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Energy efficiency trade-offs in small to large electric vehicles

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Abstract

Background: As electric kick scooters, three-wheelers, and passenger cars enter the streets, efficiency trade-offs across vehicle types gain practical relevance for consumers and policy makers. Here, we compile a comprehensive dataset of 428 electric vehicles, including seven vehicle types and information on certified and real-world energy consumption. Regression analysis is applied to quantify trade-offs between energy consumption and other vehicle attributes.

Results: Certified and real-world energy consumption of electric vehicles increase by 60% and 40%, respectively, with each doubling of vehicle mass, but only by 5% with each doubling of rated motor power. These findings hold roughly also for passenger cars whose energy consumption tends to increase $0.6 \pm 0.1 \text{ kWh}/100 \text{ km}$ with each 100 kg of vehicle mass. Battery capacity and vehicle mass are closely related. A 10 kWh increase in battery capacity increases the mass of electric cars by 15 kg, their drive range by 40–50 km, and their energy consumption by 0.7–1.0 kWh/100 km. Mass-produced state-of-the-art electric passenger cars are $2.1 \pm 0.8 \text{ kWh}/100 \text{ km}$ more efficient than first-generation vehicles, produced at small scale.

Conclusion: Efficiency trade-offs in electric vehicles differ from those in conventional cars—the latter showing a strong dependency of fuel consumption on rated engine power. Mass-related efficiency trade-offs in electric vehicles are large and could be tapped by stimulating mode shift from passenger cars to light electric road vehicles. Electric passenger cars still offer potentials for further efficiency improvements. These could be exploited through a dedicated energy label with battery capacity as utility parameter.

Keywords: Electric vehicles, Efficiency trade-offs, e-boards, e-bikes, Electric kick scooters, Electric motorcycles, Electric three- and four-wheelers, Electric cars, Electric light commercial vehicles, Electric trucks, Climate policy, Sustainable road transport, Urban mobility

Background

Policy makers support the electrification of road transport for several reasons—to decrease urban air and noise pollution, to mitigate transport-related CO₂ emissions, and to secure energy supply for the mobility of citizens [1, 2]). In Europe, most attention is paid to electric passenger cars, for which subsidies and other incentives opened a growing market [3, 4]. The policy focus is

justified because passenger cars account for the bulk of road transport [5, 6] and its health and environmental impacts [7, 8]. But there is also a risk of overlooking the larger potentials of electromobility for transforming road transport in general.

Not only do electric powertrains allow operating vehicles without direct CO₂ and air pollutant emissions, but also they relax important design constraints of conventional vehicles that need to accommodate a voluminous cylinder block, a crankshaft, and a transmission. Electric powertrains can generate high torque and power by multiple small motors placed in versatile configurations on one or multiple axles or directly in the wheel hub [9–14].

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Traction batteries still offer a 50–100 times lower energy density than gasoline [15] and require more space than comparable fuel tanks. However, they allow for flexible integration into the rolling chassis and their size may decrease once occasional charging—at home, work, or in the public space—becomes feasible.

Without the design constraints of internal combustion engines, more diverse road vehicles can emerge. Electric kick scooters, tandem scooters [16], and e-bikes [17] represent just examples of new mobility solutions (see Table 3 in the Appendix) for urban areas where trip distances are short and required drive ranges low. This way, electromobility facilitates niche applications, situational mode choice, and frequent shifts between transport modes.

As diverse electric vehicles enter the market, trade-offs between energy consumption and other vehicle attributes become relevant. Efficiency trade-offs have been studied for conventional passenger cars [18–23] but not yet for a wider range of electric vehicles.

Here, we analyze such trade-offs for a comprehensive set of vehicles, ranging from light electric skate- and hover-boards, e-bikes and kick scooters to passenger cars and heavy-duty trucks. We hypothesize that:

- the energy efficiency of electric vehicles is strongly related to vehicle mass and power;
- state-of-the-art and mass-produced electric passenger cars are more efficient than first-generation cars produced at small scale;
- despite high overall efficiencies, there is scope for further efficiency improvements, specifically for electric cars, which are covered by the CO₂ labeling scheme for passenger cars in the European Union [24] but not yet by a dedicated energy label.

The results can provide policy makers with rationale for shaping the electrification of road transport, thereby contributing to a climate neutral European economy [25].

Methods

General aspects

This article covers seven major types of electric vehicles: (i) hover-boards and skateboards (vehicle Type 0 in this analysis), (ii) stand-up and kick scooters (Type 1), (iii) e-bikes, including bicycle-like three-wheelers (Type 2), (iv) larger two- and three-wheelers such as mopeds and step-through scooters classified as L1e vehicles, motorcycles classified as L3e and L4e vehicles, and three-wheelers classified as L2e and L5e vehicles (Type 3; [5]), (v) light four-wheelers classified as L6c and L7e vehicles (Type 4; [26]), (vi) passenger cars classified as M1 vehicles (Type 5; [27]), and (vii) light commercial and heavy-duty vehicles

classified as N1-3 vehicles (Type 6; [11]). An indicative taxonomy of electric vehicles is provided in Table 3 in Appendix.

We consider certified and real-world energy consumption as both parameters can deviate from each other depending on the operating conditions of vehicles. Certified energy consumption is understood here as the consumption value declared by a manufacturer or certification body. For larger vehicles, such as passenger cars, the energy consumption is certified in a standardized regulatory test procedure [28]. For light vehicles such as e-bikes or kick scooters, the energy consumption is not yet certified with a standardized test but declared by manufacturers according to their own test protocol. Real-world energy consumption refers to the energy consumption observed by vehicle users on the road. For conventional passenger cars in the European Union, real-world CO₂ emissions (g/km)—being proportional to energy consumption—systematically exceeded certified values (on average 40% in 2015; [22]). Similar deviations were already observed for electric cars, whose energy consumption (kWh/100 km) tends to exceed certified values, e.g., at low ambient temperature [29, 30].

Data collection and processing

Electric passenger cars

Based on Wikipedia [31], we identify which models of electric passenger cars are or have been available on the market. We identify for each model in an extended web search the following attributes: brand, model version, year of market introduction, country of production and certification, vehicle mass (kg), power (kW), battery capacity (kWh), motor and battery type, and certified energy consumption (kWh/100 km). We complement the data with information on the real-world energy consumption (kWh/100 km) and the country of vehicle operation. The bulk of data are obtained from Spritmonitor [32] reflecting vehicle use in Germany. However, from miscellaneous web sources, we also collect information about the real-world energy consumption of electric cars in China, Norway and the USA. The resulting dataset comprises 218 electric car models (Additional file 1: Table S1).

Other electric vehicles

To identify vehicles and their technical attributes, we scanned market portals, technical magazines, product tests, and the web pages of vehicle manufacturers with a focus on the German market (e.g., [33–35]). This search was subsequently extended to cover also vehicles sold and operated elsewhere by combining search terms such as “hover-board”, “skateboard”, “kick scooter”, “e-bike”, “three-wheeler” “electric motorcycle”, “moped”,

“step-through scooter”, “motorcycle”, “light-weight vehicle”, “transporter”, “heavy-duty vehicle” with “electric”, “energy consumption” and “real-world energy consumption”. This approach adds 210 vehicle models to our dataset but it does not allow us to cover all models offered globally. Yet, we think our overall dataset of 428 models, which includes 218 passenger cars and 210 models of other vehicle types, captures the broad range of electric vehicles and can be considered a representative sample of electric vehicle types available to date (see also discussion in “Strengths and limitations” section).

Data processing

Before proceeding with the data analysis, we calculate for all vehicles certified and real-world drive range (km) by dividing battery capacity (kWh) by the respective energy consumption (kWh/100 km). We consider vehicles in running order by including the mass of a 70-kg driver. This correction acknowledges that the driver can exceed the mass of light electric vehicles and, thus, have an impact on their energy consumption. The vehicle mass presented in the “Results” section, thus, includes the vehicle and the driver, unless otherwise stated.

Data analysis

We characterize the vehicle data by calculating mean, standard deviation, minimum and maximum value of attributes separately for each vehicle type (Table 1). We then apply regression analyses to quantify efficiency trade-offs across all electric vehicles. We begin by modeling energy consumption E_i of vehicle i as a function of its mass M_i and rated motor power P_i in separate bivariate linear relationships as (Models 1, 2):

$$E_i = \alpha_1 + \beta_1 M_i + \varepsilon_i, \quad (1)$$

$$E_i = \alpha_2 + \beta_2 P_i + \varepsilon_i, \quad (2)$$

where $\beta_{1,2}$ represents the regression coefficients, $\alpha_{1,2}$ stands for the constants, and ε_i denotes the unexplained residuals. The two regression models are applied separately to certified and real-world energy consumption.

