Which EV available today is the best in long distance trip ability and price?

November 18, 2019

In my previous article, I argued that EVs need to have a 250-300mi range and fast charging in order to be usable as an only car for most. In this follow-up, I will look at how much more time different EVs need to complete a long distance trip compared to an average ICE car.

Long distance trip All trip time calculations are based on a 500mi trip (one-way), because 75% of long distance trips are 500 mi or less[1].

Trip times Trip times are calculated for each EV for such a long distance trip. The total trip time consists of the driving time at 70mph; the charging time; the time to stop (exit the interstate, drive to the charger, get back, assumed to be 5 min); and potentially a waiting time if human needs take longer than the required charging to complete the trip. The number of charges and charging durations are optimized for a given EV's charge curve (power over SOC[2]). The trip starts with a fully charged battery to 100%, and ends with the lowest SOC at which a particular EV is typically recharged[3], i.e. EVs arrive with 5-21mi range remaining; only the Audi e-tron has the lowest recharging SOC at 0% and arrives with 0mi range remaining[4].

The increase in trip time over an average ICE car is calculated for each EV. The ICE car trip time is the sum of the driving time at 70mph (identical to EV); one refueling, and two stops because of human needs (the refueling is assumed to happen at one of the two human-required stops). Refueling is assumed to be required once, since the median range in a ICE car is $\sim$ 400mi[5], which is less than the trip distance even when assuming a full tank at the start. The two stops for human reasons are to limit the continuous driving time to 3h or less. Since the total driving time is $>$7h, one of them is assumed to be a meal break.

[1] http://www.princeton.edu/~alaink/Orf467F16/NTS_Entire_16Q1.pdf, Table 1-42, Personal use vehicle-miles, roundtrip distance

[2] Charge curves in the appendix.

[3] I am assuming charging availability at the destination.

[4] The Audi e-tron has a very large buffer built into the battery, so it seems reasonable to me to use most of the accessible SOC.

[5] https://evadoption.com/statistics-of-the-week-comparing-vehicle-ranges-for-gas-bevs-and-phevs/

This results in a total trip time with an ICE car of 7:49h (469min), consisting of 429min driving time, 10min stopping time for two stops (5min each), 5min for refueling, and a 25min meal break. This baseline is optimistic even for an ICE car and represents a good target for EVs to match.

Trip time calculations The calculations of EV trip times use three pieces of information: rated (not advertised) range from the EPA; net battery capacity from ABRP (A Better Routeplanner) for Teslas, and ev-database.org for all other EVs; and charging curves from ABRP for Teslas, Fastned for others.

Based on the rated EPA highway range, the amount of range that need to be recharged to complete the trip is calculated. The number of charging stops and the best starting and stopping SOCs is optimized by numerically integrating the charge curves over the required SOC increase for the needed range. Numerical integration is the calculation of the value of a definite integral, in this case for the charging curve $f(\mathrm{SOC})$.

$$\int_{\mathrm{SOC-start}}^{\mathrm{SOC-end}} f\left(\mathrm{SOC}\right) d\mathrm{SOC}$$

The integral is the energy (in kWh) taken in by the battery, which is used to calculate the range gained. The charge curve is also used to calculate the average charging speed for a charging stop and the time needed.

Assumptions There are a lot of assumptions necessary for the calculations, mostly because for many EVs little data is available to model trips more accurately. In some cases where more data is available, it is not used to keep the results comparable between EVs.

For range, EPA data is used. The EPA describes the regulations for vehicle testing[6]; this includes the controlled laboratory conditions and the series of tests that are performed. This testing is done by manufacturers, which report the results to the EPA. The EPA reviews and confirms only 15-20% of the results[7]. This testing by manufacturers that might interpret regulations differently might potentially lead to less comparable results that desired. However, the available range-vs-speed data is very limited and would exclude many EVs in this comparison.

To make EPA data as comparable as possible, the EPA rated range is used, not EPA advertised range. This excludes any modifications to the advertised numbers that manufacturers voluntarily do, up or down, e.g. Tesla[8]. This also means that driver characteristics (aggressive vs smooth driving), temperature, weather (rain, snow, wind), elevation changes, etc. are not taken into account beyond what is already accounted for in the EPA testing procedure. The rated EPA highway range is assumed to be representative of the range achievable

[6] https://www.epa.gov/vehicle-and-fuel-emissions-testing/vehicle-testing-regulations
[7] https://www.fueleconomy.gov/feg/how_tested.shtml
[8] https://teslike.com/range/

driving at a constant speed of 70mph[9] in fairly warm conditions (accelerating to speed and regenerating to a stop is assumed to be negligible overall).

