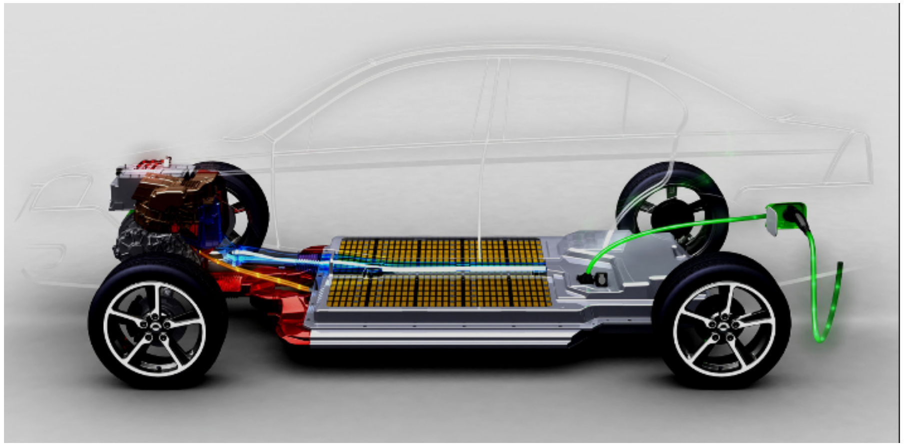
OPTIMIZING AUTOMOTIVE DRIVE TRAINS

FROM ENERGY SOURCE TO WHERE THE RUBBER MEETS THE ROAD

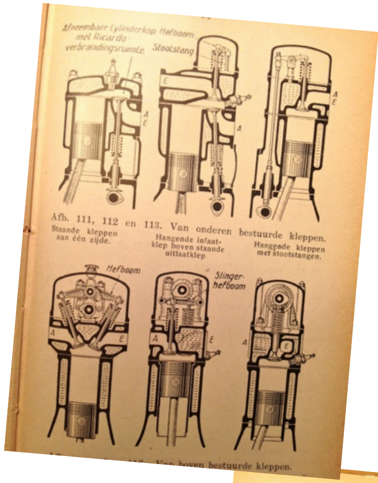


PATRICK GROENEVELD

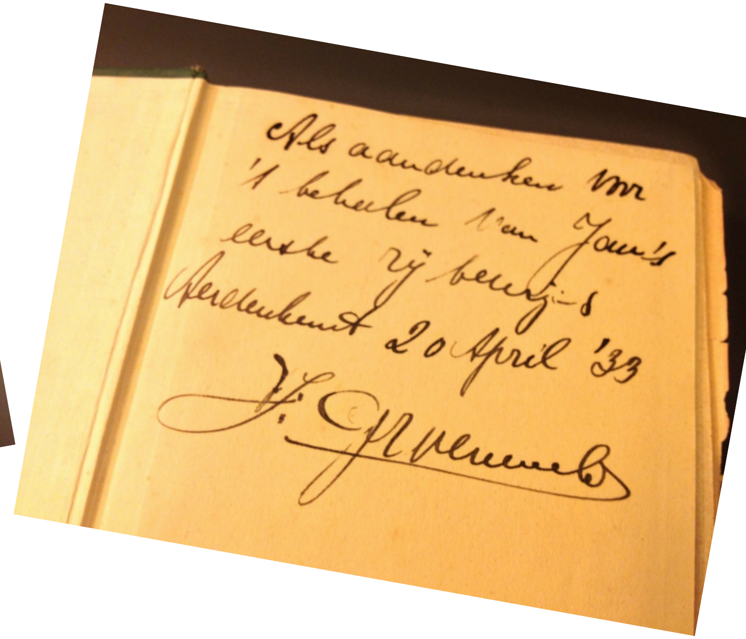
SYNOPSYS SCIENTIST

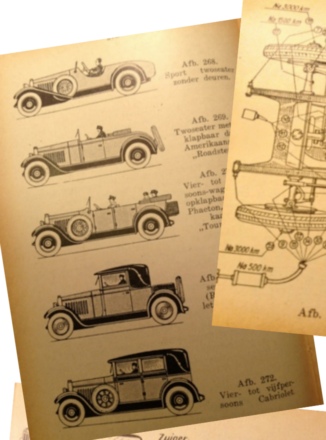
MOUNTAIN VIEW, CA, USA

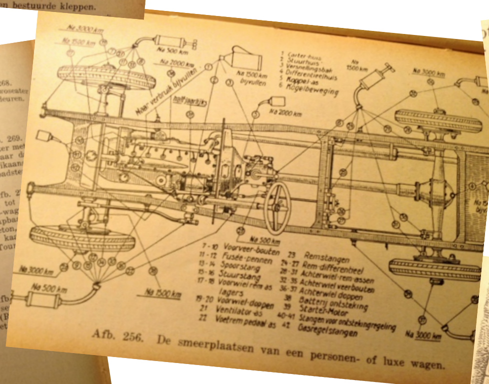
ASYNC 2016 PORTO ALEGRE

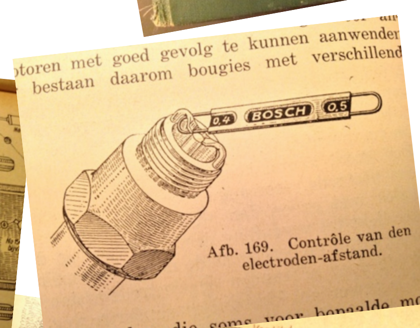

Afneembare cylinderkop met Ricardo-verbrandingsruimte
Hefboom
Stootstang
Afb. 111, 112 en 113. Van onderen bestuurde kleppen.
Staande kleppen aan één zijde.
Hangende inlaatklep boven staande uitlaatklep
Hangende kleppen met stootstangen.
Hefboom
Slinger-hefboom
Van boven bestuurde kleppen.

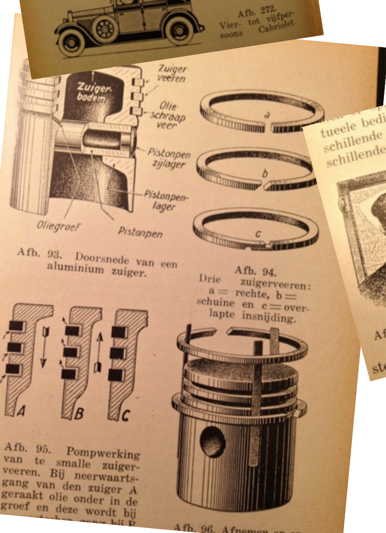

MARTINI
HET HANDBOEK DER AUTO- EN RIJTECHNIEK
N.V. GEBR. GRAAUW'S UITG. MIJ.


Als aandenken van
't behalen van Jan's
eerste rijbewijs
Aerdenhout 20 April '33

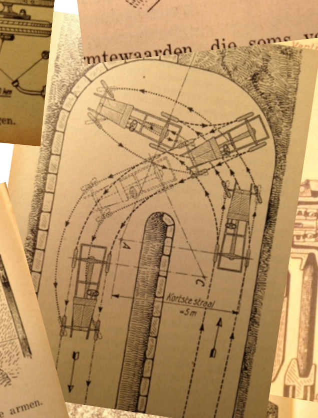

Afb. 268.
Sport tweeseater zonder deuren.
Afb. 269.
Afb. 272.
Vier- tot vijfpersoons Cabriolet


Afb. 256. De smeerplaatsen van een personen- of luxe wagen.

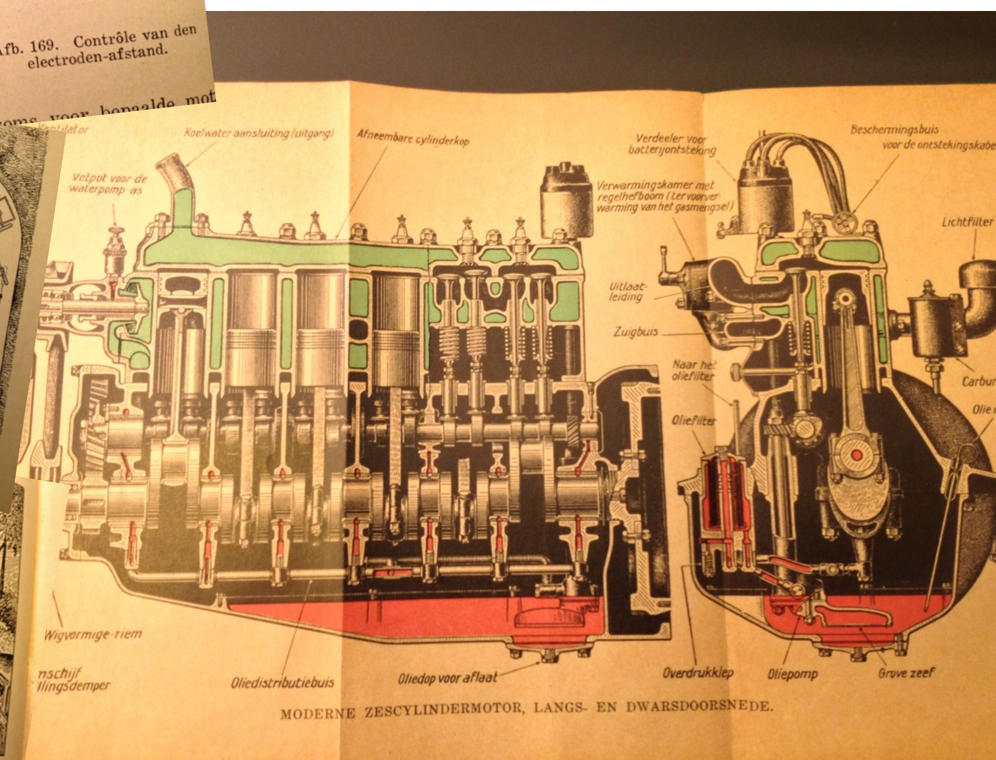

motoren met goed gevolg te kunnen aanwenden
bestaan daarom bougies met verschillende
0,4
BOSCH
0,5
Afb. 169. Contrôle van den electroden-afstand.


Zuigerbodem
Zuigerveeren
Olie-schraapveer
Pistonpen zijlager
Pistonpen-lager
Oliegroef
Pistonpen
Afb. 93. Doorsnede van een aluminium zuiger.
Afb. 94. Drie zuigerveeren: a = rechte, b = schuine en c = overlapte insnijding.
Afb. 95. Pompwerking van te smalle zuigerveeren. Bij neerwaartsgang van den zuiger A geraakt olie onder in de groef en deze wordt bij


tueele bediening met de hand niet ontbreekt. Verschillende ruitenwisschers kunnen op twee verschillende snelheden worden ingeschakeld. Voor
Afb. 290. Electrische ruitenwisscher met twee armen.
sterken regenslag schakelt men in op snel en lang-


Kortste straal ≈5 m

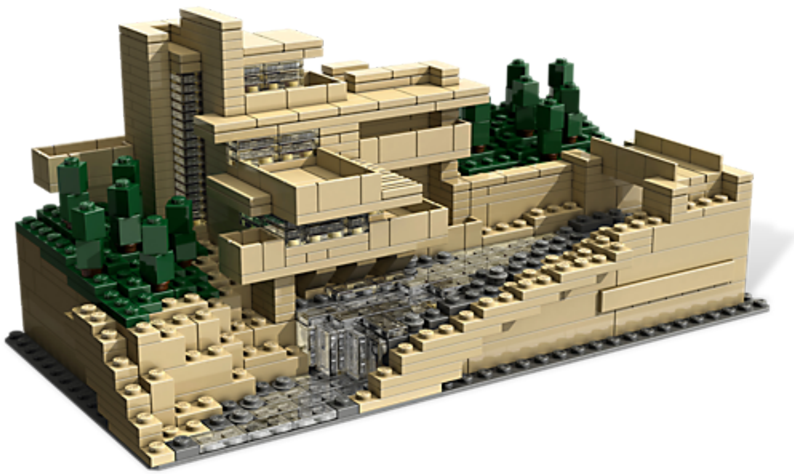

Afb. 308. Foutief parkeeren van


Koelwater aansluiting (uitgang)
Afneembare cylinderkop
Verdeeler voor batterijontsteking
Beschermingsbuis voor de ontstekingskabels
Vetpot voor de waterpomp as
Verwarmingskamer met regelhefboom (ter voorverwarming van het gasmengsel)
Lichtfilter
Uitlaatleiding
Zuigbuis
Naar het oliefilter
Oliefilter
Carburateur
Wigvormige riem
Oliedistributiebuis
Olieldop voor aflaat
Overdrukklep
Oliepomp
Grove zeef
MODERNE ZESCYLINDERMOTOR, LANGS- EN DWARSDOORSNEDE.

OUTLINE: MULTI-MODE MULTI-CORNER AUTOMOTIVE!

- Introduction
    - IC design vs EV Design, EDA's role
- What really matters: Cost, Performance and Emissions
    - Volkswagen scandal
- Drive Train Design
    - System and transmission design
    - Design and simulation tools
- Dollars and sense:
    - Economic
    - Environmental
- What can improve efficiency?
    - Battery, driving, etc.
- Battery Technology
    - Tesla, GM, BMW

THE PRICE OF A ROUGH ABSTRACTION

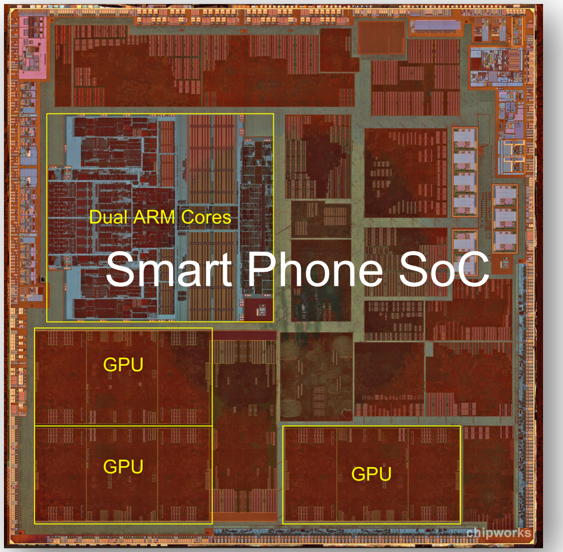


Model

- built from very few distinct types of components
- Simplified abstractions

- **Reality**
  - Many different components
  - Different abstractions

ELECTRONIC DESIGN AUTOMATION VS MECHANICAL DESIGN AUTOMATION



- 100,000,000 parts
- Development cost: $50,000,000
- Development time: <1 year
- Development team size: 50

4,000,000 parts (0.04x)

Development cost: $17,000,000,000 (340x)

Development time: 10 years (10x)

Development team size: 10,000 (200x)

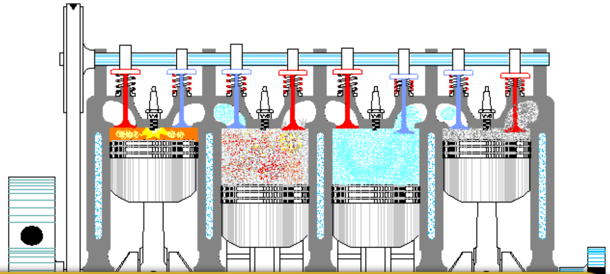
IC vs AUTOMOTIVE

	IC Design	EV Design
Current	0.0000001Amp- 10Amp	1A-1000A
Voltage	1Volt-3.6Volt	12V-360V
Power consumption	0.0000001Watt-5Watt	25W-250,000W
Li-Ion Battery	5 Watthour	500Wh-85,000Wh
Performance Metrics	Geekbench, MHz	Torque, hp/kW, 0-60
Efficiency Metrics	MIPS/Watt, battery life, area	Miles/kWh, range
Product cycle (lifespan)	1 year (4 years)	4 years (20 years)
Design tools	Well Automated	Trial-and-Error
Verification tools	STA/Solid at all levels	Fin. Elem. /Multi-physics
Design Abstractions	Strong and well defined	Intricate
Big objective	Time-to-Market, correctness	(Re)liability, looks
Ecosystem	Few IP suppliers	Huge parts supply chain
Design tool Market size	~$6B/year **($50K/designer)**	< $1B **($5K/designer)**

OUTLINE: ELECTRIC VEHICLES & EDA

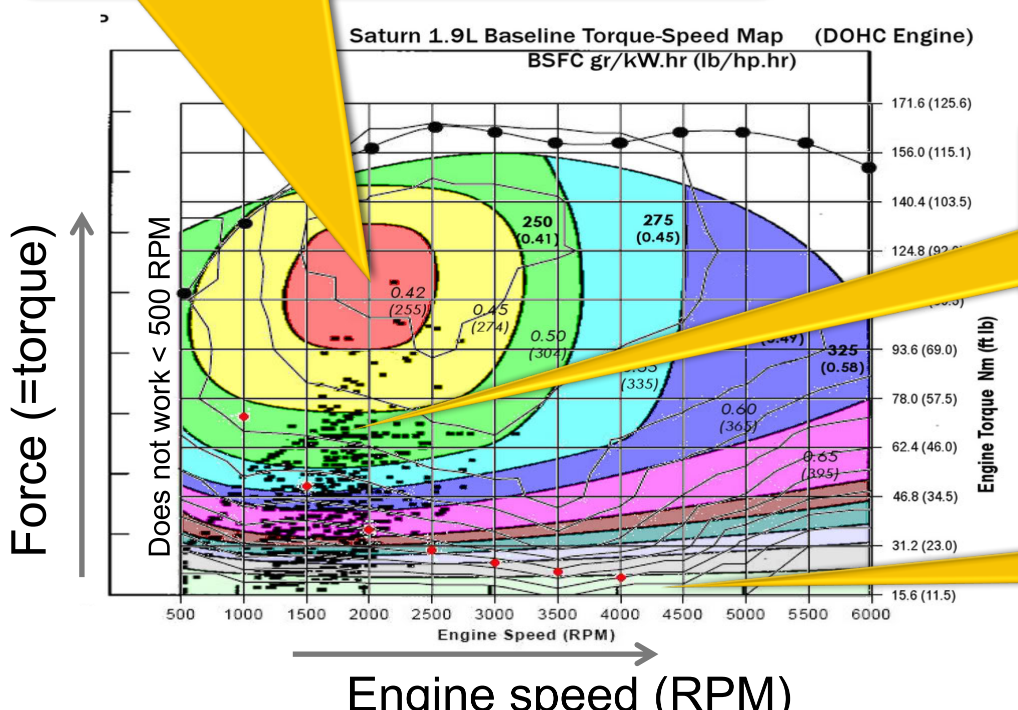
- Introduction
  - IC design vs EV Design, Synopsys' role
- What really matters: performance, cost and Emissions
  - Volkswagen emission scandal
- Drive Train Design
  - System and transmission design
  - Design and simulation tools
- Dollars and sense:
  - Economic
  - Environmental
- What can improve efficiency?
  - Battery, driving, etc.
- Battery Technology
  - Tesla, GM, BMW
  - Electric Airplanes

THE GOOD OLD INTERNAL COMBUSTION ENGINE



BSFC Fuel consumption **sweet spot**. Most efficient at 2000 RPM with 100 Nm torque

- Proven technology
- Works only between 500 – 6000 RPM
- Low force (torque) at low RPM
- So needs gearbox and clutch
- Overall energy conversion is only about 15-30% efficient



Dots show 1 second intervals during EPA standard test cycle. Despite gearbox, it does not hit the sweet spot well…

Sweet spot is very narrow: 100% worse here

AUTOMOTIVE POLLUTION

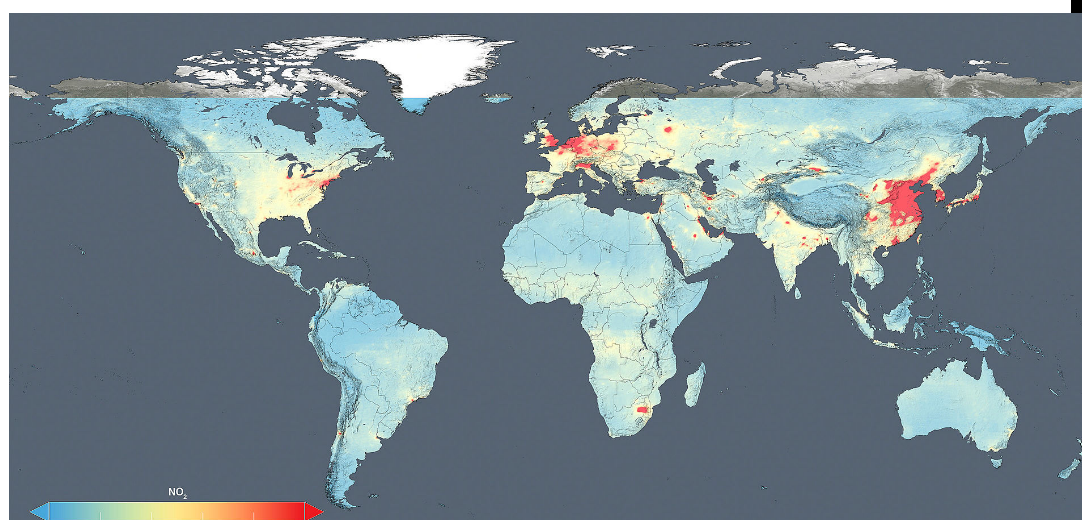
	Gasoline	Diesel	Electric
CO_2	☹	😐	😐/☺☺
NO, NO_2	😐	☹☹☹☹	😐/☺☺

Carbon Dioxide – 1/3rd comes from cars

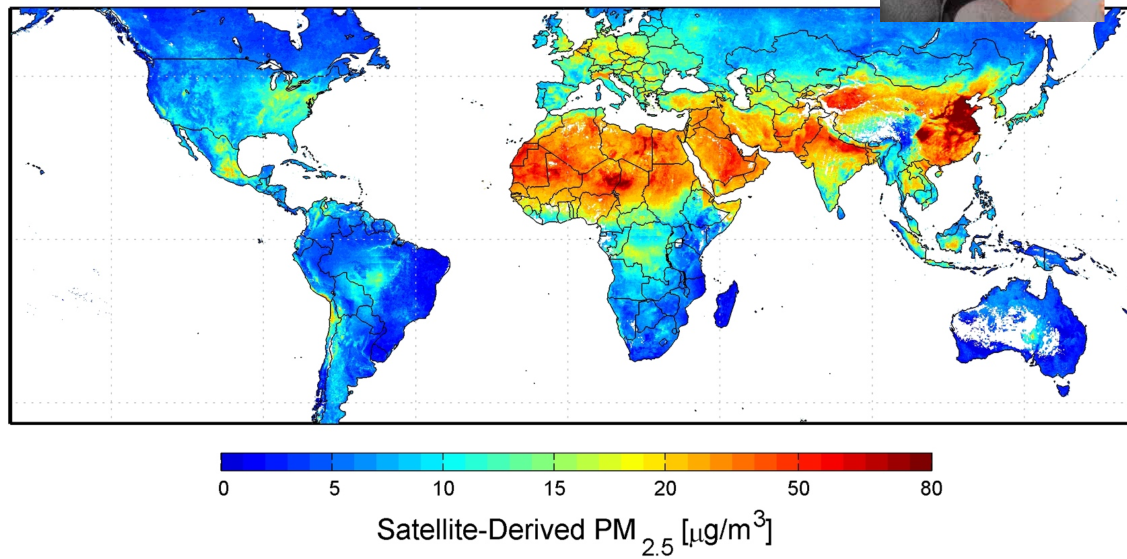
-> Causes Global Climate Change

Nitrogen Oxides – Mainly Affects Health

-> Local smog, Respiratory diseases



AUTOMOTIVE POLLUTION



	Gasoline	Diesel	Electric
PM2.5 dust – Fine particulates < 2.5micrometer -> Causes Respiratory diseases, cancer	😐	☹	😐
Smell	😐	☹☹	☺☺
Noise	😐/☹	☹/☹	☺/☹
Geopolitical Issues (e.g. oil-fueled wars)	☹	☹	☺

MEASURING EMISSION: DYNAMOMETER

COMPARE 'OFFICIAL' MPG BETWEEN GERMANY AND USA

2016 Mercedes E-350 Sedan

USA www.mbusa.com:

The 2016 E350 Sedan	MSRP $53,100*
Passenger capacity	5
Trunk capacity	12.9 cu ft
Transmission type	7-speed automatic
Engine	3.5L gasoline V-6
Power	302 hp @ 6,500 rpm
Acceleration, 0-60 mph	6.5 sec
City fuel economy	20 mpg
Highway fuel economy	29 mpg 23 mpg combined

US EPA test:
23 MPG combined
237 g CO_2/km

48% more!?!?!