Models 1 and 2 neglect relevant attributes such as powertrain efficiency or vehicle type. To account for these, we follow Mellios et al. [21] and Tietge et al. [22] and apply a multiple linear regression model. In this model, we approximate powertrain efficiency by the variable year Y_i in which a vehicle was introduced to the market and we include vehicle type T_i as categorical variable. The energy consumption of electric vehicles is then modeled as (Model 3):

$$E_i = \alpha_3 + \beta_3 M_i + \beta_4 P_i + \beta_5 Y_i + \beta_6 T_i + \varepsilon_i. \quad (3)$$

This model is also applied separately to certified and real-world energy consumption. Models 1–3 assume a linear relationship between dependent and independent variables, which may not hold across all vehicle categories. To address this shortcoming, we follow Knittel [19] and also model energy consumption as a power-law function of vehicle attributes, which equates to a linear relationship between the logarithms of dependent and explanatory variables. The model specifications are as follows (Models 4, 5 and 6):

$$\log E_i = \alpha_4 + \beta_7 \log M_i + \varepsilon_i, \quad (4)$$

$$\log E_i = \alpha_5 + \beta_8 \log P_i + \varepsilon_i, \quad (5)$$

$$\log E_i = \alpha_6 + \beta_9 \log M_i + \beta_{10} \log P_i + \beta_{11} Y_i + \beta_{12} T_i + \varepsilon_i, \quad (6)$$

where \log depicts the common logarithm to the base 10. Sample sizes for vehicle types differ from each other; thus, sampling biases are likely to affect our results. To control for sample size, we apply in a sensitivity analysis Models 1–6 to the median attribute values for the seven vehicle types.

Accounting for the needs of policy makers, we then zoom in on passenger cars and apply Models 3 and 6 to this vehicle type only. As battery size contributes to the mass of electric cars, trade-offs between battery capacity, drive range, and energy consumption can become relevant. To analyze effects, we expand the regression models for passenger cars by: (1) considering energy consumption as a function battery capacity and drive range, respectively, and (2) exploring the inter-relation between vehicle mass, battery capacity, and drive range.

A preliminary screening of residual plots reveals heteroscedasticity, which can bias the regression errors. To minimize this effect, we follow Tietge et al. [22] and estimate heteroscedasticity-robust standard errors for all regression coefficients with the R package ‘estimatr’ [37]. All regression analyses are conducted with R [38].

Results

Descriptive statistics of vehicle attributes

Vehicle attributes span over a wide value range (Table 1; Fig. 1). Vehicle mass ranges from 6.3 kg (76.3 kg including the driver) for skateboards to 27070 kg for trucks. Rated motor power ranges from 0.25 kW for e-bikes to 575 kW for passenger cars; battery capacity ranges from 0.10 kWh for skateboards to 300 kWh for trucks.

Certified and real-world energy consumption vary between 0.17 and 2.25 kWh/100 km for e-bikes and 13 kWh/100 km to 153 kWh/100 km for light commercial

Table 1 Descriptive statistics of vehicle attributes; mass includes the vehicle and a generic driver of 70 kg; SD standard deviation; indirect CO₂ emissions from electricity consumption during vehicle use is calculated based on a carbon intensity of 300 ± 230 g CO₂/kWh (mean of the European Union ± standard deviation of country data; [36])

Vehicle type and variable (sample size)	Mean	SD	Min	Max
Hover- and skateboards (16)				
Mass (kg) (14)	86	15	76	124
Power (kW) (15)	0.97	0.83	0.40	3.00
Battery capacity (kWh) (16)	0.23	0.15	0.10	0.60
Certified energy consumption (kWh/100 km) (16)	1.02	0.31	0.63	1.58
Real-world energy consumption (kWh/100 km) (7)	1.37	0.51	0.89	2.14
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (16)	3.0	2.5		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (7)	4.1	3.5		
Stand-up and kick scooters (26)				
Mass (kg) (25)	90	11	77	115
Power (kW) (26)	0.46	0.21	0.25	1.00
Battery capacity (kWh) (26)	0.42	0.24	0.20	1.20
Certified energy consumption (kWh/100 km) (26)	1.25	0.42	0.75	2.33
Real-world energy consumption (kWh/100 km) (11)	1.46	0.44	0.84	2.25
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (26)	3.7	3.1		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (11)	4.3	3.6		
E-bikes and bike-like three-wheelers (55)				
Mass (kg) (45)	98	10	82	140
Power (kW) (53)	0.29	0.14	0.25	1.00
Battery capacity (kWh) (55)	0.47	0.11	0.30	0.80
Certified energy consumption (kWh/100 km) (51)	0.54	0.36	0.17	2.25
Real-world energy consumption (kWh/100 km) (30)	0.71	0.20	0.41	1.45
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (51)	1.6	1.6		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (30)	2.1	1.7		
Larger two- and three-wheelers, including mopeds, step-through scooters, motorcycles (48)				
Mass (kg) (47)	250	115	115	550
Power (kW) (47)	15.0	22.2	0.25	107
Battery capacity (kWh) (48)	5.8	5.1	0.50	18
Certified energy consumption (kWh/100 km) (48)	4.62	3.20	1.07	17.5
Real-world energy consumption (kWh/100 km) (4)	9.3	3.3	6.0	13.5
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (48)	14	14		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (4)	28	23		
Car-like three- and four-wheelers (31)				
Mass (kg) (29)	675	218	275	1000
Power (kW) (31)	12	8.5	3.5	33
Battery capacity (kWh) (30)	9.6	7.6	1.7	35
Certified energy consumption (kWh/100 km) (31)	8.0	3.0	4.00	16.25
Real-world energy consumption (kWh/100 km) (12)	10.0	3.3	4.8	16.4
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (31)	24	20		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (12)	30	25		
Passenger cars (218)				
Mass (kg) (211)	1689	472	766	3370
Power (kW) (218)	150	127	5	575
Battery capacity (kWh) (216)	46	26	10	100
Certified energy consumption (kWh/100 km) (206)	16.0	3.7	4.9	29.3
Real-world energy consumption (kWh/100 km) (179)	18.4	4.5	9.6	33.3
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (206)	47	38		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (179)	54	44		

Table 1 (continued)

Vehicle type and variable (sample size)	Mean	SD	Min	Max
Light commercial and heavy-duty vehicles (34)				
Mass (kg) (33)	4812	6679	670	27070
Power (kW) (34)	88	90	14	370
Battery capacity (kWh) (32)	80	85	10	300
Certified energy consumption (kWh/100 km) (32)	51	44	13	153
Real-world energy consumption (kWh/100 km) (2)	38	8	33	44
Indirect CO ₂ emissions—certified energy consumption (g CO ₂ /km) (32)	151	175		
Indirect CO ₂ emissions—real-world energy consumption (g CO ₂ /km) (2)	112	90		

vehicles and trucks (Table 1, Fig. 1). Light-commercial and heavy-duty vehicles appear to consume less energy on the road than during certification. But this observation is likely the result of the small data sample on real-world energy consumption, which only includes two observations.

Passenger cars account for 218 out of 428 data points; their power, mass, and battery capacity span over a factor five to one hundred between the smallest and largest value (630–3370 kg; 5–575 kW; 8–100 kWh). Certified and real-world energy consumption only span over a factor of six and three (5–29 kWh/100 km and 10–33 kWh/100 km, respectively; Table 1). This observation suggests that vehicle mass, which spans a similar range, could indeed be the most relevant factor for the energy consumption of electric cars.

E-bikes and electric kick scooters save more than 90% (around 17 kWh/100 km per vehicle) of the energy consumed by electric passenger cars; light four-wheelers still save around half (9 kWh/100 km per vehicle) of the energy consumed by cars. At a carbon intensity of 300 ± 230 g CO₂/kWh (mean of the European Union \pm standard deviation of country data; [36]), these savings decrease the indirect carbon emissions from electricity by 50 ± 39 g CO₂/km and 39 ± 21 g CO₂/km, respectively, per vehicle.