Range is assumed to be maximal driving range according to vehicle spec minus a mileage-dependent battery degradation[10]. This includes tires inflated to spec, and no wear that is influencing range. The battery is assumed to be fully charged at the start of the trip. Battery degradation is calculated from the average mileage for a used car; it is assumed zero for new cars.

Chargers are assumed to be located at the exact spot (distance from trip start) where they are needed for an optimal trip. They are assumed to always be able to provide the maximum power the vehicle can accept, and are assumed to always be operable and available at time of arrival at the charger.

Cost of buying For new cars, the manufacturer's MSRP (Manufacturer Suggested Retail Price) was utilized. For used cars the average of Cargurus Instant Market Value[11] and Edmunds dealer retail price for a clean vehicle in Columbus, OH, without mileage adjustment was used; KBB prices were evaluated as for used EVs, but seemed inconsistent.

Two modifications to the average used prices were made; Model S 85 prices were increased after verifying that available prices were much higher; Model X 90D and X 100D prices were adjusted down and up respectively (nobody would buy a Model X 90D if a X 100D costs less, everything else being equal).

EVs included All EVs available (new, or sold in high enough numbers to be available used) and with at least 120mi range were included, if sufficient charging data could be found. Table 1 lists all 23 EVs, including 14 from Tesla[12].

[9]For some EVs range-vs-speed data is available; it shows a similar range at 70mph as the EPA highway range; EPA highway range and 70mph-range respectively are available for Model S 100D (337mi, 341mi, +1.2%); Model X 100D (300mi, 294mi, -2%); Model 3 LR (307mi, 312mi, +1.6%); Bolt (217mi, 220mi, +1.4%), Ioniq (110mi, 129mi, +17%); all data from ABRP.

[10]See appendix.

[11]https://www.cargurus.com/Cars/instantMarketValue.action

[12]Excluded EVs are listed in the appendix.

Brand	Model	MY	Data
Audi	e-tron	2019	Fastned[13], nextmove[14], ev-db[15], EPA19[16]
BMW	i3 120Ah	2019	Fastned[17], ev-db[18], EPA19
Chevrolet	Bolt	2017-9	Fastned[19], ABRP-Bolt[20], ev-db[21], EPA19
Hyundai	Ioniq EV 28kWh	2017-9	ev-database[22], EPA17[23]
Hyundai	Kona EV	2019-20	Fastned-Hyundai-Kia[24], EPA19
Jaguar	I-Pace	2019-20	Fastned[25], ev-db[26], EPA19
Kia	Niro EV	2019	Fastned-Hyundai-Kia, ev-db[27], EPA19
Nissan	Leaf 40kWh	2018-9	Fastned[28], ev-db[29], EPA19
Tesla	Model S 85	2012-6	ABRP-Tesla-1[30], ABRP-Tesla-2[31], EPA16[32]
Tesla	Model S 85D	2014-6	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model S 70	2016	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model S 70D	2015-6	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model S 75	2016-7	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model S 75D	2016-9	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model S 90D	2015-7	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model S 100D	2017-9	ABRP-Tesla-1, ABRP-Tesla-2, EPA17
Tesla	Model X 100D	2017-9	ABRP-Tesla-1, ABRP-Tesla-2, EPA17
Tesla	Model X 90D	2016-7	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model X 75D	2016-9	ABRP-Tesla-1, ABRP-Tesla-2, EPA16
Tesla	Model 3 LR	2017-9	ABRP-Tesla-1, ABRP-Tesla-2, EPA19
Tesla	Model 3 LR AWD	2018-9	ABRP-Tesla-1, ABRP-Tesla-2, EPA19
Tesla	Model 3 SR+	2019	ABRP-Tesla-1, ABRP-Tesla-2, EPA19
VW	e-Golf 36kWh	2017-9	Fastned[33], ev-db[34], EPA17

Table 1: Included EVs

[13] https://support.fastned.nl/hc/en-gb/articles/360000815988-Charging-with-an-Audi-e-tron