EU NEFZ test:
34 MPG combined (7.1liter/100km)
165 g CO_2/km

Germany: same car, www.mercedes.de:

Kraftstoff	Superkraftstoff
Tankinhalt/davon Reserve (l)	59/8
Kraftstoffverbrauch innerorts (l/100 km) [3]	– (9,6–9,4)
Kraftstoffverbrauch außerorts (l/100 km) [3]	– (5,6–5,5)
Kraftstoffverbrauch kombiniert (l/100 km) [3]	– (7,1–6,9)
CO2-Emissionen (g/km) kombiniert [3]	– (165–161)

FUEL ECONOMY: EUROPEAN TEST VS US EPA TEST

vs EPA

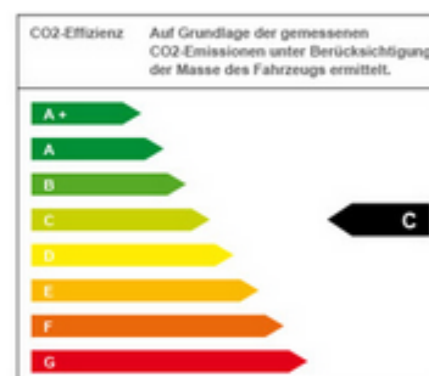
Car	US MPG (EPA)	Fuelly.com (actual)	German MPG (NEFZ)	Reality gap
BMW 328i	**26**	**24**	**37**	**42%**
BMW 535i	**24**	**23**	**44**	**83%**
BMW 740i	**24**	**19**	**34**	**42%**
BMW X535i	**18**	**19**	**28**	**56%**
Cadillac ATS	**25**	**25**	**31**	**24%**
Cadillac Escalade	**17**	**15**	**18**	**6%**
VW Passat CC	**25**	**25**	**44**	**76%**
VW Beetle	**28**	**27**	**44**	**57%**
Mercedes E350	**23**	**22**	**34**	**48%**

Combined usage
www.fueleconomy.gov

Real-life
usage

Official European
manufacturers data

Why? Because cheating with the emission test helps meet fleet-wide European manufacturer CO2 emission goals.



HOW MANUFACTURERS CHEAT THE EUROPEAN EMISSION TEST

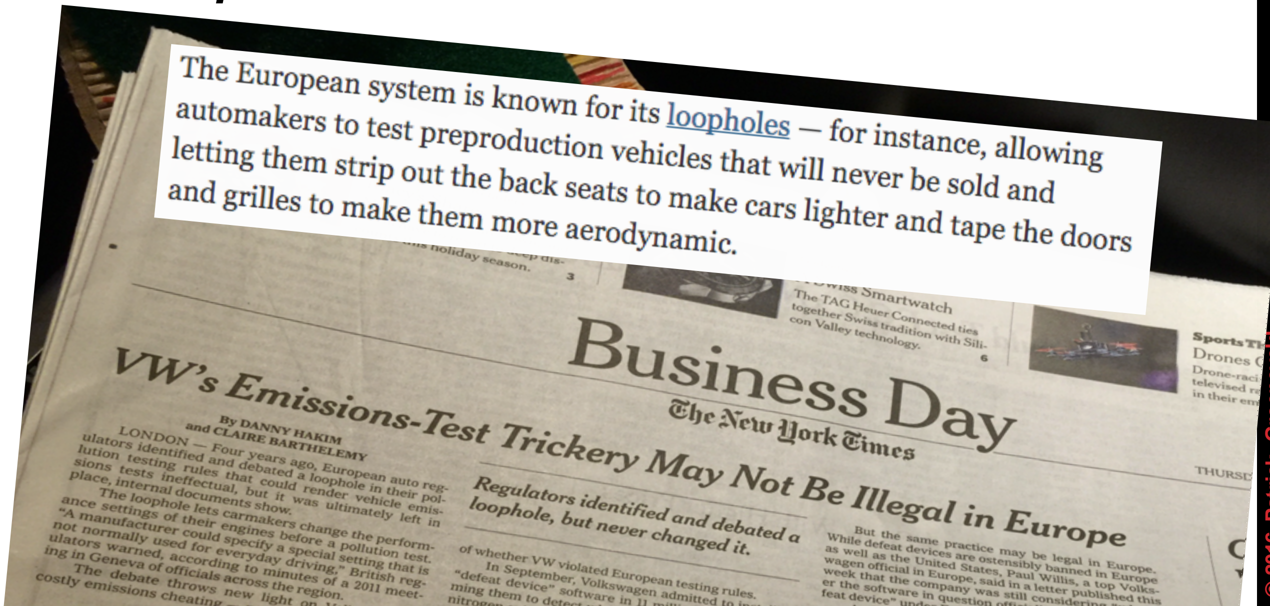
- **Multi-Mode:** ECU mode switches
  - Performance
  - Fuel Economy
  - Emissions

- **Multi-Corner:** Artificially hit most advantageous corner:
  - Non-production car with reduced weight
  - Special low-resistance tires
  - Extra aerodynamic tweaks (tape door gaps, spoilers)

VOLKSWAGEN EMISSION SCANDAL

VW CEO Matthias Müller: *"Frankly spoken, it was a technical problem. We made a default, we had a ... **not the right interpretation of the American law**. And we had some targets for our technical engineers, and they solved this problem and reached targets with some **software solutions which haven't been compatible to the American law**."*

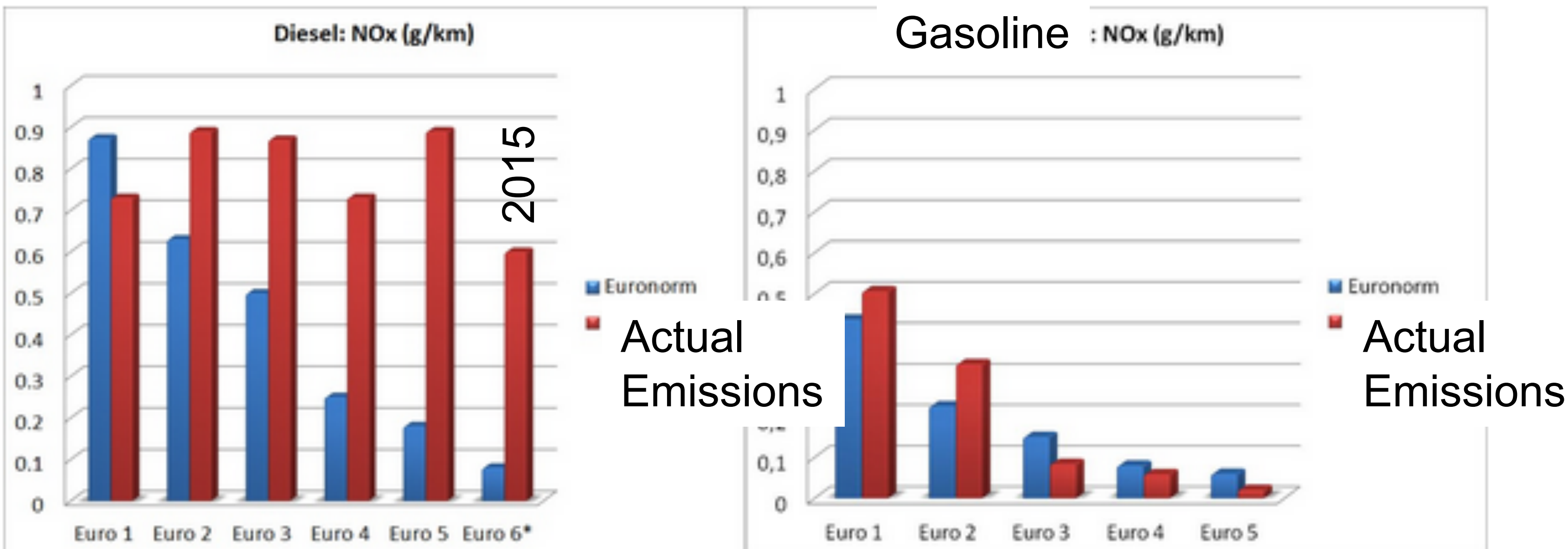
(NPR interview
Detroit, Jan 11, 2016)



DIESEL NOx EMISSIONS

Improved in theory on the dynamometer (blue bars)

… but not in practice (red bars):



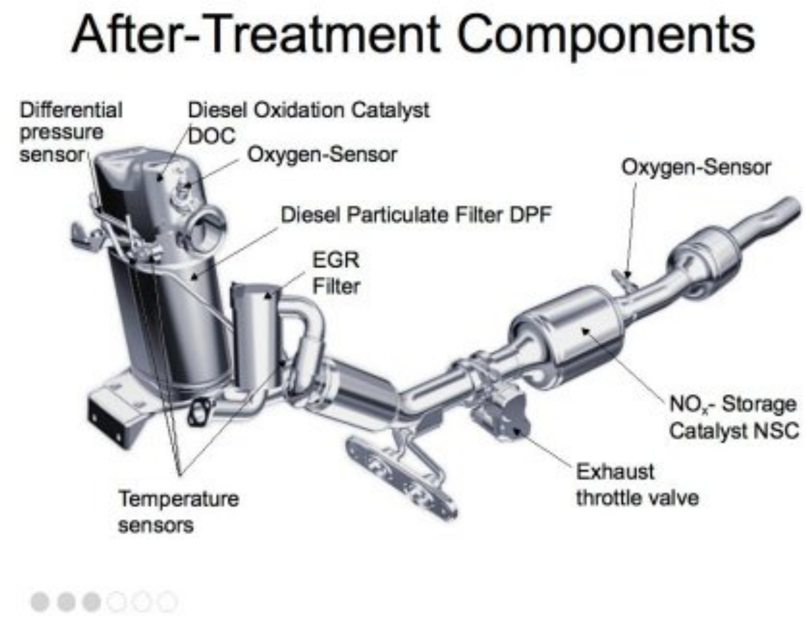
Diesel **does not** meet norm

Gasoline meets emission norm

50% of all passenger cars in Europe are diesels (!),

Diesel gets ~20% better MPG and is cheaper per liter than gasoline

VOLKSWAGEN'S DIESEL-DILEMMA



Burn Diesel lean at high temperature:

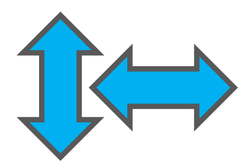
- ☺ Best MPG = best CO2/km
- ☺ Lower PM25 fine dust
- ☹ High NOx

Solutions:

- Exhaust Gas Recirculation with cooling
- Lean NOx trap (NOx Absorber)
- Selective Catalytic Reduction (Urea/BlueTec)
- Diesel Particulate Filter

MPG & low CO2

Hard to get at the same time:



Low Cost

Low NOx

OUTLINE

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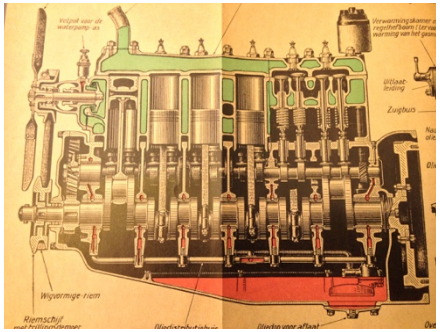
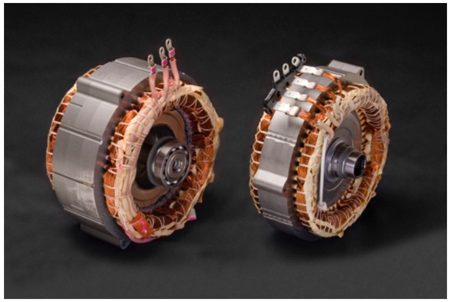
INTERNAL COMBUSTION ENGINE VS ELECTRIC MOTOR





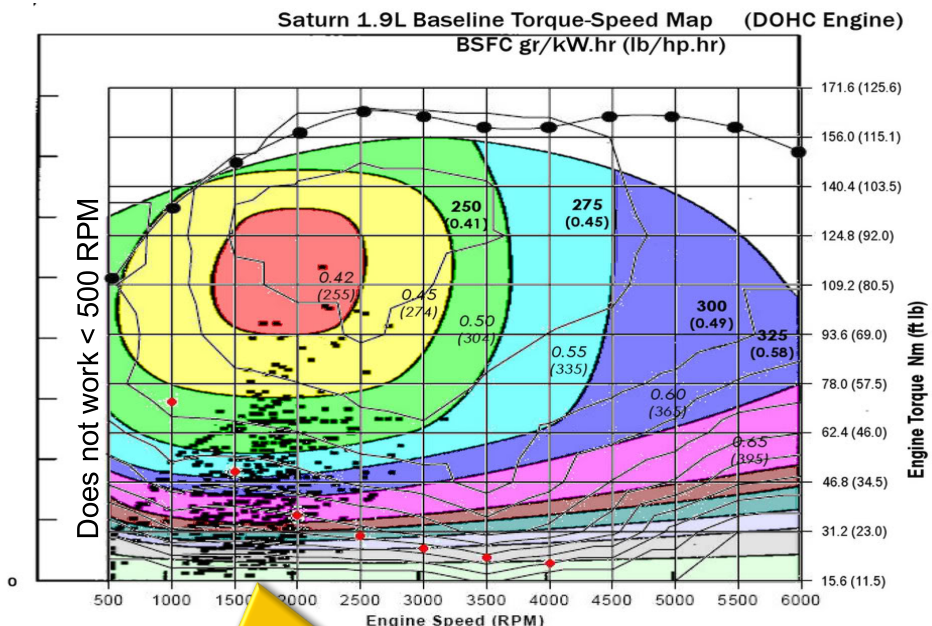
- Motor only
- 17%-25% efficient
- Gets hot, needs cooling
- Needs gearbox + clutch
- Needs maintenance
- Big and complicated
- Vibrates, noisy, stinks

- Motor *and* Generator
- > 90% efficient
- Cool
- No gearbox
- Maintenance free
- Small and simple
- Smooth, silent, 0-emission

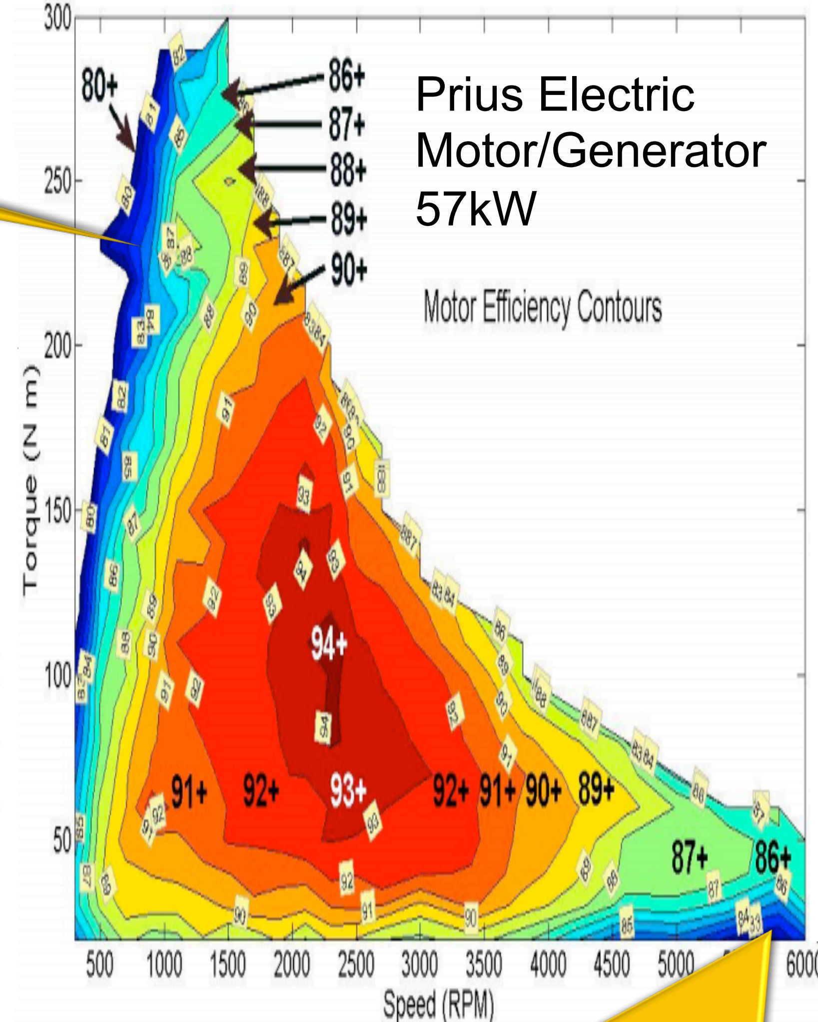
ELECTRIC MOTORS: BIG SWEET SPOT

High torque at low RPM
So no need for multi-speed transmission

Car Internal Combustion Engine (ICE)
92kW (100hp)



Prius Electric Motor/Generator
57kW



ICE: 100% less energy efficient when off the sweet spot

Electric motor: only 15 % efficiency loss when off sweet spot

W(H)AT(T) IS A KWH ?

Average home in the USA uses 11kWh/day

Electric cars drive on electric power:

- The unit of power is **Watt**
- We pay for electrical energy per **kilo Watt hour (kWh)**

1 kWh = a big Mac + small Fries + Coke (860 kCal)

The efficiency of an EV is expressed in:

- ***Miles per kWh*** *"*Plug-to-wheel"
- Plug-to-wheel includes battery losses (17%)

Typical EV: **3.0 miles/kWh** Plug-to-wheel

1 mile = 1.6 km

1 US gallon = 3.8 liter

1 lb = 0.45 kg

WAT(T) IS A KWH ?
MPG VS MPGE

Electric cars drive on electric power:

- The unit of power is **Watt**
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The efficiency of an EV is expressed in:

- ***Miles per kWh*** *"*Plug-to-wheel"
- Plug-to-wheel includes battery losses (17%)

Typical EV: **3.0 miles/kWh** Plug-to-wheel

EPA uses MPGe to rate electric cars:

- 33.7 kWh = 1 gallon of gas
- So 100 MPGe = 2.92 miles/kWh.

Because the EPA thinks that people do not understand miles/kWh

Since regular cars are 25 MPG, and EVs are 100 MPGe

- Are EVs 4x cheaper?
- Are EVs 4x cleaner?
- Are EVs 4x more energy efficient?

No, No and No!

