Electric Vehicle Efficiency Ratios for Light-Duty Vehicles Registered in the United States

Mark Singer, Caley Johnson, Edward Rose, Erin Nobler, and Luna Hoopes

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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List of Acronyms

2WD	two-wheel drive
4WD	four-wheel drive
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
BEV	battery-electric vehicle
CARB	California Air Resources Board
EER	energy efficiency ratio
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
EVER	electric vehicle efficiency ratio
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HDV	heavy-duty vehicle
ICE	internal combustion engine
LDV	light-duty vehicle
MPG	miles per gallon
MPGE	miles per gallon equivalent

Executive Summary

Electric vehicles (EVs) use energy more efficiently than gasoline vehicles, a primary attribute enabling other benefits such as improved torque and reduced operating costs and greenhouse gas emissions. An electric vehicle efficiency ratio (EVER)—representing the distance a given amount of energy propels an EV divided by the distance it propels a gasoline vehicle—is therefore important when calculating the financial and environmental benefits of EVs. Researchers have been indirectly estimating EVERs since at least 2007, but most of these estimates came from small fleets or vehicle simulators. This paper improves upon these estimates by calculating the EVER for all 2021 light-duty vehicles registered in the United States, pairing extensive data sets from the U.S. Department of Energy's Fuel Economy Guide, Environmental Protection Agency (EPA) vehicle testing, and Experian vehicle registration. The analysis also benchmarked EVERs across various vehicle classes, drive systems, drive cycles, and horsepower-to-weight ratios. The overall EVER in the United States was calculated as 4.4, meaning that the average EV travels 4.4 times farther on a given amount of energy than the average gasoline vehicle. This ratio is greater (5.1) in EPA city testing, largely due to regenerative braking, and less (3.6) in highway testing. The EVER is also greater in four-wheel-drive vehicles and vehicles with a high power-to-weight ratio. This information is valuable to scientists modeling the environmental and economic benefits of EVs, drivers and fleet managers assessing the benefits of EVs, and policymakers incentivizing EV purchases in the most beneficial market sectors.

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1 Introduction

1.1 The Need for and Uses of an Electric Vehicle Efficiency Ratio

Electric vehicles (EVs) use energy more efficiently than gasoline vehicles. This is one of their primary attributes, enabling other benefits such as improved torque and reduced operating costs and greenhouse gas emissions. An electric vehicle efficiency ratio (EVER) is therefore important when calculating the financial and environmental benefits of EVs,[1] calculating the impact that EVs have on a manufacturer's Corporate Average Fuel Economy rating (DOE 2021), calculating credits in trading schemes such as California's Low Carbon Fuel Standard (CARB 2022), fuel price leveling, designing electricity tariffs from utility-owned public charging infrastructure (Florida Public Service Commission 2020), creating EV alternatives to gasoline excise taxes, and more.

The first step in quantifying the EVER is establishing its definition and equation. The EVER is the ratio of energy (in joules or British thermal units [Btu]) used to power a gasoline vehicle over a given drive cycle divided by the energy used to power an EV over that same drive cycle. Therefore, larger EVERs imply greater efficiency advantages of EVs. Drive cycles are always the same distance and aim to represent a fleet drive cycle or typical driving conditions in a given country or region. This study uses the U.S. Environmental Protection Agency (EPA) established combination of five adjusted test cycles to calculate EVERs, per Equation 1. The miles per gallon equivalent (MPGE) ratings that EPA gives gasoline and electric vehicles on fuel economy labels and in the Fuel Economy Guide (FEG) can be used as a shortcut to calculate EVERs, as described in Equation 2.

$$\text{EVER} = \frac{\left(\frac{1\ gal\ gas}{X\ \text{"}miles\ per\ gal\ gas\text{"}}\right)\left(\frac{115{,}000\ Btu}{1\ gal\ gas}\right)}{\left(\frac{Y\ \text{"}kWh\ per\ 100\ miles\text{"}}{100\ miles}\right)\left(\frac{3{,}412\ Btu}{1\ kWh}\right)}$$

Equation 1. EVER over a given drive cycle, where *X* is the rated miles per gallon (MPG) and *Y* is the rated kilowatt-hours (kWh) per 100-mile efficiency[2,3]

$$\text{EVER} = \frac{\text{MPGE of EV}}{\text{MPG of gasoline vehicle}}$$

Equation 2. EVER using EPA's MPGE ratings

[1] The Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool uses EVER to estimate the return on investment of EVs, and the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model uses EVER to estimate the life cycle greenhouse gas benefits of EVs.

[2] Lower heating values come from the *Federal Register* 10 CFR 474 and are used by EPA in fuel economy calculations.

[3] Battery-electric vehicle efficiency ratings in both calculations assume AC charging. Adjustments would be needed to account for DC fast chargers.

1.2 Previous EVERs and How They Were Derived

Researchers have been indirectly estimating EVERs since at least 2007 to better capture the efficiency benefits of electric vehicles. These past estimates vary widely in vehicle type, sample size, and other fundamental methodologies. Most of these studies did not calculate an EVER, but rather reported the efficiency of both EVs and conventional vehicles and allowed us to do the final calculation of the EVER.

