ECE 398GG – ELECTRICAL VEHICLES

3b. Vehicle Basic Dynamics: Energy and Power Needs of Electric Vehicles

P. T. Krein

Department of Electrical and Computer Engineering

University of Illinois at Urbana–Champaign

Key Considerations in EV Design and Operation, Part 2

P. T. Krein

Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign, USA

Electric vehicle size and weight issues

- The traction force results push for low drag, low tire loss, low vehicle weight.
- This is true for any vehicle. For an EV, we are trying to keep stored energy as low as possible and get the best result.
- Batteries are expensive even though this is dropping. Today, wholesale Li-ion batteries are about \$200/kWh. Implies \$8000 wholesale for that Nissan 40 kWh pack.
- A gas tank is nowhere near this costly.

Electric storage ←→ Electric energy
(expensive) (cheap)

Fuel storage ←→ Fuel energy
(cheap) (expensive)

Electric vehicle size and weight issues

- One other way to look at this: What do I get by adding 1 kg of battery (Li-ion)?
- Optimistically, an extra 1000 kJ → 280 Wh.
- Force need went up, mgR_t, 0.08 N. At 20 m/s, this would be 1.6 W.
- To drive for 5 hours, this would consume an extra 8 Wh, but we added an extra 280 Wh, so almost all of the extra energy can be used to add to vehicle range.

- Keep in mind that 1 kg of gasoline is about 1.3 L (about 1/3 gallon).

Electric vehicle size and weight issues

- What are the limits?
  - Structural limits. 60 L of gasoline – manage about 50 kg. 40 kWh of batteries (at 180 Wh/kg) – manage about 220 kg.
  - Money. Gas tank is only a few dollars. Batteries above $200/kWh.
- Structural design becomes much different in the EV context.
- Batteries: large but amenable to many shapes.
- Other points: No fuel or fuel system, no engine.
- Electric motors have high power to weight ratio compared to passenger car engines.

Electric vehicle size and weight issues

- A safety aspect: What happens to batteries in a wreck?
  - This question also applies to gasoline, but think about what could happen to a vehicle carrying a heavy load of rocks.
  - Many modern designs use an under-carriage *glider* concept.
- Tesla has models with a 100 kWh pack.
- At 180 Wh/kg, this is 560 kg (1200 lb).

www.carmagazine.co.uk

Vehicle parameters and performance metrics

- The drive train must deliver force (torque), speed, power, and so on.
- Each will be limited by some aspect of motor, inverter, battery, or other ratings.
- Instead, let us look at the other end: What is needed?

Force and torque

- We need a force at the tire contact patch to propel a vehicle.
- The axle torque for this is f x r, where r is the tire radius.
- Measuring lots of passenger cars, r ≈ 0.3 m (1 foot) is typical. We will just use it. Trucks have larger r, etc.

$$f_{traction} = mg\sin\theta + mgR_t + \frac{1}{2}\rho C_d A_f v^2 + m_{eq} a$$

- At low speeds and minimal acceleration, drag does not matter. R_t ~ 0.01, so a slope can dominate.

Force and torque

- Slope is defined for road design in terms of tan θ rather than sin θ For 10% or less, there is minimal difference.
- There is a street in Pittsburgh claiming a 37% grade, which is about 20°.
- Maybe there are some steeper parking ramps.
- For tan $\theta = 0.4$, we get $\theta = 22°$ and sin $\theta = 0.37$ (still not much difference).

Gradability

- The low-speed force need defines what is called a *gradability* specification.
- Ability to move on a 30% slope is considered a minimum.
- As you can tell, a 40% slope would be a more plausible rating. A 50% slope gives sin $\theta = 0.45$.
- At 40%, need to deliver $(0.37 + R_t)$ mg for grade and tires.
- For our 2000 kg reference vehicle, we need 7414 N.
- The axle torque is 2224 N-m.

Acceleration

- It is conventional to specify 0-60 mph (or 0-100 km/h) acceleration, and 40-70 mph acceleration.
- These numbers are linked to both force and power.
- Highest power at highest speed.
- BUT, what about RATINGS needs?
- How much time to enter a freeway?
- How much time to conduct a passing maneuver?
- I will let *you* think about whether a 0-60 mph time of 2.0 s is safe, practical, or useful in a passenger car.
  (This would be 13.4 m/s^2, 1.36g.)