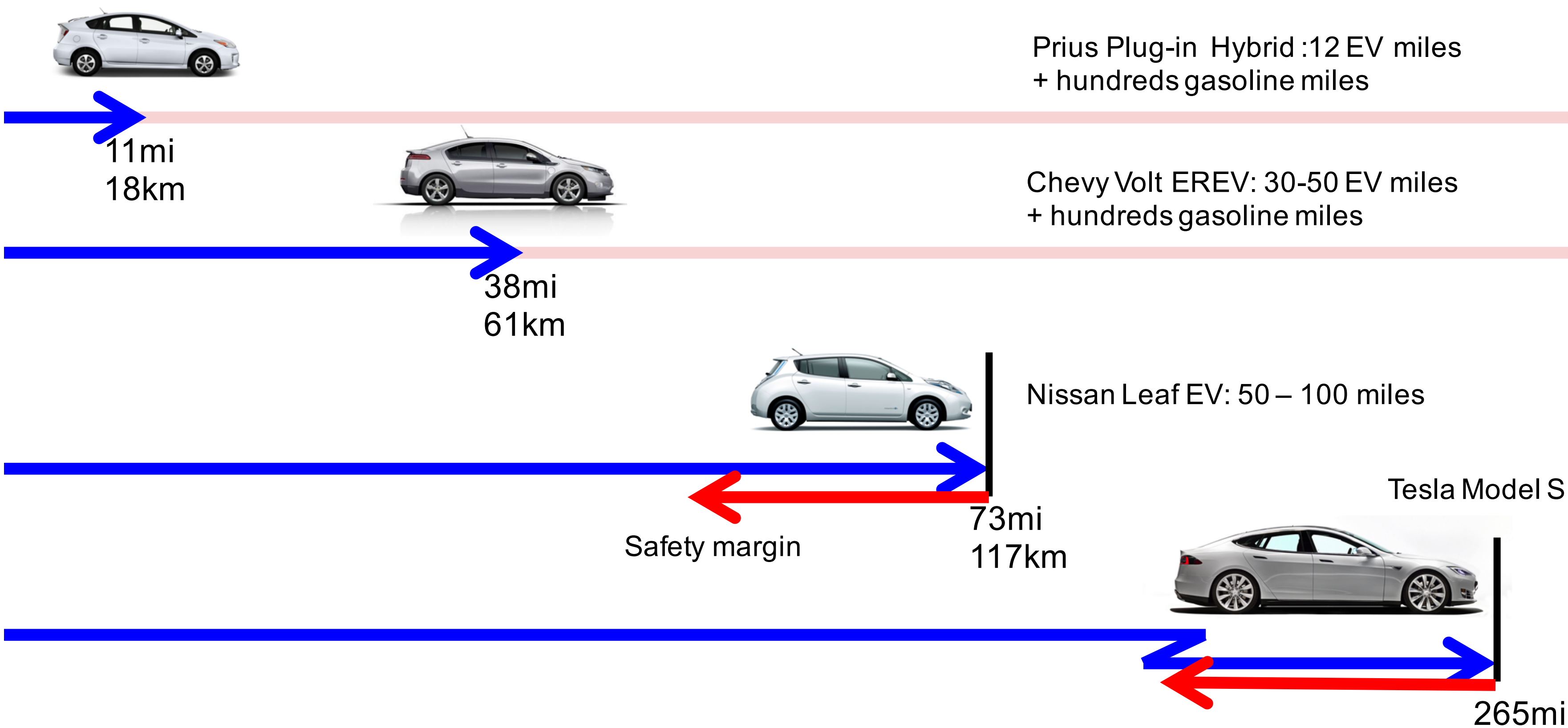
BATTERY-POWERED VEHICLE CATEGORIES

Plug-In Hybrid: Gasoline-Electric hybrid with larger battery

Extended Range EV: Electric Vehicle with Gasoline ICE as backup

Commute EV: Electric Motor only, mid-sized battery

Full-EV: Electric Motor only, large battery



TYPICAL EV DRIVING: 0 –> 45MPH –> 0 IN 1 MINUTE

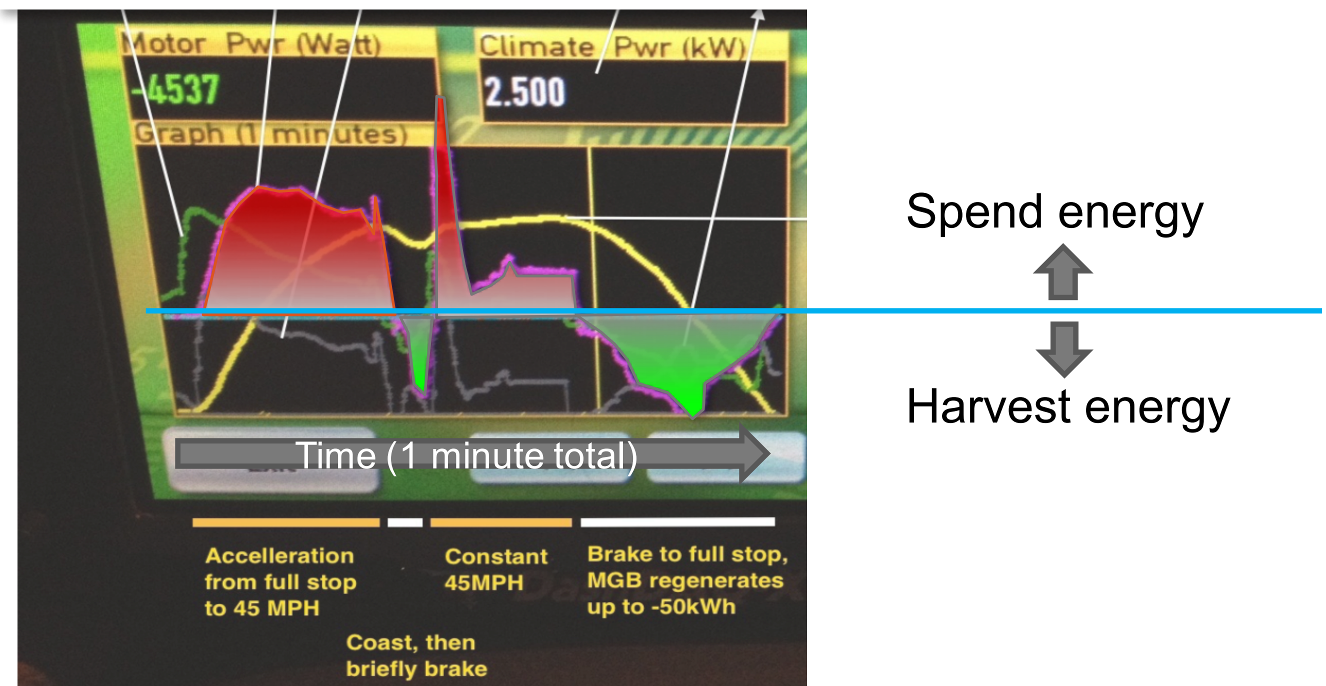
EV OPERATION: BURNING AND HARVESTING ELECTRIC ENERGY

Purple = net energy flow to/from the Electric Motor (-50kW to +110kW)
Above blue line = Motor converts electrical energy into mechanical
Below Blue line = Motor regenerates electrical energy

Yellow = Vehicle speed

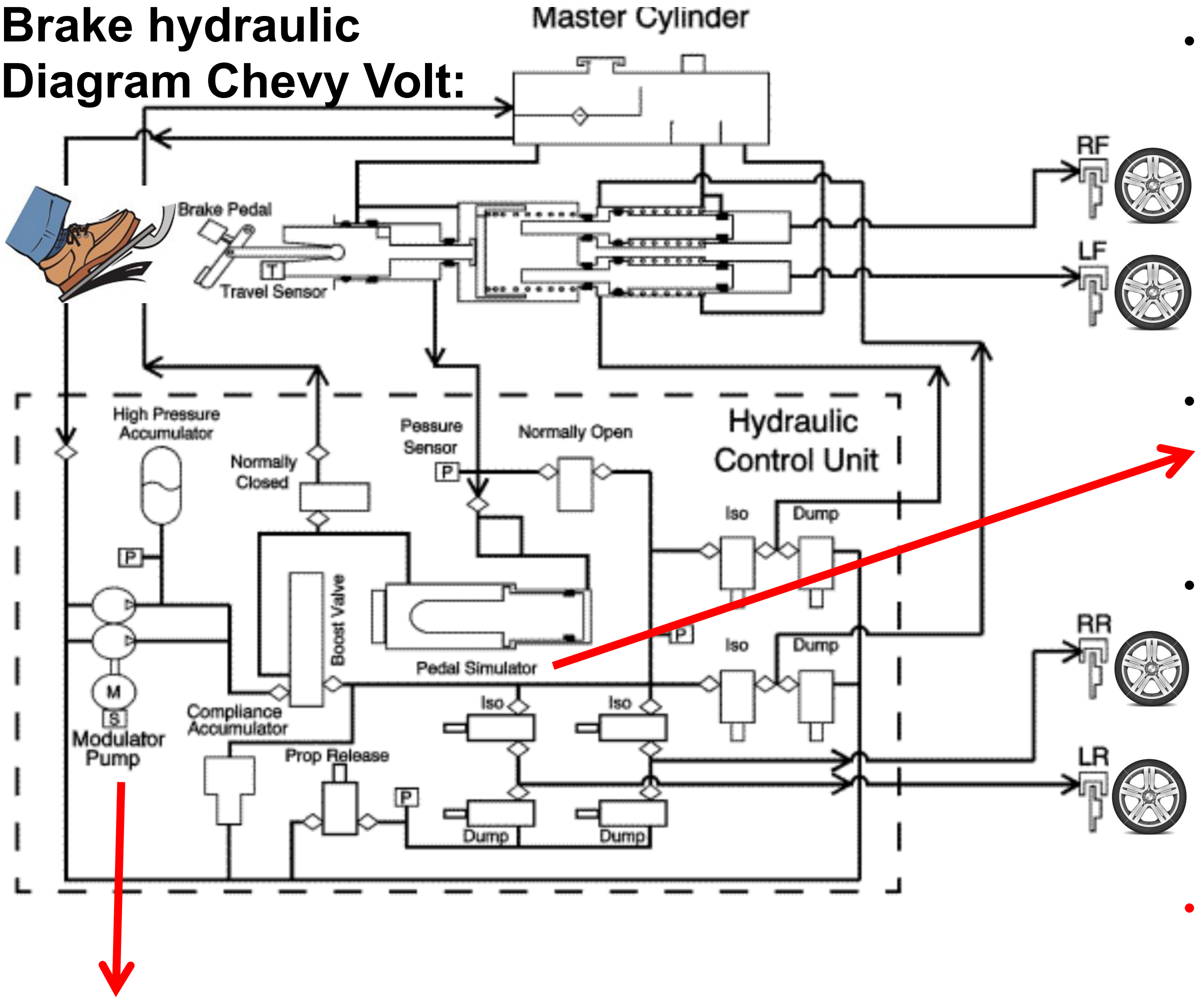
Red area = Battery discharges, car accelerates

Green area = Battery charges, car brakes trough ***regenerative braking***.



BLENDING REGENERATIVE BRAKING WITH FRICTION BRAKING

Brake hydraulic Diagram Chevy Volt:

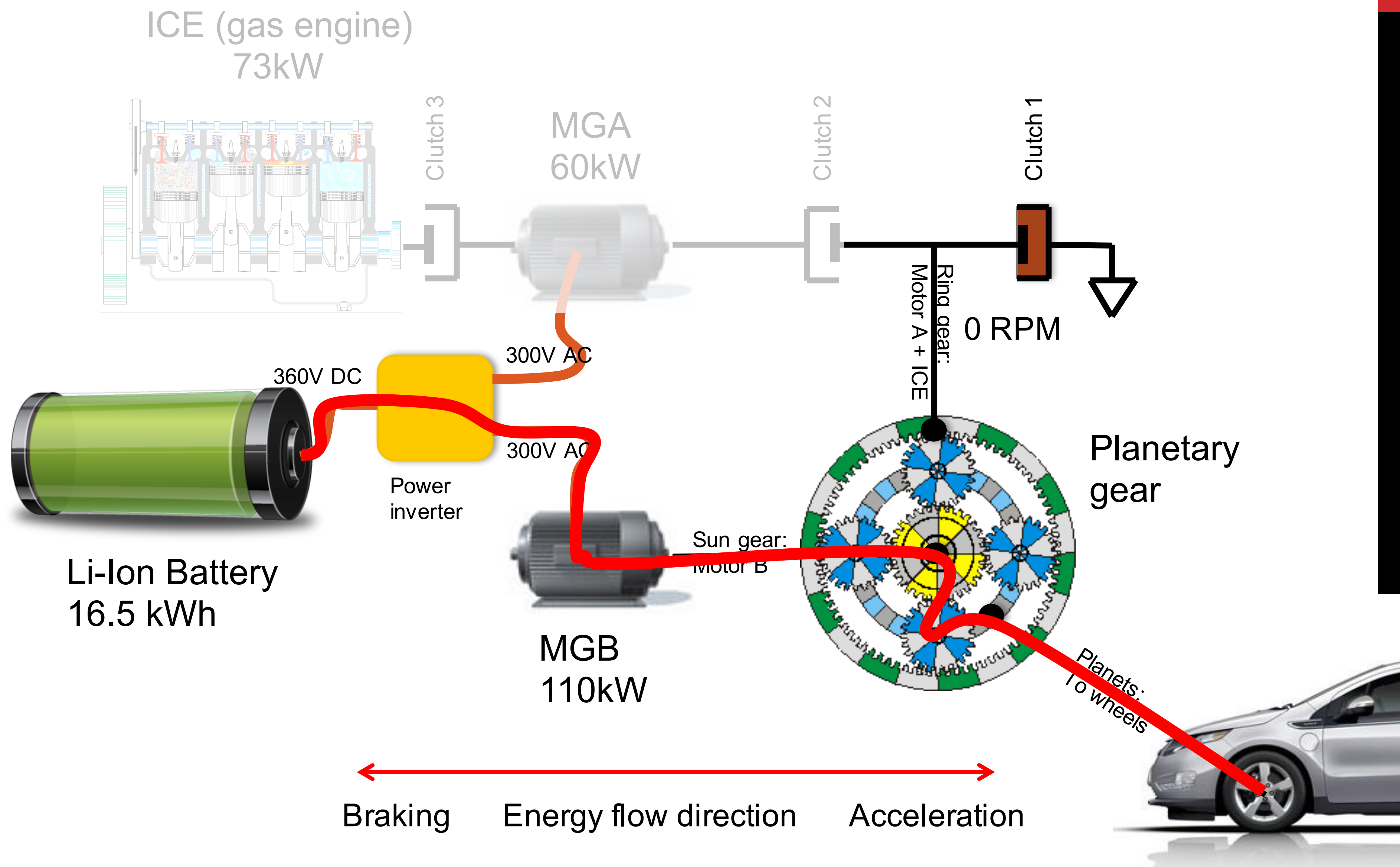


- **At low brake torque demand:**
  - Uses **regenerative** braking

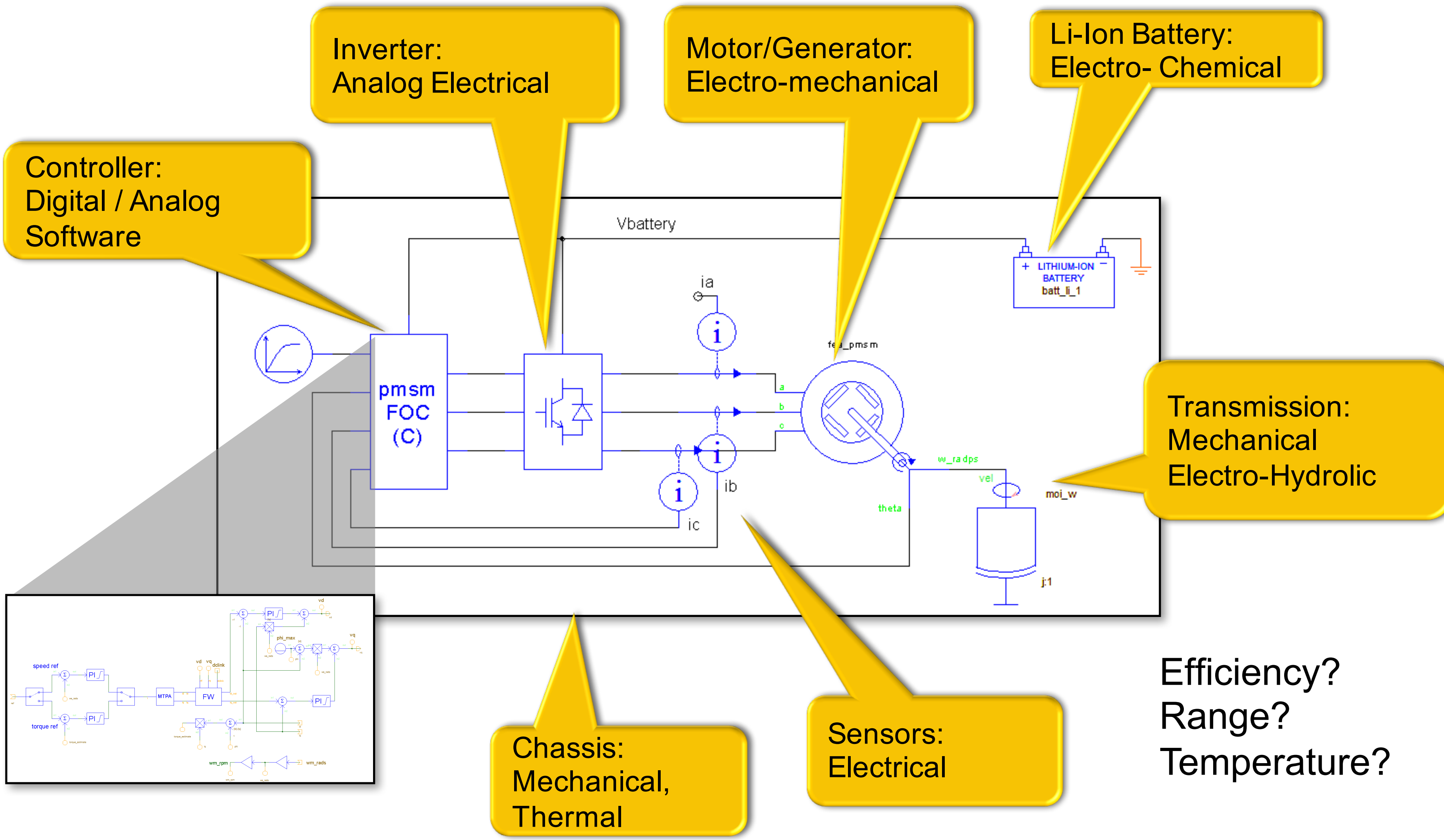
  Higher brake torque demand and low speed:
  - Blend in **friction** braking.
- **Uses '*brake pedal pressure simulator*' to create natural feel.**
- **BMW i3 and Tesla use a simpler system:**
  - Friction braking only
  - Yet accelerator peal is in 'high-regen' mode
- **Round-trip regeneration energy losses ~30% = 70% efficient**

Note: since the ICE is not running, need electric pump for brake fluid pressure.

ELECTRIC DRIVING: EV MODE 1



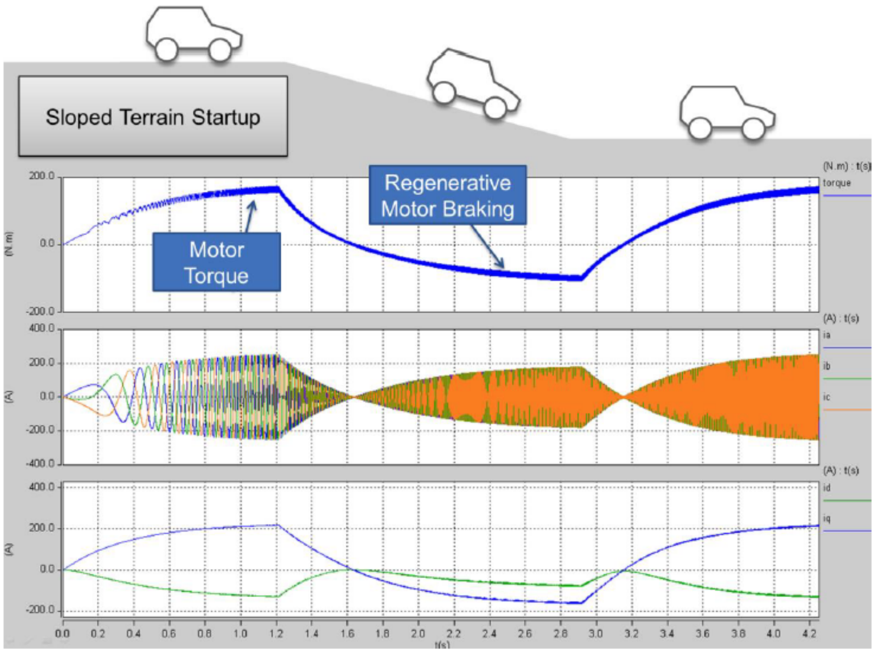
VIRTUAL EV DRIVETRAIN DESIGN



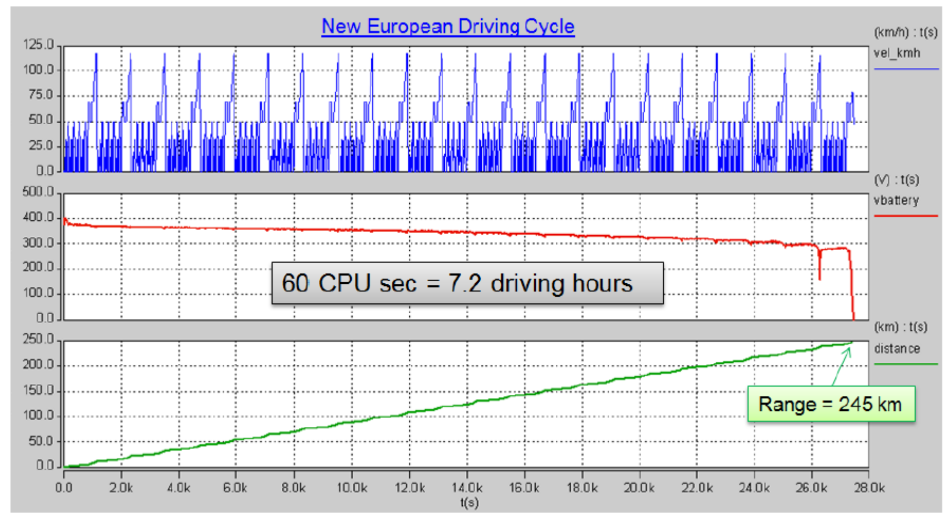
Efficiency?
Range?
Temperature?