Regression analysis—all vehicle types

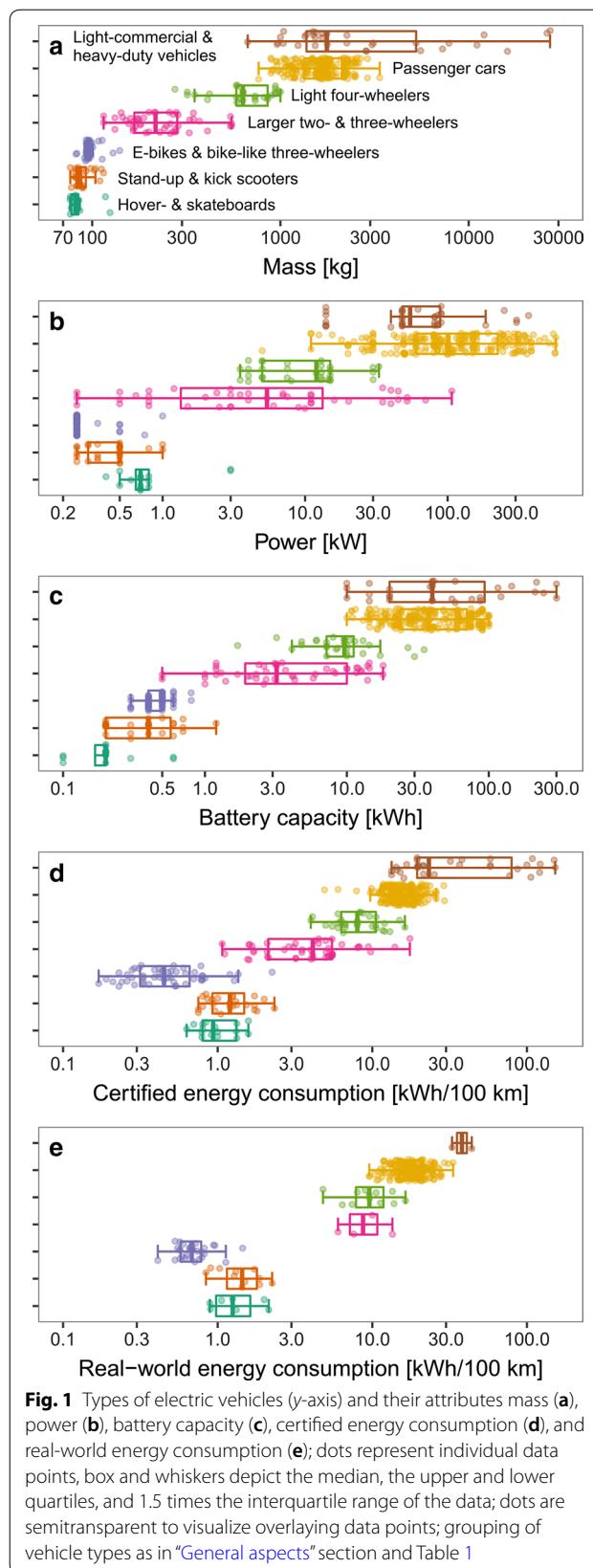
The bivariate regression Models 1 and 2 suggest mass and power are significant, each explaining 74% and 15% of the certified energy consumption and 81% and 40% of the real-world energy consumption of electric vehicles, respectively (5% significance level; Table 2; Fig. 2). Applying a log-transformation to variables increases the coefficients of determination, suggesting changes in mass and power can explain individually 89% and 84% of changes in certified energy consumption and 92% and 90%, respectively, of changes in real-world energy consumption (Models 4 and 5 in Table 2). Consistently, the bivariate models reveal a stronger relation of mass and power with

real-world energy consumption than with certified energy consumption. Overall, power appears to be less relevant than mass for the energy consumption of electric vehicles.

The explanatory power of the regression models increases, if we include year of market introduction and vehicle type as explanatory variables. Together, the four independent variables explain 93% and 84% of the certified and real-world energy consumption of electric vehicles, respectively (Model 3). Log-transforming variables increase the coefficients of determination to roughly 97% (Model 6; Table 2).

Considering all vehicle types, the multiple regression analysis indicates that:

- each 100 kg increase in vehicle mass increases certified and real-world energy consumption by 0.4 kWh/100 km and 0.6 kWh/100 km, respectively (linear Model 3); each doubling of mass increases certified and real-world energy consumption by 58% and 42%, respectively (power-law Model 6);
- rated vehicle power is weakly correlated with energy consumption; coefficients are not significant at a 5% level in Models 3 and 6 for certified energy consumption; Model 6 suggests each doubling of rated vehicle power increases the real-world energy consumption by 6%;
- despite overall high efficiencies, electric vehicles still become 0.8% and 1.0% more efficient each year during certification and real-world use, respectively (Model 6); under real-world conditions, their energy consumption has been decreasing by 0.1 kWh/100 km each year (linear Model 3; Table 2);
- vehicle types differ significantly in their energy consumption even after correcting for mass and power (Models 3 and 6 in Table 2); larger vehicles consume more energy than smaller ones; certified energy consumption of light vehicles (Types 0–3) increases more steeply with vehicle mass than the energy consumption of larger three–four-wheelers and passenger cars (Fig. 3).



The effect of vehicle attributes on energy consumption depends on whether certification or real-world operating conditions are considered and whether a linear or power-law relationship between variables is assumed. Vehicle mass has a larger effect on certified than on real-world energy consumption in the linear Model 3, while it is the other way around in the power-law Model 6. This observation suggests our findings are subject to uncertainty. The sensitivity analysis based on the median attribute values for each vehicle type confirms this expectation (Additional file 2: Table S3). Models 1 and 2 now yield high coefficients of determination. Given the small sample size of only 7 data points, the coefficients of the multiple regression Models 3 and 6 are not significant at a 5% level. Moreover, the sensitivity analysis (Additional file 2: Table S3) suggests:

- each 100 kg increase in vehicle mass increases certified and real-world energy consumption by 1.0 kWh/100 km and 1.3 kWh/100 km, respectively (Model 1; Additional file 2: Table S3), which is more than the 0.7 kWh/100 km and 0.9 kWh/100 km determined by Model 1 in Table 2; a doubling of vehicle mass roughly doubles energy consumption (108% and 96% increase in certified and real-world energy consumption, respectively (Model 4), which is consistent with the 102% and 99% previously observed by Model 4);
- power is un-correlated with energy consumption at the 5% significance level in Model 2 but there is a significant relationship in the power-law Model 5, suggesting each doubling of vehicle power leads to a 61% and 54% increase in certified and real-world energy consumption of electric vehicles;
- electric vehicles have not become significantly more efficient in recent years of their manufacturing.

Taken together, our regression analyses reveal that vehicle mass is the most important parameter for the energy consumption of electric vehicles. Each 100 kg vehicle mass increases the energy consumption by some 0.4–1.3 kWh/100 km, which is equivalent to 1.2 ± 0.9 – 3.8 ± 3.0 g CO₂/km of indirect emissions from electricity at a carbon intensity of 300 ± 230 g CO₂/kWh (mean of the European Union±standard deviation of country data; [36]).

Regression analysis—passenger cars

Passenger cars follow the same pattern as electric vehicles in general (Fig. 4). Table 4 in Appendix shows that:

- each 100 kg increase in vehicle mass increases both certified and real-world energy consumption by

Table 2 Summary statistics—regression analysis of certified and real-world energy consumption as function of vehicle attributes; significance at 1% level (*)^a, 5% level (**), and 10% level (*)^b; light commercial and heavy-duty vehicles are excluded from the regression analysis of real-world fuel consumption in Models 3 and 6 as sample size is insufficient; vehicle type 0: hover- and skateboards, type 1: stand-up and kick scooters, type 2: e-bikes, type 3: larger two- and three-wheelers, type 4: light four-wheelers, type 5: passenger cars, type 6: light commercial and heavy-duty vehicles**