Acceleration

- This also tells us about *dynamic ratings*. A vehicle can deliver much more than the continuous ratings for ~2 s.
- We also car about *continuous ratings*.
- Example: Nissan Leaf, Cd =0.28, Af = 2.28 m^2, 2000 kg.
- Grade to 40%: 7414 N force, 2224 N-m torque.
- Acceleration 0-60 mph, 6 s, 4.47 m/s^2:
  - Force: 9454 N at zero speed, 9730 N at 60 mph.
  - Power at highest speed: 261 kW.
- You do not really need this much across the range.
- Good rule of thumb: power at 50 mph and 4 m/s^2.

Acceleration

- You do not really need this much across the range.
- Good rule of thumb: power at 50 mph and 4 m/s^2 estimates a vehicle capable of about a 5 s 0-60 mph time.
- Here this is 194 kW.
- What about 5 s for 40 mph to 70 mph? This is 2.68 m/s^2.
- For this car, P for 70 mph and 2.68 m/s^2 is 191 kW. Just about the same number.

- We have identified a dynamic peak power rating.

Top speed

- *Top speed* is another vehicle rating that does not really have direct value.
- From our perspective, it is the highest speed that can be maintained continuously (until energy runs out).
- It matters on German autobahns, for example.
- For our Nissan, what if the continuous rating is ~55% of the peak value? That is 107 kW – right at the motor rated 110 kW.
- Trying out numbers, I get 143 mph. (Tesla model 3 is about this value as well.)
- Gear ratios and transmission details might not support this.

Gearing

- Any vehicle has a *final drive ratio.* Simple for an EV: the ratio of the motor shaft rotation speed to the axle rotation speed.
- Most cars have multi-speed transmissions and therefore multiple ratios.
- Many EVs use a single fixed ratio. Sometimes this is called “direct drive,” but this is misleading because a 1:1 final drive ratio yields an extremely heavy motor.
- The Nissan Leaf has a final drive ratio of 8.193:1.

Gearing

- What does this mean? For a rotating wheel, the rim speed is $v = r\omega$, where ω is angular speed.

- A tire with r = 0.3 at vehicle speed of 75 mph (33.5 m/s), this means that $\omega = 33.5$ m/s ÷ 0.3 m = 112 rad/s, 1067 RPM.
- A final drive ratio of 8.193:1 means a motor speed of 8742 RPM.
- The Leaf has a motor speed limit of 9795 RPM, so this will determine the top speed (about 84 mph).
- At 143 mph, the motor needs to spin at 16,700 RPM.

Gearing

- What about torque?
- We wanted 2224 N-m.
- Gears are “mechanical transformers” with $P_{in} \approx P_{out}$, speeds in proportion to the ratio, torques in inverse proportion to the ratios.
- With a final drive ratio of 8.193:1, the motor torque requirement is 2224/8.193 = 271 N-m.
- This is 200 lb-ft. The Leaf is rated to 236 lb-ft.

What else?

- Continuous power also enters for other cases of long-range driving.
- What power is needed to hold 80 mph up a 5% grade?
- For this car, 58 kW.
- What if it is towing, adding another 1000 kg and doubling the frontal area? Power at 80 mph up a 5% grade will be 96 kW.

- You can see where this is going.