Source: Synopsys Sabre tool

SYSTEM LEVEL SIMULATION RESULTS



Torque and current responses on sloped terrain.

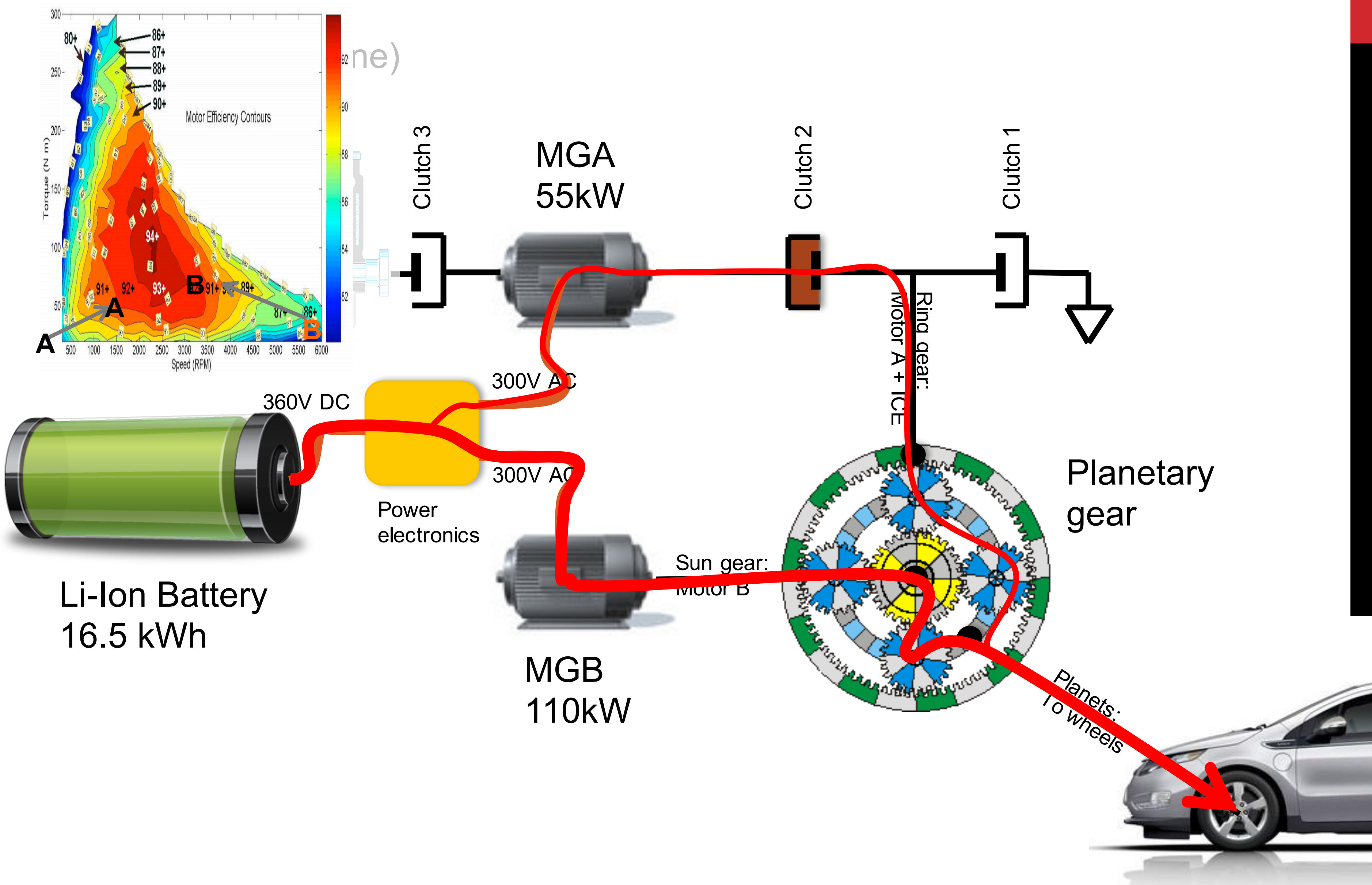


powertrain1.ai_sch (/) | Analyze_system_performance | **Analyze_system_performance.ai_exptlog**

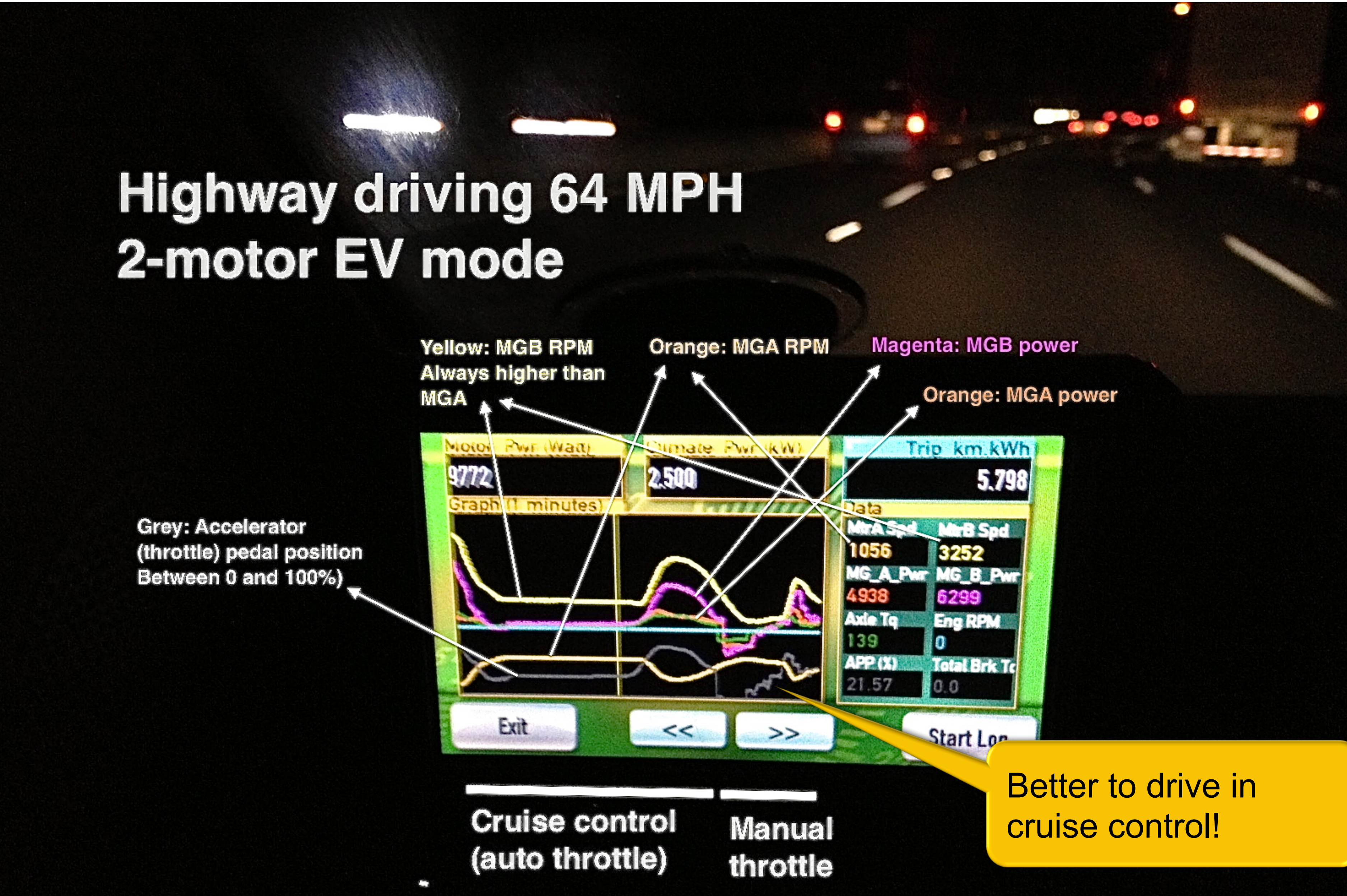
Task Label	T	D	Task Result	Task Status
Vehicle_Performance	V			Complete
Range	R		247.17216862087	Complete
Motor_and_inverter_Efficiency	M			Complete
Inverter_Efficiency	I		0.79311800440691	Complete
Motor_Efficiency	M		0.85257481201341	Complete

