Women's Transportation Seminar (WTS)

- Organization dedicated to creating a more diverse transportation industry through the advancement of women. UC Davis has a local student chapter that organizes many different events.
- If you're interested in being a member: https://forms.gle/mde41zVm24bBihQR8
- Join the list-serv: http://eepurl.com/hb6GN9
- Info-session for Kimley-Horn Engineering and Planning Thursday April 7 at 7pm, Ghausi 1007

EV Showcase cancelled

- Picnic day showcase cancelled but a separate event happening in Southside Park in Sac on 4/24 (driveelectricearthday.org)
- Possibly will organize a different showcase event…

Vehicle efficiency

Lecture 5

Dan Sperling
Alan Jenn
Spring 2022

Efficiency versus Efficacy

- Energy efficiency is strictly defined as a dimensionless number (and <1)
  - Units of numerator are the same as units of denominator

$$Efficiency = \frac{\text{Work or Energy Output}}{\text{Energy Input}}$$

- Efficiency is often used to refer to the ratio of output to input even if they don’t have the same units:
  - For example: miles per gallon, lumens per watt
  - Efficacy is the correct term to use here

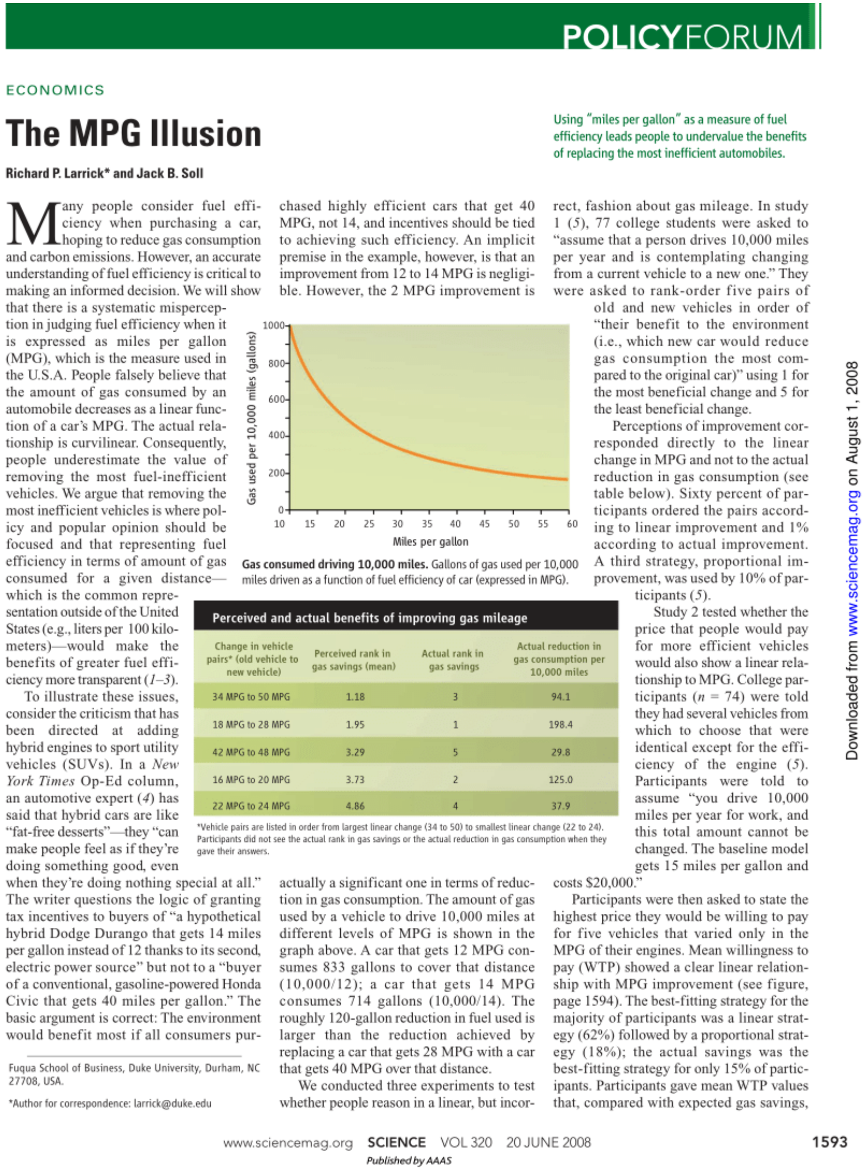
$$Efficacy = \frac{\text{Service Output}}{\text{Energy Input}}$$

Gasoline fuel efficiency

- Gasoline fuel efficiency describes the distance a car can drive given some amount of fuel—this allows us to directly compare between different vehicles
- In the United States we measure fuel efficiency in:
  - Miles per gallon (MPG), this indicates the number of miles you can drive on 1 gallon of gasoline
- Most other countries in the world measure fuel efficiency as:
  - Liters per 100 km (L/100km), this indicates the number of liters of gasoline it takes to drive 100 kilometers

The MPG illusion

- MPG scales non-linearly with fuel consumption for a set distance—this makes calculating fuel savings *very* counter-intuitive!
- Apparently, the topic is so confusing that someone was able to publish a short paper about it in *Science*



POLICYFORUM

ECONOMICS

The MPG Illusion

Using "miles per gallon" as a measure of fuel efficiency leads people to undervalue the benefits of replacing the most inefficient automobiles.

Richard P. Larrick* and Jack B. Soll

Many people consider fuel efficiency when purchasing a car, hoping to reduce gas consumption and carbon emissions. However, an accurate understanding of fuel efficiency is critical to making an informed decision. We will show that there is a systematic misperception in judging fuel efficiency when it is expressed as miles per gallon (MPG), which is the measure used in the U.S.A. People falsely believe that the amount of gas consumed by an automobile decreases as a linear function of a car's MPG. The actual relationship is curvilinear. Consequently, people underestimate the value of removing the most fuel-inefficient vehicles. We argue that removing the most inefficient vehicles is where policy and popular opinion should be focused and that representing fuel efficiency in terms of amount of gas consumed for a given distance—which is the common representation outside of the United States (e.g., liters per 100 kilometers)—would make the benefits of greater fuel efficiency more transparent (*1*–*3*).

To illustrate these issues, consider the criticism that has been directed at adding hybrid engines to sport utility vehicles (SUVs). In a *New York Times* Op-Ed column, an automotive expert (*4*) has said that hybrid cars are like "fat-free desserts"—they "can make people feel as if they're doing something good, even when they're doing nothing special at all." The writer questions the logic of granting tax incentives to buyers of "a hypothetical hybrid Dodge Durango that gets 14 miles per gallon instead of 12 thanks to its second, electric power source" but not to a "buyer of a conventional, gasoline-powered Honda Civic that gets 40 miles per gallon." The basic argument is correct: The environment would benefit most if all consumers purchased highly efficient cars that get 40 MPG, not 14, and incentives should be tied to achieving such efficiency. An implicit premise in the example, however, is that an improvement from 12 to 14 MPG is negligible. However, the 2 MPG improvement is actually a significant one in terms of reduction in gas consumption. The amount of gas used by a vehicle to drive 10,000 miles at different levels of MPG is shown in the graph above. A car that gets 12 MPG consumes 833 gallons to cover that distance (10,000/12); a car that gets 14 MPG consumes 714 gallons (10,000/14). The roughly 120-gallon reduction in fuel used is larger than the reduction achieved by replacing a car that gets 28 MPG with a car that gets 40 MPG over that distance.

We conducted three experiments to test whether people reason in a linear, but incorrect, fashion about gas mileage. In study 1 (*5*), 77 college students were asked to "assume that a person drives 10,000 miles per year and is contemplating changing from a current vehicle to a new one." They were asked to rank-order five pairs of old and new vehicles in order of "their benefit to the environment (i.e., which new car would reduce gas consumption the most compared to the original car)" using 1 for the most beneficial change and 5 for the least beneficial change.

Perceptions of improvement corresponded directly to the linear change in MPG and not to the actual reduction in gas consumption (see table below). Sixty percent of participants ordered the pairs according to linear improvement and 1% according to actual improvement. A third strategy, proportional improvement, was used by 10% of participants (*5*).

Study 2 tested whether the price that people would pay for more efficient vehicles would also show a linear relationship to MPG. College participants (n = 74) were told they had several vehicles from which to choose that were identical except for the efficiency of the engine (*5*). Participants were told to assume "you drive 10,000 miles per year for work, and this total amount cannot be changed. The baseline model gets 15 miles per gallon and costs $20,000."

Participants were then asked to state the highest price they would be willing to pay for five vehicles that varied only in the MPG of their engines. Mean willingness to pay (WTP) showed a clear linear relationship with MPG improvement (see figure, page 1594). The best-fitting strategy for the majority of participants was a linear strategy (62%) followed by a proportional strategy (18%); the actual savings was the best-fitting strategy for only 15% of participants. Participants gave mean WTP values that, compared with expected gas savings,

Gas consumed driving 10,000 miles. Gallons of gas used per 10,000 miles driven as a function of fuel efficiency of car (expressed in MPG).

Perceived and actual benefits of improving gas mileage

Change in vehicle pairs* (old vehicle to new vehicle)	Perceived rank in gas savings (mean)	Actual rank in gas savings	Actual reduction in gas consumption per 10,000 miles
34 MPG to 50 MPG	1.18	3	94.1
18 MPG to 28 MPG	1.95	1	198.4
42 MPG to 48 MPG	3.29	5	29.8
16 MPG to 20 MPG	3.73	2	125.0
22 MPG to 24 MPG	4.86	4	37.9

*Vehicle pairs are listed in order from largest linear change (34 to 50) to smallest linear change (22 to 24). Participants did not see the actual rank in gas savings or the actual reduction in gas consumption when they gave their answers.