Targets so far

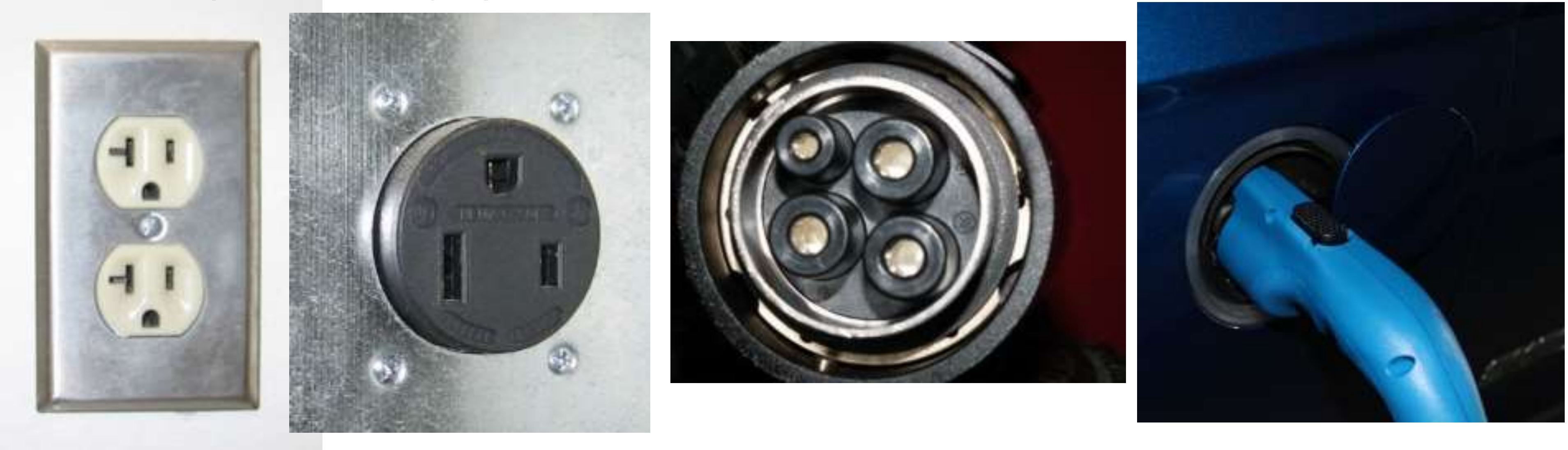
- Gradability determines axle torque.
- Acceleration determines peak power.
- Top speed is linked to continuous power.
- Continuous power is also linked to speed on grade and to towing.
- Strong passenger car performance: 100 kW continuous, 200 kW peak.
- Solid performance: 60 kW continuous, 120 kW peak.
- Few drivers exceed the latter numbers even when the higher ones are possible.
- Motor torque rating related to gear ratio(s).

Limits?

- What limits power?
  - – Motor thermal capability (efficiency is not 100%).
  - – Inverter thermal capability.
  - – Inverter electrical ratings.
  - – Battery pack *C* rates (and thermal management).
  - – Keep the tires on the pavement!
- What limits torque?
  - – Motor torque is inherent to mass – electric motors have a general torque to weight ratio. 2 N-m/kg is a very good value.

Electric Charger Levels

- Level 1 – convenience outlet, 0 to 3.8 kW (typical 1.4 kW).
- Level 2 – dedicated charge point, 4 to 17 kW (typical 6 kW).
- Level 3 – fast charging, 25 kW and up (typical 50 kW).
  - Some are direct dc chargers.
  - Special charge points, not usual at homes or small businesses.



Some rating examples

- Nissan Leaf (2020)
  - Battery options, 40 kWh battery is what we have been exploring
  - 110 kW motor
  - 320 N-m motor torque, from 0 to 3283 RPM
  - Full motor power available, at reduced torque to 9795 RPM
  - Final drive ratio 8.193:1, single speed
  - Unloaded weight 3540 lb
  - Gross vehicle weight rating 4751 lb
  - Drag coefficient 0.28
  - 6.6 kW charger

Some rating examples

- Kia Niro EV (2022)
  - 64 kWh battery
  - 150 kW motor
  - 395 N-m motor torque, from 0 to 3800 RPM
  - Full motor power available, at reduced torque to 8000 RPM
  - Final drive ratio 8.206:1, single speed
  - Unloaded weight 3854 lb
  - Gross vehicle weight rating 4916 lb
  - Drag coefficient 0.29
  - 7.2 kW charger

Some rating examples

- Ford F-150 Lightning (2022)
  - 110 kWh battery
  - 159 kW motor, two in place
  - 1050 N-m motor torque
  - Final drive ratio, manufacturer has not released
  - Unloaded weight 6250 lb
  - Gross vehicle weight rating 8250 lb
  - Drag coefficient, manufacturer has not released
  - 7.7 kW charger