Source: Synopsys Sabre tool

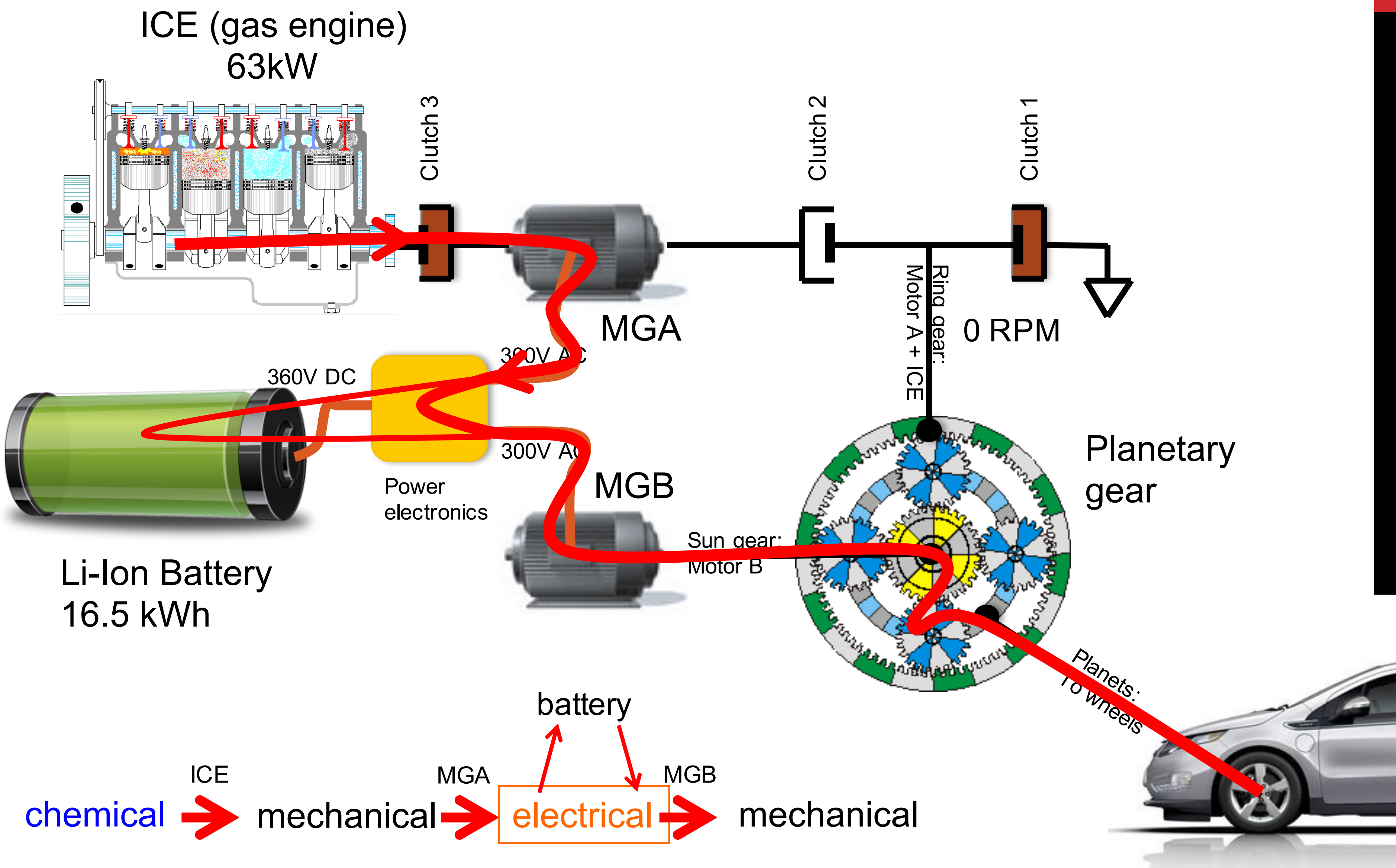
ELECTRIC DRIVING: EV MODE 2 FOR EFFICIENT HIGH-SPEED



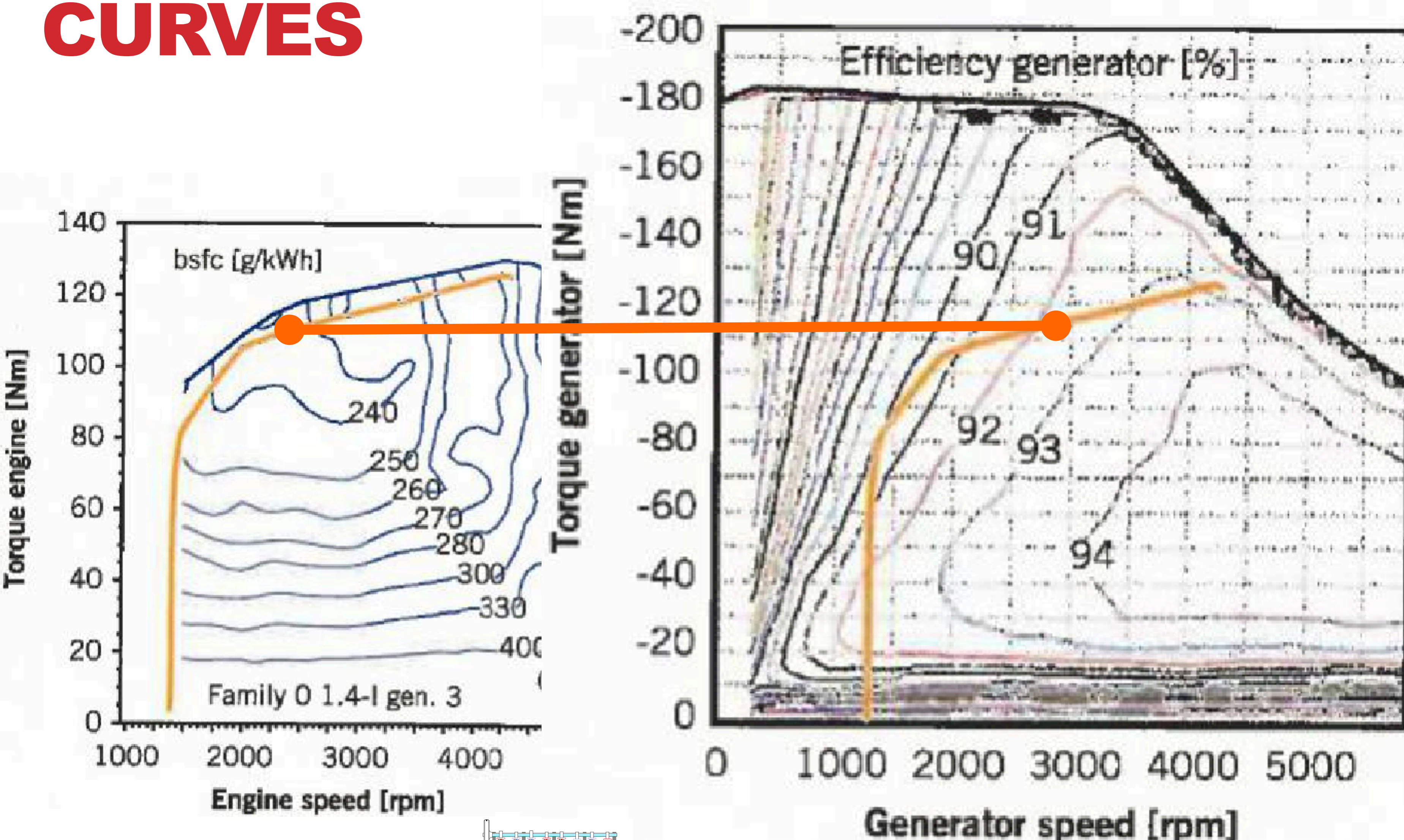
HIGHWAY DRIVING



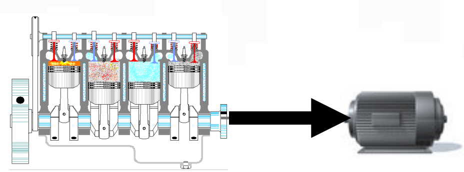
SERIES-HYBRID MODE



ICE-GENERATOR OPERATING CURVES



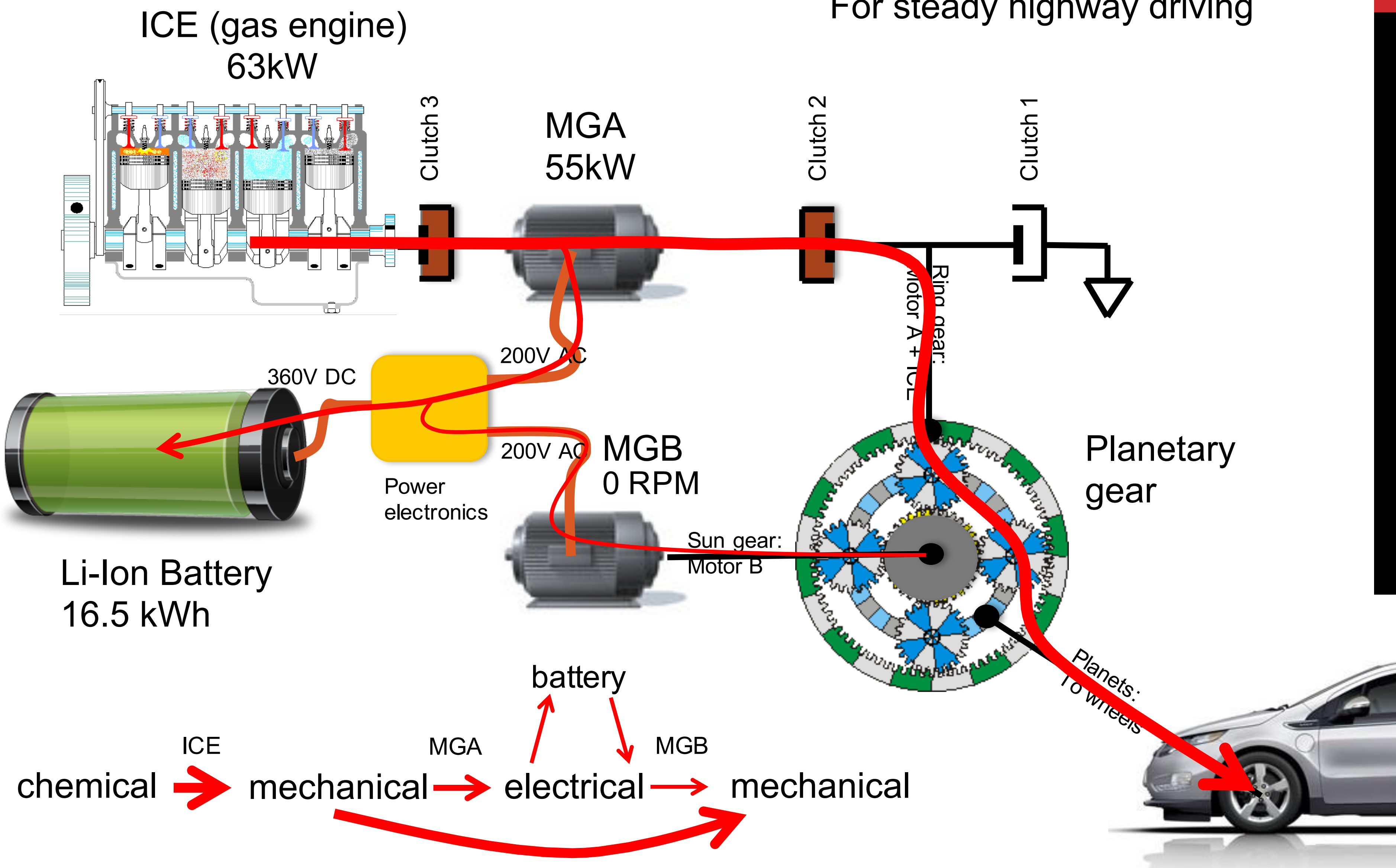
ICE
63kW



MGA
55kW

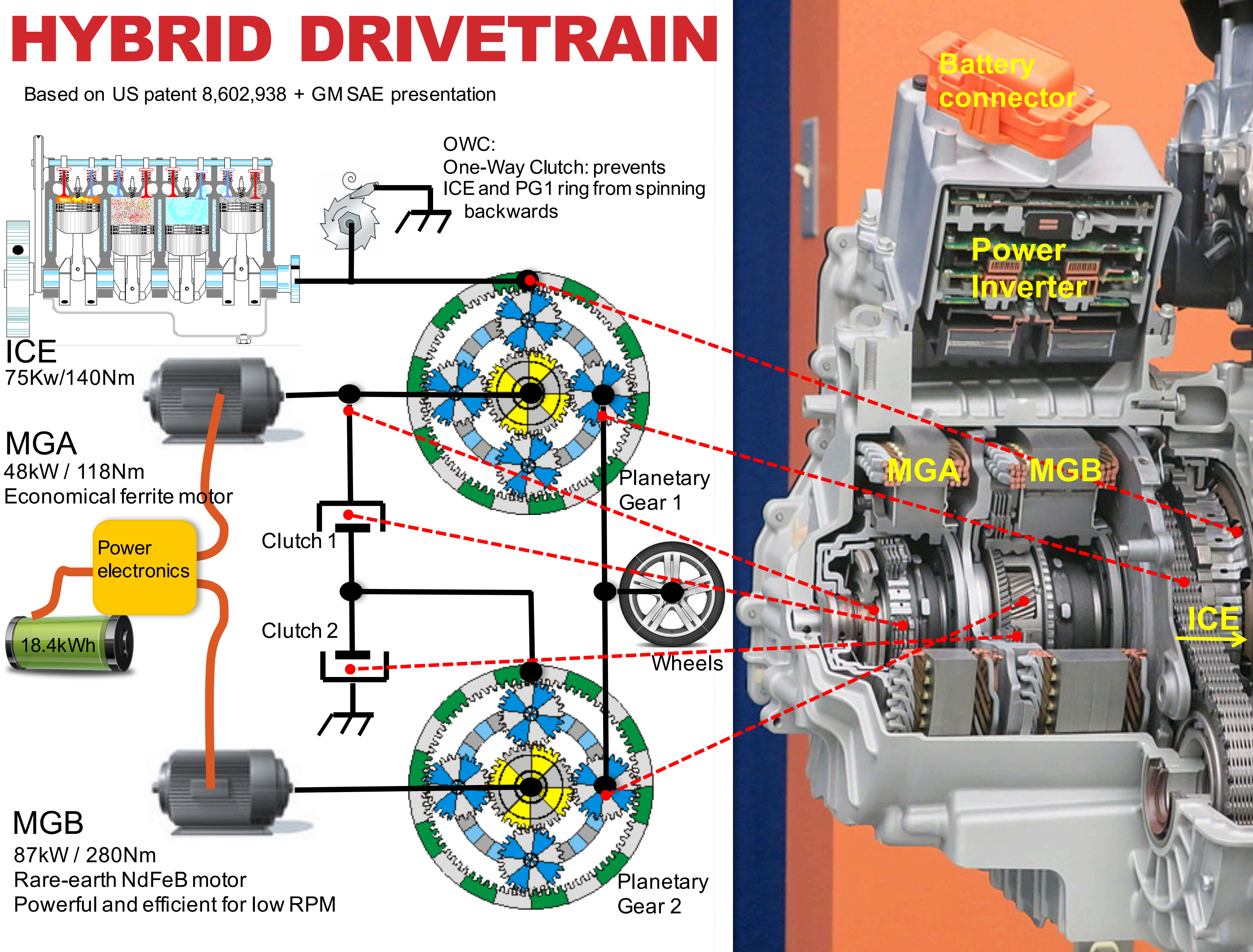
HYBRID: POWER-SPLIT MODE

For steady highway driving

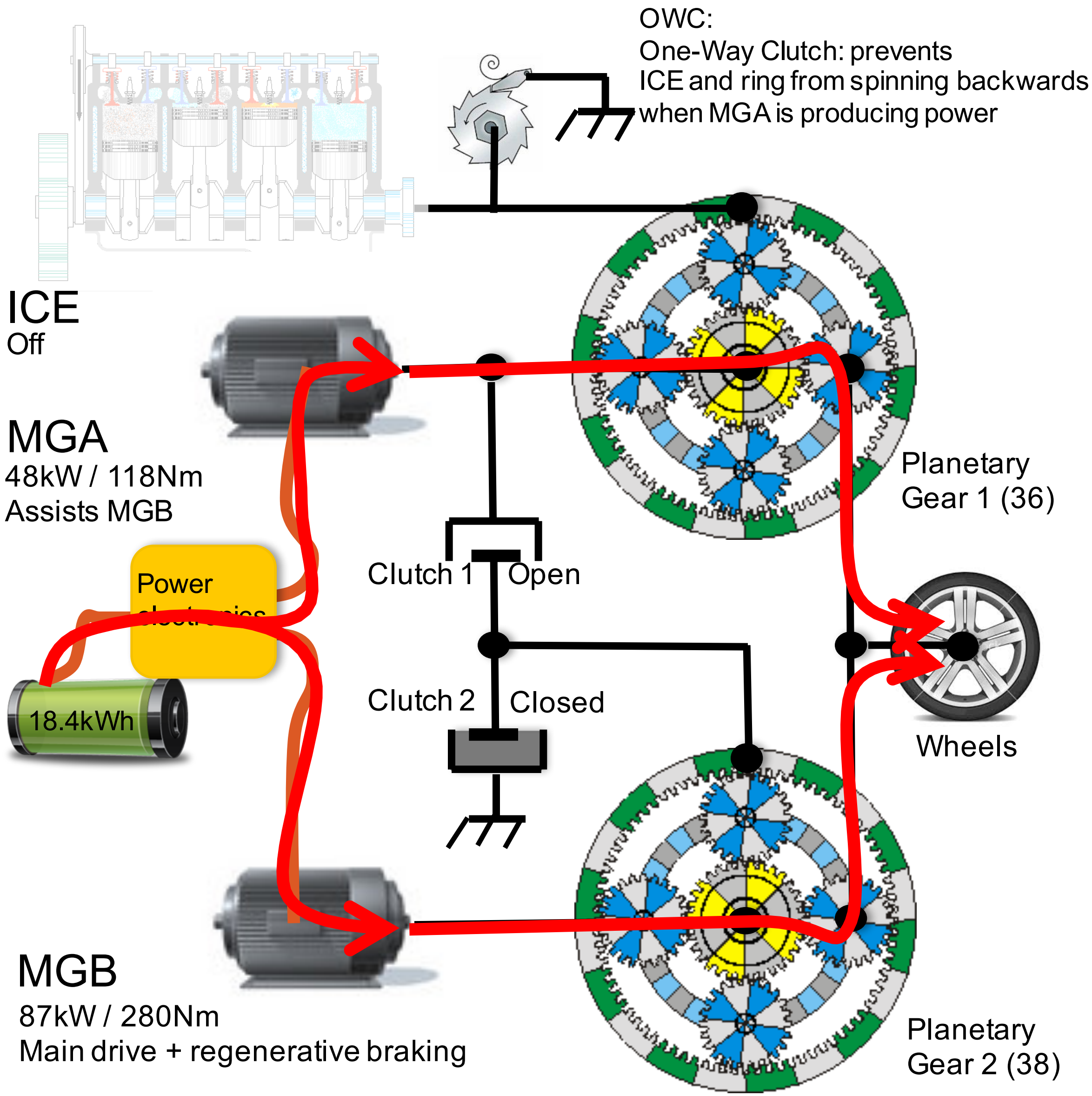


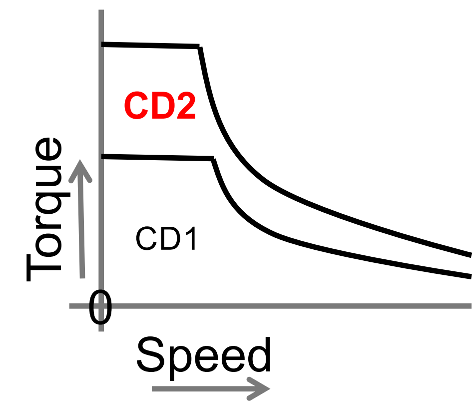
HYBRID DRIVETRAIN

Based on US patent 8,602,938 + GM SAE presentation



CD2: TWO MOTOR EV MODE





Mode **CD2**: (74)
Two Motor EV

When: Electric drive CD
High torque demand, any speed

How: MGB+MGA are on. ICE is off
Clutch 1 is open, Clutch 2 is closed

Only MGB does regenerative braking.
Fast, seamless transition between
CD1 & CD2 or regen braking.

Why: Both motors work in parallel.
More peak output from smaller motors.

OUTLINE: ELECTRIC VEHICLES

- Introduction
  - IC design vs EV Design
- Drive Train Design
  - System and transmission design
  - Design and simulation tools
  - Operating modes
- **Dollars and sense:**
  - **Economic**
  - Environmental
- What can improve efficiency?
  - Battery, driving, etc.
- Battery Technology
  - Tesla, GM, BMW
  - Electric Airplanes

DOES IT MAKE FINANCIAL SENSE TO DRIVE ELECTRIC?

Annual cost = Efficiency * Unit Energy Cost * 12,000 miles

Miles/ kWh

Miles/ Gallon

$/kWh

$/Gallon

Average annual distance for US driver

Chevy Volt, Driven electric

Chevy Volt, Driven in Hybrid mode on Gasoline

Nissan Leaf All-electric

Toyota Prius Gasoline Hybrid

Tesla Model S All-Electric

Porsche Panamera S Gasoline

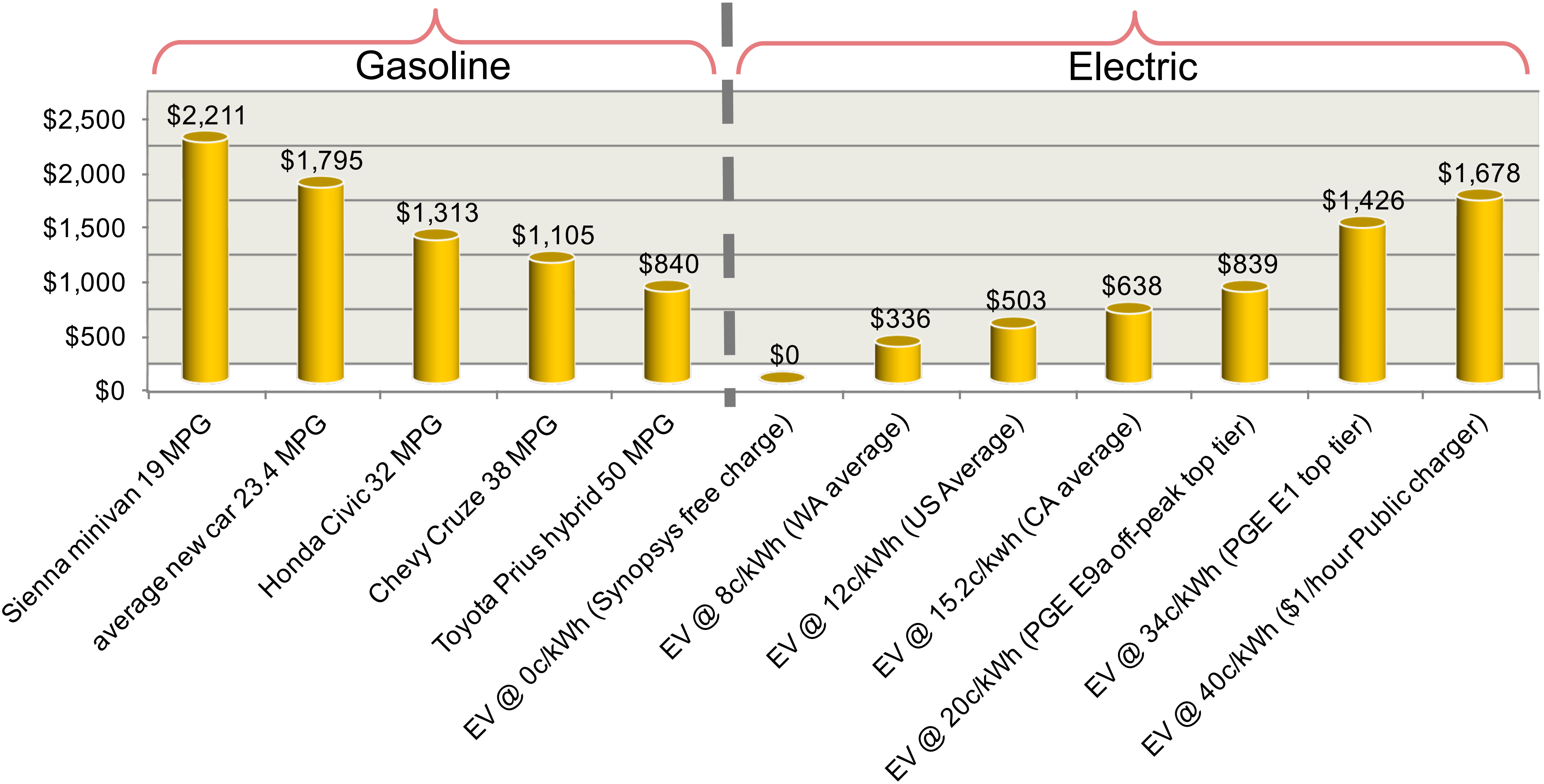
Chevy Volt, Driven electric	Chevy Volt, Hybrid mode on Gasoline	Nissan Leaf All-electric	Toyota Prius Gasoline Hybrid	Tesla Model S All-Electric	Porsche Panamera S Gasoline
2.9Miles/kWh = 4.6 km/kWh	38Miles/Gal = 6.2 l/100km	3.4Miles/kWh = 5.4 km/kWh	50Miles/Gal =4.7L/100km	2.6Miles/kWh = 4.2 km/kWh	17Miles/Gal = 13.8 l/100km

Apples-to-apples comparison: cars in the same class

TRUE ANNUAL ENERGY COST FOR 12000 MILES DRIVEN

Gasoline-powered car at $3.5/gallon (June 2014, multiply x2 for Europe)

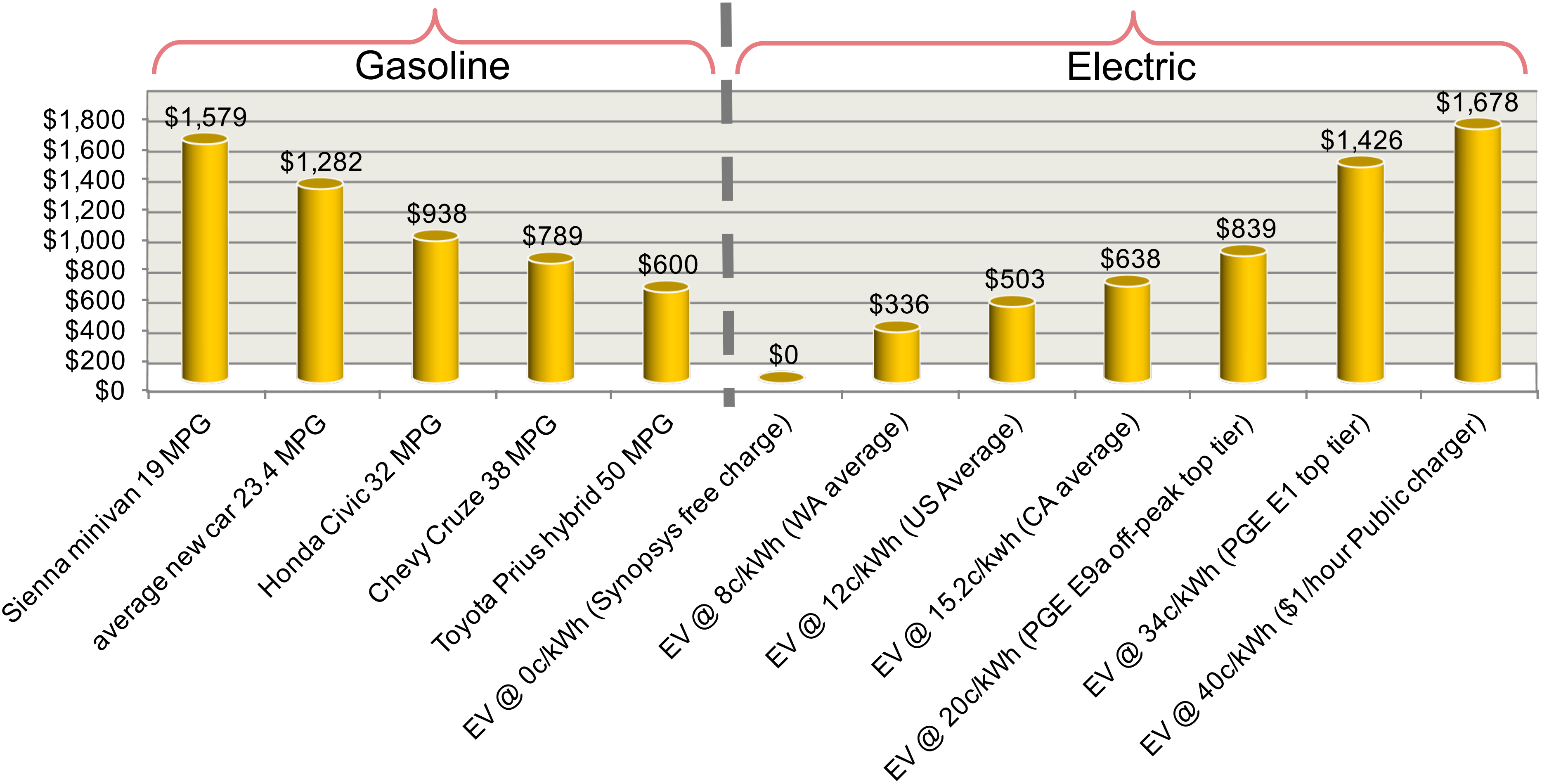
Electric Vehicle @ 98 MPGe = 2.861 miles/kWh Volt, Leaf, Prius-PI, Tesla cost for 4194 kWh



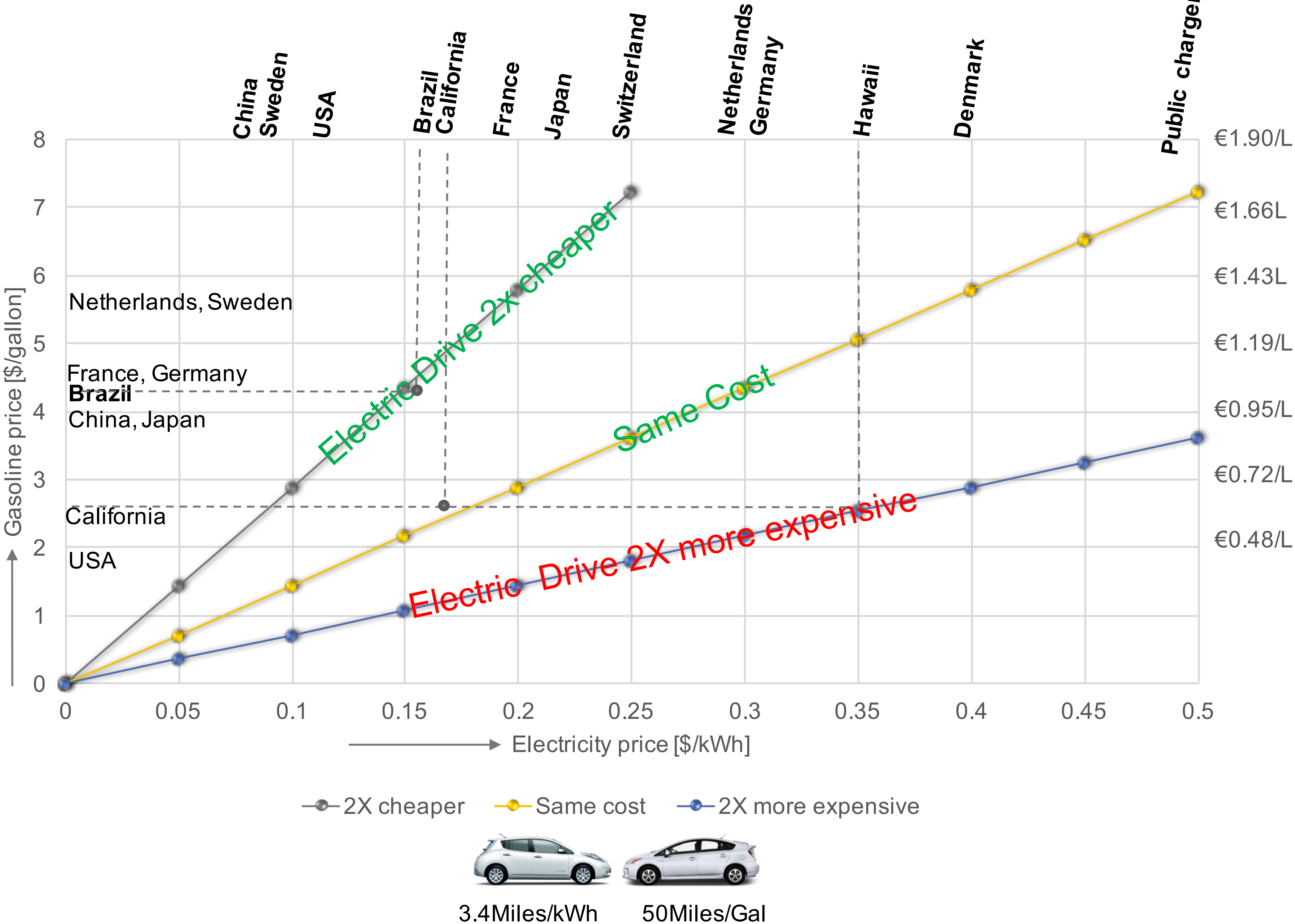
TRUE ANNUAL ENERGY COST FOR 12000 MILES DRIVEN

