMO contains only two model files for gasoline and Diesel powered passenger cars. For all other models a license from TU Graz is needed.

2.3 EVM

EVM stands for the Electric Vehicle Model and has been developed and implemented by T. Kurczveil and P. A. López from the Technical University Braunschweig [6]. This model only calculates the battery consumption of BEVs, and requires detailed vehicle information (12 parameters), such as weight, maximum power, air drag coefficient, rolling resistance coefficient, constant power consumption for auxiliary consumption etc. Thus, the investigated BEVs and their vehicle information need to be collected instead of just defining one or several vehicle categories. Sometimes, certain information, such as radial drag coefficient, rolling resistance coefficient, drive efficiency and recuperation efficiency are not easy to find.

In contrast to directly using the model version name to define the emission class, this model's emission class is referred to as Energy/unknown in SUMO. Moreover, the parameterization of this model has already been integrated into SUMO's vehicle type definition. This means that all parameters can be defined directly using <param> under <vType>. The format remains the XML-format.

2.4 MMPEVEM

MMPEVEM has been developed by the Teaching and Research Area Mechatronics in Mobile Propulsion (MMP) of the RWTH Aachen University [7] and the model name stands for MMP's Electric Vehicle Emission Model. This model considers the powertrain components of each given EV individually to calculate battery consumption at each simulation step. This model only calculates the battery consumption of BEVs.

16 vehicle specific parameters are considered and, like EVM, can be defined directly under <vType>. Some of them are identical to those of EVM. Besides, this model also takes into account the information e.g. torques (recuperation and maximum generative torque), internal battery resistance, gear ratio, gear efficiency, wheel size and electric motor's power loss map. The last one can be generated with the use of the Electric Machine Design Tool from the Technical University of Munich [11]. The program parameters need to be adapted sensibly to obtain a plausible result. Similar to EVM the model only provides one emission class but the parameters for some selected vehicle models are provided with SUMO.

2.5 Model summary

HBEFA and PHEMlight in SUMO have been adapted so that they correspond to the resolution of the traffic simulation and can also reflect future compositions of the vehicle fleet. Unlike EVM and MMPEVEM, these two models can calculate not only battery consumption, but also emissions (PMx is still an issue even for EVs) and fuel consumption. Once the appropriate settings are made, vehicular emissions and energy consumption can be calculated and for instance delivered into a pre-defined tripinfo-file right after running a simulation or retrieved online. The model characteristics are summarized in Table 1.

3 Extension and unification of the model parameterization

As mentioned in Section 2, the parameterization for EVM and MMPEVEM can already be defined directly under the respective vehicle types in XML format, while there is no option for parameterization in HBEFA. To increase the flexibility to deal with different vehicle types and to enable a fair model comparison, the parameterization of PHEMlight has been extended. The selected parameterizable variables correspond to those in EVM and MMPEVEM as listed and explained below. In addition, for all three models, vehicle weight has been further divided into vehicle mass and loading weight. This facilitates to increase the accuracy of energy consumption calculation under dynamic loading conditions, e.g. load changes caused by passengers boarding and alighting from public transport or by goods delivery.

- maximumPower: this is the maximum power which the vehicle can achieve.
- frontSurfaceArea: this is the front surface area of the vehicle.
- airDragCoefficient: this is the air resistance coefficient of the vehicle.
- rollDragCoefficient: this is the rolling resistance coefficient of the vehicle.
- constantPowerIntake: this is the constant power consumption of additional devices and internally converted to the auxiliary factor in PHEMlight.
- wheelRadius: this is internally converted to wheel diameter in PHEMlight.
- mass: this is the curb weight of the vehicle with standard equipment and all necessary operating consumables.
- loading: this is an additional loading, that the vehicle has, e.g. passengers, goods.

Table 1. *The characteristics of the emission and energy models in SUMO.*

Characteristics	**HBEFA**	**PHEMlight**	**EVM**	**MMPEVEM**
Data source	vehicle data across Europe and data from PHEM	data from PHEM	Individual vehicle data	Individual vehicle data
Required inputs	the names of the vehicle categories	the names of the vehicle categories	12 parameters per vehicle type	16 parameters per vehicle type
Versions	HBEFA2: SUMO 0.10.2+ HBEFA3: SUMO 0.21.0+ HBEFA4: SUMO 1.14.0+	PHEMlight: SUMO 0.20.0+ PHEMlight5: SUMO 1.14.0+	SUMO 0.24.0+	SUMO 1.11.0+
Battery consumption - BEVs	x (Version 4+)	x	x	x
Battery consumption - HEVs	x (Version 4+)	x	-	-
Number of BEV types/classes*	PC: 1; MC: 1; Coach: 3; LCV: 3; HGV: 4	PC: 1; MC: 1; CB: 1; LCV: 3	unlimited; individually defined	unlimited; individually defined
Fuel vehicle types	x	x	-	-
Fuel consumption	x	x	-	-
Emissions	CO_2, CO, NO_x, PMx, HC	CO_2, CO, NO_x, PMx, HC	-	-
Separable auxiliary consumption	-	x	x	x
Specific vehicle parameters	-	x (per vehicle category)	x (per vehicle type)	x (per vehicle type)
License required**	-	x for multiple emission classes	-	-

*: PC: passenger car, MC: Motorcycles; CB: City bus; LCV; Light vehicle; HGV: heavy goods vehicle; **: The public version includes two emission classes.

- rotatingMass: this is the mass during vehicle rotation, which corresponds to the mass of the internal rotating elements and a respective conversion is needed.