Energy consumption	Coefficient	Value	Standard error	t value	Pr (>abs t)	p value	Adjusted R ²
<i>Model 1: energy consumption = $\alpha_1 + \beta_1 \text{mass}$</i>							
Certified	(Intercept)***	4.44	1.41	3.15	1.78e-03	<0.001	0.74
	Mass***	6.69e-03	1.26e-03	5.32	1.78e-07		
Real-world	(Intercept)***	2.26	0.39	5.87	1.42e-08	<0.001	0.81
	Mass***	9.32e-03	2.71e-04	34.43	8.01e-95		
<i>Model 2: energy consumption = $\alpha_2 + \beta_2 \text{power}$</i>							
Certified	(Intercept)***	8.22	0.73	11.21	1.35e-25	<0.001	0.15
	Power***	5.98e-02	1.10e-02	5.46	8.31e-08		
Real-world	(Intercept)***	9.91	0.63	15.82	3.53e-39	<0.001	0.40
	Power***	4.07e-02	3.52e-03	11.59	5.53e-25		
<i>Model 3: energy consumption = $\alpha_3 + \beta_3 \text{mass} + \beta_4 \text{power} + \beta_5 \text{year} + \beta_6 \text{type}$</i>							
Certified	(Intercept)*	141	75	1.89	5.95e-02	<0.001	0.93
	Mass***	4.43e-03	6.86e-04	6.45	4.43e-10		
	Power	2.19e-03	2.53e-03	0.87	0.39		
	Year	-6.98e-02	3.72e-02	-1.88	0.61		
	Type 1	0.44	0.48	0.39	0.35		
	Type 2	-0.32	0.43	-0.75	0.45		
	Type 3***	4.28	0.69	6.16	2.41e-09		
	Type 4***	4.88	0.66	7.37	1.73e-12		
	Type 5***	7.83	0.94	8.37	2.34e-12		
	Type 6***	14.92	1.82	8.20	7.38e-15		
Real-world	(Intercept)***	236	88	2.69	7.66e-03	<0.001	0.84
	Mass***	5.85e-03	9.07e-04	6.45	7.36e-10		
	Power	3.86e-03	2.80e-03	1.38	0.17		
	Year***	-0.12	4.38e-02	-2.68	8.01e-03		
	Type 1**	1.93	0.76	2.52	1.23e-02		
	Type 2	0.53	0.65	0.81	0.42		
	Type 3***	8.50	1.85	4.59	7.63e-06		
	Type 4***	5.86	1.12	5.24	3.89e-07		
	Type 5***	8.10	1.21	6.71	1.63e-07		
	<i>Model 4: log(energy consumption) = $\alpha_4 + \beta_7 \log(\text{mass})$</i>						
log(Certified)	(Intercept)***	-4.75	0.17	-28.05	2.84e-95	<0.001	0.89
	log(Mass)***	1.02	2.34e-02	43.68	1.18e-151		
log(Real-world)	(Intercept)***	-4.46	0.18	-24.28	1.37e-66	<0.001	0.92
	log(Mass)***	0.99	2.49e-02	39.91	6.18e-108		
<i>Model 5: log(energy consumption) = $\alpha_5 + \beta_8 \log(\text{power})$</i>							
log(Certified)	(Intercept)***	0.43	4.55e-02	9.42	3.38e-19	<0.001	0.84
	log(Power)***	0.52	1.22e-02	42.74	2.24e-152		
log(Real-world)	(Intercept)***	0.64	4.95e-02	12.88	3.01e-29	<0.001	0.90
	log(Power)***	0.48	1.06e-02	44.92	2.19e-119		

Table 2 (continued)

Energy consumption	Coefficient	Value	Standard error	t value	Pr (> abs t)	p value	Adjusted R ²
<i>Model 6: log(energy consumption) = $\alpha_0 + \beta_9 \log(\text{mass}) + \beta_{10} \log(\text{power}) + \beta_{11} \text{year} + \beta_{12} \text{type}$</i>							
log(Certified)	(Intercept)*	13.41	5.98	2.24	2.56e-02	<0.001	0.97
	log(Mass)***	0.58	7.04e-02	8.23	5.93e-15		
	log(Power)	4.78e-02	3.07e-02	1.56	0.12		
	Year***	-7.90e-03	2.94e-03	-2.69	7.64e-03		
	Type 1	-5.21e-02	0.12	-0.42	0.67		
	Type 2***	-1.15	9.86e-02	-11.70	2.89e-26		
	Type 3***	0.80	8.08e-02	9.86	4.85e-20		
	Type 4***	0.70	0.11	6.67	1.22e-10		
	Type 5***	0.74	0.12	6.32	9.64e-10		
	Type 6***	1.13	0.15	7.35	1.98e-12		
log(Real-world)	(Intercept)***	18.08	5.88	3.08	2.36e-03	<0.001	0.97
	log(Mass)***	0.42	8.62e-02	4.92	1.74e-06		
	log(Power)***	6.06e-02	2.18e-02	2.78	5.96e-03		
	Year***	9.72e-03	2.92e-03	-3.33	1.02e-03		
	Type 1	0.29	0.24	1.23	0.22		
	Type 2***	-0.70	8.41e-02	-8.35	8.15e-15		
	Type 3***	1.21	0.24	5.04	1.00e-06		
	Type 4***	0.85	0.19	4.57	8.28e-06		
	Type 5***	0.97	0.18	5.48	1.17e-07		

0.6 kWh/100 km (linear Model 3); a doubling of vehicle mass leads to a 60% and 46% increase in the certified and real-world energy consumption of electric cars, respectively (power-law Model 6);

- power does generally not affect energy consumption at a 5% level of significance; an exception is real-world energy consumption that tends to increase 6% with each doubling of vehicle power according to Model 6;
- over the years, electric passenger cars have not become more efficient during certification; however, their real-world energy consumption appears to decrease on average by 0.1 kWh/100 km (linear Model 3) or 1% (power-law Model 6) each manufacturing year.

Modern mass-produced and purpose-designed electric cars consume under real-world conditions on the road 2.1 ± 0.8 kWh/100 km less energy than the first-generation electric cars produced at small scale based on chassis component of conventional cars (Fig. 5). This observation and the large spread of consumption values for cars of similar mass suggests scope for future efficiency improvements. As batteries are relatively heavy, such improvements could be attained by simply decreasing battery size and the drive range of vehicles (Fig. 6, Additional file 2: Table S2). We find that each 10 kWh of battery capacity increases vehicle mass

by 15 kg, drive range by 40–50 km, and energy consumption by 0.7–1.0 kWh/100 km (Fig. 6, Additional file 2: Table S2).

A visual breakdown of certified and real-world energy consumption of passenger cars for several countries reveals that in China, real-world energy consumption scatters around certified values; whereas in Germany, Norway, and the USA, electric cars tend to consume more energy on the road than during certification (Fig. 7).

Discussion

Strengths and limitations

We compile a comprehensive dataset of vehicle attributes for the major types of electric road vehicles (Additional file 2: Table S1). Our analysis reveals: (i) large mass-related efficiency trade-offs that could be tapped by mode shift from passenger cars to light electric vehicles and (ii) scope for improving the already high energy efficiency of electric passenger cars, which could be exploited through dedicated energy labeling. The results provide climate, energy, and transport policy with rationale for shaping the transition towards a sustainable transport system. Our findings are robust, albeit subject to several limitations.

First, vehicle types are not equally represented in our dataset. Passenger cars alone account for half of all data points (Table 1). This sampling bias introduces an error,