Gasoline-powered car at $2.5/gallon (Jan 2016, multiply x2 for Europe)

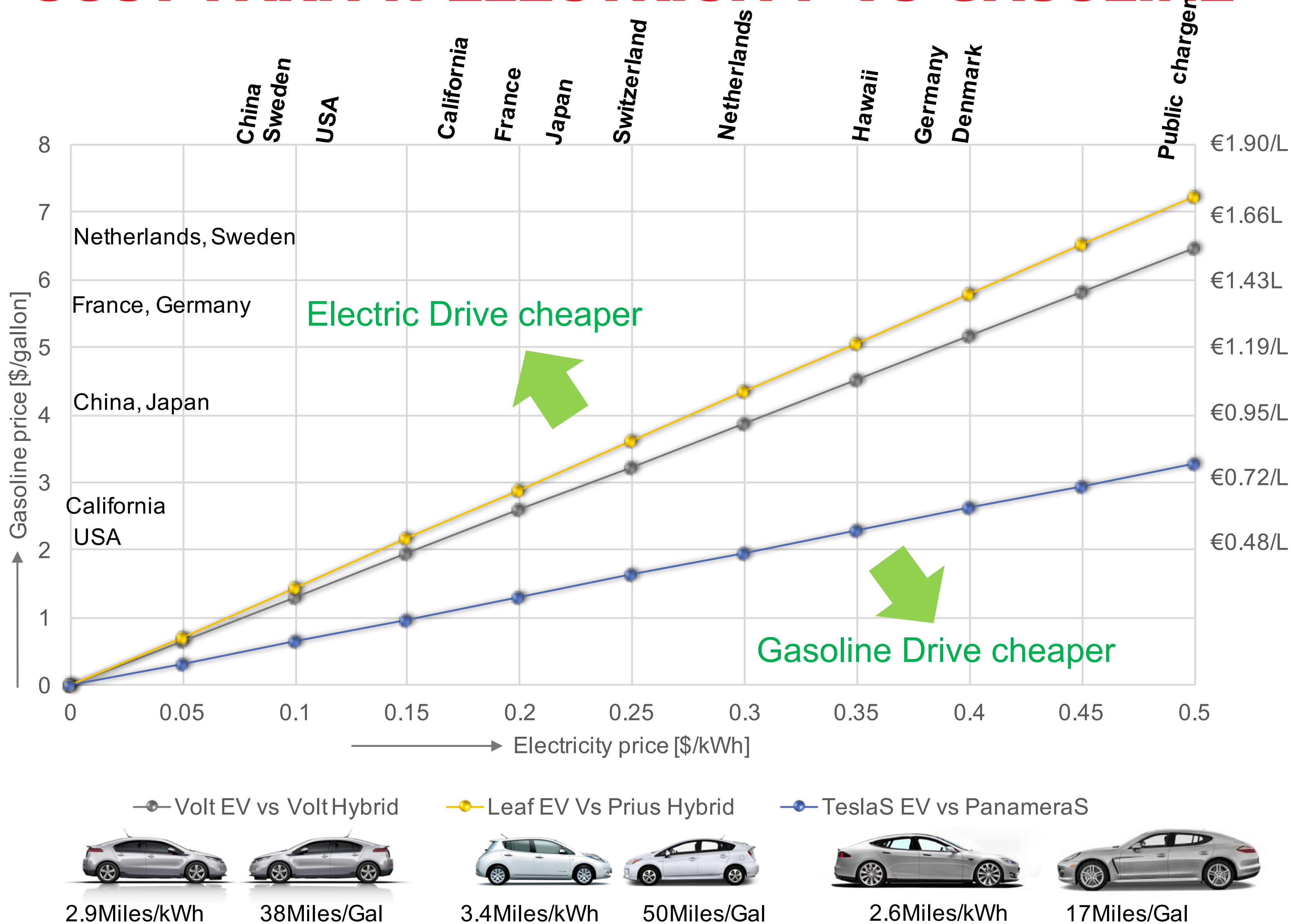
Electric Vehicle @ 98 MPGe = 2.861 miles/kWh Volt, Leaf, Prius-PI, Tesla cost for 4194 kWh



COST PARITY: ELECTRICITY VS GASOLINE



COST PARITY: ELECTRICITY VS GASOLINE



PERK: CHARGING AT SYNOPSYS

80 free charging spots available on the Mountain View Campus

Currently:

45 Nissan Leaf EV

14 Chevy Volt EREV

10 Toyota Prius Plug-in

8 Ford Fusion Plug-in

5 Ford C-Max Plug-in

4 Tesla Model S EV

2 Toyota Rav-4 EV

1 Fiat 500e EV

1 Chevy Spark EV

THE REALITY OF PLUGGING IN

110V/20A receptors (max 2.2kW)

- **4** miles/hour = 32 miles during 8-hour work day.

220V/20A receptor (max 4.6kW).

- **10** miles/hour = 80 miles/day typical

220V/30A (Clothes dryer)

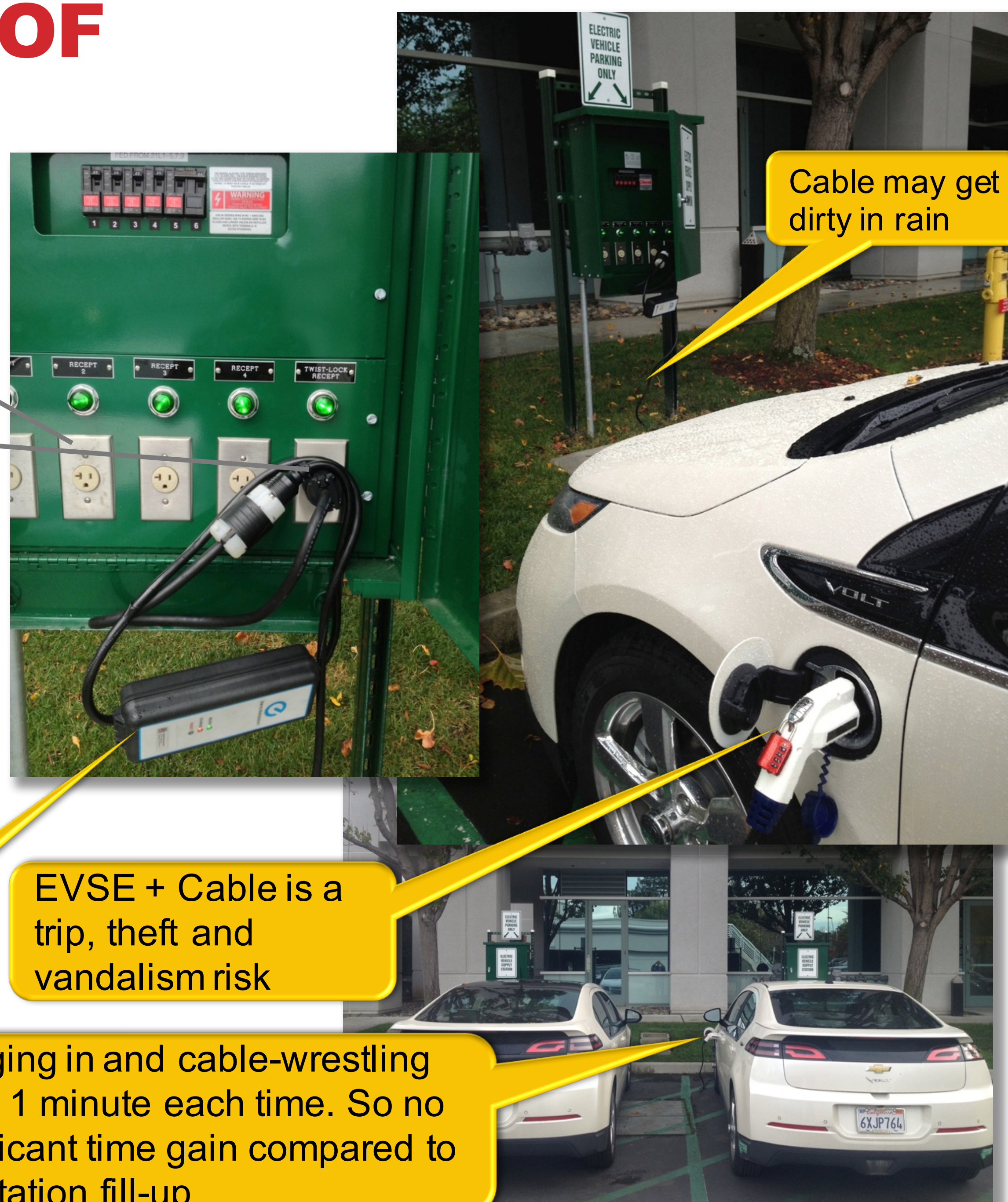
- **15** miles/hour

Tesla DC supercharger (90kW)

- **300** miles/hour

Gas station fill up:

- **3600** miles/hour



Cable may get dirty in rain

EVSE + Cable is a trip, theft and vandalism risk

Portable EVSE with adapter cable. Stores in trunk

Plugging in and cable-wrestling takes 1 minute each time. So no significant time gain compared to gas station fill-up

OUTLINE: ELECTRIC VEHICLES

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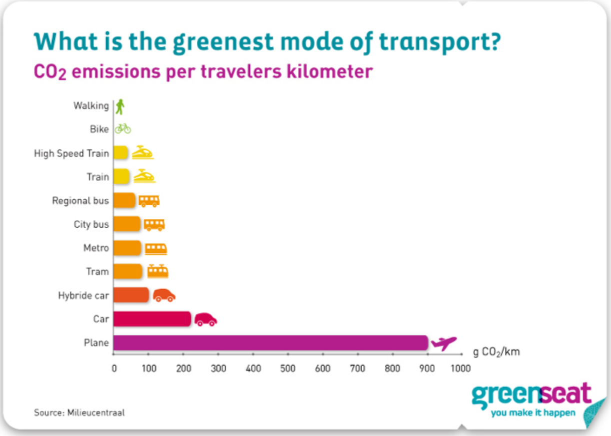
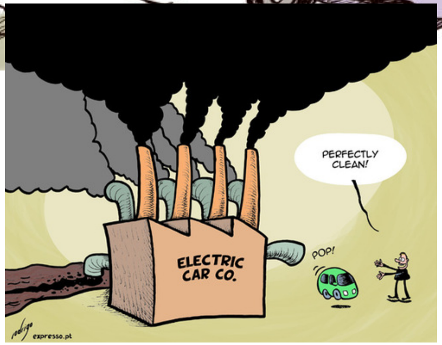
  - Operating modes
- Dollars and sense:
  - Economic
  - **Environmental**
- What can improve efficiency?
  - Battery, driving, etc.
- Battery Technology
  - Tesla, GM, BMW
  - Electric Airplanes

BETTER FOR THE ENVIRONMENT?

Who is right?






BUSINESS INSIDER

Tech | Finance | Politics | Strategy | Life | Sports

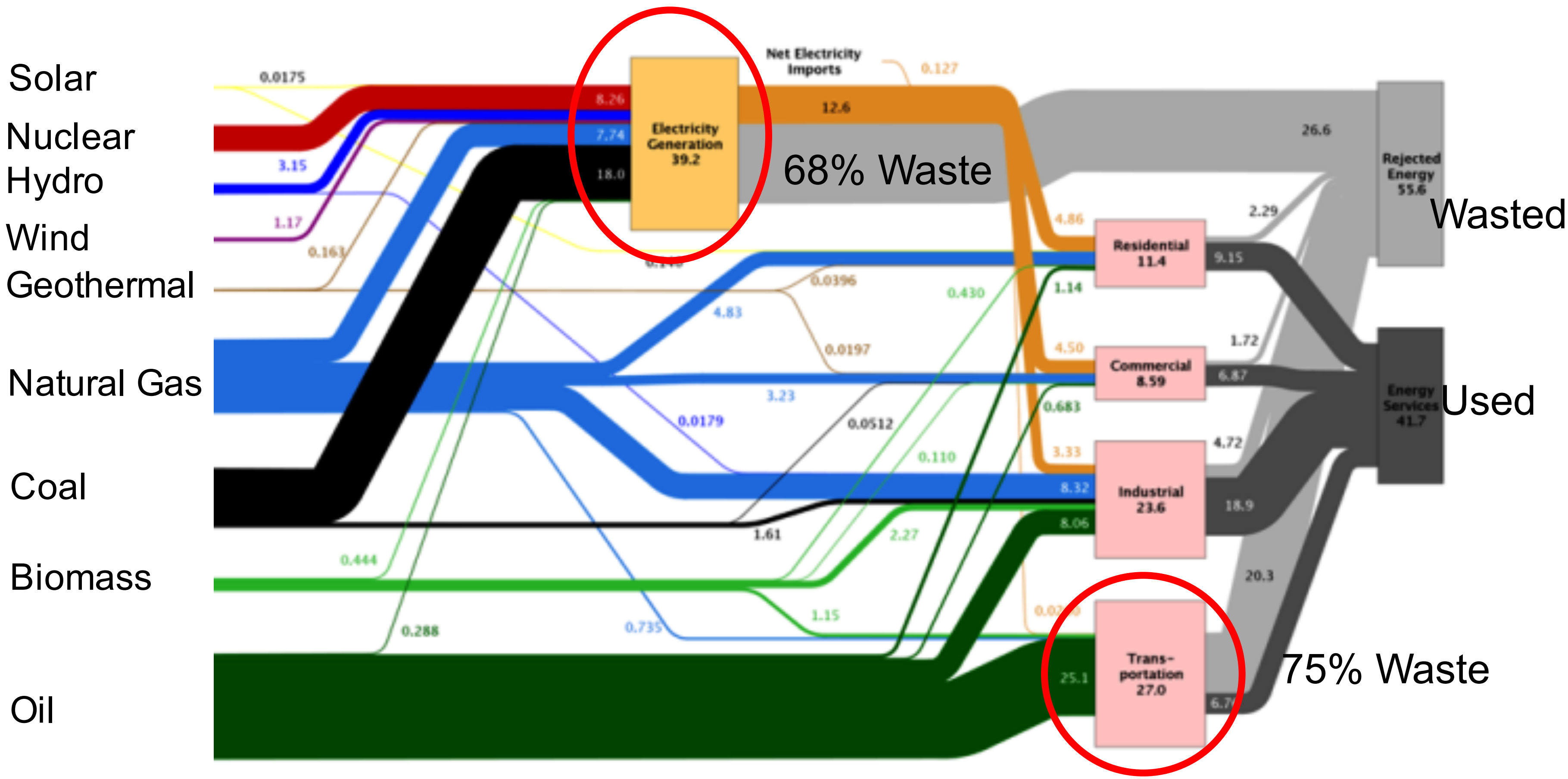
TRANSPORTATION

Why Electric Cars May Be Much Dirtier Than Gas-Powered Ones

More: Electric Cars Tesla Coal Electr

THE ECONOMIST
DEC. 28, 2014, 11:47 AM
17,610
50

WELL-TO-SINK ENERGY FLOW GRAPH

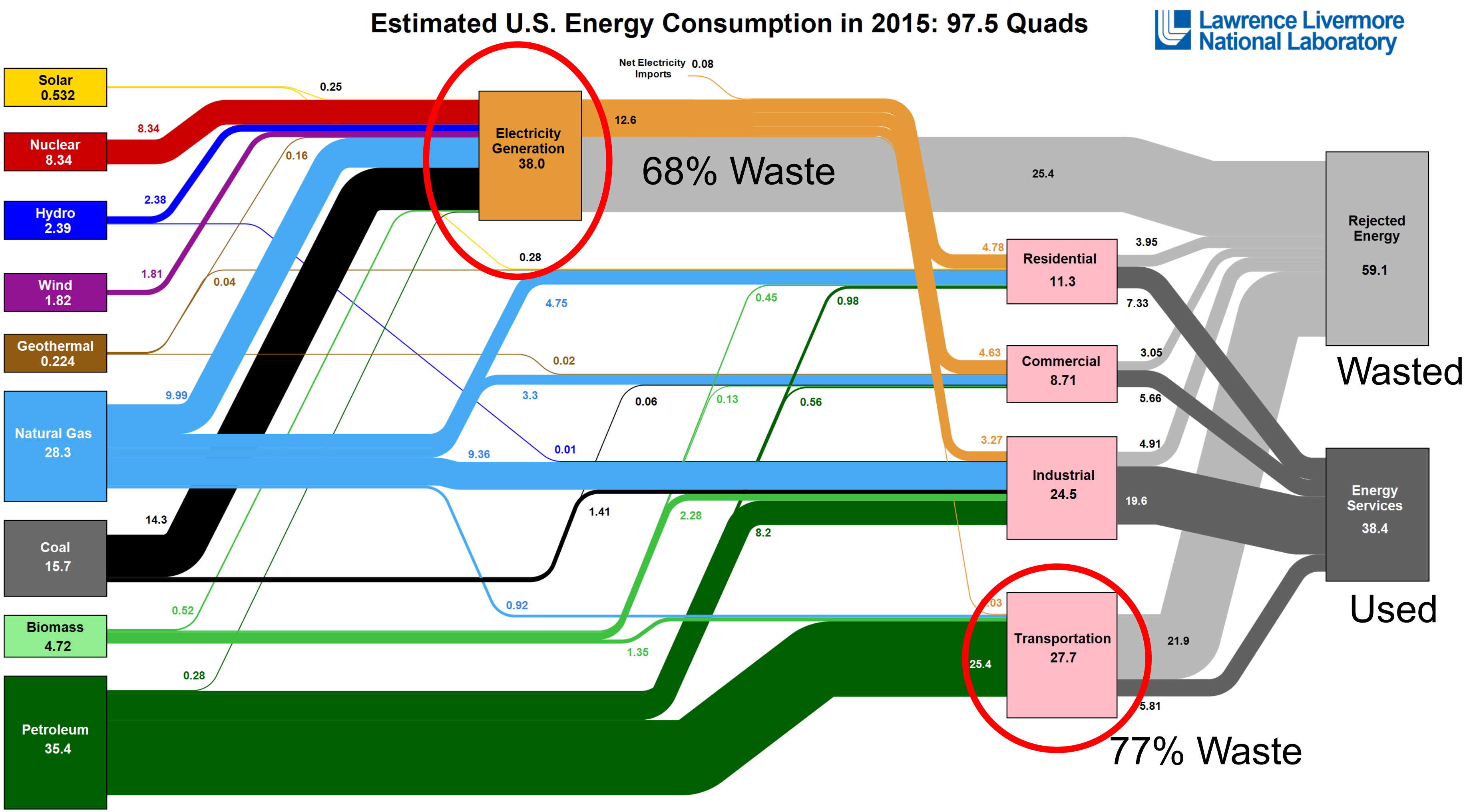


Source: LLNL 2012. Data is based on DOE/EIA-0384(2011), October, 2012. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA

Source: Lawrence Livermore Labs, 2012
Data: US Dept of Energy 2011 report

Unit: Quadrillion BTU = ~ 10^18 joule = [Quintillion Joule]