1.2.1 California Air Resources Board Energy Efficiency Ratio

The California Air Resources Board (CARB) first derived an energy efficiency ratio (EER) in 2007 (CARB 2018). CARB based this study on a small sample size of battery-electric trucks compared to diesel trucks and found the EER to be 2.7. In 2018 (CARB 2018), CARB updated the original 2007 EER by including in-use test data on non-standardized drive cycles for 40-foot transit buses, Class 8 drayage trucks, and parcel delivery trucks. The EERs showed a statistically significant inverse correlation with average drive cycle speed, meaning that slower drive cycles with more stopping and idling provided EVs with a greater advantage, as shown by a larger EER. The overall average EER for this 2018 study was 4.2—a significant increase from the 2007 study.

1.2.2 Intergovernmental Panel on Climate Change

In their 2014 report *Climate Change 2014: Mitigation of Climate Change*, the Intergovernmental Panel on Climate Change included the following information on battery-electric vehicle (BEV) efficiency: "BEVs operate at a drive-train efficiency of around 80% compared with about 20–35% for conventional ICE [internal combustion engine] LDVs [light-duty vehicles]" (Sims et al. 2014). No further information is given regarding vehicle type or methodology used to arrive at these figures. These percentages are comparable to those found on the U.S. Department of Energy's fueleconomy.gov website, and when converted, show an efficiency ratio between 2.3 and 4.

1.2.3 U.S. Department of Energy's Fueleconomy.gov Vehicle Energy Efficiency

The U.S. Department of Energy's fueleconomy.gov website (DOE 2022) provides information on energy losses for ICE vehicles and BEVs. The ICE vehicle type loses 64% to 75% of energy compared to the BEV, which loses 15% to 20% of energy while operating. These percentages were derived from comparing common conventional gasoline engines to similar electric vehicles based on test data from the EPA vehicle database (Thomas et al. 2014). It did not, however, systematically account for the ICE models that can be categorized with given EVs or weight those models according to sales. While not initially calculated as a ratio, when converted, these bookend energy loss percentages show an EVER of 3.75 to 4.20.

1.2.4 Electric and Conventional Vehicle Performance Over Baseline and Eco-Driving Cycles

In 2019, Gao and LaClair (2019) evaluated the effectiveness of eco-driving on energy consumption of BEVs and conventional vehicles. The evaluation is based on modeling a compact light-duty vehicle (based on the Nissan Leaf) and a Class 7 delivery truck. The authors developed these models and aligned them with the Autonomie tool[4]. Although the study focused

[4] https://www.anl.gov/taps/autonomie-vehicle-system-simulation-tool

on eco-driving, the researchers derived baseline efficiencies for both the EV and ICE versions of the LDV and the heavy-duty vehicle (HDV). These baselines covered a mix of city and highway drive cycles under "normal" operating conditions. From their baseline efficiency numbers, we can calculate that their EVER for LDVs was 707 Wh/km ÷ 147 Wh/km = 4.8, and their EVER for HDVs was 3,320 Wh/km ÷ 1,370 Wh/km = 2.4. The study concluded that eco-driving has a high potential to reduce energy consumption.

1.2.5 Electric Vehicle Efficiency Factor Used in AFLEET/GREET Models

The EVER is an essential part of the environmental and economic calculations used in Argonne National Laboratory's GREET and AFLEET models. Therefore, researchers at Argonne used the Autonomie model to calculate an EVER based on a hypothetical electric vehicle acting as a direct counterpart to gasoline vehicle test data.[5] Based on this vehicle system simulation tool, Argonne derived an EVER of 4.37 for EV passenger cars with 100-mile ranges and 3.93 for EVs with 300-mile ranges. Argonne uses these as default input values for their GREET and AFLEET models.

1.2.6 Methodologies Developed by Argonne and EPA

Two studies helped lay the groundwork for sales-weighted vehicle efficiency without calculating an EVER. Gohlke and Zhou (2021) determined that the average new BEV sold in 2020, when accounting for model variants in 21 states, had an efficiency of 29.4 kWh/100 miles. EPA (2022) estimated that the fuel economy for the average sales-weighted model year 2020 vehicle was 25.4 MPG. The studies show that average efficiency is improving for both BEVs and conventional vehicles. Calculating the EVER from these combined reports would be 4.5, which is helpful for validation purposes. However, this number should not be used as an established EVER due to the differing methodologies and the fact that EPA's fuel economy includes vehicles powered by fuels other than gasoline. Nevertheless, both studies provide value by developing methods of categorizing, tracking, and weighting the fuel economy of vehicles at the variant level.

1.2.7 Literature Review Summary

Table 1 shows that previous EVERs have been derived with values between 2.7 and 4.8, with lower estimates for HDVs and higher for LDVs. Over time, the estimates have been increasing—largely due to improving EV technologies. However, these studies have largely been reliant on two methodologies: (1) comparisons of small fleets without standardized drive cycles and (2) simulations of single vehicle models compared to identical, hypothetical vehicles with a different powertrain. These methodologies can provide adequate apples-to-apples comparisons for specific vehicles and drive cycles. However, current vehicle offerings and consumer tastes don't allow for such an apples-to-apples comparison. In reality, the EVs that are manufactured and purchased are not identical to their gasoline counterparts.