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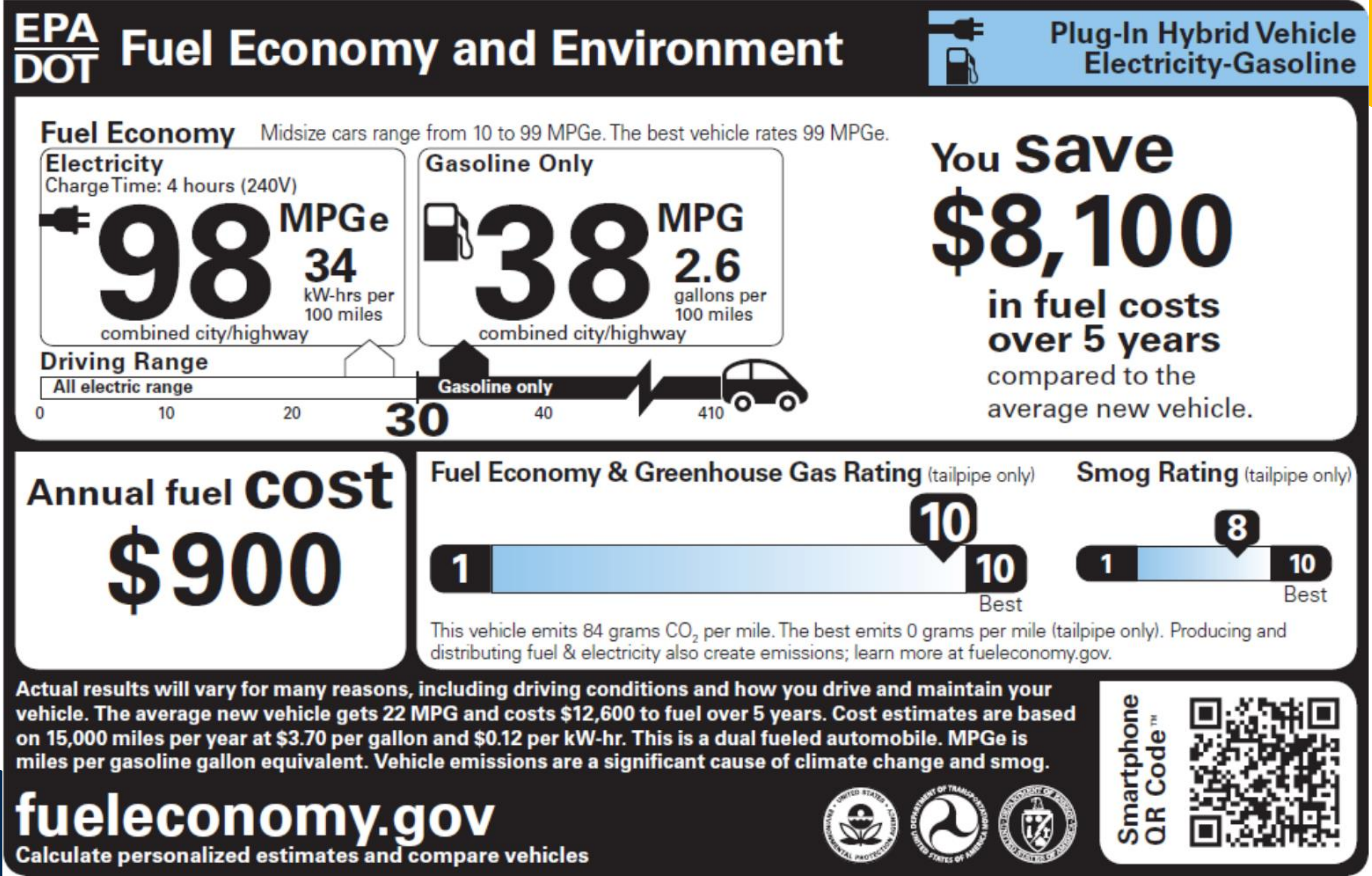
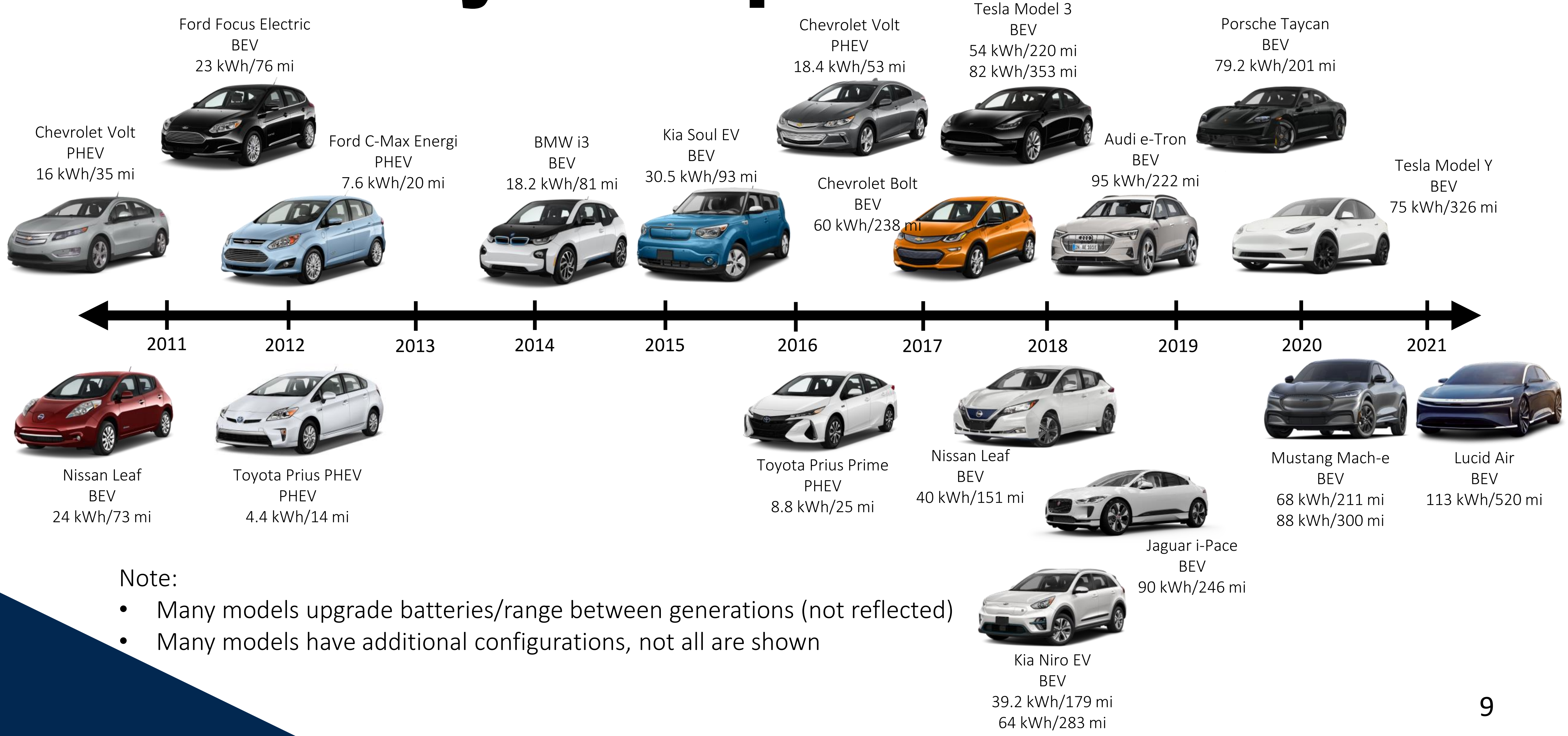

EPA DOT
Fuel Economy and Environment
Plug-In Hybrid Vehicle Electricity-Gasoline
Fuel Economy
Midsize cars range from 10 to 99 MPGe. The best vehicle rates 99 MPGe.
Electricity
Charge Time: 4 hours (240V)
98 MPGe
34 kW-hrs per 100 miles
combined city/highway
Gasoline Only
38 MPG
2.6 gallons per 100 miles
combined city/highway
Driving Range
All electric range
Gasoline only
0
10
20
30
40
410
You save $8,100 in fuel costs over 5 years compared to the average new vehicle.
Annual fuel cost
$900
Fuel Economy & Greenhouse Gas Rating (tailpipe only)
10
1
10
Best
Smog Rating (tailpipe only)
8
1
10
Best
This vehicle emits 84 grams CO_2 per mile. The best emits 0 grams per mile (tailpipe only). Producing and distributing fuel & electricity also create emissions; learn more at fueleconomy.gov.
Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs $12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $3.70 per gallon and $0.12 per kW-hr. This is a dual fueled automobile. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.
fueleconomy.gov
Calculate personalized estimates and compare vehicles
Smartphone QR Code™

What is MPGe?

- MPGe stands for miles per gallon equivalent, devised as a way to compare gasoline cars to electric cars (since EVs don't consume any gas…)
- Convert the electricity used by the EV into "gasoline" based on the energy content of the fuel:
  - 1 gallon of gasoline = 33.7 kWh electricity
- Consider some examples of efficiency:

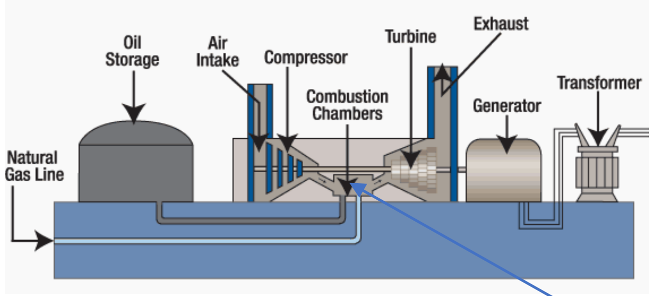
Efficiency examples



Note:

- Many models upgrade batteries/range between generations (not reflected)
- Many models have additional configurations, not all are shown

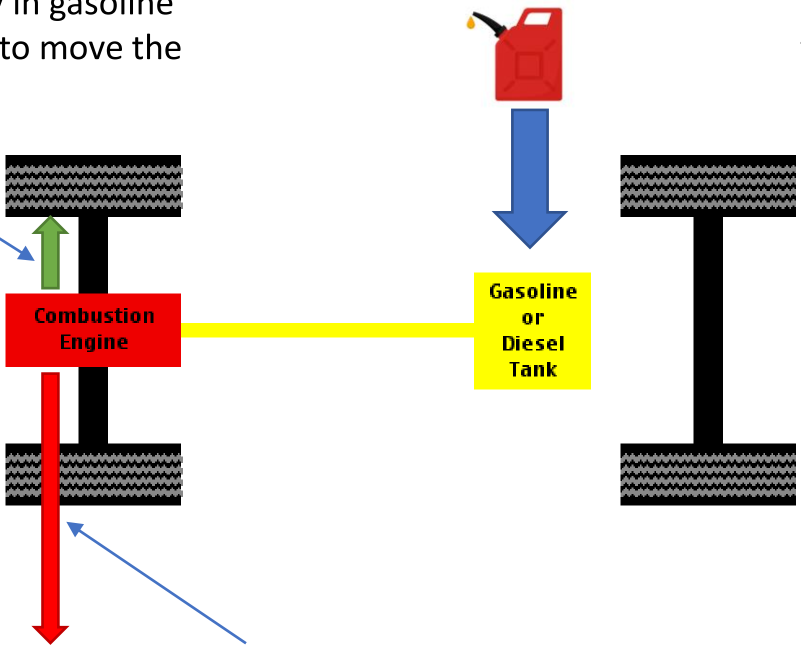
EVs are more efficient than gasoline…kind of!