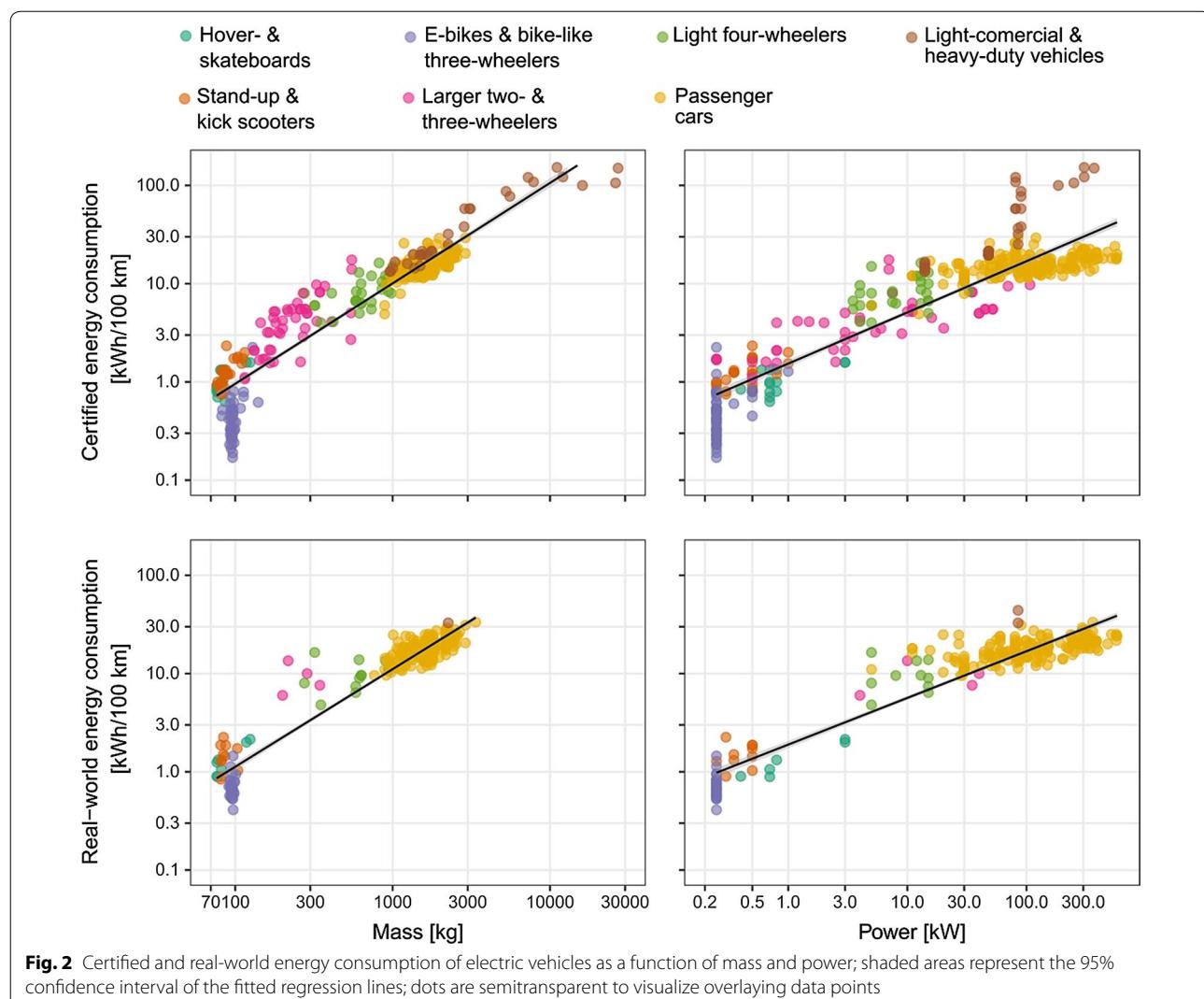


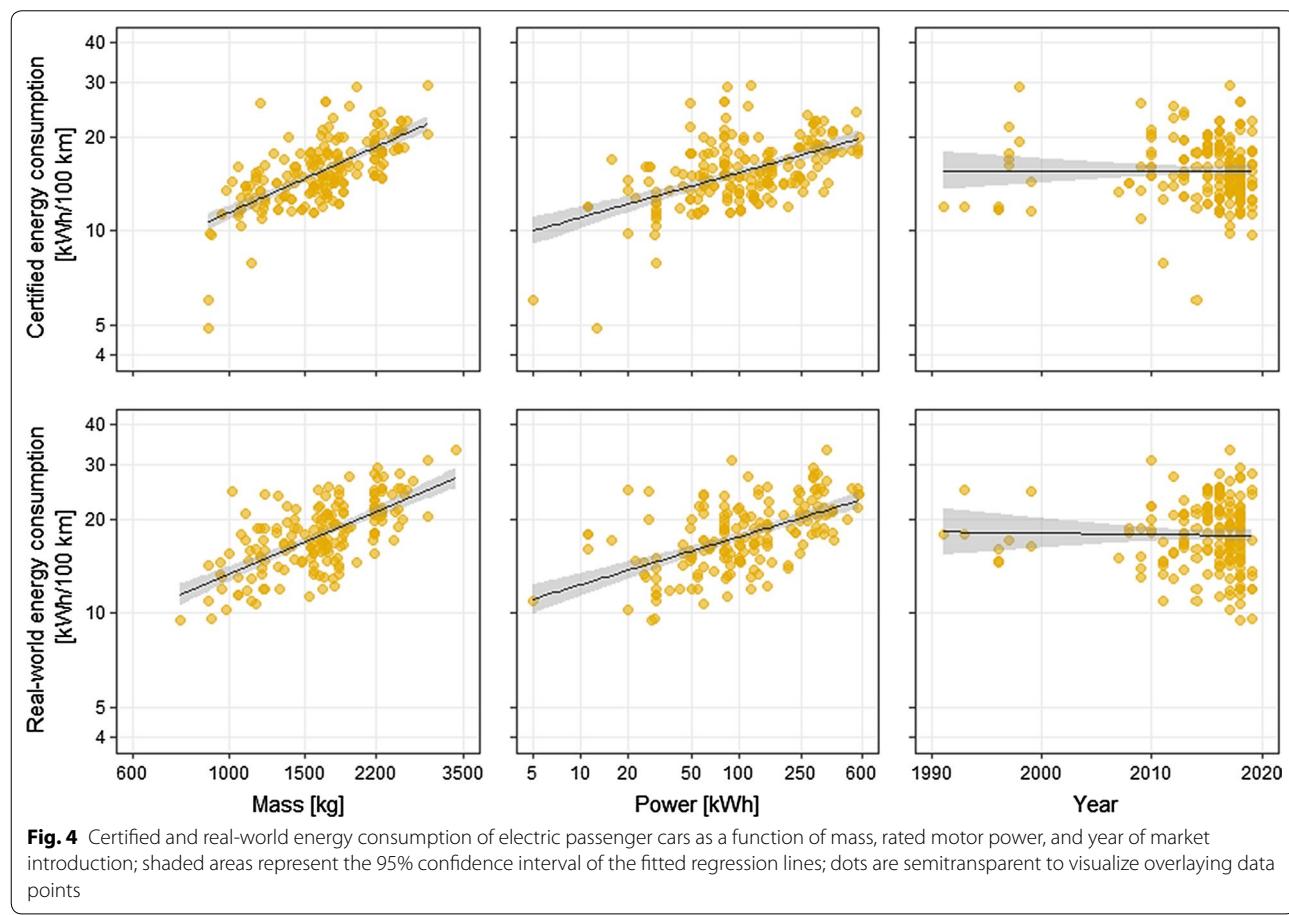
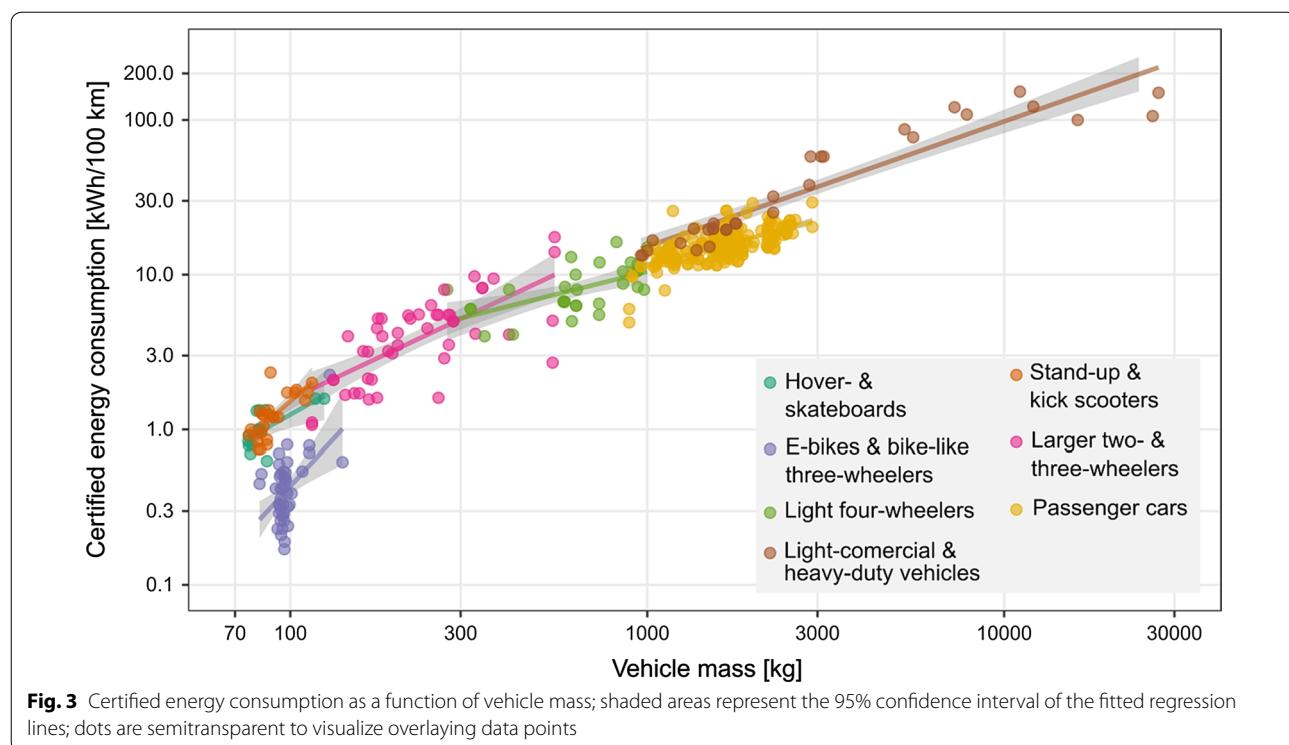
Fig. 2 Certified and real-world energy consumption of electric vehicles as a function of mass and power; shaded areas represent the 95% confidence interval of the fitted regression lines; dots are semitransparent to visualize overlaying data points