[5] Per documentation in the AFLEET 2020, Background Data tab

Table 1. Summary of Previous Studies and Their EVERs

Source	Year	Vehicles	EVER	Methodology
CARB	2007	HDV trucks	2.7	Test data of battery-electric trucks vs. diesel trucks
Intergovernmental Panel on Climate Change	2014	LDVs	2.3–4	Unknown
Fueleconomy.gov	2014–2016	LDVs	3.75–4.2	EPA test data comparisons of single models
CARB	2018	HDVs	4.2	Test data of electric vs. diesel Class 8 drayage, 40-foot transit buses, and parcel delivery trucks
Gao and LaClair	2019	LDVs and HDVs	4.8 LDV 2.4 HDV	Simulated comparison of compact LDVs and Class 7 delivery trucks
GREET and AFLEET models	2020	LDVs (EVs with 100- and 300-mile ranges)	4.37 (100-mi range) and 3.93 (300-mi range)	Simulated comparison of ICE vs. hypothetical EV counterpart in Autonomie

2 Methodology

2.1 Calculations, Assumptions, and Conversion Factors

This study aims to go beyond the current set of studies by accounting for actual vehicle availability and consumer preference. It does this by comparing the EPA-rated efficiencies of categories of ICE vehicles with those of available EV models within the same categories. It accounts for consumer preference by weighting these results by the number of vehicle registrations. Finally, it compares the city and highway fuel economy ratings within these categories to document the impact of drive cycle on the EVERs of these vehicle categories.

As described in Section 1.1, the EVERs calculated in this study are based on the EPA-established city and highway fuel economy ratings, which are publicly available on the FEG website fueleconomy.gov (DOE 2022). Each reported EVER is calculated via Equation 2 by dividing the MPGE rating of the BEV group by the MPG rating of the ICE group.

The EVER equation relies on a battery-electric vehicle MPGE rating that describes the efficiency of the BEV in terms of the amount of energy in a gallon of gasoline. The conversion of a BEV efficiency rating in kilowatt-hours per 100 miles to MPGE rating compares the amount of energy contained in a gallon of gasoline with that in a kilowatt-hour of electricity. Both lower heating values come from the *Federal Register* 10 CFR 474 and are used by EPA in fuel economy calculations.

To maximize the LDV grouping categories for comparison and to weight the vehicles by registration numbers, we had to utilize a number of databases.

2.2 Databases

The primary EVER input data set is the U.S. Department of Energy/EPA model year 2021 *Fuel Economy Guide* fuel economy ratings (DOE and EPA, 2021). In addition to the finalized city, highway, and combined fuel economy ratings published on vehicle window stickers, the data set includes vehicle attributes that identify vehicle class (i.e., the vehicle type or body style as categorized for rating purposes), vehicle drive (two-wheel drive [2WD] and four-wheel drive [4WD]), and fields identifying those ICE vehicles that are hybrid electric vehicles. These fields provide a structure for grouping vehicles for comparisons.

In addition to the final fuel efficiency ratings, EPA publishes the vehicle test data (EPA 2022b) that feed the *Fuel Economy Guide* rating process. The test data contain vehicle weight and horsepower ratings that provide additional options for comparing vehicles.

Data from Experian Information Solutions that provide counts of vehicle registrations by make and model, as well as additional vehicle attributes, was used for this analysis. This analysis relies on counts of U.S. model year 2021 vehicle registrations. Vehicle registration counts allow the analysis to estimate on-road EVERs that weight the published *Fuel Economy Guide* ratings by the consumer preferences as evidenced by vehicle registrations. This analysis has been done for model year 2020 registrations with similar findings, indicating that 2021 was not an anomaly. The most recent year was chosen because it includes the most robust and modern set of vehicles.

2.3 Merging Databases

The data in each database were first cleansed in preparation for a merge; the databases were then merged based on vehicle attributes. The FEG and EPA test data databases were merged first to create an initial database that combined the FEG ratings with the weight and horsepower ratings (from the EPA database) by vehicle. This initial database was then merged with the Experian vehicle registration database, which finally created a single database that contained all vehicle attributes to support the analysis.

2.3.1 Data Cleansing

Because only a subset of the data from each database was needed for this analysis, there were excess data for each vehicle creating redundancy throughout the data set, and most vehicle models had multiple rows of duplicate or similar data. To address this, two steps were taken to try to get each vehicle down to a single row. First, empty rows, duplicate rows, and unwanted fuel types were removed. The remaining duplication was a result of variations within vehicle models, like weight or fuel economy ratings. The second step was grouping each vehicle model to combine all like attributes and calculate an inverse average for the fuel economy ratings, an average for the weight and horsepower columns, and sum the vehicle count column.

Mfr Name	Division	Carline	Verify Mfr Cd	Eng Displ	City FE (Guide) - Conventional Fuel	Hwy FE (Guide) - Conventional Fuel	Comb FE (Guide) - Conventional Fuel	Drive Sys	Drive Desc	Fuel Usage - Conventional Fuel	Fuel Unit - Conventional Fuel	Descriptor - Model Type (40 Char or less)	Carline Class	Carline Class Desc
General Motors	Chevrolet	CAMARO	GMX	2	22	30	25	R	2-Wheel Drive, Rear	GPR	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	2	19	29	22	R	2-Wheel Drive, Rear	GPR	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	3.6	18	29	22	R	2-Wheel Drive, Rear	G	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	3.6	16	26	20	R	2-Wheel Drive, Rear	G	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	6.2	13	21	16	R	2-Wheel Drive, Rear	GPR	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	6.2	16	26	20	R	2-Wheel Drive, Rear	GPR	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	6.2	16	24	19	R	2-Wheel Drive, Rear	GPR	MPG	SIDI;	3	Subcompact Cars
General Motors	Chevrolet	CAMARO	GMX	6.2	14	20	16	R	2-Wheel Drive, Rear	GPR	MPG	SIDI;	3	Subcompact Cars