This is about 1 kWh per mile

~.03-.04 gal per mile

20%-35% of energy in gasoline translated to work to move the vehicle

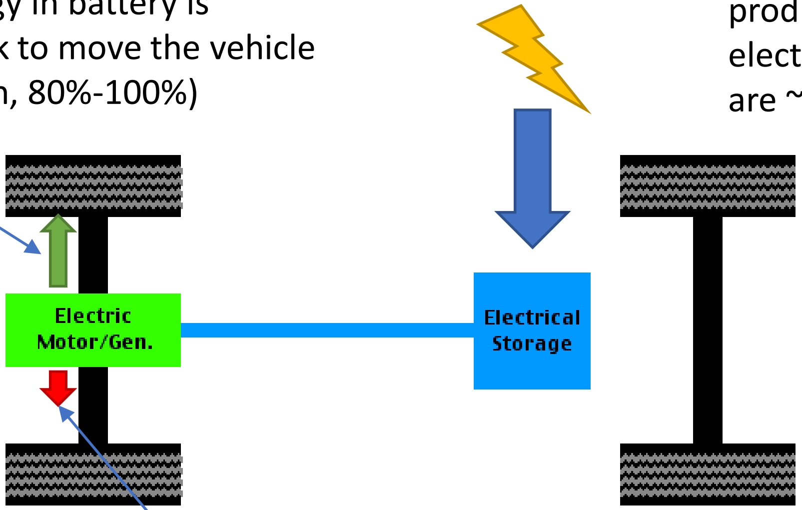


65%-80% of energy in gasoline **lost** to heat in combustion and friction

~.35 kWh per mile

Depends on what is producing the electricity, NGCC plants are ~50%-60% efficient

60%-75% of energy in battery is translated to work to move the vehicle (higher with regen, 80%-100%)

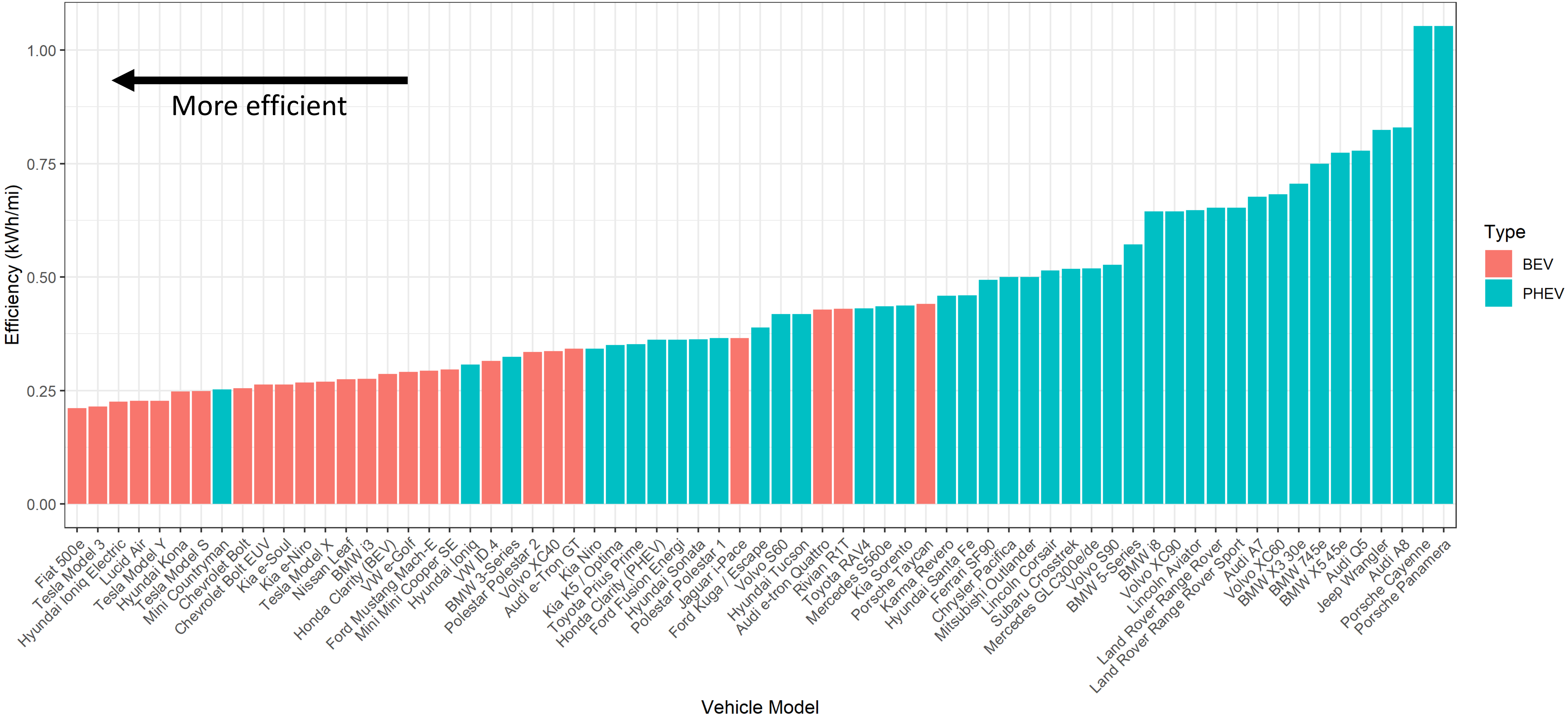


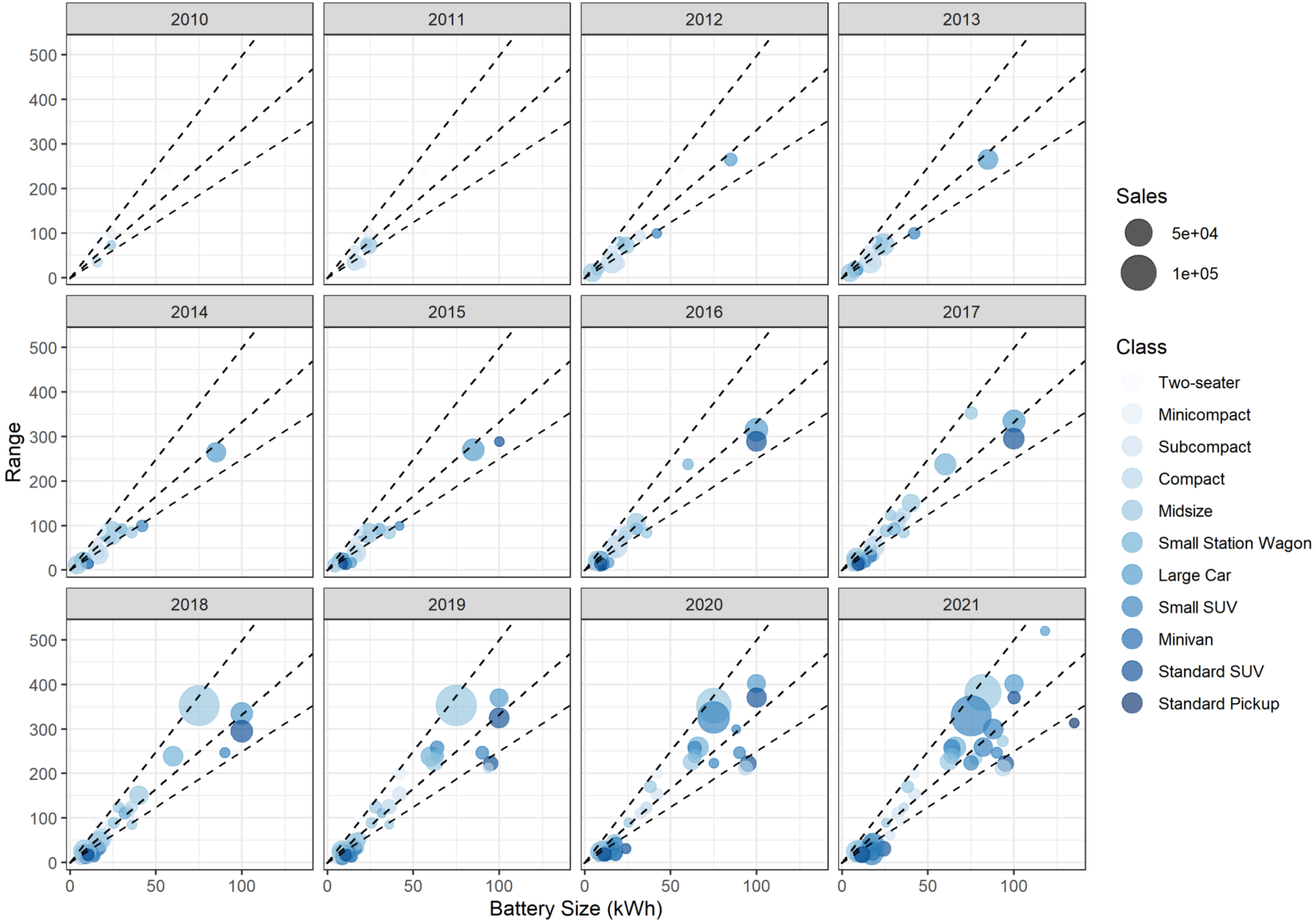
25%-40% of energy from battery is **lost** to friction (less with regen, 0%-20%)