[14] https://www.youtube.com/watch?v=8ng1-TDJx8k

[15] https://ev-database.org/car/1092/Audi-e-tron-55-quattro

[16] http://www.fueleconomy.gov/feg/epadata/19data.zip

[17] https://support.fastned.nl/hc/en-gb/articles/204784718-Charging-with-a-BMW-i3

[18] https://ev-database.org/car/1145/BMW-i3-120-Ah

[19] https://support.fastned.nl/hc/en-gb/articles/115000019368-Charging-with-an-Opel-Ampera-e

[20] https://forum.abetterrouteplanner.com/topic/517-bolt-charging-times-to-optomistic/

[21] https://ev-database.org/car/1051/Opel-Ampera-e

[22] https://ev-database.org/car/1057/Hyundai-IONIQ-Electric

[23] http://www.fueleconomy.gov/feg/epadata/17data.zip

[24] https://support.fastned.nl/hc/en-gb/articles/360007699174-Charging-with-a-Kia-e-Niro

[25] https://support.fastned.nl/hc/en-gb/articles/360000788848-Charging-with-a-Jaguar-I-PACE

[26] https://ev-database.org/car/1097/Jaguar-I-Pace

[27] https://ev-database.org/car/1125/Kia-e-Niro-64-kWh

[28] https://support.fastned.nl/hc/en-gb/articles/204784998-Charging-with-a-Nissan-Leaf-e-or-e-NV200

[29] https://ev-database.org/car/1106/Nissan-Leaf

[30] https://forum.abetterrouteplanner.com/blogs/entry/30-tesla-supercharging-summer-2019-update/

Information not included EVs, especially from Tesla, are a fast moving target. Tesla has updated range and charging speed of its Model 3[35][36] since the preparation of the data and this document; this information could not be included here.

Results: Trip times In the fastest EV the trip takes the same time as in the ICE car (469min, Tesla Model 3 LR); it actually doesn't even need to charge the complete time of the two stops (30min), but only 18min to be able to complete the trip. Two other Teslas also complete the trip in the same time (Model S 100D, 3 LR AWD)).

The slowest trip was 149min (31.8%) longer than the baseline ICE car trip (618min for the VW e-Golf 36kWh). It's range is only 125mi, much less than 250mi argued for long-distance trips. The slowest trip in an EV with >200mi range is the Chevrolet Bolt (540min, +71min, +15.2%), due to its slow charging ability.

The complete list of trip times is in Table 2.

A few interesting results come out of these calculations.

1. Tesla has figured this out. All Teslas except two (12/14) are on the top of the shortest travel times. The slowest two Teslas[37] (Tesla Model S 70, 70D) are only 4.8% and 5.9% (22min and 28min) slower than the ICE car baseline. And even the oldest EV in this list, the Tesla Model S 85 built from 2012 only needs 14min (2.9%) longer than baseline.

2. The Audi e-tron has the fastest non-Tesla trip time, an unexpectedly good result given it's low range of $\sim$ 200mi and low efficiency. This highlights the importance of fast charging as the Audi is the second fastest charging EV (after the Model 3).

3. The Hyundai Kona, Jaguar I-Pace, and Kia Niro (from +43min to +51min) have the slower-but-still-reasonable trip times due to their long range and reasonably fast charging.

4. The Chevrolet Bolt has good range, but is severely limited by its slow charging. The Hyundai Ioniq has reasonably fast charging, but lacks range.

5. All other EVs lack both range and fast enough charging ability.

[31] https://forum.abetterrouteplanner.com/blogs/entry/6-tesla-battery-charging-data-from-801-cars/

[32] http://www.fueleconomy.gov/feg/epadata/16data.zip

[33] https://support.fastned.nl/hc/en-gb/articles/205205168-Charging-with-a-Volkswagen-e-Golf-or-e-up-

[34] https://ev-database.org/car/1087/Volkswagen-e-Golf

[35] https://insideevs.com/news/379946/tesla-model-3-lr-more-range-price/

[36] https://insideevs.com/news/380519/tesla-model-3-sr-supercharge-170-kw/

[37] Data for the Tesla Model S 60(D) and X 60D were incomplete and excluded. They can use three different batteries, BT60, or software-locked BT70 or BTX5.