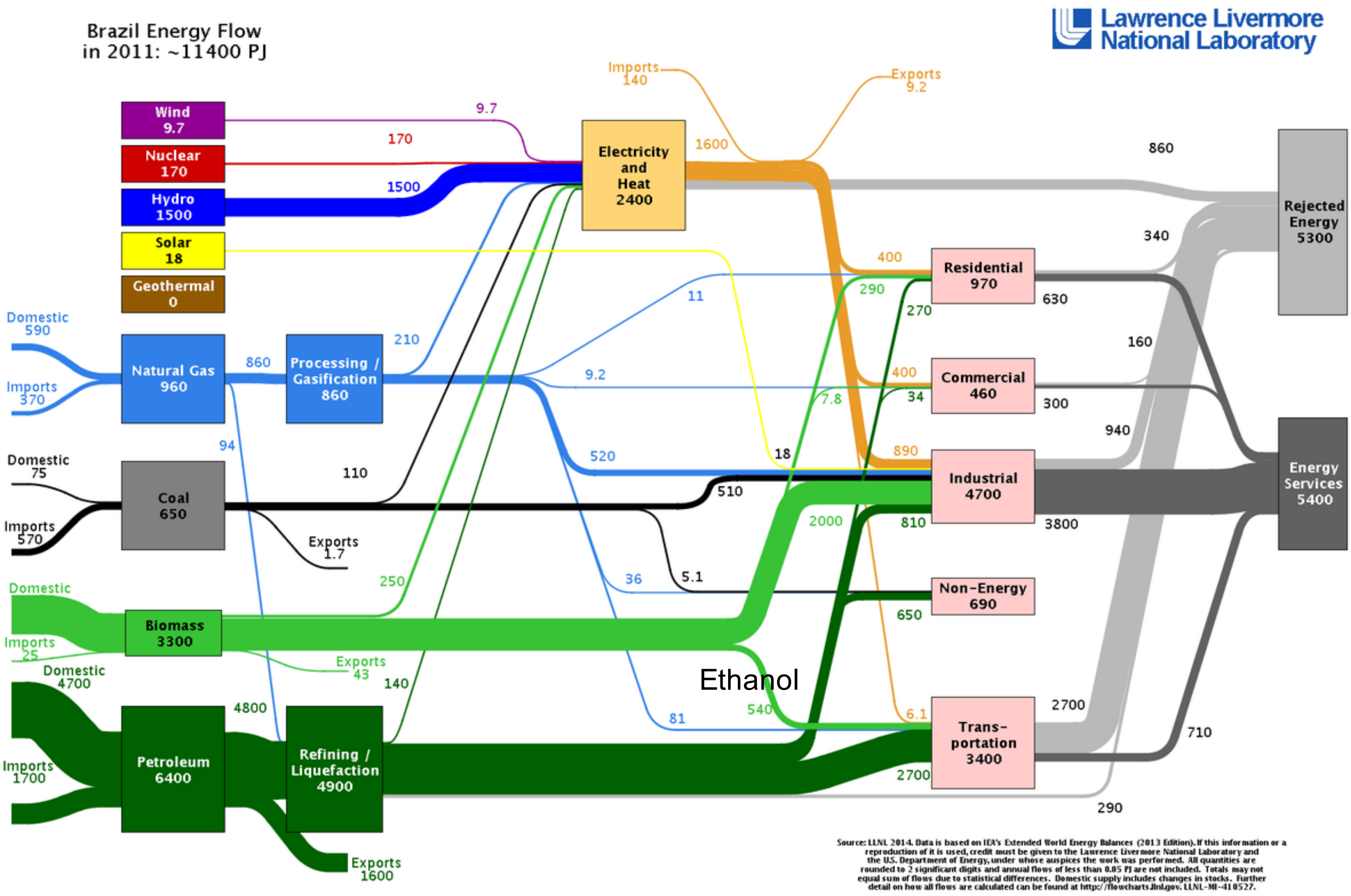
WELL-TO-SINK ENERGY FLOW GRAPH



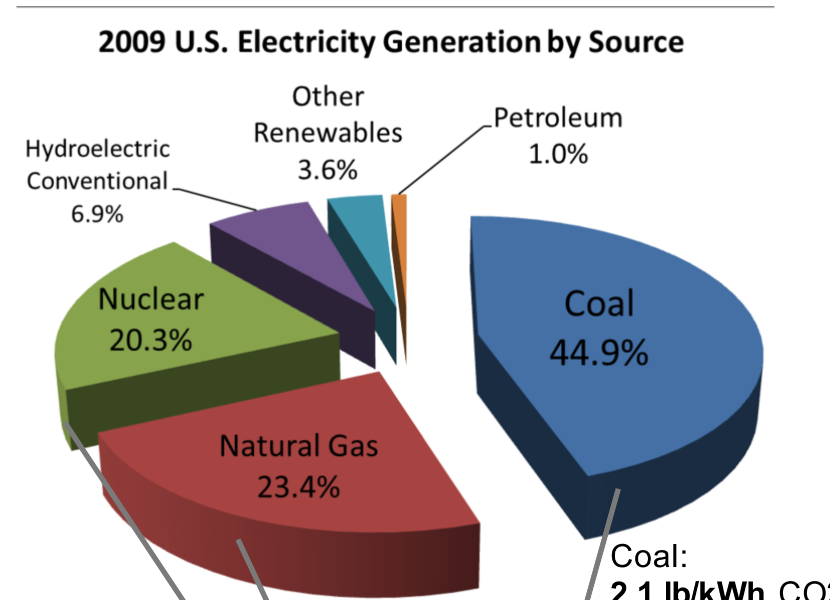
Unit: Quadrillion BTU = ~ 10^18 joule = [Quintillion Joule]

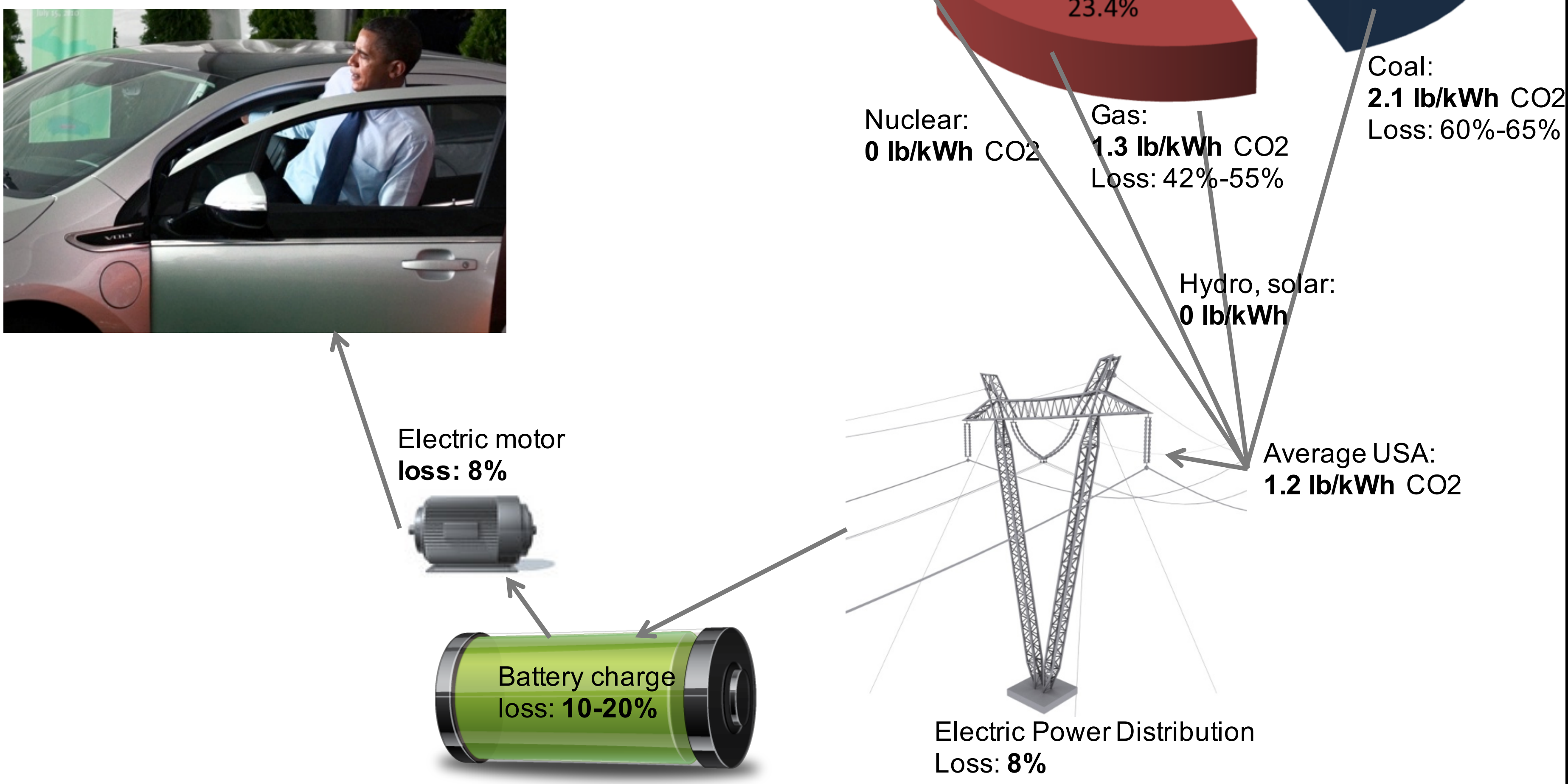
Source: LLNL March, 2016. Data is based on DOE/EIA MER (2015). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production

BRAZIL ENERGY FLOW GRAPH

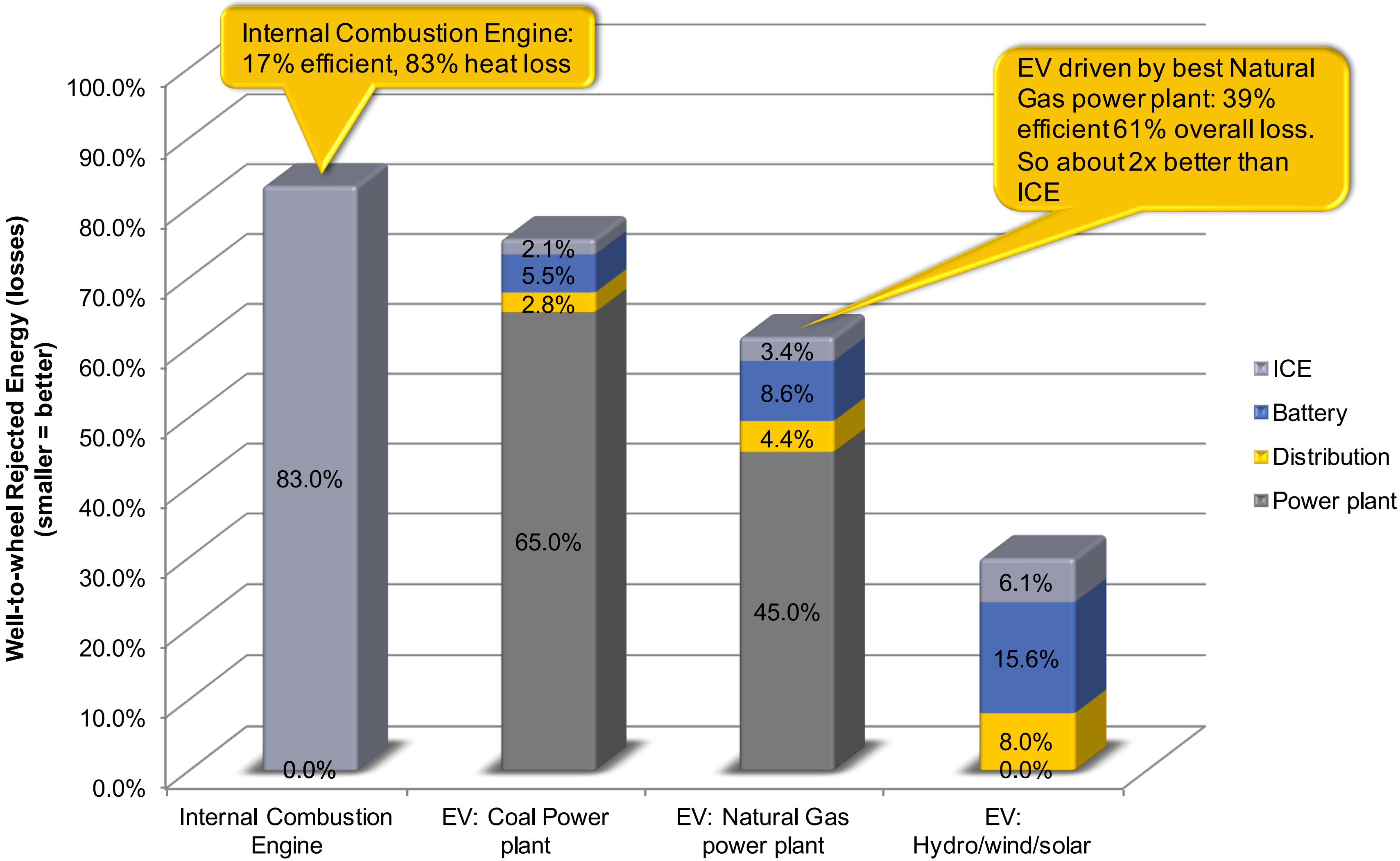


SYSTEM-WIDE LOSSES & POLLUTION

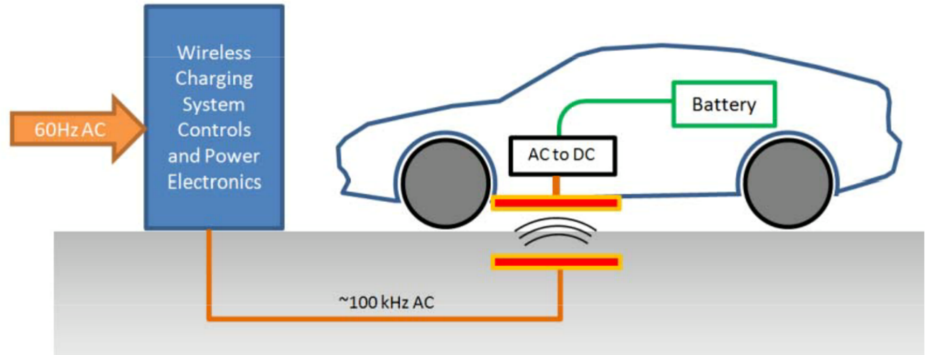


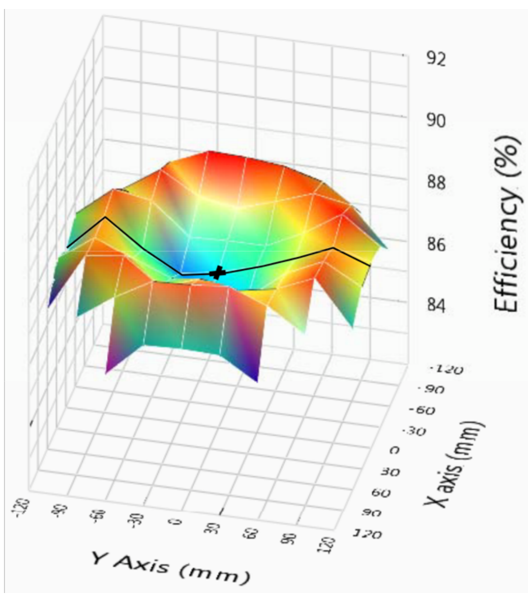


ENERGY CONVERSION LOSSES: INTERNAL COMBUSTION ENGINE VS ELECTRIC

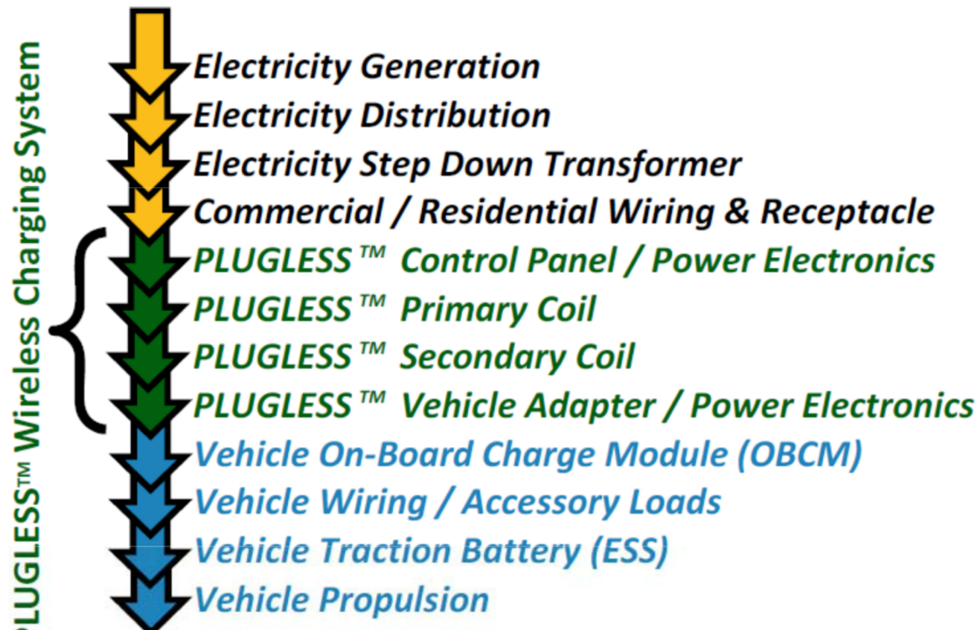


WIRELESS EV CHARGING





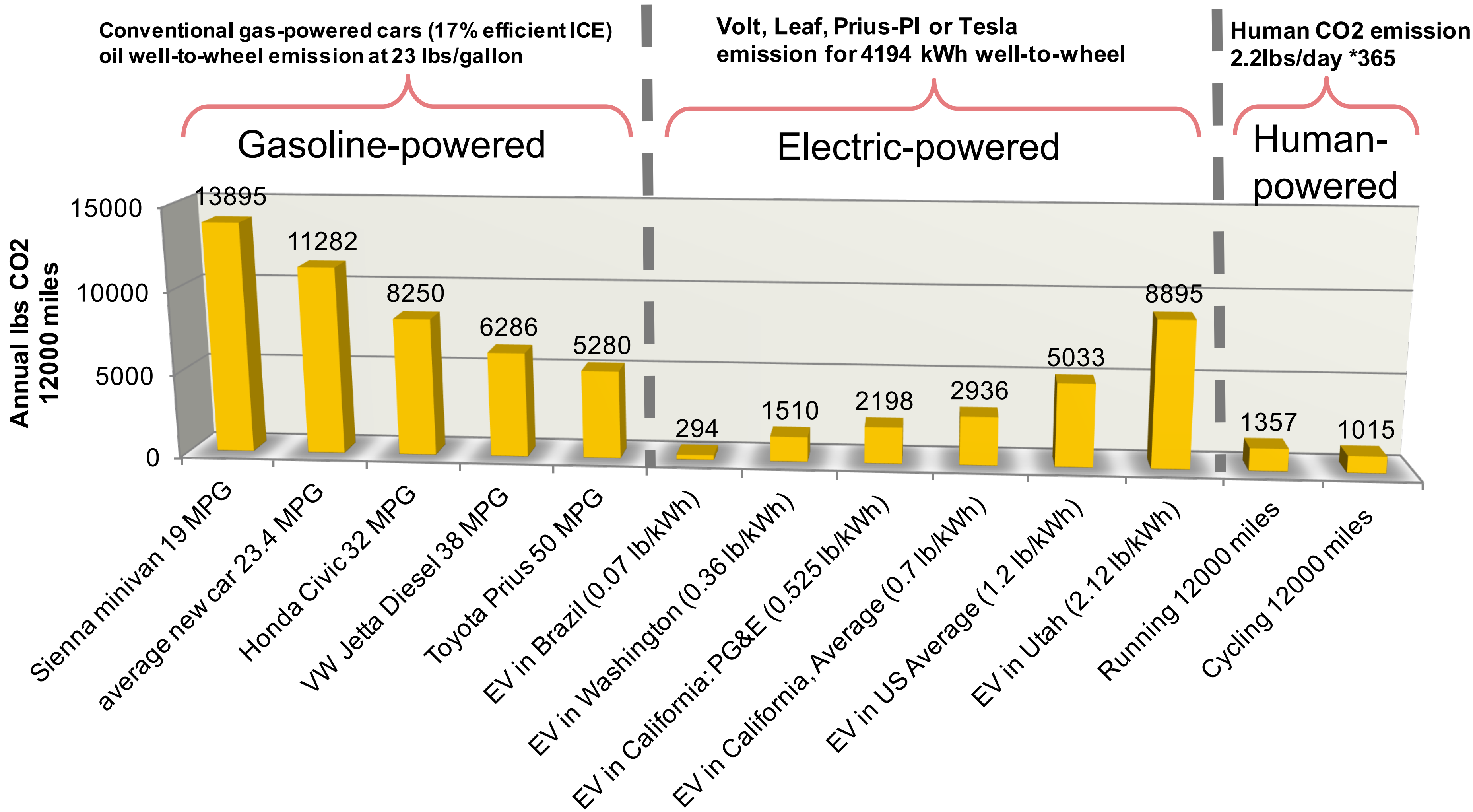
Source: Idaho National Laboratory



Bottom line: adds 10-15% to system loss…

ARE EVS CLEANER CO2-WISE?

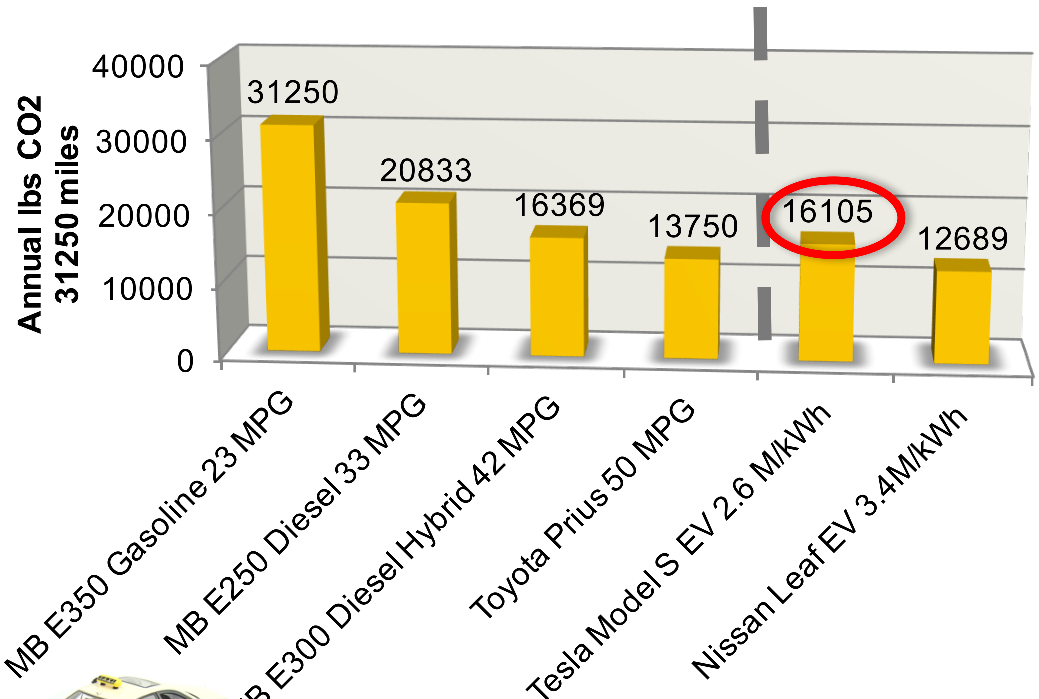
…. That depends on how electricity is generated



TESLA AIRPORT TAXI IN AMSTERDAM..