From SUMO version v1_19_0+1922-8d2c24cf0a1 onwards, the above parameters can be used to define BEVs in EVM, MMPEVEM and PHEMlight, where wheelRadius is not concerned in EVM. rotatingMass in EVM and PHEMlight correlates to internalMomentOfInertia in MMPEVEM, i.e. $\mathrm{rotatingMass} = \frac{\mathrm{internalMomentOfInertia}}{\mathrm{wheelRadius}^2}$. In addition, EVM and MMPEVEM still require information for other parameters. The aforementioned SUMO version was used for model comparison.

4 Model comparison

To map out the differences in the model performances, three different scenarios were considered. Firstly, the models were compared with the use of the Worldwide harmonized Light vehicles Test Cycle (WLTC) and the data reported by the manufacturers. Secondly, the real energy consumption data measured on highways, also reported by the manufacturers, was used and compared. In the end, the published SUMO scenario Acosta was used to get an idea of how the model results may differ in a more complex traffic environment, where (un-)regulated intersections, bus exclusive lanes and different kinds of BEVs were involved.

In addition, different loads and auxiliary consumption were considered to examine the parameterization work mentioned in Section 3. Five vehicle types: BMW i3, SUV, VW e-Up, VW ID.3, VW ID.4, used in [7], were applied here for a consistent comparison.

4.1 Worldwide harmonized Light vehicles Test Cycle

The New European Driving Cycle (NEDC) has been successively replaced by the new official EU measurement method Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) [12], [13] since 2017. This new procedure is intended to provide more realistic assessments for measuring standardized energy consumption and pollutant emissions from cars, and comes together with the WLTC. This test procedure is designed with a more demanding test procedure and driving profile for being able to provide figures closer to real-world driving behavior.

According to the characteristics of the five selected vehicle types, the WLTC class 3b dataset was used as input data for the SUMO tool emissionsDrivingCycle, which corresponds to the WLTP. In order to be able to compare the results fairly with the results reported in [7], the same consideration was made as in [7], i.e. the model output was divided by a charging efficiency of 0.9, as the battery consumption was measured behind a charging station and was the actual electricity drawn from the energy grid. A lesser charging loss of 5% and no charging loss were also considered as charging loss varies depending on charging devices. All constant power consumption is 360 W.

Table 2 shows that the results of MMPEVEM highly correspond to the results from [7], and are within the respective data ranges specified by the manufacturers, when a charging loss of 10% is considered. Moreover, the results of EVM are slightly lower than those of MMPEVEM, and the corresponding battery consumption is underestimated by 2 percents (VW ID.3/ID.4) – 5 percents (BMW i3), compared to the lower bounds of the manufacturers' data. Both models show a similar consumption tendency between the five types of vehicle, and the consumption ranking is SUV, VW ID.4, VW.ID.3, BMW i3, and then VW e-Up.

In comparison to the above-mentioned model results, PHEMlight has the same consumption ranking, but it tends to give higher energy consumption values. The possible reason for this is that the values of the non-parameterizable variables are based on the annual averages of the collected data. Due to the nature of the model, the result of HBEFA4 is constantly 17.66 kWh/100 km with a charging loss of 10% regardless of the vehicle types. The tests were also performed using the current default parameter setting for each model in SUMO. Each model result represents the energy consumption of a different type of vehicle, for instances the result of PHEMlight5 represents the energy consumption of a SUV when using the respective SUMO default setting. In addition, the WLTC-based course of the cumulative energy consumption of the VW ID.3 is shown as an example in Figure 1 and reflects the result mentioned above. The increasing difference in energy consumption between PHEMlight5 and HBEFA4 begins at around 1200 sec and occurs primarily at higher speeds and accelerations.

Table 2. *Battery consumption of the selected vehicle types with the use of the SUMO tool emissionsDrivingCycle, the WLTC class 3b dataset and a charging lost of 0, 5, 10% (unit: kWh/100 km).*

Vehicle type (mass)	**HBEFA4**	**PHEMlight5**	**EVM**	**MMPEVEM**	**MMPEVEM [7]**	**Data from the manufacturers [7]**
BMW i3 (1417 kg)	15.89(0%) 16.73(5%) 17.66(10%)	16.79(0%) 17.67(5%) 18.65(10%)	13.06(0%) 13.75(5%) 14.51(10%)	13.94(0%) 14.68(5%) 15.49(10%)	- - 15.5(10%)	15.3 - 16.3
VW e-Up (1235 kg)	15.89(0%) 16.73(5%) 17.66(10%)	16.05(0%) 16.90(5%) 17.84(10%)	12.51(0%) 13.17(5%) 13.90(10%)	13.27(0%) 13.97(5%) 14.75(10%)	- - 14.8(10%)	14.5 - 14.9
VW ID.3 (1794 kg)	15.89(0%) 16.73(5%) 17.66(10%)	17.78(0%) 18.72(5%) 19.76(10%)	13.65(0%) 14.36(5%) 15.16(10%)	14.27(0%) 15.02(5%) 15.86(10%)	- - 15.9(10%)	15.4 - 15.9
VW ID.4 (2124 kg)	15.89(0%) 16.73(5%) 17.66(10%)	20.66(0%) 21.75(5%) 22.95(10%)	16.14(0%) 16.99(5%) 17.93(10%)	16.77(0%) 17.65(5%) 18.64(10%)	- - 18.6(10%)	18.2 - 18.5
SUV (2100 kg)	15.89(0%) 16.73(5%) 17.66(10%)	24.46(0%) 25.75(5%) 27.18(10%)	19.96(0%) 21.01(5%) 22.18(10%)	21.34(0%) 22.46(5%) 23.71(10%)	- - 23.71(10%)	-
SUMO default (1500 kg)	15.89(0%) 16.73(5%) 17.66(10%)	24.15(0%) 25.42(5%) 26.84(10%)	13.58(0%) 14.30(5%) 15.09(10%)	13.25(0%) 13.94(5%) 14.72(10%)	- - -	-