Some rating examples

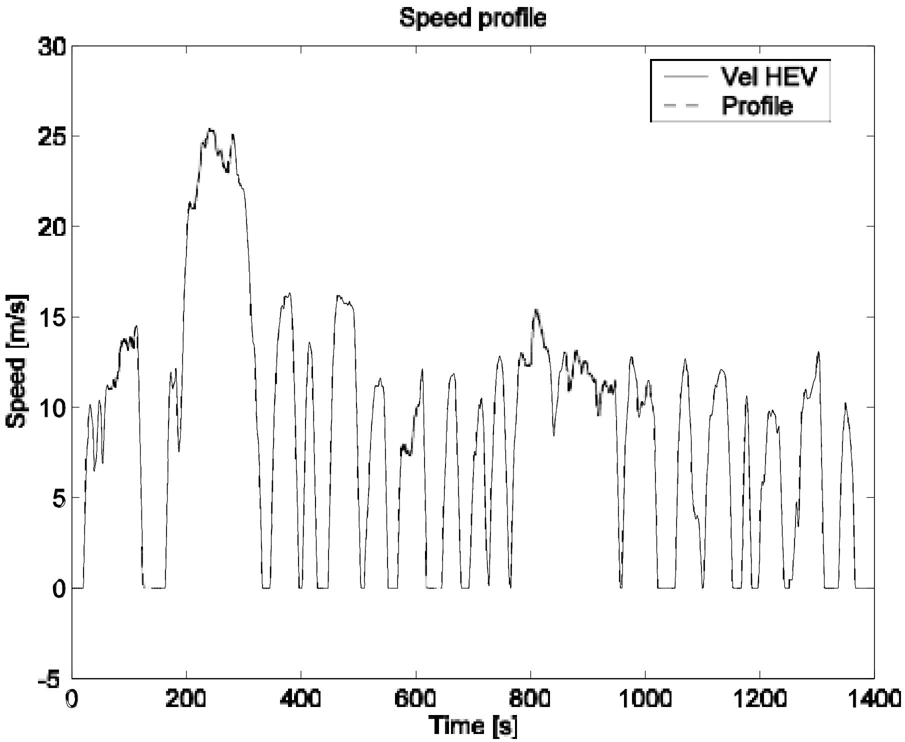
- BYD T3 van (2018)
  - 50 kWh battery
  - 94 kW motor
  - 180 N-m motor torque
  - Final drive ratio ??
  - Unloaded weight 1740 kg
  - Gross vehicle weight rating 2420 kg
  - Drag coefficient ??
  - 6.6 kW charger
  - Gradability >20%
  - Top speed 100 km/h

Some rating examples

- Chrysler Pacifica Plug-In Hybrid (2021)
  - (32 miles EV only range)
  - Motor power ??
  - Motor torque ??
  - Final drive ratio ??
  - Unloaded weight 5010 lb
  - Gross vehicle weight rating 6300 lb
  - Drag coefficient 0.30
  - Charger: probably 4.8 kW

Drive cycles

- In fuel-driven cars, it is difficult to model energy usage.
- Standard *drive cycles* are defined to support consistent comparison.
- Classic example: FTP-75