Figure 1. Example of fueleconomy.gov vehicle duplication before grouping

Mfr Name	Division	Carline	Verify Mfr Cd	Eng Displ	City FE (Guide) - Conventional Fuel	Hwy FE (Guide) - Conventional Fuel	Comb FE (Guide) - Conventional Fuel	Drive Sys	Drive Desc	Fuel Usage - Conventional Fuel	Fuel Unit - Conventional Fuel	Descriptor - Model Type(40 Char or less)	Carline Class	Carline Class Desc
General Motors	Chevrolet	CAMARO--CAMARO	GMX	2	20.3902	29.4915	23.4043	R--R	2-Wheel Drive, Rear	GPR--GPR	MPG	SIDI; --SID	3	Subcompact Cars
General Motors	Chevrolet	CAMARO--CAMARO	GMX	3.6	16.9412	27.4182	20.9524	R--R	2-Wheel Drive, Rear	G--G	MPG	SIDI; --SID	3	Subcompact Cars
General Motors	Chevrolet	CAMARO--CAMARO	GMX	6.2	14.6332	22.5039	17.5723	R--R--R--R	2-Wheel Drive, Rear	GPR--GPR	MPG	SIDI; --SID	3	Subcompact Cars

Figure 2. Example of fueleconomy.gov vehicle after grouping

2.3.2 Creating Join Key and Merging Databases

To preserve the original imported values for reference and use in the final database, the columns containing information for the vehicle manufacturer, vehicle model, drive system, engine displacement, and fuel type were copied into new columns to be cleansed. These duplicate columns were then used to create a join key unique to each vehicle. The join key is a combination of the manufacturer, model, drive system, engine displacement, and fuel type columns joined with an underscore, representing a simplified identifier for the vehicle to enable matching like vehicles from the different databases to accomplish the merge.

<manufacturer_model_drive system_engine displacement_fuel type>

Join key format

nsx_altima_f_2.5_gas

Example join key

Figure 3. Join key format and example join key

2.3.3 Evaluating Matches and Correcting Mismatches

After merging the FEG and EPA test data databases, many vehicles did not immediately match and needed to be analyzed and adjusted manually. The two primary causes of mismatches were differences in the vehicle model name and drive system. Some vehicles could not be matched and were excluded from the final data set if vehicle registration counts were zero or minimal.

Model Name Differences

Model name mismatches were usually caused by one database having a more detailed model description than the other. For example, the vehicle's model name in one database included the trim level or drive system information and the other did not. In these situations, the more detailed description was simplified to allow the vehicles to be matched.

Data Source	Join Key	fueleconomy.gov Model	EPA test data Model
fueleconomy.gov	nsx_roguesport_f_2.0_gas	ROGUE SPORT	
fueleconomy.gov	nsx_roguesportawd_a_2.0_gas	ROGUE SPORT AWD	
EPA test data	nsx_roguesportawdsv_a_2.0_gas		Rogue Sport AWD SV
EPA test data	nsx_roguesportsv_f_2.0_gas		Rogue Sport SV

Before simplifying the model by removing the vehicle's trim information from the EPA record

Data Source	Join Key	fueleconomy.gov Model	EPA test data Model
both(joined)	nsx_roguesport_f_2.0_gas	ROGUE SPORT	Rogue Sport SV
both(joined)	nsx_roguesportawd_a_2.0_gas	ROGUE SPORT AWD	Rogue Sport AWD SV

Completed join after simplifying the model

Figure 4. Example of model name differences between databases and remedy

Drive System Differences

Drive systems were often labeled differently across the databases. In addition, the EPA test data often showed a discrepancy between the drive system identified in the vehicle model description and drive system column. In these cases, the vehicle model was used to determine the drive system.

Data Source	Join Key	fueleconomy.gov Model	EPA test data Model	EPA test data Drive System	fueleconomy.gov Drive System
EPA test data	nsx_altimaawd_f_2.5_gas		ALTIMA AWD	F	
fueleconomy.gov	nsx_altimaawd_a_2.5_gas	ALTIMA AWD			A

Example of a discrepancy between the drive system shown in the vehicle's model column vs. the drive system column

Figure 5. Example of a drive system difference between databases

Another common cause of drive system mismatches was naming differences between all-wheel drive and four-wheel drive systems. One database might identify a vehicle as an all-wheel-drive vehicle, and the other database identified the same vehicle as a four-wheel-drive vehicle. As long as the vehicle indicated a drive system capable of driving all four wheels, the drive system of one of the vehicles was changed to match the other, as the necessary distinction for the EVER calculations was simply the number of driven wheels.

In a few rare cases, there were vehicles with drive system differences between the databases that could not be resolved through either of the aforementioned methods. This was the case with many of the Subaru models. The EPA test data identified these vehicles as front-wheel drive, and fueleconomy.gov identified the vehicles as all-wheel drive. Because this affected so many models, Subaru's website was referenced. All-wheel drive is a standard option on the affected models, so these vehicles were changed to all-wheel drive.