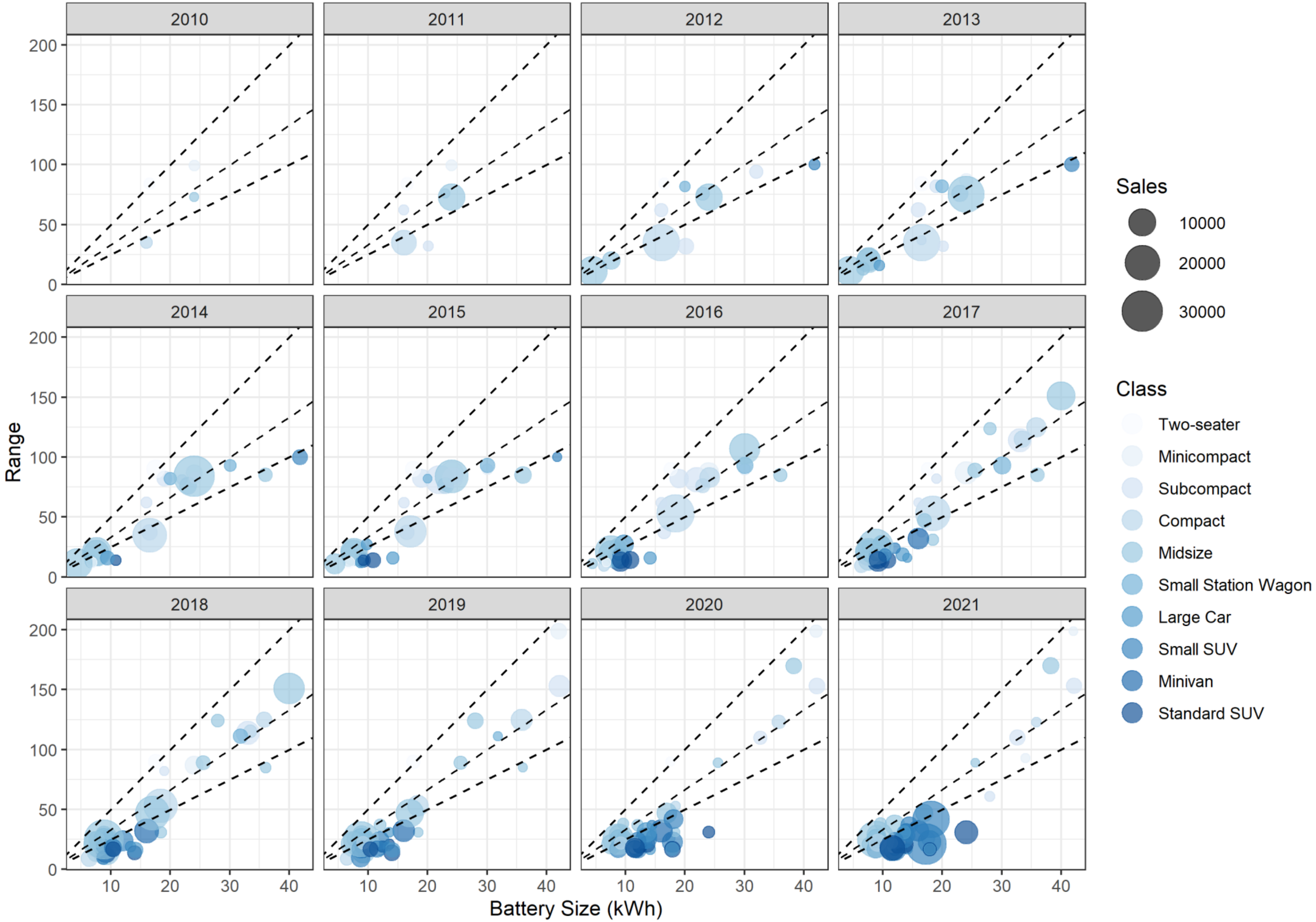
MPGe vs mi/kWh

- MPGe doesn't really make sense! We don't "combust" the electricity—so how do we measure EV efficiency?
- Similar to the concept of "amount of gasoline to travel a certain distance"…what is the "amount of electricity to travel a certain distance"?
- Miles per kWh is the same as MPG, though I would much prefer kWh per mile (think MPG illusion, let's get away from miles in the numerator while we have the chance!!)

EV efficiencies



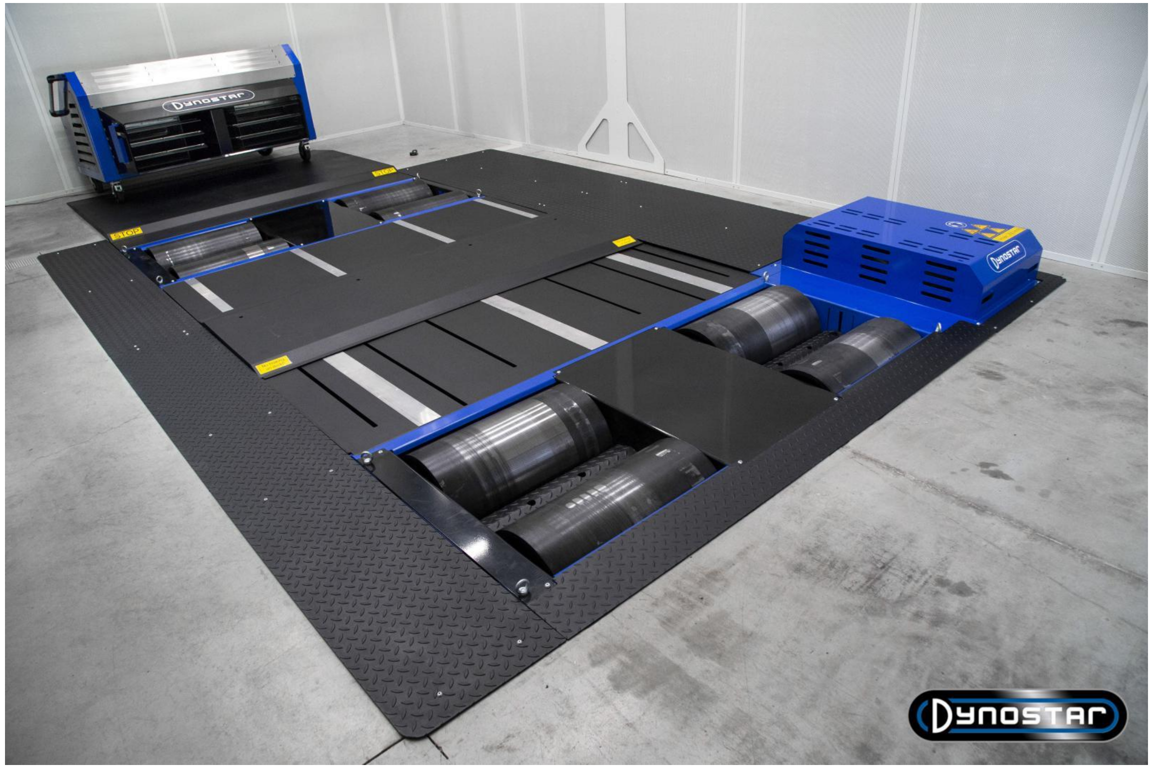

2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Range
Battery Size (kWh)
0
100
200
300
400
500
0
50
100
Sales
5e+04
1e+05
Class
Two-seater
Minicompact
Subcompact
Compact
Midsize
Small Station Wagon
Large Car
Small SUV
Minivan
Standard SUV
Standard Pickup



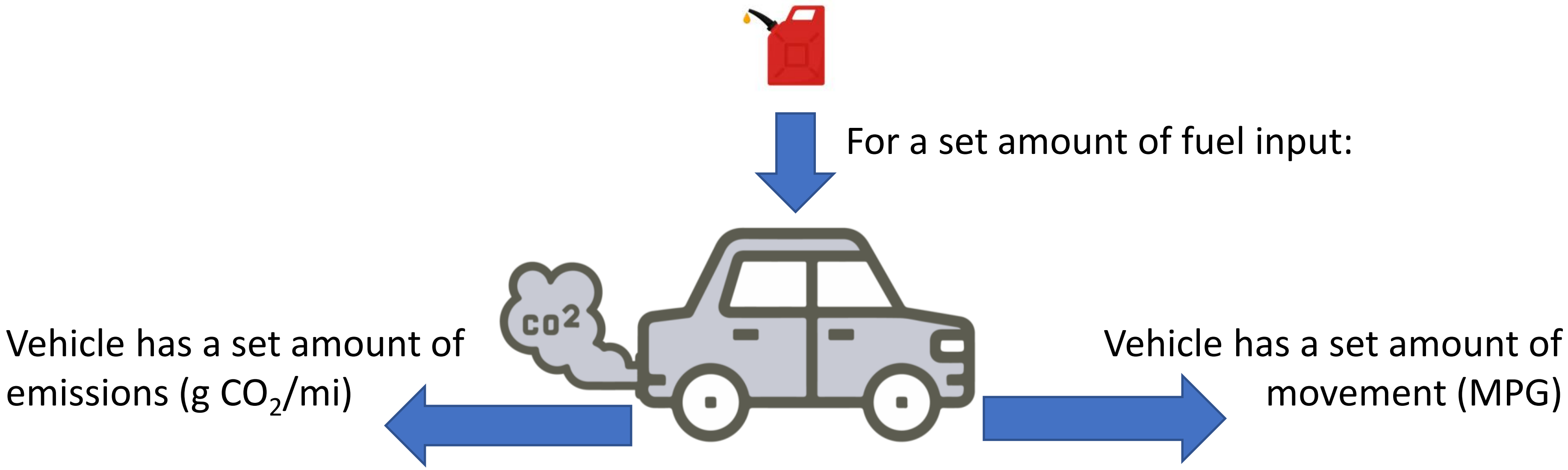
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Range
Battery Size (kWh)
0
50
100
150
200
10
20
30
40
Sales
10000
20000
30000
Class
Two-seater
Minicompact
Subcompact
Compact
Midsize
Small Station Wagon
Large Car
Small SUV
Minivan
Standard SUV

How are efficiencies calculated?