EV	Trip Time Increase	Trip Time	Range till first charge	Charge count	Charge time (total)	Wait time	Range at end
Model 3 LR	0.0%	469min	299.6mi	1	18min	12min	7.4mi
Model 3 LR AWD	0.0%	469min	290.1mi	1	20min	10min	7.1mi
Model S 100D	0.0%	469min	329.1mi	1	22min	8min	8.1mi
Model X 100D	0.0%	469min	292.3mi	2	30min	0min	7.2mi
Model S 90D	0.2%	470min	282.8mi	2	31min	0min	7.0mi
Model S 85D	1.5%	476min	266.1mi	2	37min	0min	5.4mi
Model S 75D	1.9%	478min	245.8mi	2	39min	0min	6.0mi
Model X 90D	2.5%	481min	244.8mi	2	42min	0min	6.0mi
Model S 75	2.7%	482min	235.7mi	2	43min	0min	5.8mi
Model S 85	2.9%	483min	248.9mi	2	44min	0min	5.1mi
Model 3 SR+	3.1%	483min	218.9mi	2	45min	0min	5.2mi
Model X 75D	3.6%	486min	226.9mi	2	47min	0min	5.86mi
e-tron	4.1%	488min	202.9mi	2	50min	0min	0.0mi
Model S 70D	4.8%	491min	229.4mi	3	48min	0min	5.2mi
Model S 70	5.9%	497min	218.1mi	3	53min	0min	4.9mi
Kona EV	9.2%	512min	203.4mi	3	69min	0min	22.6mi
I-Pace	9.5%	513min	203.1mi	3	70min	0min	17.7mi
Niro EV	10.8%	520min	192.2mi	3	76min	0min	21.4mi
Bolt	15.2%	540min	208.1mi	3	97min	0min	9.3mi
Ioniq EV 28kWh	17.1%	549min	104.4mi	5	96min	0min	5.6mi
i3 120Ah	24.1%	582min	124.0mi	4	134min	0min	12.4mi
Leaf 40kWh	28.3%	602min	117.8mi	5	144min	0min	14.6mi
e-Golf 36kWh	31.8%	618min	104.5mi	5	165min	0min	13.2mi

Table 2: Trip times for the newest MY (model year), ordered by Trip Time Increase, the increase over ICE car baseline (Battery degradation increases Trip Time by no more than 5min).

6. Battery degradation, at least as modeled here, only increases the trip times up to 5 minutes (1%) and is not an issue.

Results: Prices Prices of new EVs are still rather high (Figure 1). The lowest-priced EVs in this list are ∼\$20,000, but require long charging breaks for long distance trips. EVs with reasonable long distance travel times are not much below \$40,000. This is about the average cost of a new car in the U.S.[38], but EVs are still more expensive within their segments and not even available in some of the higher priced segments, e.g. Pickup trucks or full-size SUV.

Used EVs can be a good choice, they roughly depreciate like ICE cars (Teslas seem to do better) and the cost is a lot lower for a two- or three-year-old EV.

[38] https://mediaroom.kbb.com/2019-06-03-Average-New-Car-Prices-Up-Nearly-4-Percent-Year-Over-Year-for-May-2019-According-to-Kelley-Blue-Book

While lower maintainance cost can be seen as an argument for buying, quickly improving abilities of EVs in terms of range, efficieny, and charging are a detriment - why would one by a vehicle that is outdated next year and new ones are substantially better?