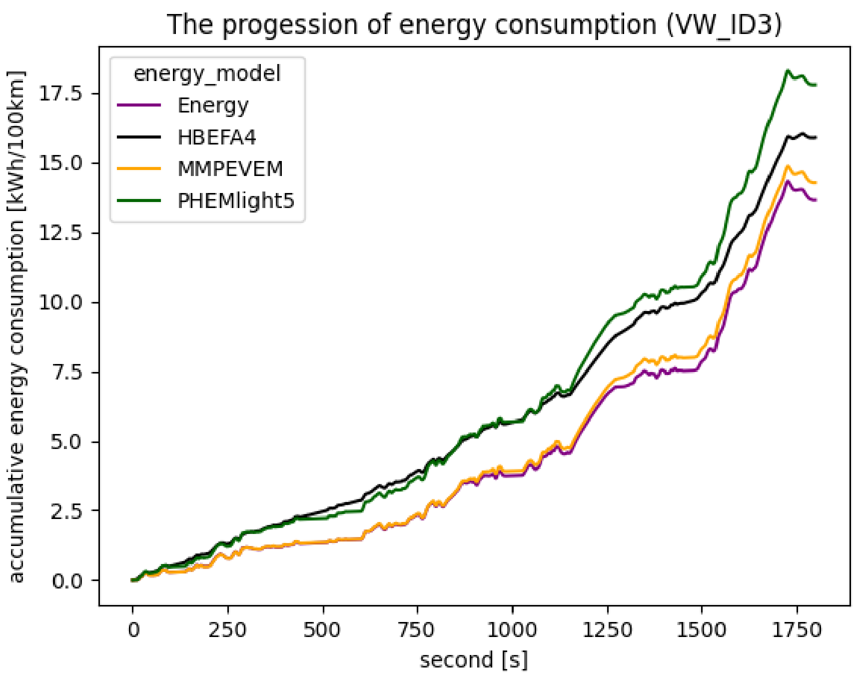


Figure 1. *The WLTC-based cumulative energy consumption of 4 energy models (VW ID.3).*

Moreover, the relationship between energy consumption, speed and acceleration was investigated with the WLTC-results of the five vehicle types. As shown as an example in Figure 2 to Figure 5, all models can address vehicular recuperation and propulsion, as energy consumption during braking and acceleration is negative and positive, respectively. Note that a recently fixed bug in the HBEFA4 implementation prevented recuperation in that model in earlier SUMO versions. EVM and MMPEVEM have the similar result. PHEMlight5 estimates more energy consumption at higher speed and acceleration than the other three models, while MMPEVEM estimates more energy recovery at higher deceleration. These statements also apply to the other four vehicle types.

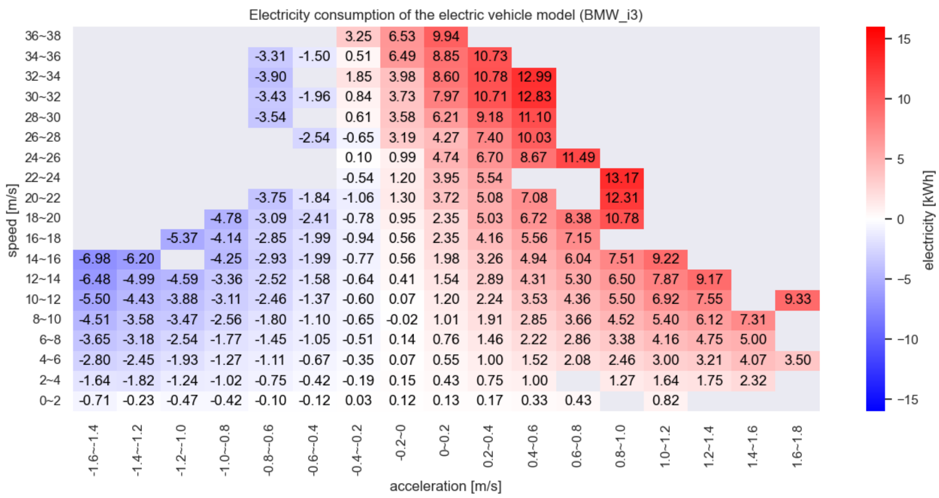


Figure 2. *The WLTC-based energy consumption per acceleration and speed class (BMW i3 - EVM).*