- Dynamometers ("dyno") are measurement tools for the torque and RPM of a vehicle (its like a treadmill for cars!)
- The US EPA uses this to also measure emissions under standardized "testing" cycles

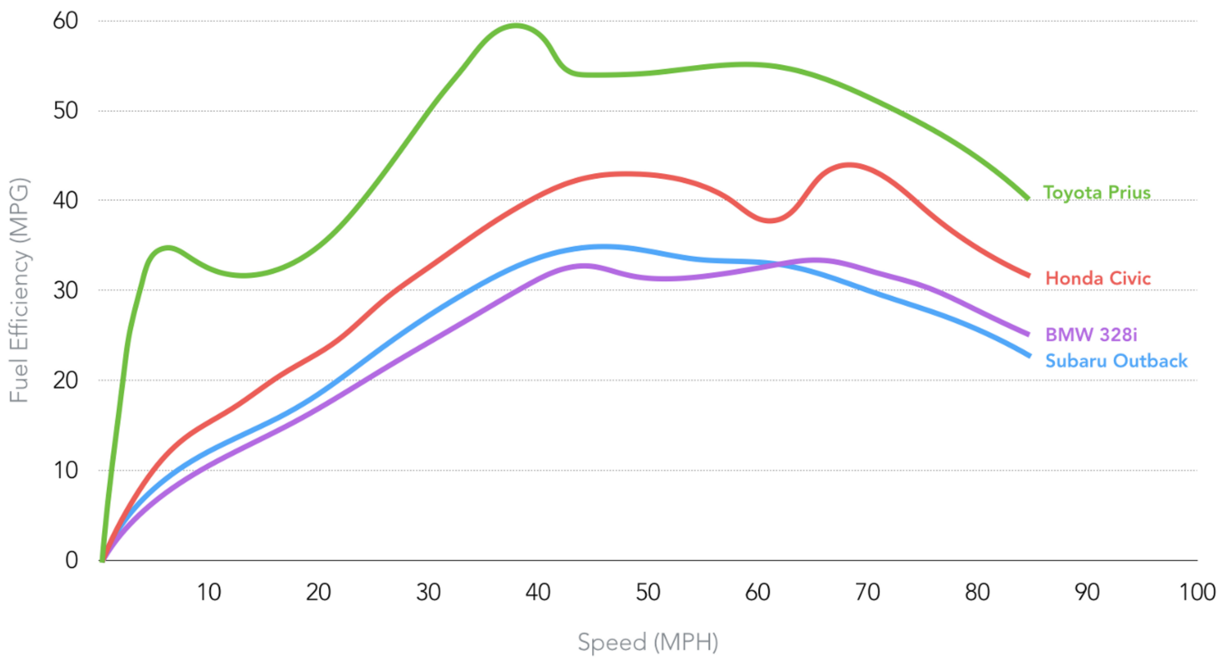


The relationship between emissions and vehicle efficiency



- Even as the fuel efficiency of the vehicle changes, the relationship between MPG and emissions per mile stays constant
- The EPA uses the following conversion metric: 8887 grams CO_2 per mile

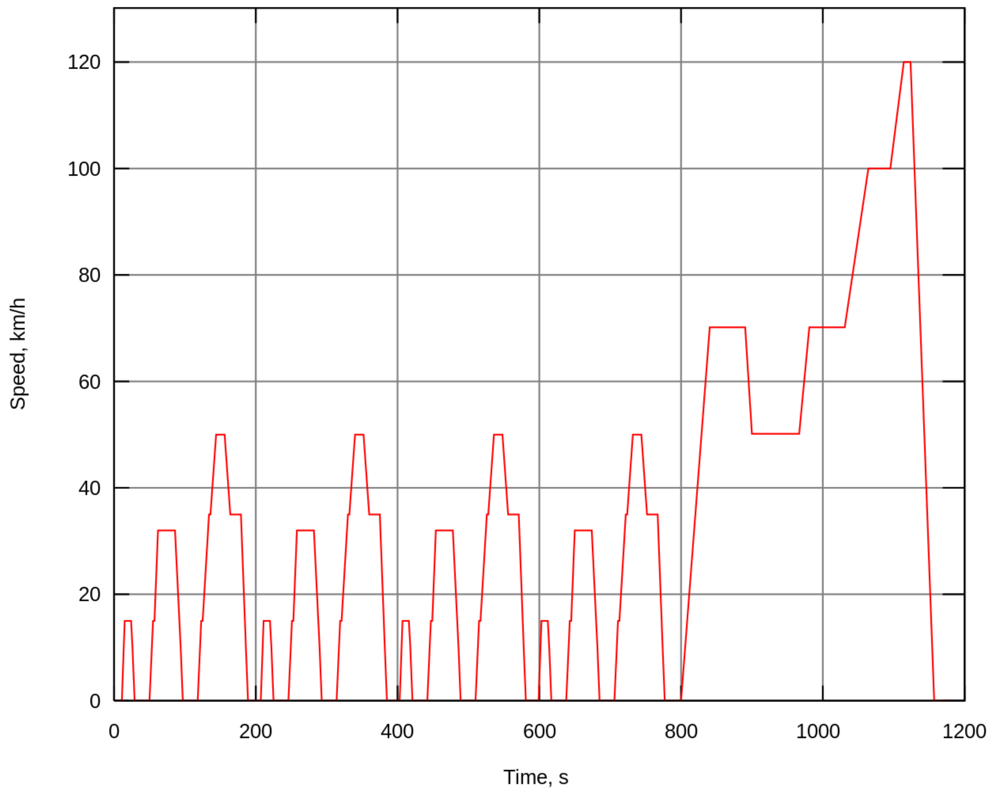
Highway vs city driving



- Vehicle efficiency varies at different vehicle speeds
- For gasoline cars, optimal speeds tend to be around 50-60 MPH while for EVs, optimal speeds tend to be ~30 MPH

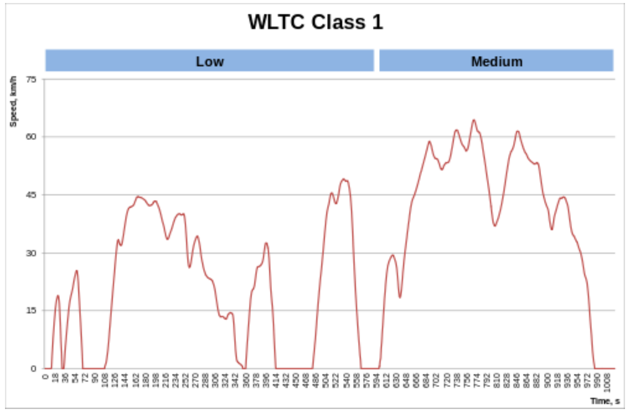
New European Driving Cycle (NEDC)

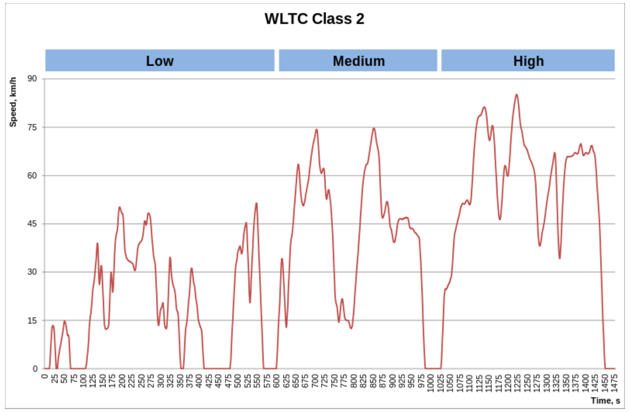
- Meant to represent the typical car usage in Europe—in reality the efficiencies are essentially unachievable
- Dyno rollers attempt to emulate resistances from aerodynamic drag and vehicle mass
- Four Urban Driving Cycles (UDC/ECE-15): driving conditions of busy European cities (low load, low exhaust gas temperatures, max speed of 50 km/h)
- One Extra-urban driving cycle (EUDC): more aggressive high-speed driving (max-speed of 90-120 km/h)

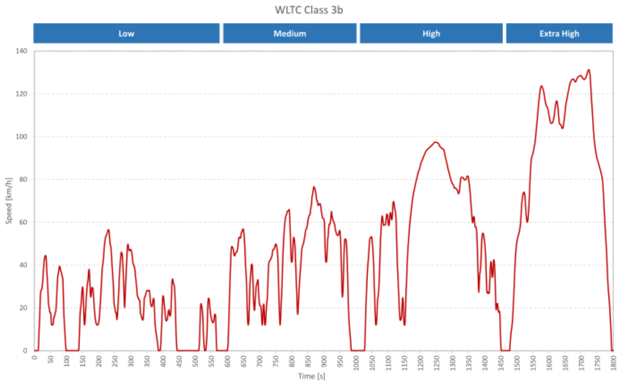


Worldwide Harmonised Light Vehicles Test Procedure (WTLP)

- Worldwide standard to replace NEDC—attempts to better match laboratory estimates and emissions with on-road driving conditions
- Test procedures meant to standardize across other countries
- Drive cycle profile is more dynamic, reaches a greater distance (23.25 km vs 11 km in NEDC) and higher maximum velocity at 131 km/hr
- Different test cycles depending on vehicle class





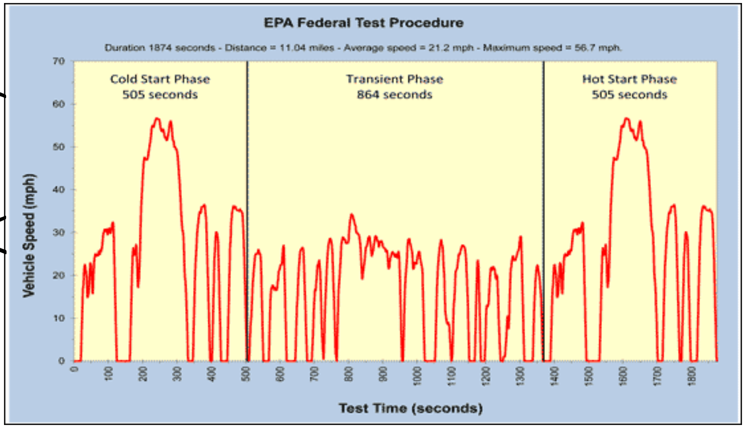


EPA Test Cycles

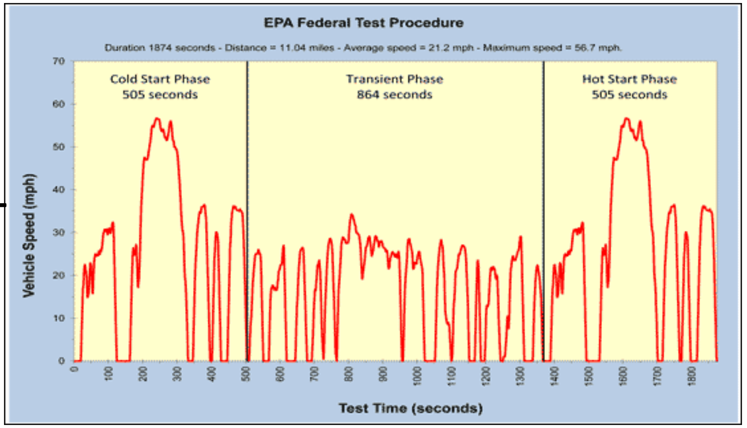
- EPA has its own test cycles to determine the efficiency and emissions associated with different vehicle models
- Prior to 2007, EPA used a city-cycle and a highway-cycle; the fuel economy associated with this combination is known as the **2-cycle test**. Highly conservative driving, known to overstate fuel efficiency figures.
- Beginning in 2008, EPA added three additional tests (high speed, air conditioning, and cold temperature); the combination of these tests is known as the **5-cycle test**. Better represents real-world efficiencies, though still conservative.