2.4 Vehicle Groupings

EVERs are calculated by comparing groups of BEVs to similar ICE vehicles as determined by available vehicle attributes. Specifically, EVERs were calculated for given carlines, drives, and a ratio of the vehicle horsepower to weight. The EVER calculations were completed to compare BEVs to conventional ICE vehicles and excluded hybrid electric vehicles and plug-in hybrid electric vehicles.

2.4.1 Vehicle Size Class

The *Fuel Economy Guide* includes 51 unique BEV models in model year 2021 segmented by the vehicle size class designations in Table 2. EVERs were calculated for each of these vehicle classes.

Table 2. *Fuel Economy Guide* Model Year 2021 BEV Vehicle Class Availability

Vehicle Class	Count of Unique BEV Model Ratings
Subcompact cars	3
Compact cars	3
Midsize cars	12
Large cars	8
Small station wagons	9
Small SUV	11
Standard SUV	5
Total	**51**

2.4.2 Vehicle Drive

Vehicle attributes beyond the class can point to varied vehicle capabilities that could make cars competitors to each other for the same prospective buyer. The drive type attribute, when included in comparisons, can highlight vehicles that might have similar capabilities on changing road conditions and provide similar driving dynamics. Additionally, drive type often impacts rated vehicle fuel economy. Grouping vehicles by drive type ensures that EVER calculations account for differences in vehicle capability and fuel economy. EVER drive groupings include 2WD (front and rear 2WD vehicles) and 4WD (all-wheel drive, four-wheel drive, and part-time four-wheel drive vehicles).

2.4.3 Horsepower-to-Weight Ratio

The horsepower and weight ratings (in pounds) in the test data provide a mechanism to group vehicles based on a ratio of their horsepower to weight ratings. This ratio of horsepower to weight is used as a proxy to performance attributes such as acceleration. Grouping by these ratios allows the EVER calculations to begin to account for varied vehicle performance capabilities. Vehicles with a high horsepower-to-weight ratio are termed high-powered vehicles, and vehicles with low horsepower-to-weight ratios are termed low-powered vehicles in EVER summaries. The high and low designations were determined by the median registration-weighted ICE vehicle horsepower-to-weight rating for each class.

Horsepower ratings varied widely across vehicle classes and other vehicle attributes. However, when comparing registered BEVs and ICE vehicles in BEV classes, BEVs were shown to generally have higher horsepower ratings than ICE vehicles (Figure 6). This higher horsepower does not directly point to improved performance, as BEVs were also shown to generally weigh more than ICE vehicles (Figure 6).

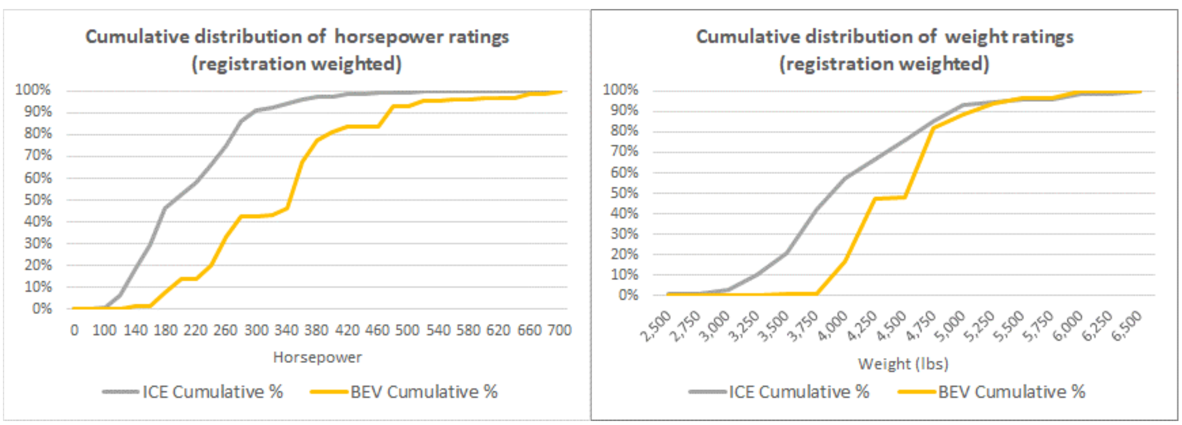

Figure 6. Registered vehicle cumulative distributions for horsepower and weight

Combining these metrics in a horsepower-to-weight ratio shows that BEVs generally have a higher horsepower-to-weight ratio and therefore are typically higher powered for a given vehicle weight (Figure 7). Creating EVERs based on these ratios allows the EVER to begin to account for vehicle performance effects on vehicle efficiency differences.