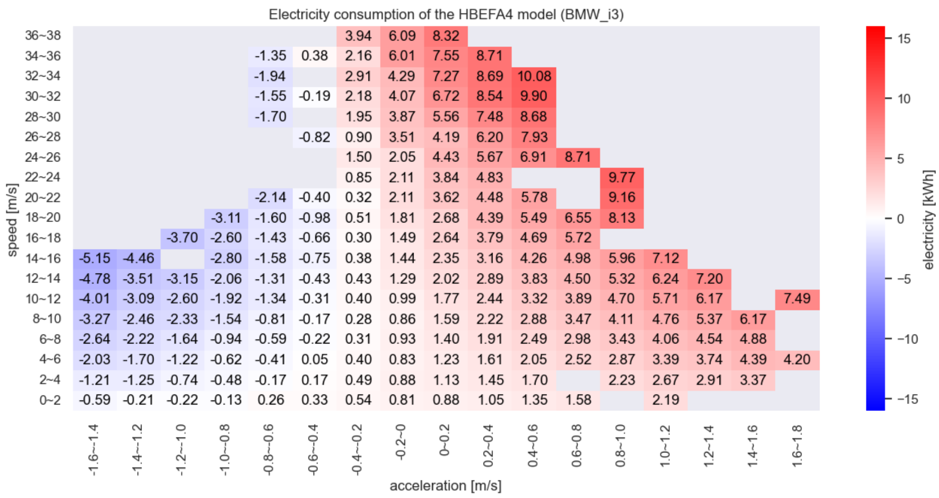


Figure 3. *The WLTC-based energy consumption per acceleration and speed class (BMW i3 - HBEFA4).*

Figure 6 to Figure 9 show the differences in energy consumption between the models for relatively light and heavy vehicle types. With very low deceleration and acceleration, all four models estimate similar energy consumption. It is also noticeable that the energy consumption of EVM differs significantly from that of HBEFA4 as the vehicle weight increases. This also applies to MMPEVEM. It should be noted that the positive values at negative accelerations mean that there is either less energy recovery or little propulsion in comparison to the base model.

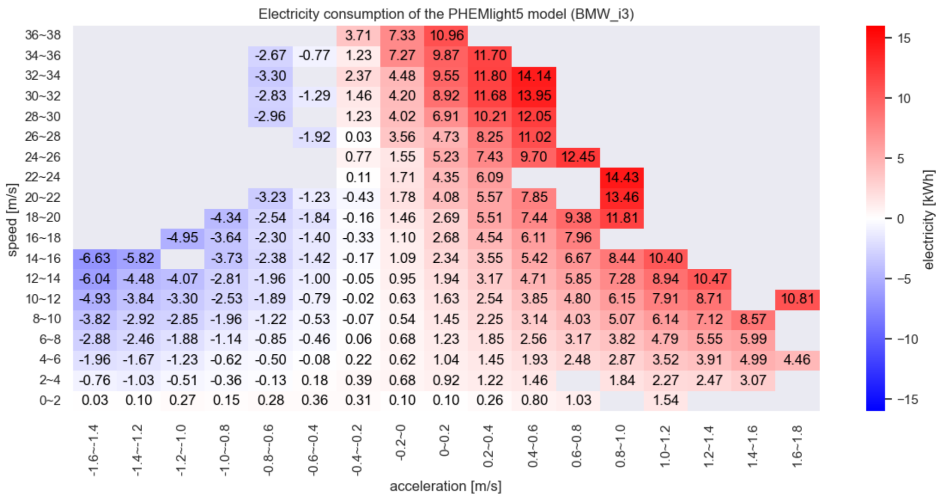


Figure 4. *The WLTC-based energy consumption per acceleration and speed class (BMW i3 - PHEMlight5).*

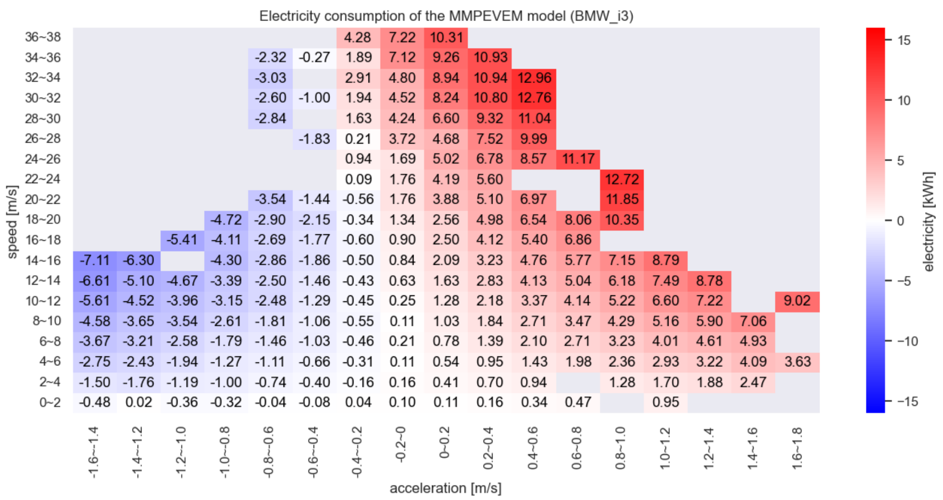


Figure 5. *The WLTC-based energy consumption per acceleration and speed class (BMW i3 - MMPEVEM).*