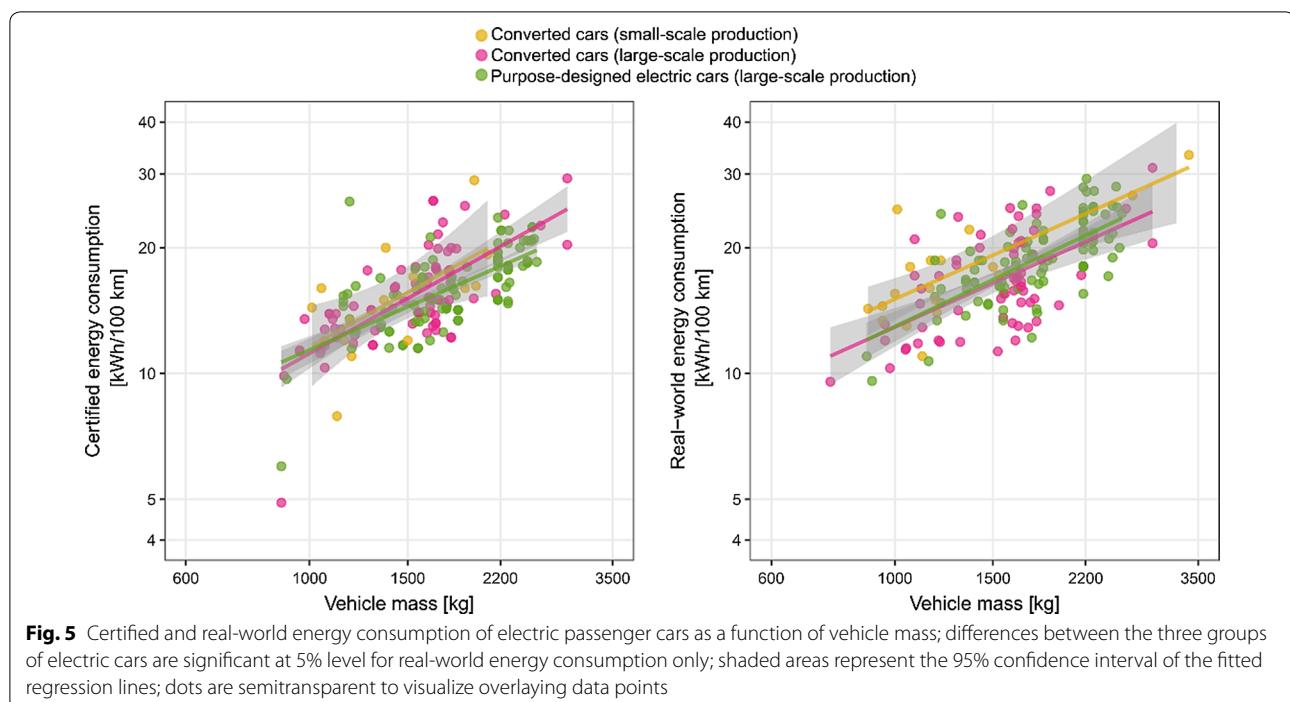
which is not negligible as the sensitivity analysis suggests. We, therefore, regard the actual relationships of parameters to be in range of—but not necessarily identical with—the coefficients of our regression models (Table 2 and Additional file 2: Table S3).

Second, real-world energy consumption reflects the actual operating conditions of vehicles but may neither captures average vehicle use nor the specific operating conditions of any individual vehicle user. Variability in real-world and declared energy consumption is particularly large for e-bikes, likely owing to modulating torque (typically ranging between 40 and 100 Nm [39]) and thus power requirements.

Third, assuming a generic driver of 70 kg introduces a random error into our results, which is large for lightweight vehicles such as e-bikes and kick scooters for which the driver's mass exceeds the mass of the vehicle.

Fourth, regression models are only robust if residuals are randomly distributed along the value range of independent variables and if explanatory variables are unrelated with each other. Both requirements are only partially met in our analysis. The diagnostic plots in Additional file 2: Figures S1–S16 suggest residuals are heteroscedastic. They appear to be clustered and not normally distributed, which is likely the result of large variability in the energy consumption of e-bikes. For passenger cars, residuals appear to scatter randomly along the range of fitted values. We address heteroscedasticity, as far as feasible, by estimating heteroscedasticity-robust standard errors for all regression coefficients [37]. Collinearity is tested for by estimating variance inflation factors (VIF) for Models 3 and 6. For Model 3, the VIF is smaller than five for certified energy consumption, which can be interpreted as unproblematic collinearity [40]. The same applies to Models 3 and 6 for passenger cars.





But for real-world energy consumption (linear Model 3) and both certified and real-world energy consumption (power-law Model 6), VIFs reach up to 15, indicating strong collinearity. Therefore, we test the robustness of Models 3 and 6 in a stepwise regression. In this analysis, power and vehicle type are excluded from the regression models and regressed separately against the residuals of the adapted Models 3 and 6. For Model 3, the residuals are uncorrelated with vehicle power at a 5% significance level. For Model 6, however, residuals are correlated with power and vehicle type. Excluding both variables from the adapted Model 6 suggests a doubling of vehicle mass leads to a 108% and 104% increase in certified and real-world energy consumption, respectively. These values are higher than our original findings in Model 6 (Table 2) but they are consistent with the univariate power-law Model 4 and the results of the sensitivity analysis (see Model 4 in Additional file 2: Table S3). We, therefore, regard the value range of 60–110% and 40–100% as indicated by Models 4 and 6 to be indicative of the increase in certified and real-world fuel consumption across all types of electric vehicles with each doubling of vehicle mass.

Finally, the coefficients of determination for Models 4–6 (Table 2) suggest energy consumption is best modeled as a power-law rather than a linear function of mass, specifically when value ranges are large and several vehicle types are covered in the analysis. If vehicle attributes vary little, then the linear model provides a reasonable approximation of parameter relationships as

a comparison of Models 3 and 6 for passenger cars suggests (Table 4).

Comparison of findings

Our findings are broadly in line with previous studies and add insight into the trade-offs between the various attributes of electric vehicles. The observation that the energy consumption of electric passenger cars increases by 0.6 kWh/100 km with each 100 kg vehicle mass is broadly consistent with the 0.4 kWh/100 km modeled by Redelbach et al. [41]. Likewise, the observed 46–60% increase in energy consumption with each doubling of vehicle mass is consistent the 34–42% increase with each doubling of vehicle mass observed by Carlson et al. [42].

The observation that the energy consumption of electric passenger cars is closely related to vehicle mass but less so to rated motor power contrasts findings for conventional passenger cars, for which power is an important, if not the most important, driver of fuel consumption: Each doubling of rated engine power tends to increase fuel consumption by around 30–50% [19, 21]. A 10 kW increase in rated engine power raises the fuel consumption by 0.3 l/100 km in compact gasoline cars and 0.2 l/100 km in compact diesel cars [23].

Electric cars only become marginally more efficient with time, mainly under real-world driving conditions on the road. By contrast, conventional passenger cars have been showing considerable efficiency improvements in the past, both during certification and