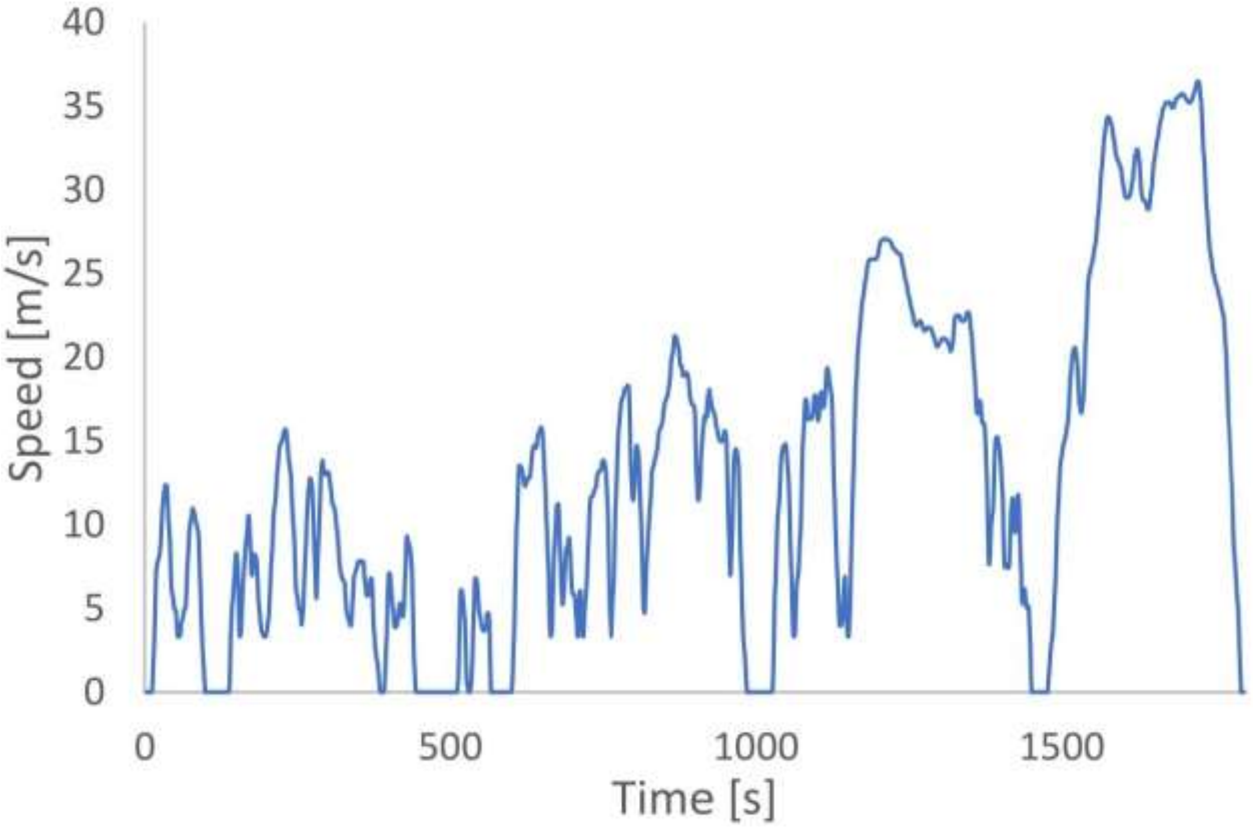


Drive cycles

- FTP-75, the EPA Federal Test Procedure, follows a test developed from instrumenting a postal truck in Philadelphia in the 1970s.
- FTP-75 uses the older Urban Dynamometer Driving Schedule, repeating the first 505 seconds at the end.
- There are many other standard drive cycles:
  - US-06
  - SC-03
  - NEDC
  - WLTP

Drive cycles

- Several “Worldwide Harmonised Light Vehicles Test Procedures”



Beltrami, Iora, Tribioli, Uberti, “Electrification of Compact Off-Highway Vehicles—Overview of the Current State of the Art and Trends,” *Energies 2021, 14, 5565.*

Why?

- Seek to capture realistic driving conditions.
- Trying to support consistent comparisons.
- Try to get results likely to reflect real-world driver experience.

www.fueleconomy.gov

How?

- A trained driver controls the car to track a speed vs. time curve shown on a display.
- A chassis dynamometer sets the load to match traction requirements at each operating point.
- With experience, this is highly consistent and repeatable.