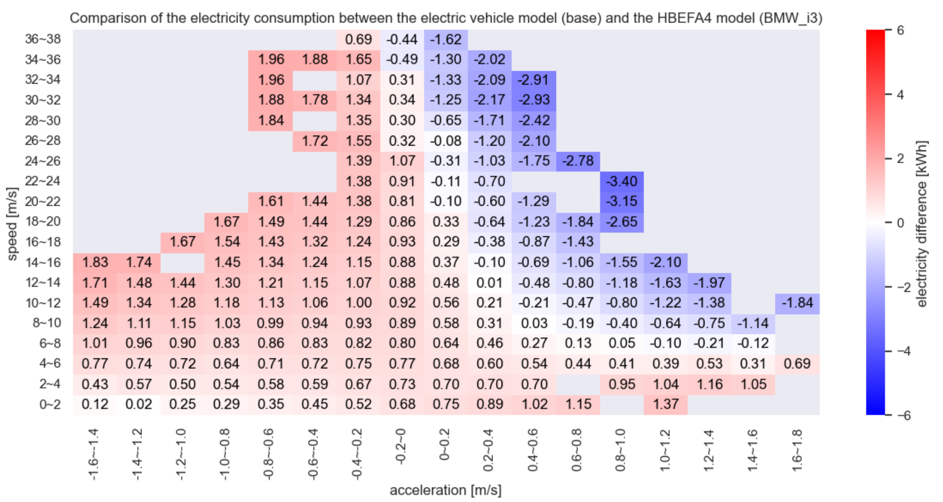


Figure 6. *The difference in energy consumption between EVM and HBEFA4 (BMW i3).*

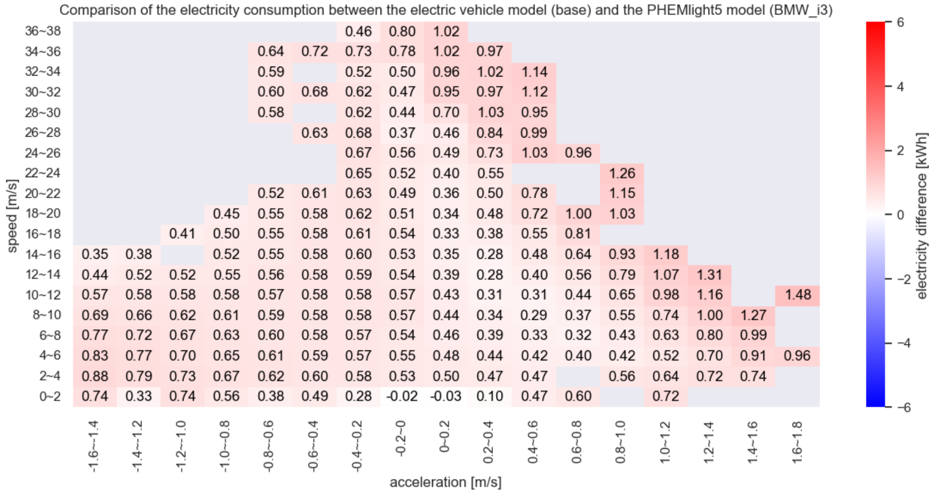


Figure 7. *The difference in energy consumption between EVM and PHEMlight5 (BMW i3).*

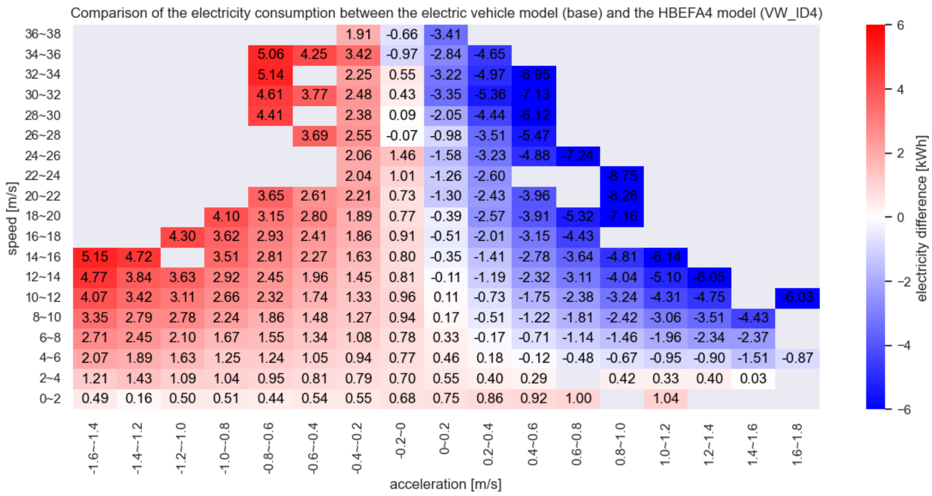


Figure 8. *The difference in energy consumption between EVM and HBEFA4 (VW ID.4).*

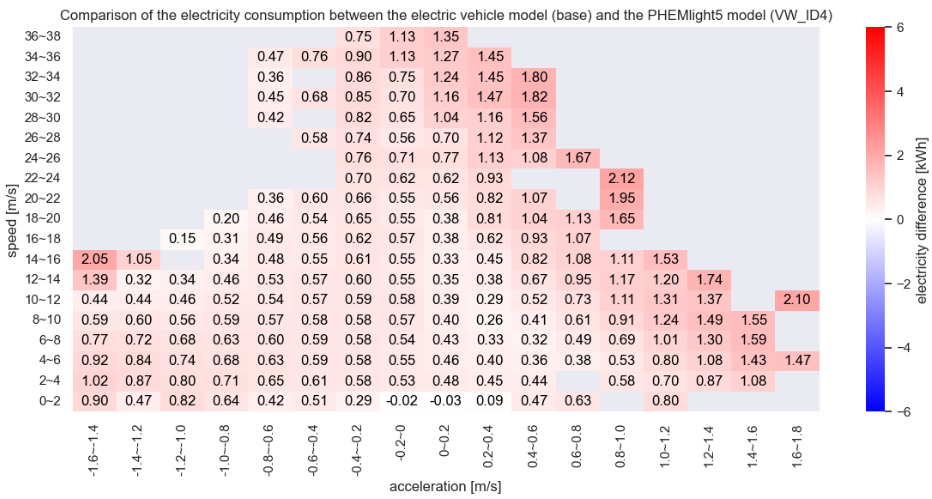
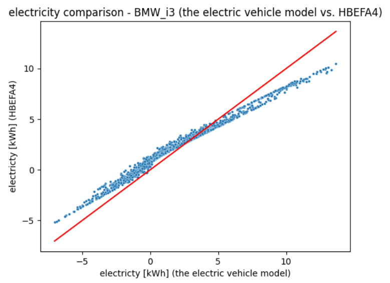
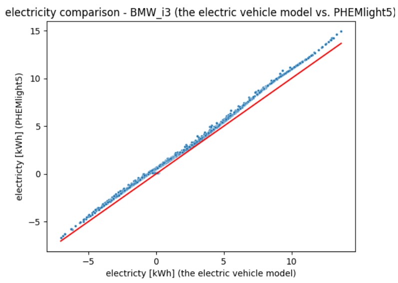