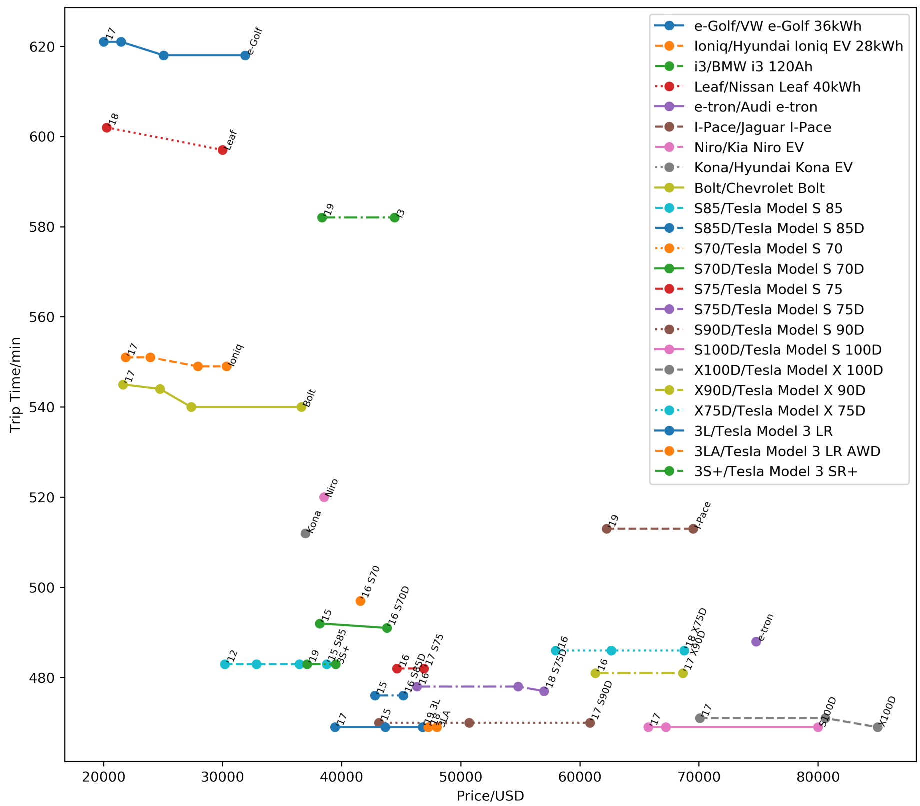

Figure 1: The EV trip time over their cost to buy (new or used). For used EVs, the first and last of a series is labeled by MY (Model Year); the last in a series adds a short abbreviation of the car and model to the label (see legend).

With their combination of good trip times and relatively low price, a few EVs stand out.

1. New Model 3 SR+, Kona, and Niro;
2. Used Model S (75, 75D, 85D, 90D);
3. Bolt as lowest-priced EV with best trip time; Ioniq as a close second when taking its real-world efficiency into account.

Summary The above results show that EVs available today can complete long-distance trips, but only very few are capable of doing so within a time comparable to that of an ICE car. All Teslas[39] and the Audi e-tron can complete a 500mi trip with $<6\%$ additional time; Hyundai Kona, Jaguar I-Pace, and Kia Niro are within 11% added time; all other EVs take longer.

Of course all of these results come with assumptions about driving conditions (e.g. speed, temperature), battery condition (degradation), and most importantly charger conditions and locations. Currently, careful trip planning that ensures driveability is a requirement; route planning apps that combine car, trip, and charging information can help.

If for reasons of range, refueling speed, or price, the available EVs are insufficient for a particular use case, BEVx[40], PHEV, and HEV can be an alternative.

[39] Note that the Tesla Model S/X 60 were not included here.

[40] A BEVx is a battery electric vehicle with a range-extending generator and fulfulling additional California Air Resources Board (CARB) criteria, see https://en.wikipedia.org/wiki/Range_extender_(vehicle)#CARB_regulation.

Appendix Table 3 contains all excluded EVs and their reason of exclusion; Figure 2 shows the charging curves used for the calculations.

EV	Reason	Trim MY: Range
e-Golf	Range<120mi	2015-6: 83mi
Leaf	Range<120mi	2011-3: 73mi; 24kWh 2014-6: 84mi; 30kWh 2016-7: 107mi
Leaf	Missing data	62kWh 2019: 226mi; 62kWh SV/SL 2019: 215mi
i3	Range<120mi	i3-60 2014-7: 81mi; i3s 2018: 107mi; i3-94 2017-8: 114mi
Soul	Range<120mi	2015-7: 93mi; 2018-9: 111mi
Soul	Unavailable[41]	2020: 243mi
500e	Range<120mi	2013-9: 84mi
Clarity	Range<120mi	2017-9: 89mi
Smart fortwo	Range<120mi	2013-6: 68mi, 2017-9: 58mi
i-MiEV	Range<120mi	2016-7: 59mi
Spark	Range<120mi	2014-6: 82mi
Focus	Range<120mi	2012-6: 76mi; 2017-8: 115mi
B250e	Range<120mi	2014-7: 87mi
RAV4	Range<120mi	2012-4: 103mi
Model S/X 60	Missing data	S 60 2013-7: 208mi; S 60D 2016-7: 218mi; X 60D 2016-7: 200mi
Model S/X SR/LR	Missing data	S SR 2019: 285mi; S LR 2019: 370mi; X LR 2019: 325mi
Model 3 SR/MR	Missing data	3 SR 2019: 220mi, 3 MR 2018-9: 260mi
Model S/X/3 P	Less relevant	S P85, P85D, P90D, P100D, P19, P21; X 90D, 100D, P22; 3 P

Table 3: Excluded EVs.