EPA 5-cycle test procedures

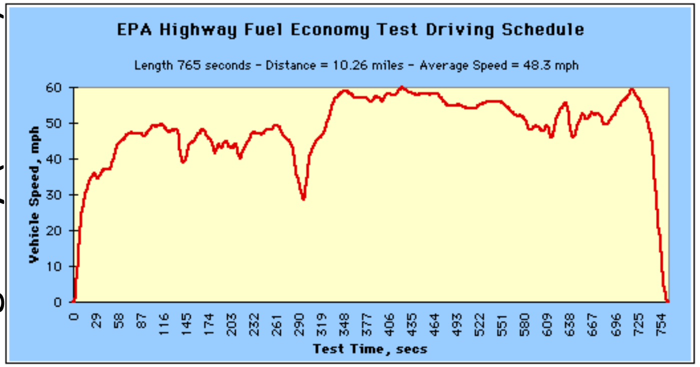
City (UDDS)



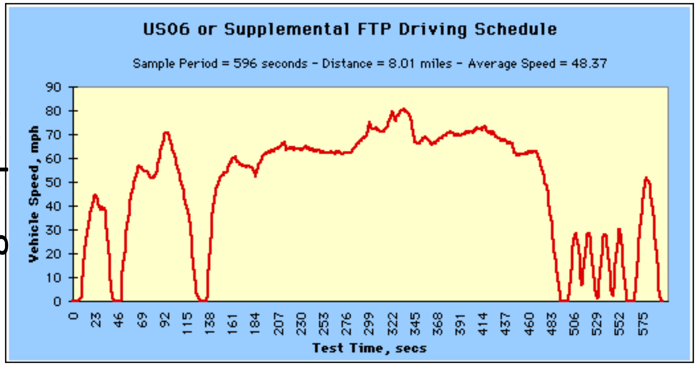
Cold Temperature



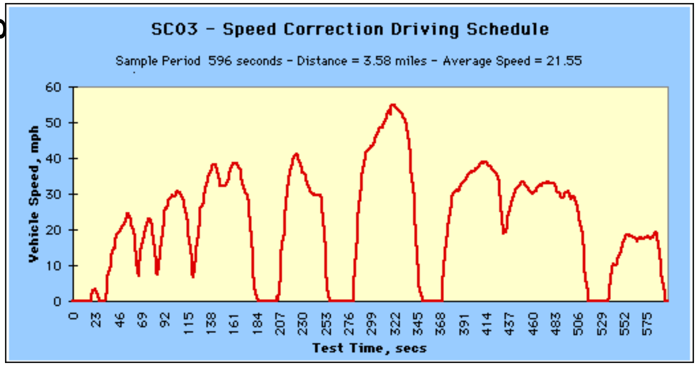
Highway (HWFET)



High Speed



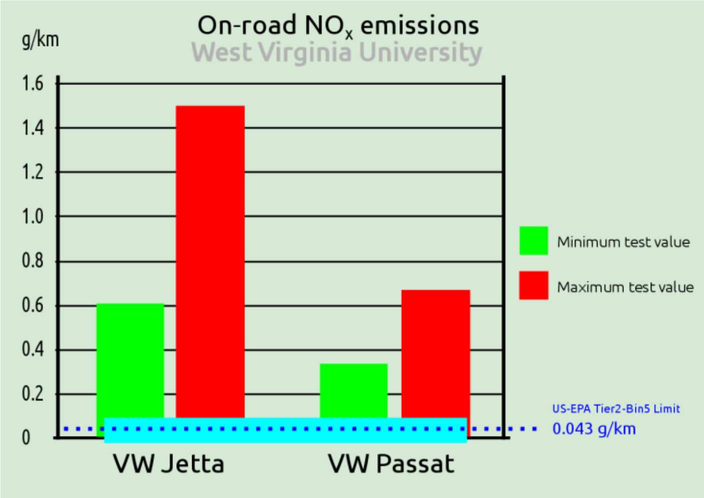
Air Conditioning

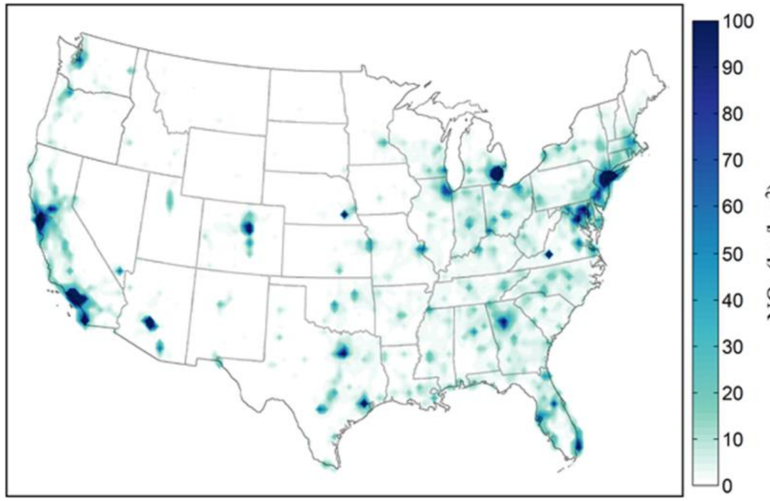


Test Cycle Attributes	Test Cycle				
	City	Highway	High Speed	A/C	Cold Temp
Trip Type	Low speeds in stop-and-go urban traffic	Free-flow traffic at highway speeds	Higher speeds; harder acceleration & braking	A/C use under hot ambient conditions	City test w/ colder outside temp.
Top Speed	56 mph	60 mph	**80 mph**	54.8 mph	56 mph
Average Speed	21.2 mph	48.3 mph	48.4 mph	21.2 mph	21.2 mph
Max. Acceleration	3.3 mph/sec	3.2 mph/sec	**8.46 mph/sec**	5.1 mph/sec	3.3 mph/sec
Simulated Distance	11 mi.	10.3 mi.	8 mi.	3.6 mi.	11 mi.
Time	31.2 min.	12.75 min.	9.9 min.	9.9 min.	31.2 min.
Stops	23	None	4	5	23
Idling time	18% of time	None	7% of time	19% of time	18% of time
Engine Startup*	**Cold**	Warm	Warm	Warm	**Cold**
Lab temperature	68ºF–86ºF			**95ºF**	**20ºF**
Vehicle air conditioning	Off	Off	Off	**On**	Off
Vehicle heater	Off	Off	Off	Off	**On**

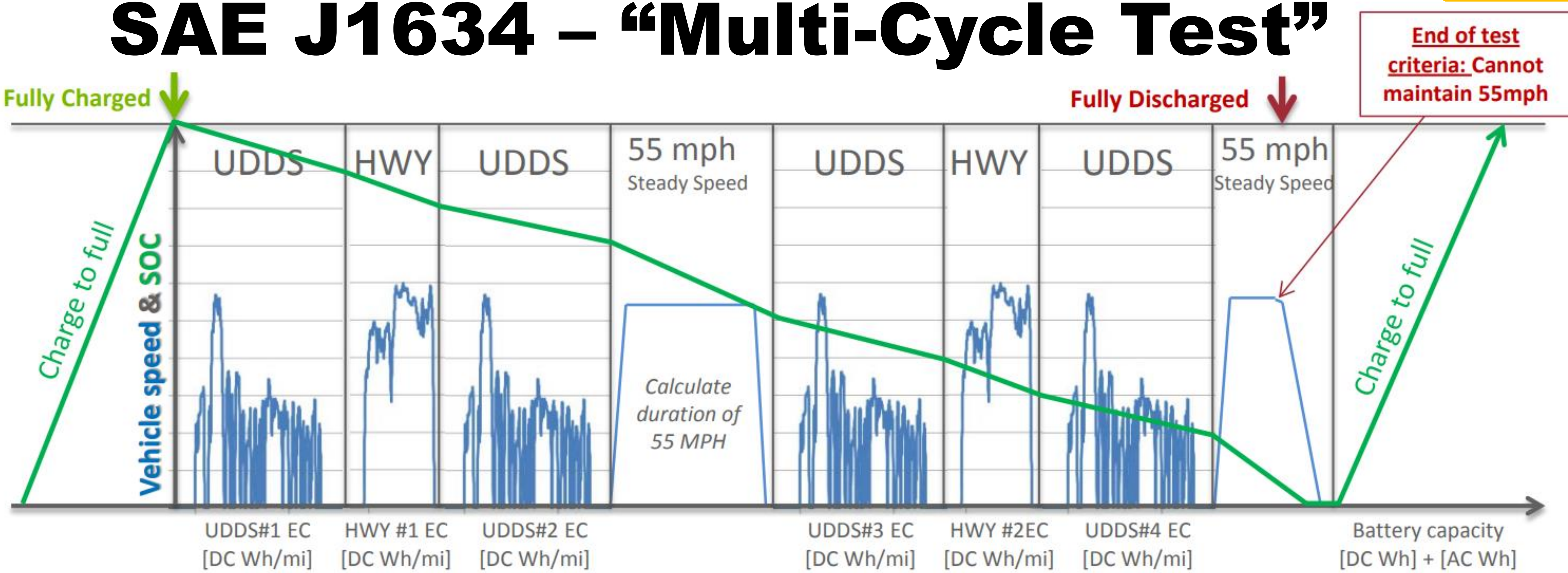
Volkswagen "Dieselgate" Scandal

- CARB discovered emissions discrepancies between EU and US models of vehicles—specifically from live road tests on diesel cars
- It was discovered that Volkswagen Group deliberately deployed software to 11 million vehicles to activate emissions controls *only during testing*
- Criminal charges on executives, $2.8 billion in criminal fines, $1.5 billion in civil penalties





SAE J1634 – "Multi-Cycle Test"



- Electric vehicles use a multi-cycle test as seen above to determine their range and efficiency

Tesla and EPA's adjustment factor

In 2021, *Car and Driver* compared the performance of the Porsche Taycan 4S versus the Tesla Model S

Tested Highway Range: 220 mi

EPA Highway Range: 227 mi

Tested Highway Range: 320 mi

EPA Highway Range: 402 mi

Tesla range and efficiency have *consistently trumped other vehicles* in their class! Focused on **improving efficiencies** of various vehicle components: inverter, motor, battery, electric oil pump, etc.