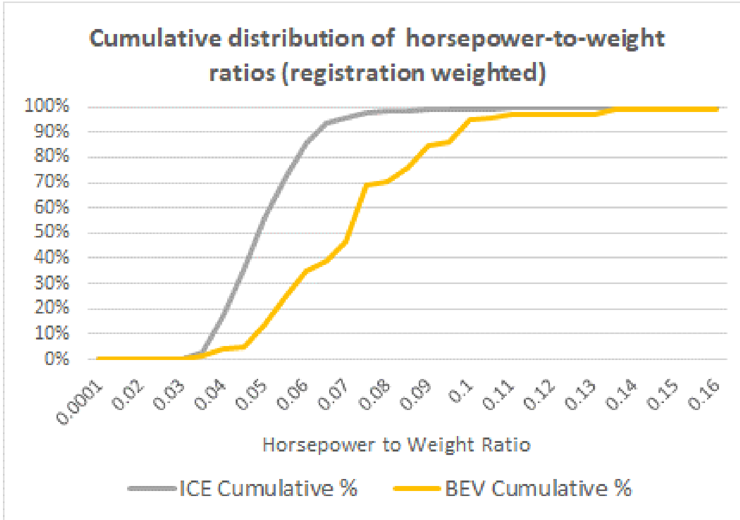

Figure 7. Registered vehicle horsepower-to-weight cumulative distributions

2.5 Highway, City, and Combined Fuel Economy Ratings

Fuel Economy Guide ratings are published for city, highway, and combined driving. ICE vehicles typically are comparatively more efficient during consistent higher-speed highway driving when they can stay closer to their optimal engine speed. Conversely, BEVs are comparatively more efficient during city driving when the vehicles can take advantage of regular stopping to recharge batteries through regenerative braking. Combined fuel economy ratings alone do not account for these varied use cases. Therefore, EVERs have been calculated for city, highway, and combined driving.

3 Findings

3.1 Fuel Economy Variation

Fuel economy ratings vary within vehicle classes by make, model, and individual trim levels. For illustration purposes, the combined MPG ratings of conventional ICE small SUVs range from 14 MPG to 33 MPG, and the combined MPGE ratings of BEV small SUVs range from 76 MPGE to 129 MPGE (Figure 8). Figure 8 also reminds us that the lineup of EVs is much less robust than for the ICE vehicles and therefore is highly influenced by individual models. Broad efficiency ranges could allow for diverse comparisons. Weighting fuel economies by vehicle registrations accounts for vehicle availability and consumer preference for on-road EVERs.

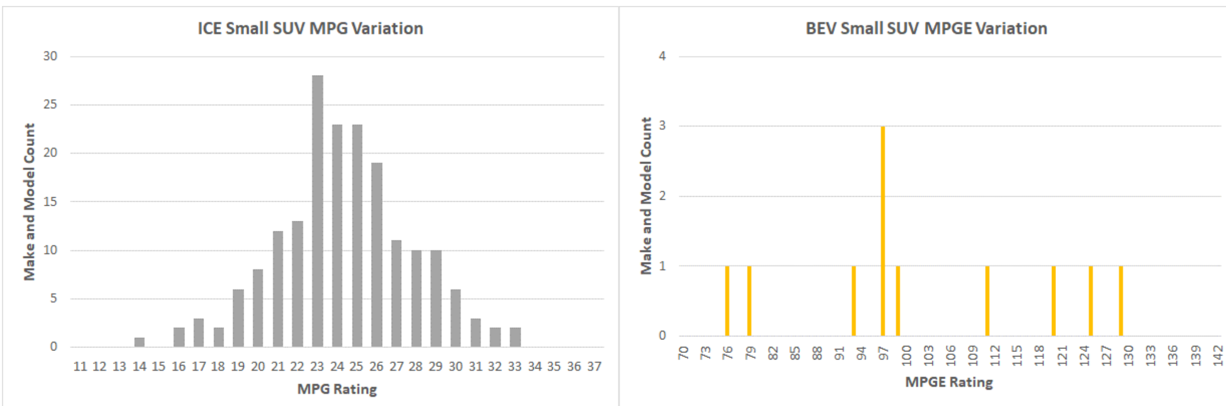

Figure 8. Small SUV fuel economy variation

3.2 EVER by Vehicle Size Class

Registration-weighted EVERs for city, highway, and combined drive cycles were calculated at the vehicle class level for all classes with at least one BEV make and model fuel economy rating and BEV registrations (Table 3). EVERs vary from as low as 2.3 for compact cars on the highway drive cycle to 6.0 for subcompact cars on the city drive cycle. The table demonstrates the efficiency benefits of BEVs on the city drive cycle, as the city EVERs are higher for every class. The combined EVER for all the registration-weighted vehicles on the combined drive cycle is 4.4.

The vehicle class with the largest EVERs was subcompact car, whereas compact cars had the smallest EVERs. The compact car class BEV registrations were comprised of high-powered vehicles (see section 3.4) of a single make and model, the Porsche Taycan, which resulted in the low EVER when compared to a more diverse mix of compact car ICE vehicles. Conversely, the subcompact car class BEV registrations were comprised of two make and models of low-powered vehicles which resulted in a high EVER when compared to the more diverse mix of subcompact car ICE vehicles. Large cars and small station wagons had similar EVERs that were lower than those for midsize cars, small SUVs, and standard SUVs.