Figure 9. *The difference in energy consumption between EVM and PHEMlight5 (VW ID.4).*

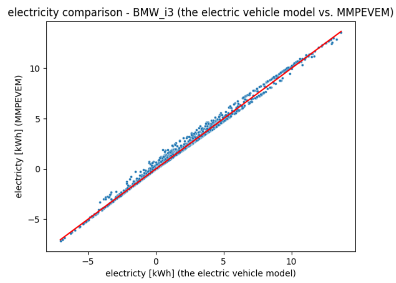
In addition, the fitness check between the model estimates was carried out using the corresponding scatter plots. As examples, the scatter plots for the lighter BMW i3 and the heavier VW ID.4 are shown in Figure 10 to Figure 11. The estimates of EVM, PHEMlight5 and MMPEVEM and their trends fit together quite well (see Figure 10b, Figure 10c, Figure 11b and Figure 11c). However, the situation is different when comparing the estimates of EVM and HBEFA4. As energy consumption increases, HBEFA4 tends to expect lower energy consumption than EVM, but with more recuperation when braking (see Figure 10a). This phenomenon becomes more obvious as the weight of the vehicle increases, as shown in Figure 11a). Such a relationship can be useful to adjust the estimates of HBEFA4 or to derive estimates of other models if only the estimates of HBEFA4 are available.



***(a)** EVM vs. HBEFA4*

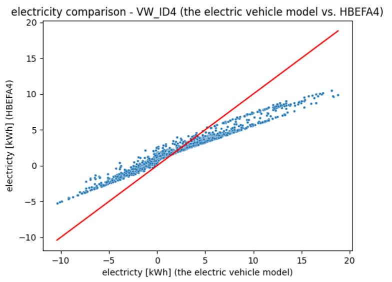


***(b)** EVM vs. PHEMlight5*

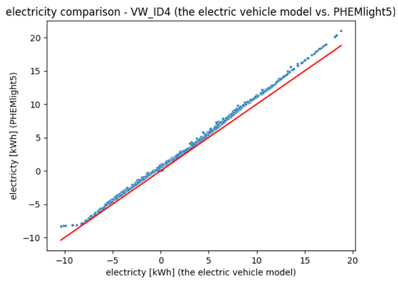


***(c)** EVM vs. MMPEVEM*

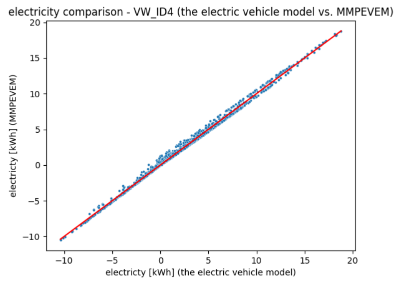
***Figure 10.** Comparison of electricity consumption between the models (BMW i3).*



***(a)** EVM vs. HBEFA4*



***(b)** EVM vs. PHEMlight5*



***(c)** EVM vs. MMPEVEM*

***Figure 11.** Comparison of electricity consumption between the models (VW ID.4).*

4.2 Real energy consumption on highways

EV manufacturers have also reported real energy consumption data both for city and highway areas under two weather conditions: cold and mild. Regarding the cold condition, the worst case was considered to be -10 degrees with the use of heating, while the best case was considered to be 23 degrees without air conditioning. In addition, a constant speed of 110 km/h was assumed for highway area. It should be noted that the collected real energy consumption depends on speed, style of driving, climate and route conditions.

Accordingly, a highway scenario with mild weather was set up with SUMO, so that the difference between the simulation environment and the reality was minimized. The scenario consists of a 100 km long, single-lane highway section with a speed limit of 110 km/h and 100 EVs, where no speed deviation, no speed factor and no driver imperfection were considered. As in the WLTC, the SUMO-default vehicle class and the auxiliary consumption of 360 W were used. Except SUV, all of the aforementioned vehicle types were used, since SUV is a general car classification and there is currently no real data available for general SUV. Vehicles entered the network at a fixed periodic interval (36 s) and were given an emission class in the repeated order of Energy/unknown, HBEFA4/PC_BEV, PHEMlight5/PC_BEV_GEN1 and MMPEVEM. A charging loss of 10% was considered.