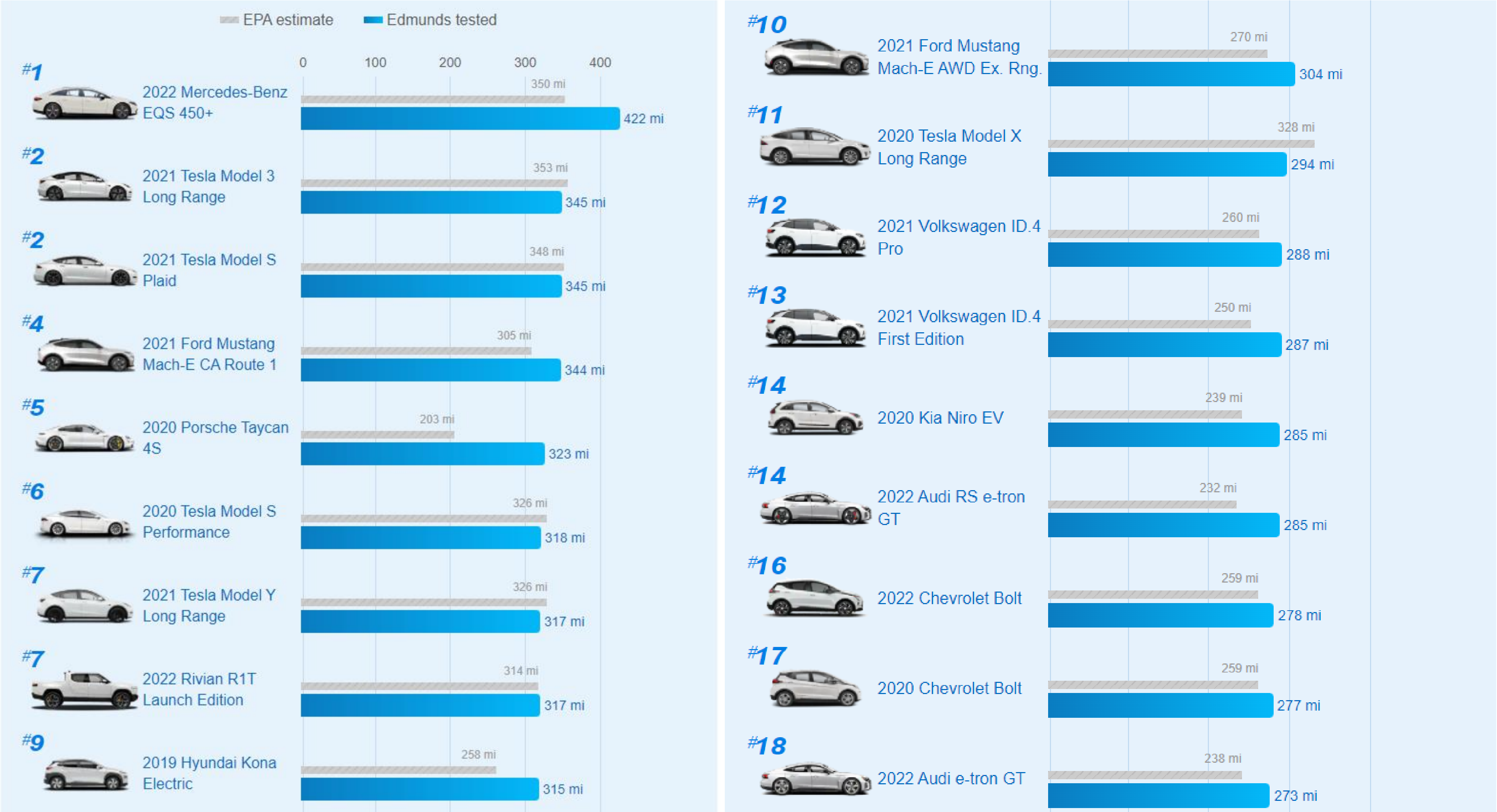
- **But!** Tesla also takes advantage of the EPA adjustment factor:
- After the MCT, the EPA automatically adjusts the range of EVs down by 30% (to better replicate real-world conditions)
- However, automakers are given the option to run three additional drive cycles to generate an alternative adjustment factor
  - Only Tesla and Audi do this!
- This leads to range adjustments that can net as high as 6% on the sticker value (can be an extra 30-40 miles!)

Real world efficiency

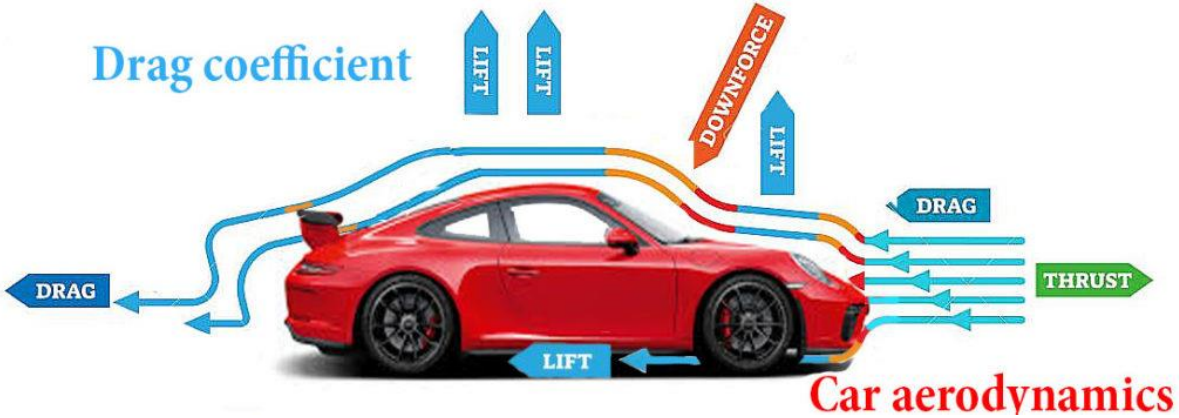
"Your mood affects your fuel efficiency more than almost any other single thing"
– Adam Savage (Mythbusters)

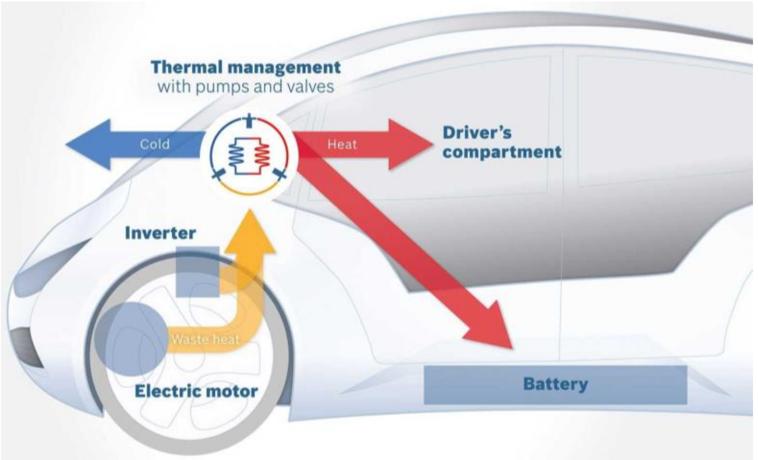
https://youtu.be/4u7I-6AcA00?t=350

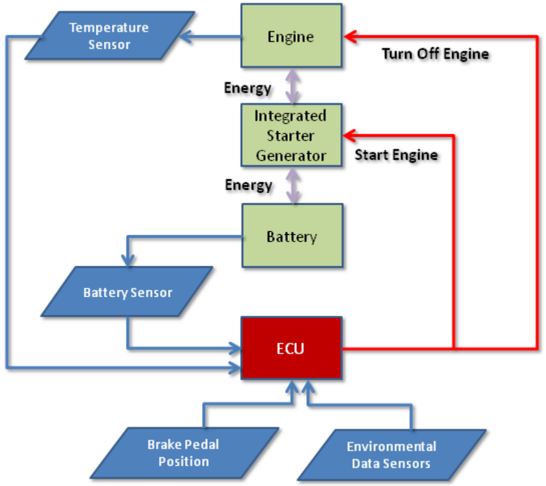
Real-world vs EPA rating



On-cycle vs off-cycle







Improving fuel efficiency in gas cars

Other Technologies

Technology	Efficiency Increase
Reducing vehicle weight means less energy is needed to propel the vehicle. Weight reduction and powertrain downsizing can significantly improve fuel economy.	1%–3% per 5% reduction in weight[1]
Low rolling resistance tires reduce the parasitic energy loss from tires rolling under load.	Up to 4%[1]

Hybrid Technologies

Technology	Efficiency Increase
Stop-Start systems stop the engine when the car comes to a stop and automatically restart it to resume driving. This reduces wasted fuel from idling.	2%[1]
Mild hybrids use Stop-Start technologies and a small regenerative braking system that can recover and reuse small amounts of energy lost from braking.	3%–6%[1]
Hybrids use Stop-Start, regenerative braking, and larger electric motors and batteries to reduce fuel use, especially in stop-and-go driving.	27%–35%[1]