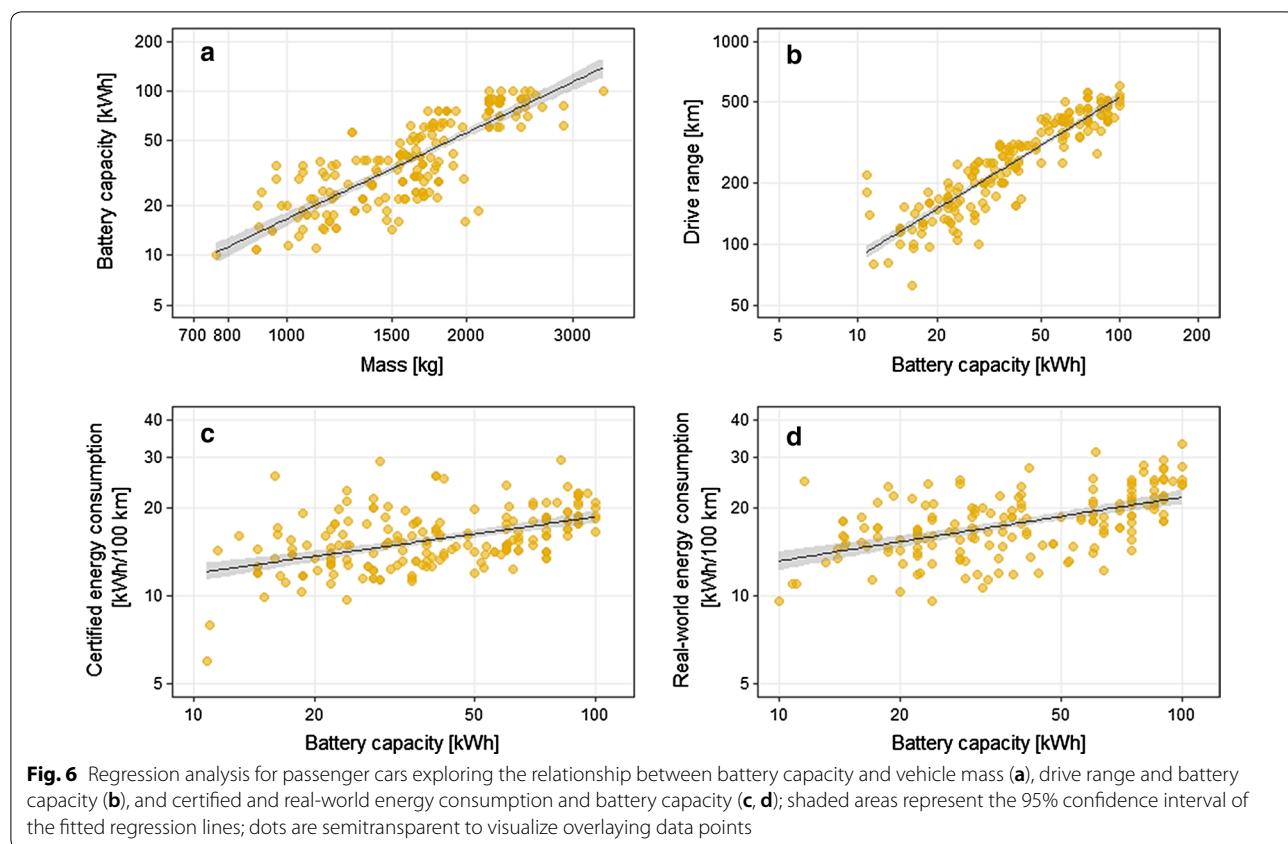


Fig. 6 Regression analysis for passenger cars exploring the relationship between battery capacity and vehicle mass (**a**), drive range and battery capacity (**b**), and certified and real-world energy consumption and battery capacity (**c**, **d**); shaded areas represent the 95% confidence interval of the fitted regression lines; dots are semitransparent to visualize overlaying data points

real-world driving [19, 23]. The differences between electric and conventional cars could be attributed to at least three factors:

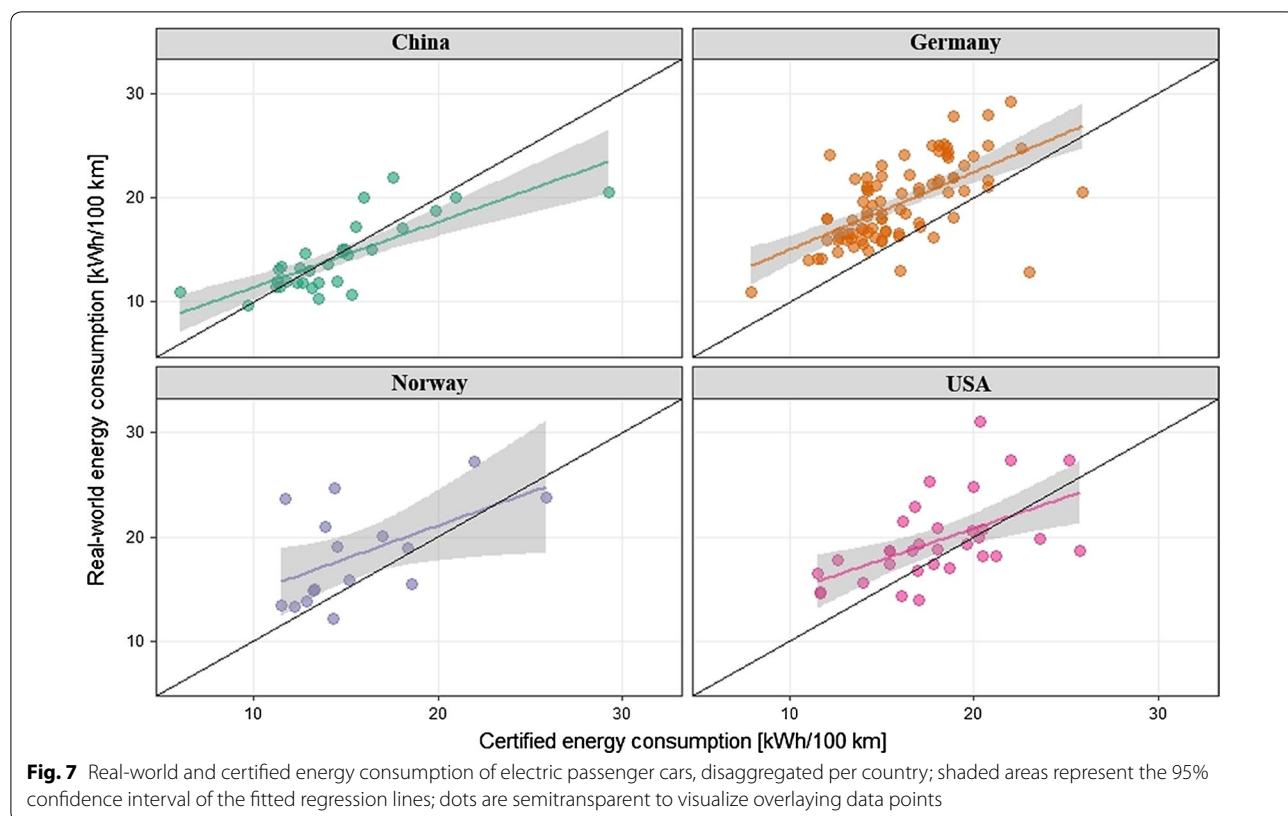
- Electric motors have a higher tank-to-wheel efficiency (73–90%) than internal combustion engines (16–37%) over all relevant engine loads and speeds [12, 13].
- Electric vehicles recuperate their kinetic energy through regenerative braking, whereas conventional vehicles do not. With energy recuperation, power and related accelerations become less relevant for energy consumption than rolling resistance and aerodynamic drag—the former being directly proportional to vehicle mass, the latter being proportional to front area and increasing with vehicle speed squared.
- Electric motors do not generate idling losses, which are proportional to displacement and rated power in naturally aspirated internal combustion engines. The energy consumption of an electric motor is, therefore, largely dependent on its *instantaneous power* output rather than its *maximum rated power*.

Together, these factors influence the energy consumption of passenger cars during certification and real-world

driving. Under real-world conditions, the energy consumption varies, moreover, depending on the actual operating conditions. Part of the low dependency of energy consumption on rated motor power in electric cars could then result from drivers who do not exploit the full acceleration and speed potential of their vehicles [43] to preserve still limited drive range. Nevertheless, occasional high-load motor operations during high speeds and uphill driving specifically for larger and comparatively powerful cars may explain why real-world energy consumption in passenger cars is more closely related to rated motor power than is certified energy consumption.

Implications for policy makers and vehicle manufacturers

Our findings have four major implications. First, the strong relationship between energy consumption and vehicle mass suggests mode shift from electric passenger cars to light electric vehicles can decrease the energy consumption of road transport. The technical characteristics of electric powertrains facilitate such shifts as the market success of electric kick scooters, e-bikes, and light three-wheelers (e.g., [44]) suggests. In urban areas, light electric vehicles can increase travel speed, mitigate ambient air and noise pollution, and decrease the direct CO₂ emissions of individual vehicles. Mode shift towards light



electric vehicles would also decrease demand for road infrastructure, which in turn opens new opportunities to revitalize cities and make them resilient to climate change by mitigating heat-island effects through enlarged vegetation areas [45, 46]). Other merits of mode shift include lower investment needs for recharging infrastructure—light vehicles can be charged with standard wall outlets in buildings—and decreased material and energy requirements (per vehicle) for manufacturing.