The result in Table 3 indicates that both HBEFA4 and EVM deliver quite good result with a deviation between -7% and 3% for all four vehicle types, while HBEFA4 underestimates the battery consumption for heavier vehicle type (VW ID.4). In contrast, PHEMlight5 and MMPEVEM tend to overestimate the respective energy consumption, especially PHEMlight5. This may be because these two models expect more energy consumption at constantly higher speeds (see Figure 4 and Figure 5), where this scenario is admittedly very artificial.

Table 3. *The simulated and the real battery consumption under the condition "Highway - Mild Weather" (unit: kWh/100km).*

Vehicle type	HBEFA4	PHEMlight5	EVM	MMPEVEM	Data from the manufacturers
BMW i3	17.92 (-1%)	20.81 (15%)	18.71 (3%)	20.78 (15%)	17.6 – 18.1
VW e-Up	17.92 (2%)	19.96 (6%)	18.11 (-4%)	18.70 (-1%)	17.5 – 18.8
VW ID.3	17.92 (1%)	20.60 (13%)	18.07 (-1%)	18.89 (3%)	17.8 - 18.3
VW ID.4	17.92 (-7%)	24.52 (16%)	21.38 (1%)	23.24 (10%)	19.3 – 21.1
SUMO default	17.92	28.38	21.87	21.62	-

4.3 Scenario Acosta

Changes in speed and acceleration along the way and at intersections significantly affect battery consumption. Thus, the SUMO scenario Acosta was used to check the model performances in a more complex traffic environment. As illustrated in Figure 12, the Acosta network is a part of the City of Bologna, Italy and there is an exclusive westbound bus lane in the middle of the network. There are totally 8779 vehicles running, 157 of which are busses. The simulation duration is around simulated 1.5 hours. The BEV types mentioned above were used here and replaced the original vehicle types. All the five vehicle types were randomly selected.

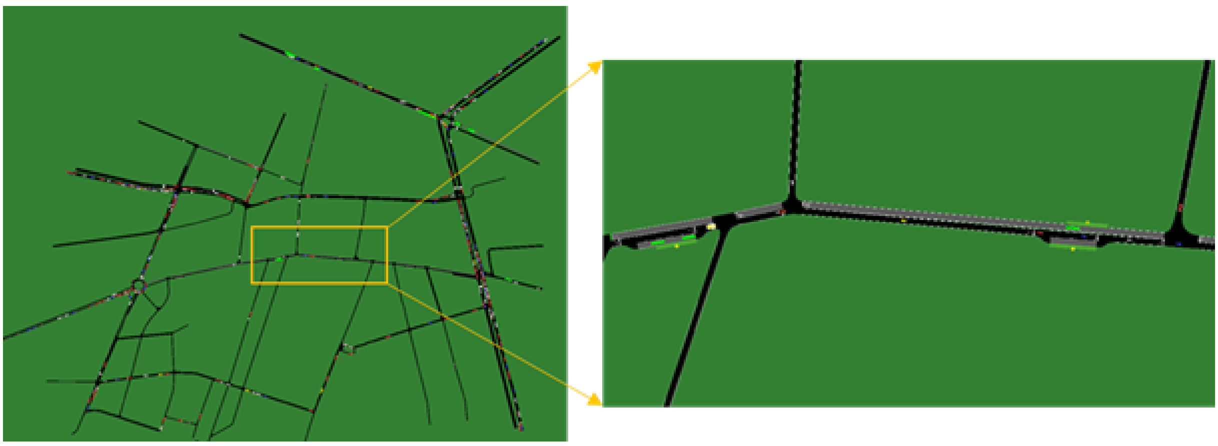


Figure 12. *The scenario Acosta: network layout (left); part of the westbound exclusive bus lane (right).*

Furthermore, loading and weather conditions were considered to see how they affect the battery consumption. An additional payload of 350 kg per vehicle was considered for the loading condition. Regarding the weather condition, the auxiliary consumption for mild weather was set at 360 W as in Sections 4.1 and 4.2. According to [14], the auxiliary consumption values for cold and warm conditions were set at 2146 W and 2520 W, respectively.

Table 4 shows the simulated battery consumption under the mild weather condition. It can be clearly seen that, except for HBEFA4, that all models reflect the loading effect on battery consumption after the parameterization extension of PHEMlight. The higher the total weight, the higher the battery consumption. With the given additional loading (350 kg), the battery consumption increases by approximately 5 kWh/100 km for each BEV when using PHEMlight4 and MMPEVEM, while this increase is 3 kWh/100 km with the use of EVM.

Table 4. *The simulated battery consumption under the mild weather in the scenario Acosta.*

Battery consumption (kWh/100km)	**HBEFA4**	**PHEMlight5**	**EVM**	**MMPEVEM**
With loading	26.06	35.91	22.79	29.41
Without loading	26.06	31.22	19.91	23.68

In addition to the loading effect, Figure 13 further illustrates the potential effects of auxiliary consumption on the overall battery consumption. It also shows that PHEMlight is able to reflect different loads and constant consumption after the parameterization extension. PHEMlights tends to estimate higher energy consumption than MMPEVEM and then EVM for all state combinations.