Table 3. Vehicle Size Class Registration-Weighted Average Fuel Economy and EVER

	Registrations		Weighted Average BEV MPGE			Weighted Average ICE MPG			EVER		
Class	**BEV**	**ICE**	**City**	**HW**	**Comb.**	**City**	**HW**	**Comb.**	**City**	**HW**	**Comb.**
Subcompact cars	2,246	152,314	119	101	110	20	28	23	6.0	3.5	4.8
Compact cars	2,736	727,627	73	82	77	27	35	30	2.7	2.3	2.6
Midsize cars	148,904	1,178,606	140	124	132	26	36	30	5.3	3.5	4.4
Large cars	25,142	534,153	104	101	103	24	33	27	4.3	3.1	3.7
Small station wagons	44,958	239,348	106	91	99	26	32	29	4.0	2.8	3.5
Small SUVs	203,567	4,839,480	125	111	119	23	29	25	5.5	3.8	4.7
Standard SUVs	13,898	1,813,072	86	84	86	17	23	19	5.1	3.7	4.5
Overall [a]	441,451	9,484,600	123	110	117	22	29	25	5.1	3.6	4.4

[a] Overall EVERs are the weighted average of the class EVERs, weighted by the total registrations in each class. They do not include ICE registrations from vehicle classes with no BEV options.

Registration-weighted EVERs were calculated at a combined level across all vehicle classes with BEV options. This measure is intended to describe the EVER of a light-duty BEV in relation to all comparable ICE vehicles. BEV registrations are distributed differently than ICE vehicle registrations across classes —BEVs have high concentrations of vehicles in the midsize car and small station wagon class, whereas ICE vehicles in classes with BEV options are even more heavily concentrated in standard SUVs and, to a lesser extent, compact cars.

3.3 EVER by Vehicle Class and Drive Systems

EVERs that account for vehicle drive show small variations from the carline level. Vehicle drive and class EVERs range from a low of 2.2 for 2WD compact cars on the highway drive cycle to 6.0 for 2WD subcompact cars on the city drive cycle. Table 4 details the combinations of class and vehicle drive that had at least one BEV fuel economy rating and vehicle registrations. ICE vehicles were excluded if they were not in one of these class and drive groupings.

Table 4. Vehicle Class and Drive System Registration-Weighted Average Fuel Economy and EVER

		Registrations		Weighted Average BEV MPGE			Weighted Average ICE MPG			EVER		
Class	**Drive**	**BEV**	**ICE**	**City**	**HW**	**Comb.**	**City**	**HW**	**Comb.**	**City**	**HW**	**Comb.**
Subcompact cars	2WD	2,246	134,938	119	101	110	20	28	23	6.0	3.6	4.8
Compact cars	2WD	2,736	618,211	73	82	77	28	37	31	2.6	2.2	2.4
Midsize cars	2WD	77,766	1,056,542	148	129	138	27	36	30	5.5	3.5	4.5
Midsize cars	4WD	71,138	122,064	132	120	126	22	31	26	5.9	3.9	4.9
Large cars	4WD	25,142	116,861	104	101	103	23	32	26	4.4	3.2	3.9
Small station wagons	2WD	24,005	131,855	116	100	109	27	33	29	4.3	3.0	3.7
Small station wagons	4WD	20,953	107,493	95	83	89	25	31	28	3.8	2.7	3.2
Small SUVs	2WD	31,454	1,561,106	118	100	109	24	30	26	5.0	3.3	4.2
Small SUVs	4WD	172,113	3,278,374	126	113	121	22	28	25	5.7	4.0	4.9
Standard SUVs	4WD	13,898	1,393,479	86	84	86	17	22	19	5.2	3.8	4.5
All 2WD [a]		138,207	3,502,652	131	114	123	25	33	28	4.8	3.2	4.0
All 4WD [a]		303,244	5,018,271	120	109	115	20	26	23	5.5	3.9	4.7

[a] All 2WD and All 4WD EVERs are the weighted average of the class and drive EVERs, weighted by the total registrations in each class and drive. They do not include ICE registrations from vehicle class and drive combinations with no BEV options.

When summarized across vehicle classes, registered 2WD BEVs had lower EVERs than 4WD BEVs (Table 4). This is likely because many of the inefficiencies of ICE vehicles are worsened by the additional friction and power requirements of a 4WD powertrain. The impacts of drive on EVERs varied by class. Compact cars continued to result in the lowest EVERs. However, since all registered BEV compact cars were 2WD, the EVER accounting for drive decreased from the class-only combined EVER of 2.6 to 2.4. Midsize cars, small station wagons, and small SUVs had both 2WD and 4WD options with BEV registrations and fuel economy ratings. Variation in drive across these vehicle classes did not result in a consistent trend. 4WD midsize cars and small SUVs had higher EVERs compared to 2WD midsize cars and small SUVs, whereas 2WD small station wagons had higher EVERs than 4WD small station wagons. This lack of trend could in part be explained by BEV make and models often only being available with a single drive option—for example, the Hyundai Kona is available as a 2WD, whereas the Jaguar I-pace EV400 is available as a 4WD. Fuel economy differences between 2WD and 4WD versions of the same models, if they existed, would provide the most direct comparison.

3.4 EVER by Class and Horsepower-to-Weight Ratio

The high and low power definitions in Section 2.4.3 are intended as a proxy for vehicle performance and provide a method to calculate EVERs based on this proxy. BEV registrations are overwhelmingly concentrated in high-power segments (Table 5). Subcompact car was the only vehicle class where BEVs were concentrated in the low-power segment. Vehicle class and power EVERs range from 2.3 for high-power compact cars on the highway drive cycle to 6.0 for high-power small SUVs on the city drive cycle.