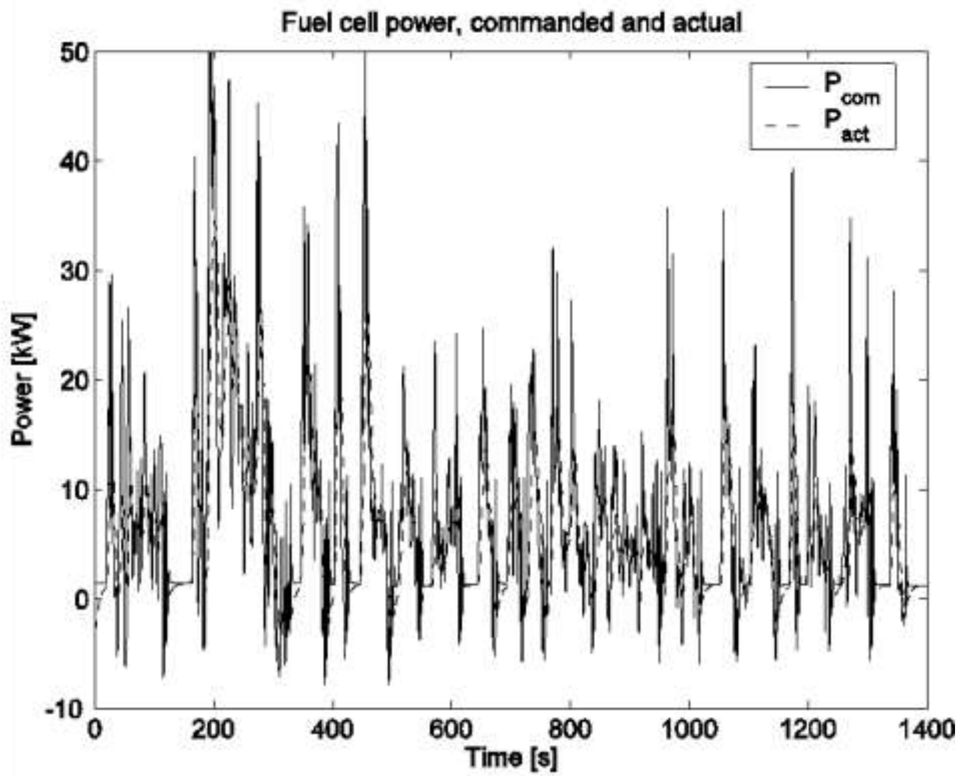
www.fueleconomy.gov

More information

- Standard drive cycles are posted as Excel files.
- See, for example, unece.org. We will post these on the course web site.
- Files include speed, second-by-second, through the test.
- Some also list acceleration. Otherwise, this can be computed from interpolation.

EV aspects

- For an electric car, speed and acceleration vs. time can be used in the basic force and power characteristics.



EV aspects

- This gives force or power vs. time.
- We know the required traction output.
- A spreadsheet computation can keep track of output energy used in each second.
- For an EV, it is straightforward to estimate energy usage over (any) complete drive cycle.
- With good motor and battery models, we can estimate energy *input*.
- For a fueled car, this is not really possible – the direct driver measurement makes more sense.

EV aspects

- Any of us can estimate the effects of various vehicle parameters and design choices on mileage for a specific drive cycle.
- EV performance evaluation starts with models and analysis.
- Tests on roadways can validate expected results.

- One simple test: Coastdown on level road (should show force vs. time).

Batteries

Battery energy and power density

- Energy stored per unit mass and per unit volume are key measures for batteries.
- Energy rate (power) per unit mass and volume or also important.
- The capacity rate (*C* rate) sets a reference point for energy and power.
- Also vital: Cycle life, cycle efficiency, self discharge, thermal capability.

Perspective

- Global battery market in 2019 was more than $100 billion. (http://www.grandviewresearch.com/industry-analysis/battery-market)
- Of this, about 30% lead acid and about 30% lithium ion.
- Familiar use for lead-acid batteries: vehicle starting, lighting, and ignition (SLI).
- Massive use: Backup and auxiliary power for telecommunications and computing.

Rechargeable types

- Rechargeable batteries (*secondary* batteries) have been around for more than 150 years.
- Lead-acid batteries date to 1859. The overall reaction involves metallic lead, lead oxide, and sulfuric acid on the one side, with lead sulfate and water on the other side.
- Nickel-iron batteries (1901) were favored by Edison and used in Detroit Electric and other electric cars.