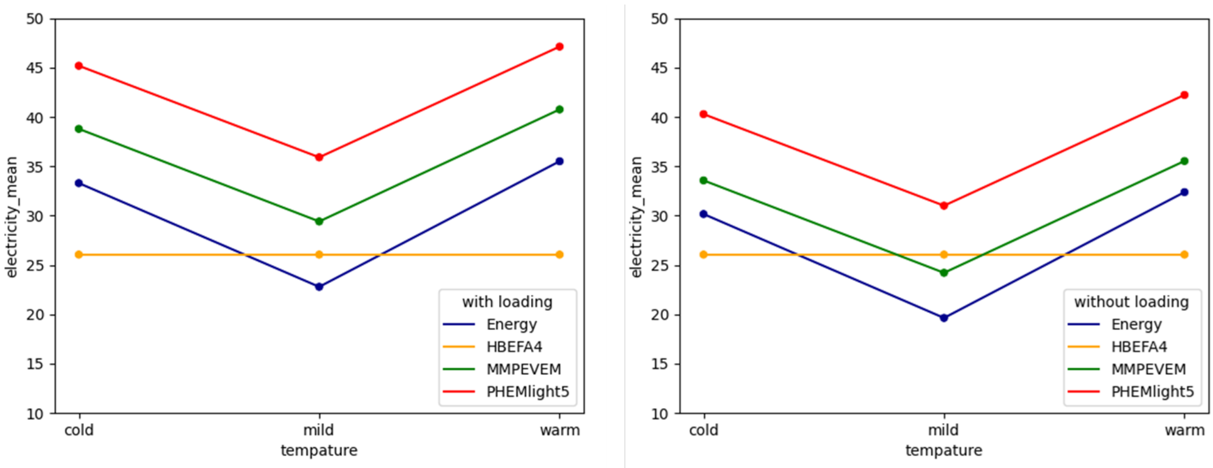


Figure 13. *Battery consumption [kWh/100km] with different auxiliary consumption and with (left) and without (right) load when using PHEMlight5.*

5 Summary and remarks

In general, HBEFA and PHEMlight are based on numerous real vehicle data and the respective vehicle data has been categorized according to the European emission standard. Accordingly, the polynomial curve fitting method was applied for HBEFA to determine the constant and coefficient terms of the respective curve for each vehicle category. There is therefore no possibility for parameterization. It is possible, that some fitting errors are quite large due to limited amount of data or a limited dependency between real data and emission/energy consumption. On the other hand, PHEMlight accounts for physical and performance differences, based on vehicle categories rather than individually. Annual averages of average vehicles have been used to determine respective parameter values. Subsequently, the required engine power for each vehicle category can be derived along with the corresponding road slope factors and further used to determine the amount of emissions using a lookup table, created according to the PHEM database. In comparison, EVM and MMPEVEM focus on battery consumption at an individual vehicle level, and aim to accurately calculate battery consumption. More vehicle-specific parameters are thus required. It is time-consuming and sometime difficult to determine the parameter values for each considered BEV.

In this work, the parametrization extension for PHEMlight has been carried out, and 9 vehicle-specific parameters can be defined. This means that different EVs' physical and performance characteristics under the same vehicle category can be considered when calculating battery consumption. This enhancement makes PHEMlight more comparable to other vehicle type-specific battery models. In addition, weather-related additional consumption can be taken into account separately for both EVs and fuel vehicles.

According to the analysis results, all models can address recuperation and propulsion. The difference in energy consumption between all models is quite limited at very low acceleration and speeds below 100 km/h. Except HBEFA4, the estimates of the other models and their trends fit together quite well. The battery consumption of MMPEVEM and EVM are mostly close to the manufacturers' WLTC data with the consideration of a charging lost of 10%, while the ones from MMPEVEM are the closest. The consumption values from PHEMlight5 are higher, which is primarily due to their model nature mentioned above. Under a constant high-speed condition (110 km/h) with minimum auxiliary consumption, the estimates from HEBFA4 and EVM come closest to the real consumption data. Then, PHEMlight5 and MMPEVEM tend to overestimate the respective consumption. This may be due to that higher energy consumption is expected by these two models. The results of the scenario Acosta provide an idea of what the difference between the four model results could be if traffic situation becomes more complex and additional loading and auxiliary consumption occur. Further sensitive analysis can help to better understand the impact of each parameter and each consumption component (e.g. air resistance, road friction and recovery) on battery consumption between the models. In addition, the relationship between the model estimates, mentioned in the fitness check in section 4.2 should be examined with more datasets, and if it does exist, a mechanism for converting estimates from one model to another one can be developed.

It is time-consuming and sometimes difficult to get all the required parameter values for the individual vehicle type-specific models. This also affects the number of considerable vehicle types and the representativeness of the results, especially for large study scopes. So, a trade-off between accuracy and data collection may need to be made. Currently, there is only one electric vehicle class for passenger cars in HBEFA4. Higher accuracy of HBEFA can be expected if the electric vehicle class can be further divided into several classes based on vehicle characteristics.

Data availability statement

The data of the applied scenario Acosta is publicly available and can be found at `https://github.com/DLR-TS/sumo-scenarios/tree/main/bologna`. All standard vehicle type parameters (including MMPEVEM values for the BMW i3 and the VW ID.4) are part of the standard SUMO distribution at https://github.com/eclipse-sumo/sumo.

Underlying and related material

N/A

Author contributions

- Conceptualization: M. Behrisch, Y.-P. Flötteröd, P. Wagner
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- Methodology: M. Behrisch, Y.-P. Flötteröd, P. Wagner
- Software: M. Behrisch
- Validation: M. Behrisch, P. Wagner, Y.-P. Flötteröd
- Visualization: Y.-P. Flötteröd, P. Wagner
- Writing – original draft: Y.-P. Flötteröd, P. Wagner, M. Behrisch
- Writing – review and editing: Y.-P. Flötteröd, P. Wagner, M. Behrisch

Competing interests

The authors declare that they have no competing interests.

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