But challenges remain. Mode shift away from passenger cars is not straightforward but requires a broader strategy to provide adequate infrastructure, strengthen inter-operability with other transport modes including public transport, and facilitate innovative mobility solutions around vehicle sharing and renting services. Users of light vehicles are vulnerable in case of accidents [47], which may require updated vehicle certification schemes, traffic rules, and safety regulation before light electric vehicles may realize their full market potential [48].

Second, large variability in the energy consumption of passenger cars with a similar mass (Figs. 3 and 4) suggests there is scope for further efficiency improvements, e.g., through purpose design, wheel-hub motors, improved energy recuperation, decreased coasting resistance, and the application of light-weight chassis components [49]. These

potentials could be tapped by introducing minimum efficiency requirements or a dedicated energy label that classifies vehicles according to their energy efficiency. If done, our findings caution against the use of vehicle mass as a utility factor to normalize energy consumption—as it is implemented for the fleet average CO₂ emissions target of conventional passenger cars [50]. Ideally, a label on efficiency would directly classify efficiency, that is, distance-specific energy consumption of electric vehicles (kWh/100 km; km/kWh). However, this way efficiency improvements could be achieved by curbing vehicle mass through a small battery, which in turn may impair vehicle utility. If policy makers prefer to use a utility factor to classify energy efficiency, battery capacity could be a suitable choice. Normalizing energy consumption by battery capacity would force both efficiency improvements of vehicles and increasing energy densities of batteries. Our study suggests the real-world energy consumption of electric passenger cars E (kWh/100 km) is related to battery capacity c (kWh) (coefficient of determination 0.34) as follows:

$$E = (0.09 \pm 0.01)c + (14 \pm 1).$$

Future research could expand the analysis (Additional file 1: Table S1) towards a concrete proposal for an efficiency label. Research could also investigate whether

there is scope for implementing energy labels to other types of electric vehicles.

Third, our findings suggest the current certification procedure of electric passenger cars in Europe may underestimate the real-world energy consumption (Fig. 7). If future research confirms systematic artifacts in the certification test, policy makers should consider adapting test procedures to ensure consumers are accurately informed about the energy consumption of vehicles when deciding about a purchase.

Fourth, electromobility is still in its infancy and rapid technological learning will likely improve cost competitiveness [51–53] and technical features, including the efficiency of battery charging [54]. Already to date, however, expensive high-power vehicles offer marketing opportunities that manufacturers began to exploit. If rated motor power is less important for the energy consumption in electric cars than in conventional ones, electric cars with high motor power, torque, and unmatched acceleration capabilities have a competitive edge over their conventional counterparts. If so, a superior driving performance may turn the high price of electric cars [51, 53] into a status symbol (as it is the case of conventional sports cars), transforming a market barrier into a purchase argument for status seeking consumers.

Conclusions

We draw the following conclusions:

- The energy consumption of electric vehicles is strongly related to vehicle mass but less so to rated power and the year a vehicle entered the market. Given the high overall efficiency of electric motors, electric vehicles become only marginally more efficient with time.
- Assuming a linear relationship between vehicle attributes suggests each 100 kg vehicle mass increases energy consumption by some 0.4–1.3 kWh/100 km, which is equivalent to 1.2 ± 0.9 – 3.8 ± 3.0 g CO₂/km of indirect carbon emissions at the current European electricity mix. Mode shift to e-bikes and kick scooters can save more than 90% (around 17 kWh/100 km per vehicle) of the ‘tank-to-wheel’ energy consumption of passenger cars; mode shift to light three- and four-wheelers can still save half of the energy consumed by electric passenger cars (9 kWh/100 km per vehicle). Climate and transport policy could support mode shift through dedicated road and recharging infrastructure, giving priority to small and light-weight electric two-four-wheelers and bicycles in urban environments.
- The energy consumption of electric passenger cars (kWh/100 km) scatters over a wide range even for vehicles of similar mass (e.g., 10–15 kWh/100 km for cars of 2000 kg; Fig. 4). This finding suggests there

is scope for efficiency improvements that could be exploited by a dedicated energy label. To this end, the prospects of using battery capacity as a utility factor should be explored.

- The weak statistical relationship between energy consumption and rated motor power implies electric cars can be positioned on the market as high-power, status revealing vehicles. Such marketing strategy would turn the high price of electric passenger cars into a sales argument for status seeking consumers. On the other hand, large high-power electric vehicles usually come with a higher vehicle mass and thus resources consumption.
- This article covers energy consumption in the use phase of electric vehicles only. The environmental costs and benefits of the electrification of road transport, however, require a holistic perspective and should be investigated by comprehensive life cycle assessments.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s12302-020-00307-8>.

Additional file 1: Table S1. Data of vehicle attributes.

Additional file 2: Additional Figures S1–S36, Tables S2, S3.

Abbreviations

g: Gram; kg: Kilogram; km: Kilometer; kW: Kilowatt; kWh: Kilowatt-hour; m: Meter; SD: Standard deviation.

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Authors' contributions

EH and MW conceived the original idea. KCC collected the data. KCC and MW analyzed the data. EH and MW wrote the manuscript. All authors read and approved the final manuscript.

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Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Appendix

See Tables 3 and 4.

Table 3 Electric vehicle types covered in our analysis

Vehicle type: name	Description	Definition (examples)
Type 0: Skate-board	Vehicles without a handlebar	"A flat, narrow board with two small wheels under each end, which a person stands on and moves forward by pushing one foot on the ground" (http://www.dictionary.cambridge.org)
Type 0: Hover-board, E-board		"A motorized personal vehicle consisting of a platform for the feet mounted on two wheels and controlled by the way the rider distributes the weight" (http://www.lexico.com)
Type 1: Stand-up scooter	Vehicles with a handlebar	As, e.g., a Segway
Type 1: Kick scooter (e-scooter)		"A kick scooter, push scooter or scooter, is a land vehicle with a handlebar, deck and wheels that is propelled by a rider pushing off the ground" (after http://wwwdefinitions.net)
Type 2: E-bike	Bicycle similar vehicles that can be operated alternatively without the electric engine.	An electrified bicycle
Type 2: Bike-like three- and four-wheeler		As, e.g., cargo- or freight bicycles including small bicycle-like three- and four-wheelers, electric rickshaws
Type 3: Larger two- and three-wheeler		Step-through scooters, mopeds, motorcycles, and larger three-wheelers (e.g., electrified Tuk Tuks) L1e – L5e vehicles ^a
Type 4: light four-wheeler		As, e.g., a Renault Twizy L6e + L7e vehicles ^a
Type 5: Passenger car		As, e.g., a Tesla M1 vehicles ^a (plug-in hybrid electric vehicles not covered)
Type 6: Light commercial vehicle, heavy-duty truck		As, e.g., a Streetscooter (http://wwwstreetscooter.com/en/) N1-3 vehicles ^a

^a Vehicle classes according to EU regulation [27, 26])

Table 4 Summary statistics—multiple regression analysis of certified and real-word energy consumption of passenger cars as a function of vehicle attributes; significance at 1% level (***)¹, 5% level (**), and 10% level (*)

Energy consumption	Coefficient	Value	Standard error	t value	Pr (> abs t)	p value	Adjusted R ²
<i>Model 3: energy consumption = $\alpha_3 + \beta_3 mass + \beta_4 power + \beta_5 year$</i>							
Certified	(Intercept)	113	101	1.12	0.27	<0.001	0.43
	Mass***	6.40e-03	8.65e-04	7.40	4.00e-12		
	Power	-4.02e-03	2.80e-03	-1.43	0.15		
	Year	-5.33e-02	5.02e-02	-1.06	0.29		
Real-world	(Intercept)**	268	112	2.39	1.81e-02	<0.001	0.47
	Mass***	5.89e-03	9.14e-04	6.45	1.08e-09		
	Power	3.87e-03	2.81e-03	1.38	0.17		
	Year**	-0.13	5.58e-02	-2.32	2.18e-02		
<i>Model 6: log(energy consumption) = $\alpha_6 + \beta_9 log(mass) + \beta_{10} log(power) + \beta_{11} year$</i>							
log(Certified)	(Intercept)	4.15	6.70	0.62	0.54	<0.001	0.45
	log(Mass)***	0.60	8.00e-02	7.47	2.69e-12		
	log(Power)	-3.99e-03	2.94e-02	-0.14	0.89		
	Year	-2.88e-03	3.24e-03	-0.89	0.37		
log(Real-world)	(Intercept)**	19	7	2.57	1.10e-02	<0.001	0.47
	log(Mass)***	0.46	7.78e-02	5.97	1.33e-08		
	log(Power)***	5.92e-02	2.27e-02	2.61	9.90e-03		
	Year***	-9.97e-03	3.65e-03	-2.73	7.02e-03		

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