Courtesy I. Pitel

Rechargeable types

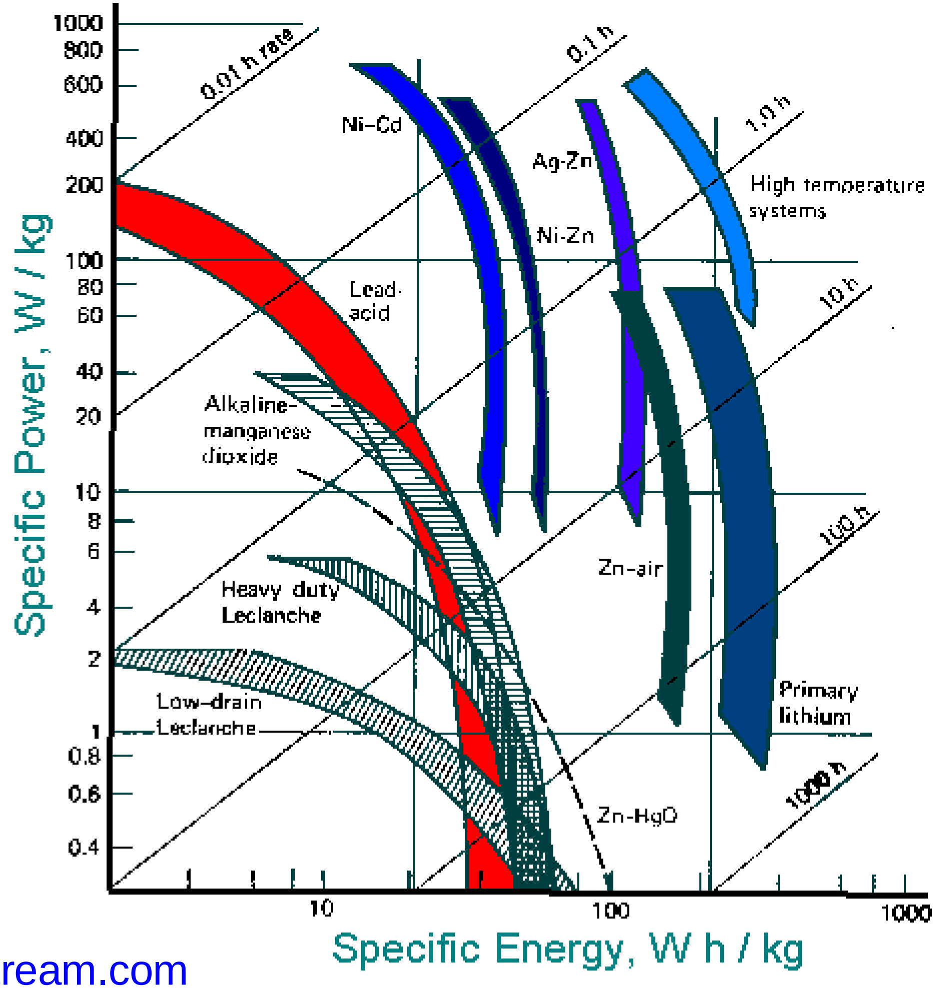
- Nickel cadmium batteries (NiCd) (1899) can have high specific power, with common commercial devices rated to 20*C*.
- Cadmium is extremely toxic, and NiCd batteries are phasing out.
- Nickel-metal-hydride (NiMH) batteries (1967) avoid cadmium but are near-drop-in replacements for NiCd.
- They are still common in hybrid cars because the power density can be higher than for lithium cells.

A few types (various sources, includes www.powerstream.com)

Type	Cell voltage (room temp)	Energy density	Power density	Self discharge	Charge efficiency (typical)	Cycle life
Lead acid	2.04 V	35 Wh/kg	600 W/kg	16% per month	80%	200
Nickel cadmium	1.30 V	60 Wh/kg	600 W/kg	10% per month	70%	>5000
Nickel metal hydride	1.35 V	100 Wh/kg	600 W/kg	10% per month (but 20% first day)	75%	500
Sodium sulfur	2.08 V (350°C)	110 Wh/kg	150 Wh/kg	--	85%	4500
Vanadium redox	1.41 V	20 Wh/kg	--	--	75%	>20,000
Lithium ion	Variable to 4.1 V	200 Wh/kg	300 W/kg	2% per month	90%+	2000
Lithium ion (polymer)	Variable to 4.1 V	200 Wh/kg	400 Wh/kg	5% per month	90%+	500

Ragone Plot

- Specific power vs. specific energy
- Notice the log-log scales



www.powerstream.com

Present, future

- Although there are many rechargeable battery chemistries, lead acid, NiMH, and lithium-ion cells are the only ones in broad commercial application.
- Lead-acid batteries for SLI, NiMH for power-dense applications, Li-ion for energy dense applications.
- Future? Dozens of chemistries in various lab stages.
  - The ultimate could be related to a combination of lithium (the most electropositive element) and fluorine (the most electronegative element. Could yield a 6 V cell.
  - Mg-ion and Na-ion cells. Both in active development.
  - Lithium-air batteries are more akin to fuel cells. As batteries, they need much improvement on reversibility, efficiency, and other challenges.