Transmission Technologies

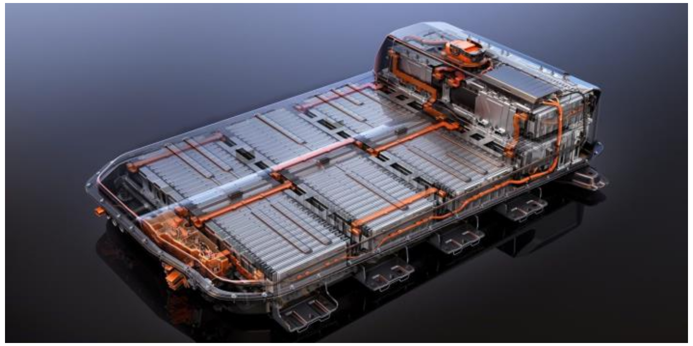
Technology	Efficiency Increase
Additional gears allow your engine to operate at efficient speeds more often.	2%–4%[1,3]
Continuously Variable Transmissions (CVTs) have an infinite number of "gears," providing seamless acceleration and improved fuel economy.	3%–4%[1,3]
Dual-clutch transmissions, which are similar to manual transmissions but add automated shifting, suffer less energy loss than automatics.	3%–4%[1,4]

Engine Technologies

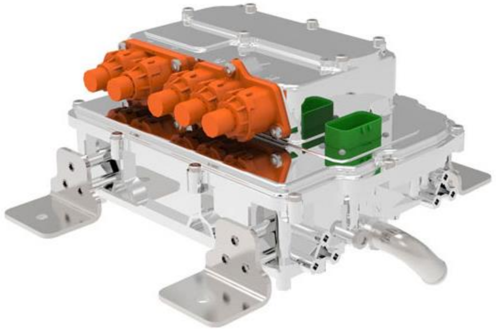
Technology	Efficiency Increase
Cylinder deactivation saves fuel by "turning off" some cylinders when they are not needed.	Up to 5%[1]
Turbochargers increase engine power. This allows manufacturers to use smaller engines without sacrificing performance or to increase performance without lowering fuel economy.	Up to 8%[1,2]
Gasoline Direct Injection (GDI) delivers higher performance with lower fuel use.	1%[1]
Valve Timing & Lift Technologies improve engine efficiency by optimizing the flow of fuel and air into the engine for various engine speeds.	3%–4%[1]

Improving drivetrain efficiency in EVs

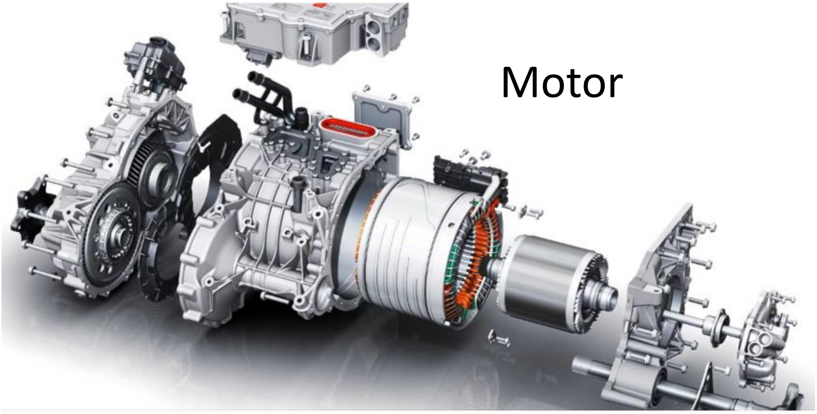
Battery



Inverter

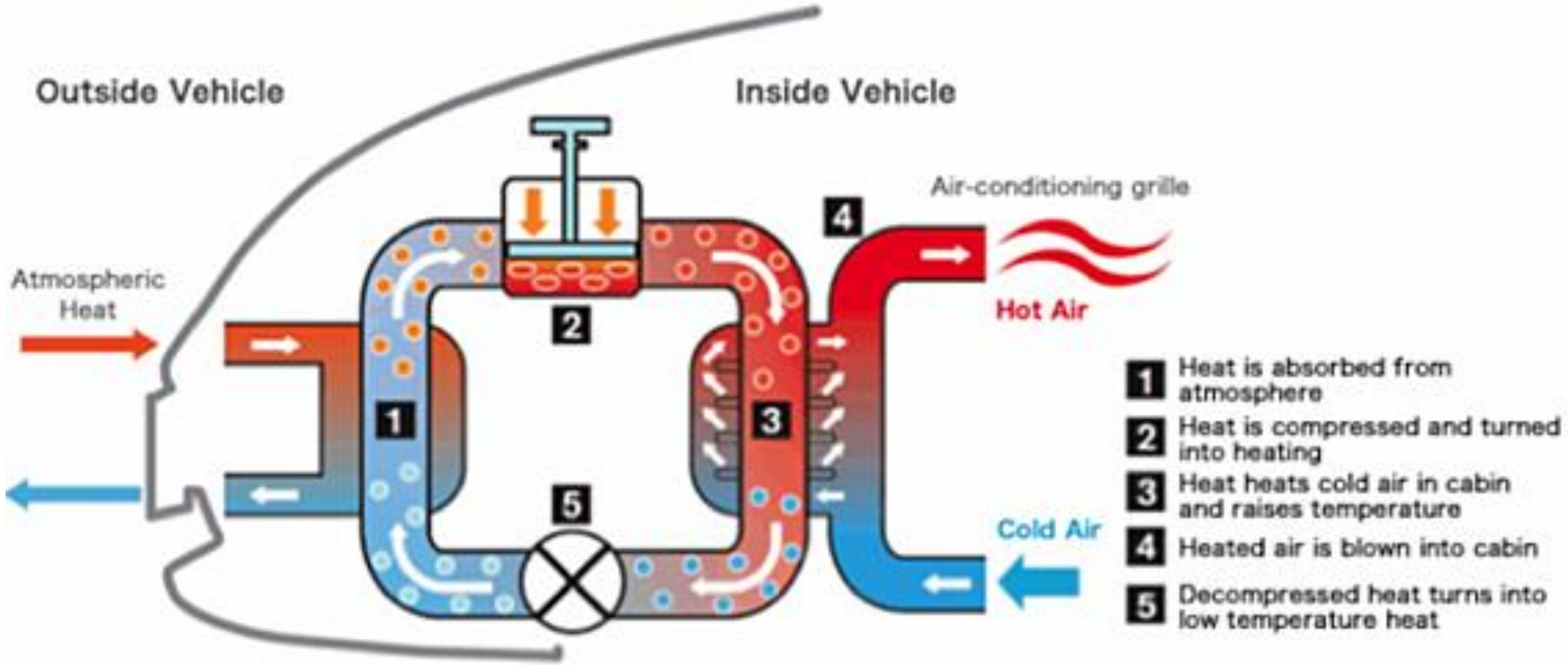


Motor



- The battery-inverter-motor system are obvious places for improvement
- Tesla has already spent considerable resources improving these components
  - Motor: +10-14% improvement
  - Inverter: @ 96-99% efficiency

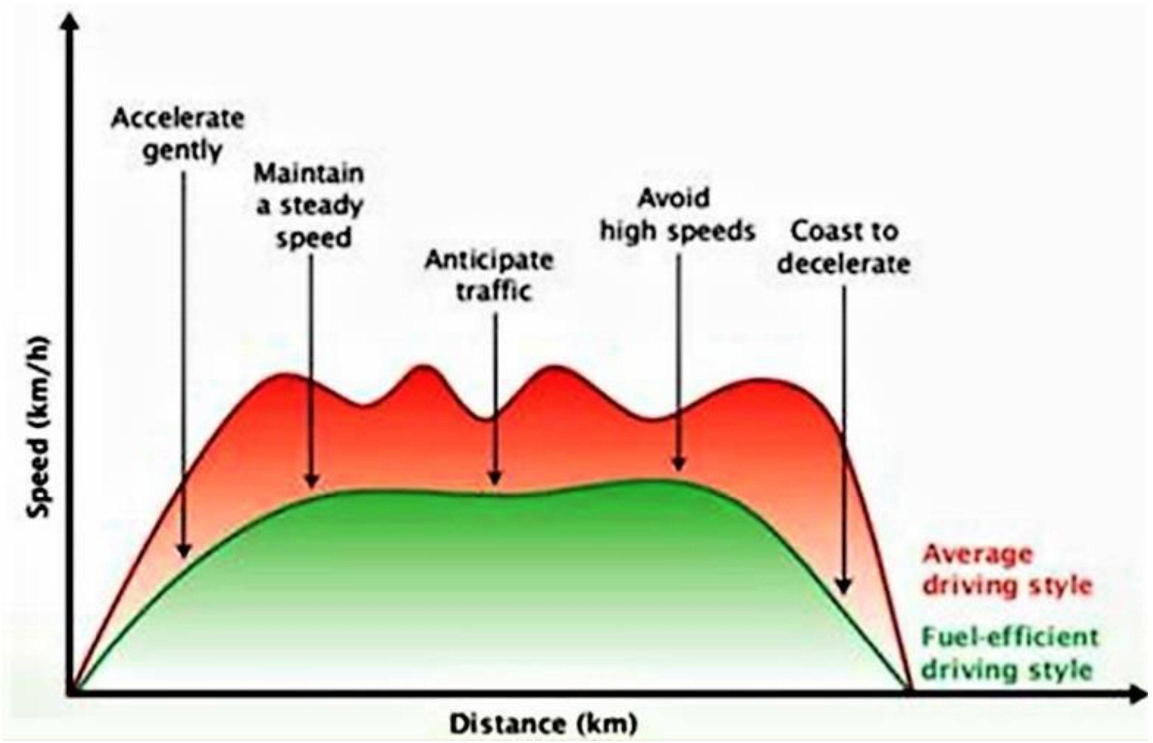
Heat pump efficiency improvements



- Extremely efficient temperature control, a 1 kW heat pump can generate the equivalent of heat of 2-3 kW (not creating heat, just moving it around!)

How to drive an EV efficiently

- Conserve momentum – avoid fast acceleration and braking
- Operate the vehicle at the motor's highest efficiency range: 20-30 MPH
- Reduce use of heating and air conditioning
- Maintain tire pressure



ECO Mode

- Many vehicles have an “ECO” mode which can vary in what they do depending on the automaker
- Generally, will dampen the sensitivity of the accelerator to reduce acceleration levels when pressing the pedal
- Can also regulate power to the vehicle’s A/C

"Hypermiling"

- At the extreme end of the efficiency spectrum: "hypermiling" – how far can you go?
- Tesla Model 3 record: *606 miles on a single charge!*
  - 20-30 mph on a 1-mile closed loop
  - Only stopped for bathroom breaks over 32 hours of driving
  - No air conditioning!