Midsize cars and small SUVs were the only classes with both high- and low-power BEV registrations. Both classes show significantly larger EVERs for the high-power group compared to the low-power group. This could be because the high-power groups of both classes are dominated by Teslas, which are lighter and have more efficient motors (Baldwin 2020). The midsize car combined EVER for high-power BEVs was 43% higher than that for low-power BEVs. Similarly, the small SUV combined EVER for high-power BEVs was 35% higher than that for low-power BEVs. Further, the combined EVERs for high-powered midsize cars and small SUVs are higher than the overall midsize car and small SUV combined EVERs detailed in Section 3.2. The EVER for these classes increased when making the more specific comparison to those vehicles with high power ratings where the registrations are heavily concentrated.

The combined EVER for all low-power BEVs is 3.7, whereas the combined EVER for all high-power BEVs (93% of all BEV registrations) is 4.5 (Table 5). The efficiency advantage of EVs is clearly greater in vehicles with a high power-to-weight ratio.

Table 5. Vehicle Class and Power Rating Registration-Weighted Average Fuel Economy and EVER

		Registrations		Weighted Average BEV MPGE			Weighted Average ICE MPG			EVER		
Class	**Horsepower to Weight [a]**	**BEV**	**ICE**	**City**	**HW**	**Comb.**	**City**	**HW**	**Comb.**	**City**	**HW**	**Comb.**
Subcompact cars	LOW	2,246	75,189	119	101	110	25	34	29	4.7	2.9	3.8
Compact cars	HIGH	2,736	706,642	73	82	77	27	35	30	2.8	2.3	2.6
Midsize cars	LOW	7,415	576,008	128	99	110	29	38	33	4.4	2.6	3.4
Midsize cars	HIGH	141,489	602,598	141	126	134	24	34	28	5.9	3.7	4.8
Large cars	HIGH	25,142	358,398	104	101	103	23	32	26	4.6	3.2	3.9
Small station wagons	HIGH	44,958	121,035	106	91	99	27	33	29	3.9	2.8	3.4
Small SUVs	LOW	22,840	2,344,034	112	94	103	25	31	27	4.5	3.1	3.8
Small SUVs	HIGH	180,727	2,495,446	127	113	121	21	27	24	6.0	4.1	5.1
Standard SUVs	HIGH	13,898	1,218,883	86	84	86	17	23	19	5.2	3.7	4.5
All LOW [b]		32,501	2,995,231	115	96	105	26	32	28	4.5	3.0	3.7
All HIGH [b]		408,950	5,503,002	124	112	118	21	28	24	5.3	3.7	4.5

[a] High and low designations were determined by the median registration-weighted ICE vehicle horsepower-to-weight rating for each class.

[b] All LOW and All HIGH EVERs are the weighted average of the class and power-to-weight EVERs, weighted by the total registrations in each class and power combination. They do not include ICE registrations from vehicle class and power combinations with no BEV options.

4 Conclusions and Discussion

EVERs provide a basis for describing the efficiency improvement of BEVs relative to conventional ICE vehicles, and their use informs calculations determining the reduction in carbon emissions and fuel cost per mile associated with replacing a conventional vehicle with a BEV. This study developed on-road light-duty EVERs that account for current BEV availability and consumer preference.

EVERs were generally consistent across vehicle classes except for lower values for compact cars. This class had relatively low vehicle registrations and therefore little impact on the cross-class overall EVERs—5.1 city, 3.6 highway, and 4.4 combined. This study focused on model year 2021 vehicle registrations. However, an investigation of model year 2020 vehicle registrations found similar overall EVERs—4.9 city, 3.4 highway, and 4.2 combined.

EVERs are consistently higher for city drive cycles where regenerative braking and low-end torque enhance BEV efficiencies. This trend is magnified when looking at vehicles with a high power-to-weight ratio. Therefore, policies and campaigns introducing BEVs into urban markets could result in greater environmental and economic benefits.

BEV registrations are concentrated in higher-power (high horsepower-to-weight ratio) vehicle groupings, and EVERs increase when vehicle groupings are restricted to more similarly high-power vehicles. This points to BEV efficiency benefits in segments focused on high performance vehicles. However, the relatively low compact car class EVER shows that high-end performance BEVs can result in lower efficiency benefits.

This study lays groundwork for related research that could improve our understanding of the benefits of BEV adoption. One area of future research involves grouping by additional vehicle attributes. The data merging methodology developed here could incorporate attributes such as vehicle acceleration, carrying capacity, towing capacity, interior volume, footprint, and vehicle cost as data sources allow. Evaluating EVERs at this level could inform how on-road EVERs might evolve with consumer choice. Another area of valuable research would be to capture hybrid electric vehicles and compare them to both BEVs and conventional vehicles.

EVERs will evolve with BEV availability and consumer adoption. The number of BEV models is a fraction of their ICE counterparts, so an addition of a high-volume model (such as the Ford F-150 Lighting) in a new vehicle class is likely to have a large impact. BEVs are currently concentrated in more expensive high-performance vehicles. As BEV offerings expand in more classes (especially pickup trucks and vans) and prices continue to decrease relative to ICE vehicles in more classes, consumer choices will impact EVERs and BEV benefits. Tracking EVERs by model year could support policy development seeking to maximize energy efficiency improvements through targeted BEV adoption. Such efficiency improvements can then be combined with electricity carbon intensity to maximize carbon reduction and combined with electricity and gasoline price to maximize fuel cost reductions.

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