Battery degradation was modeled with data from Teslas[42] and very limited data from a Bolt[43]. The Bolt data seems to agree with the Tesla data, the Tesla data was therefore used. General information about battery degradation vs. cycles and mathematical models remain difficult to find[44].

This model assumes that the charging curve (Figure 2) are SOC dependent, i.e. scale back with degradation. It is possible that charging curves are based on cell voltage, and because degradation effects the high voltage state, the charging at lower SOC and cell voltages would be unchanged.

The Tesla data contains a fitting function $c = -0.0117991 \log m + 1.07712$ (c being the remaining fraction of the original battery capacity; m mileage). This function was not used because it assumes that the battery starts at 107.7% manufacturer specified usable capacity; instead a spline-function was fit based on 100% usable capacity (Figure 3).

Battery degradation was calculated with this degradation model and average mileage for used MY based on Edmunds data.

[41] https://insideevs.com/news/377129/redesigned-kia-soul-ev-delayed-2021-later/

[42] https://cleantechnica.com/2017/05/19/show-me-the-data-the-truth-about-tesla-battery-degradation/

[43] https://www.mynissanleaf.com/viewtopic.php?t=30253

[44] https://doi.org/10.1016/S0378-7753(02)00490-1

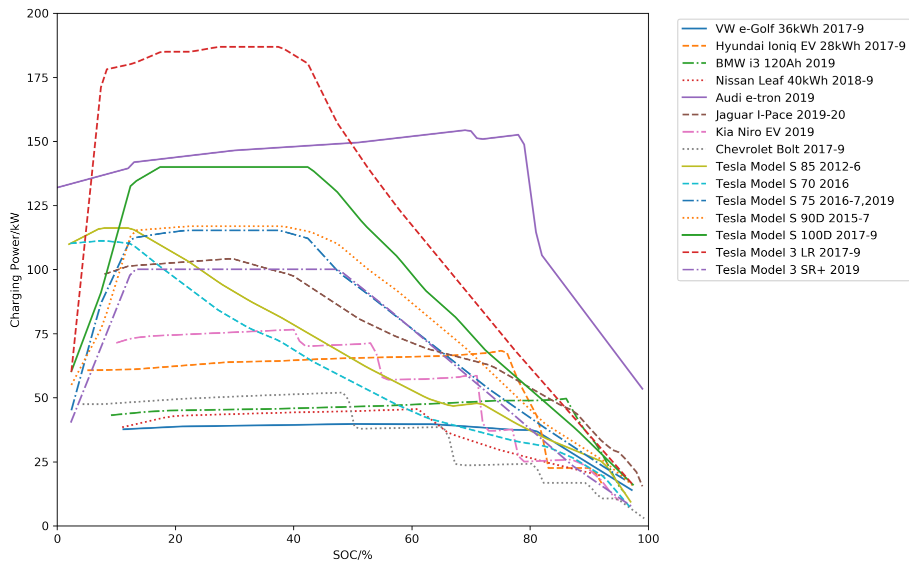

Figure 2: Charging power over SOC (state of charge) for different EVs. Tesla charging profiles from after the August 2019 update were used.

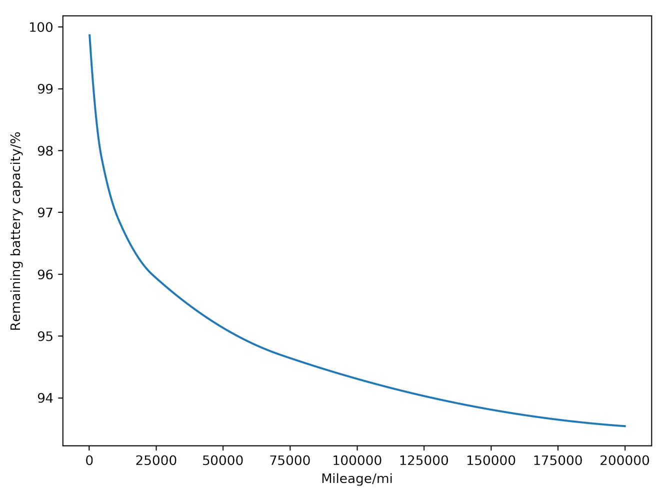

Figure 3: Battery degradation vs mileage.