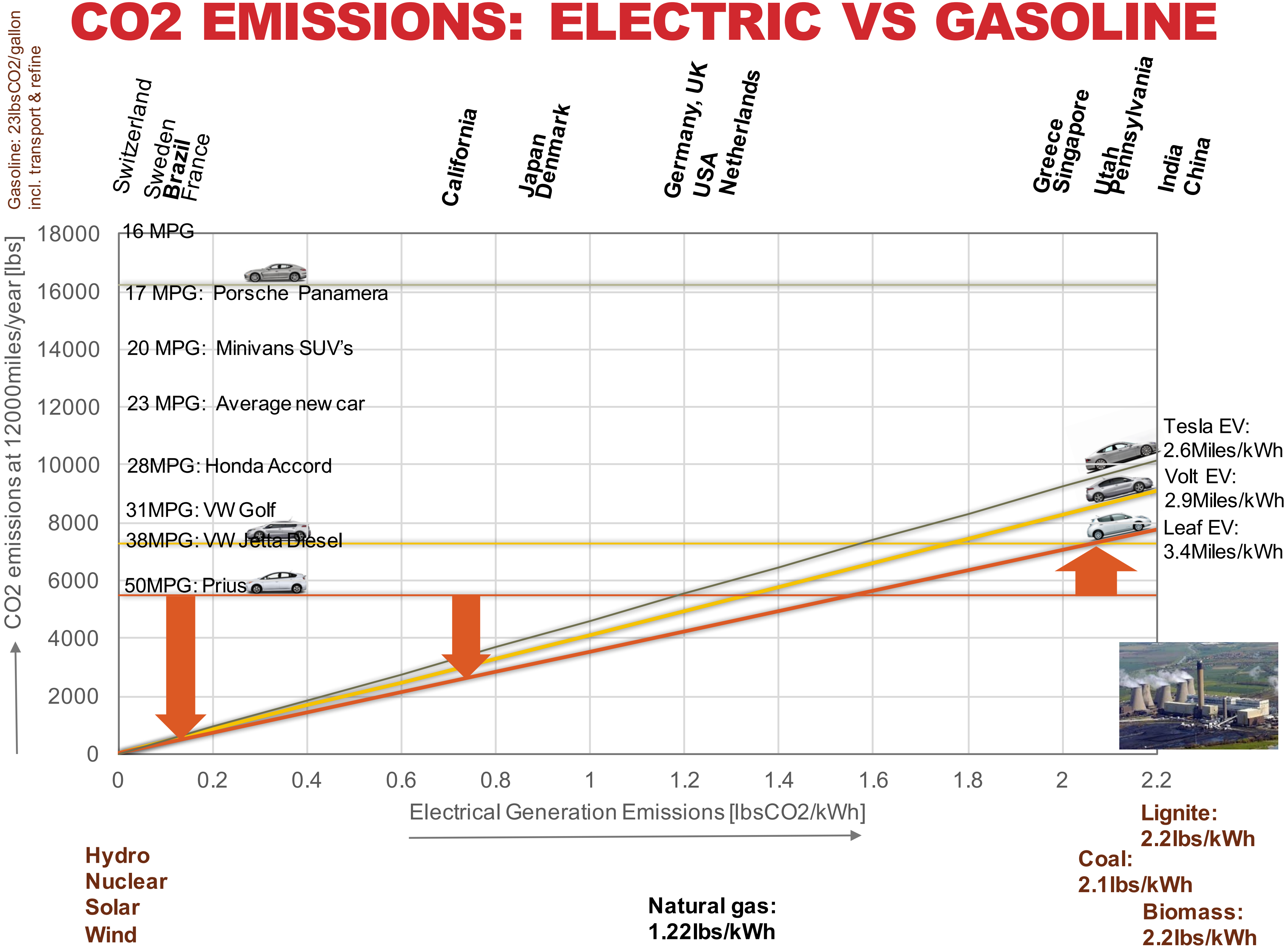
Fact check: Taxi drives 31250miles/year

Netherlands: Electric grid = 1.34lbs CO2/kWh



"This represents a crucial step in our efforts to reduce CO2 emissions and become one of the world's three most sustainable airports", explained Jos Nijhuis, Schiphol Group's President and CEO.

CO2 EMISSIONS: ELECTRIC VS GASOLINE



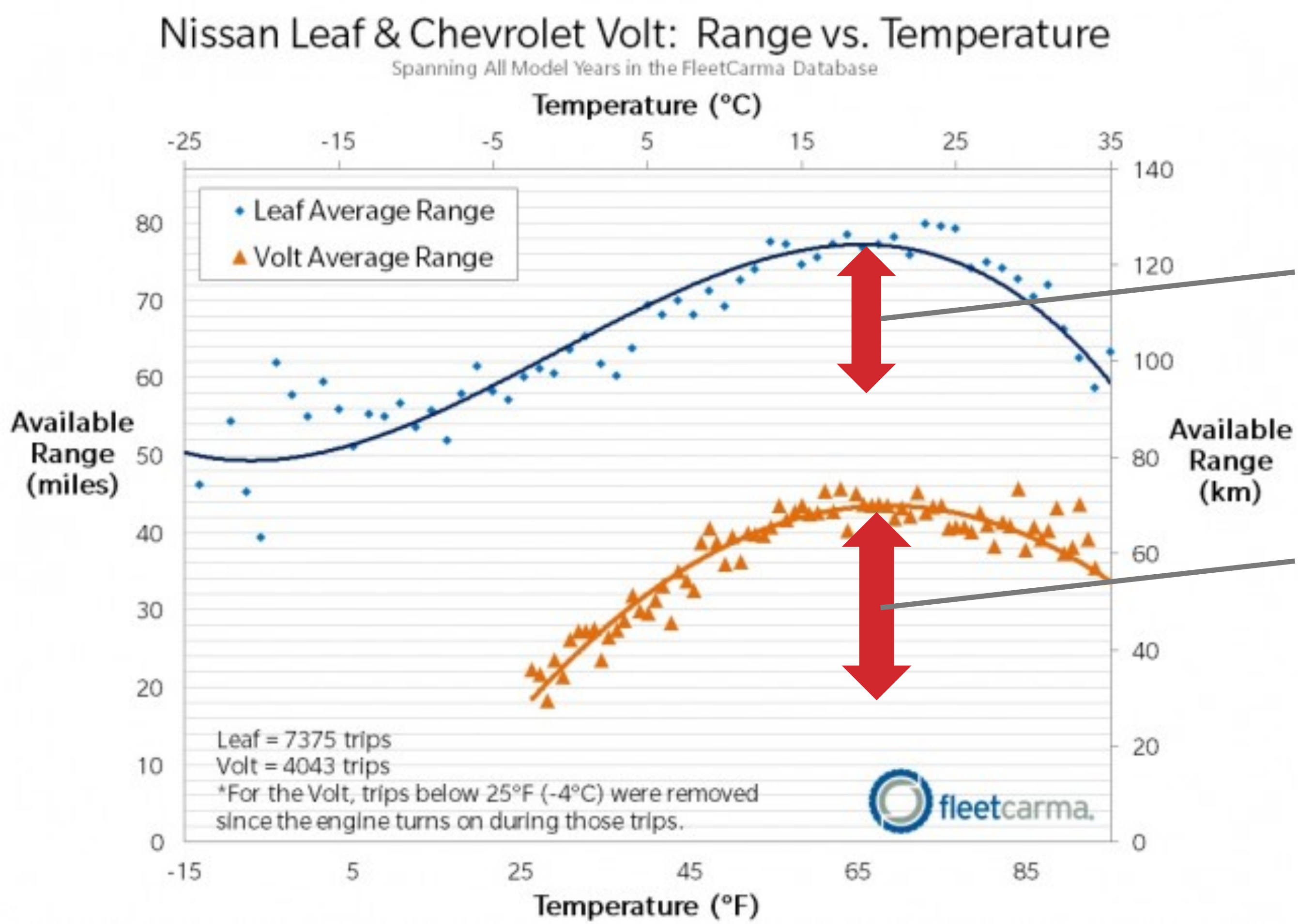
OUTLINE: ELECTRIC VEHICLES & EDA

- Introduction
  - IC design vs EV Design, Synopsys' role
- What really matters: cost performance and Emissions
  - Volkswagen scandal
- Drive Train Design
  - System and transmission design
  - Design and simulation tools
- Dollars and sense:
  - Economic
  - Environmental
- What can improve efficiency?
  - Battery, driving, etc.
- Battery Technology
  - Tesla, GM, BMW
  - Electric Airplanes

WHAT AFFECTS EFFICIENCY? WHAT AFFECTS EV RANGE?

- **Structural Design factors:**
  - Vehicle weight: ~1% for each 100lb (50kg)
  - Tires
  - Aerodynamics
  - Crash ratings and Safety
- **Market factors (subjective):**
  - Size and good looks are bad for efficiency
  - Driving style
- **Environmental factors:**
  - Temperature
  - Altitude, road conditions
- **Battery aging**

TEMPERATURE: THE ACHILLES HEEL OF ELECTRIC VEHICLES



Source: Fleetcarma Canada

Note that range equals efficiency and emissions.

Nissan Leaf at 0C/32F

30% less range =

30% more emissions

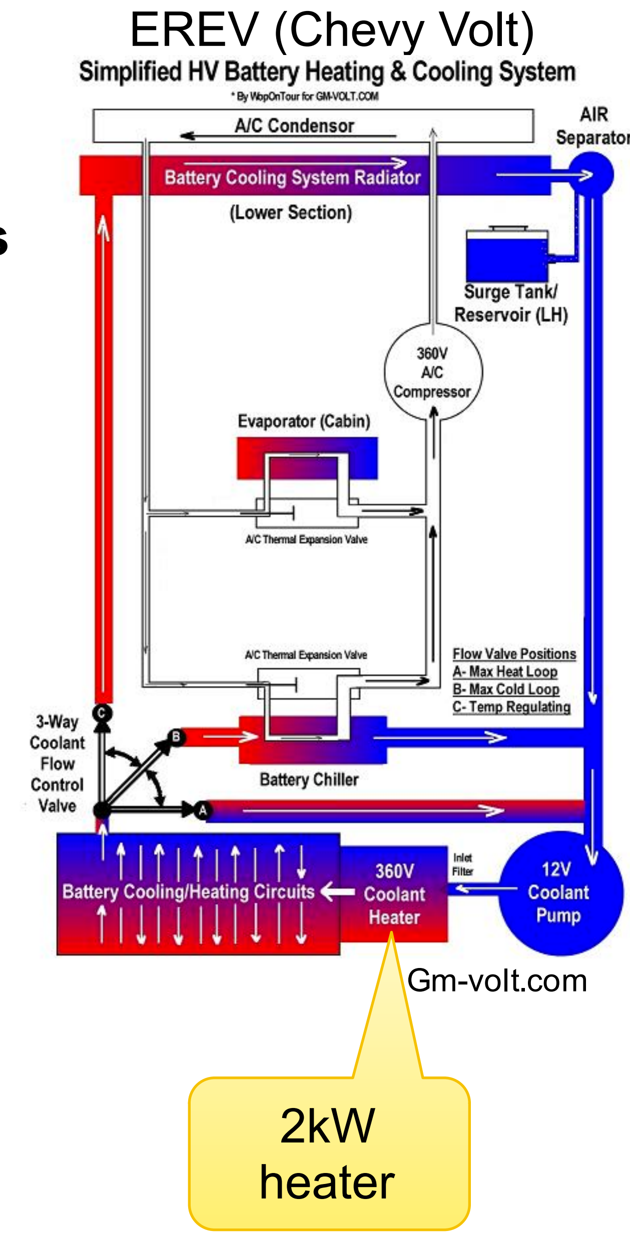
Chevy Volt at 0C/32F

2x less EV range

2x more emissions/mile

DEALING WITH LOW TEMPERATURES (1)

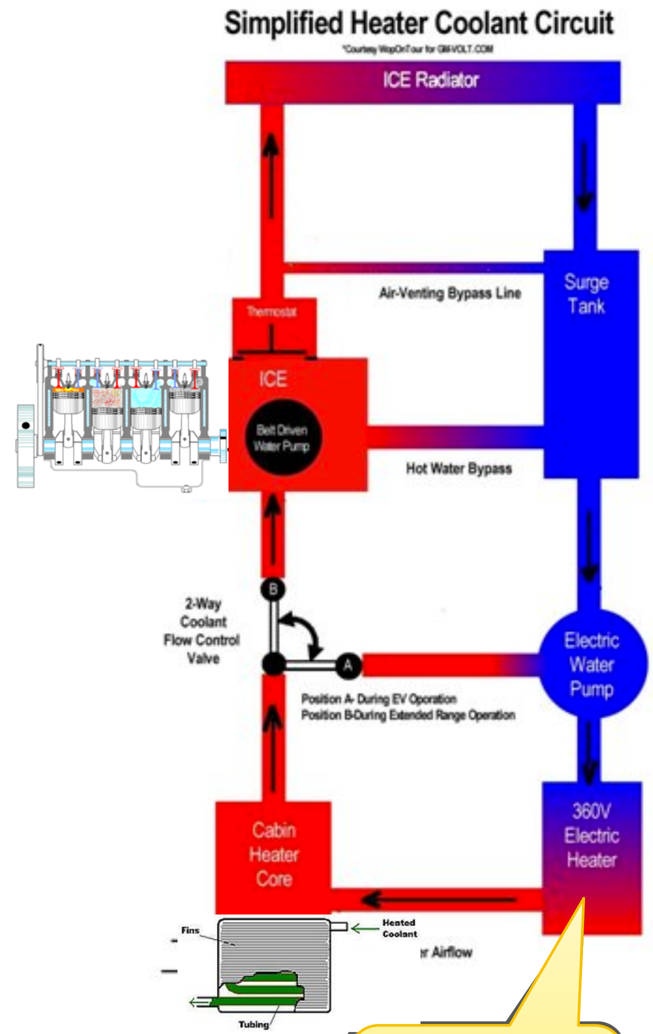
- **Problem 1: Li-Ion Battery chemistry &physics**
  - Must be kept above 10C
  - Must be kept below 30C
- **Engineering solution:**
  - Thermal isolation of battery
  - Electric battery heater (~2kW)
  - Pre-condition battery before leaving
  - Run on ICE if very cold (EREV only)



DEALING WITH LOW TEMPERATURES (2)

- **Problem 2: Cabin Comfort**
  - People: 22C
- **Engineering solution:**
  - Electric heater: 6kW: has huge impact
  - Use heat pump instead of heater coil
  - Run ICE to heat cabin up (EREV only):
    - Use abundant ICE heat for cabin
- **Masochist approach:**
  - Wear gloves

EREV (Chevy Volt)



6kW (!!) Electric heater

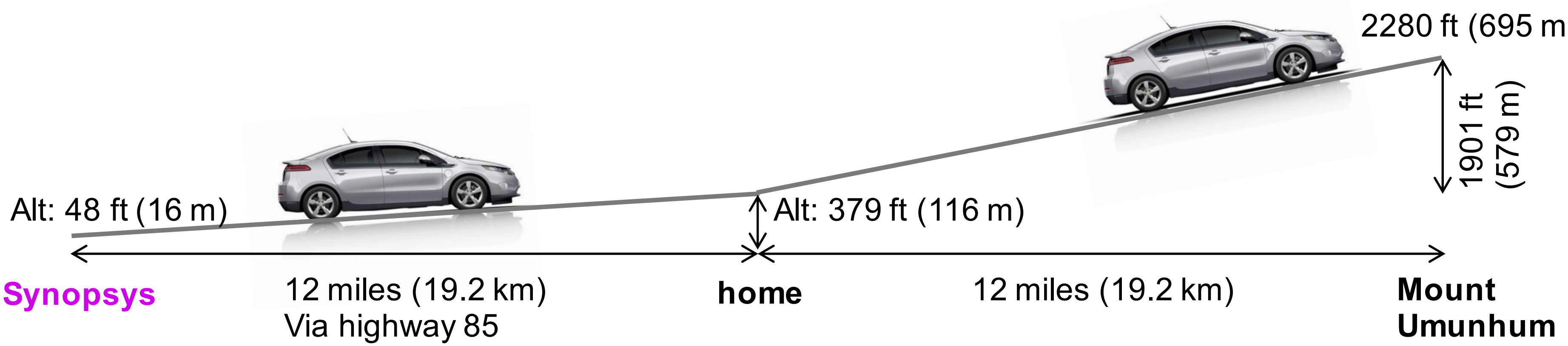
Gm-volt.com

BATTERY POWER: EV COMFORT VS RANGE

Guilty pleasure	load	Range penalty Each 10 minutes	Per 45minute full charge
Cold Battery	2.0kW	1 mile	5 miles
Cabin heat ‘Comfort’	6.0kW	4 miles	14 miles
Cabin heat ‘ECO’	2.5kW	2 miles	7 miles
Seat heater	0.06kW	0 miles	0 miles
Airco Comfort	0.7kW	0 miles	2 miles
Airco ‘ECO’	0.4kW	0 miles	1 miles
Idling at 0MPH	0.5kW	0 miles	2 miles
Driving 65 MPH		2 miles	7 miles

Note: Volt EREV has at 38miles EV range

THE EFFECT OF ALTITUDE ON RANGE



Driving home, predicted range is always 15% to optimistic, because potential energy 'investment' is unaccounted

High school physics: g = 9.8 m/s2, mass = 1715 + 75 = 1790 kg
h = height difference = 579 m
Potential energy = m * g * h = 10.157 Mega joule = 2.82 kWh

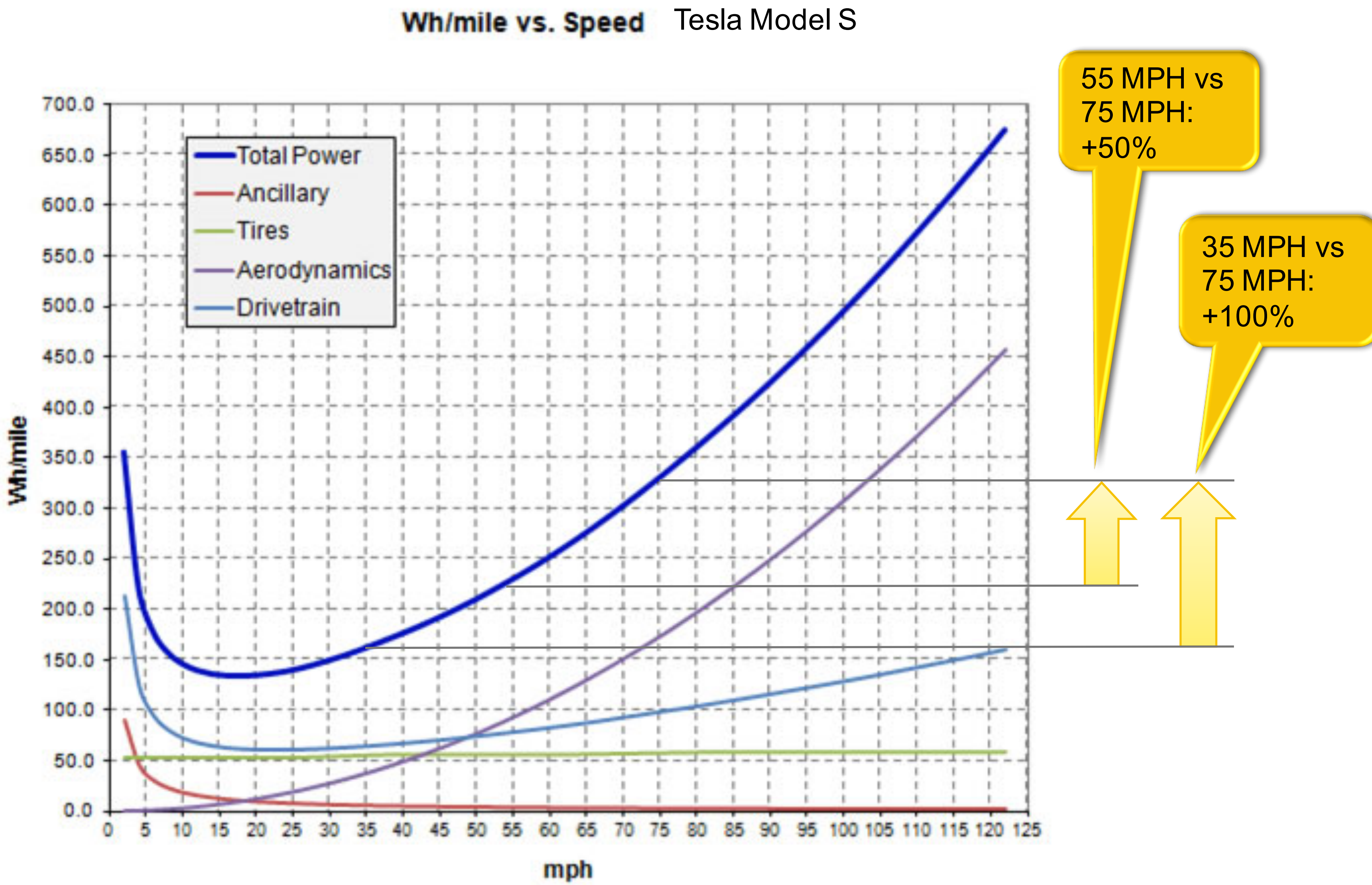
The bad news:

It 'costs' about 0.5 kWh per 100 altitude meters (320 feet) climb

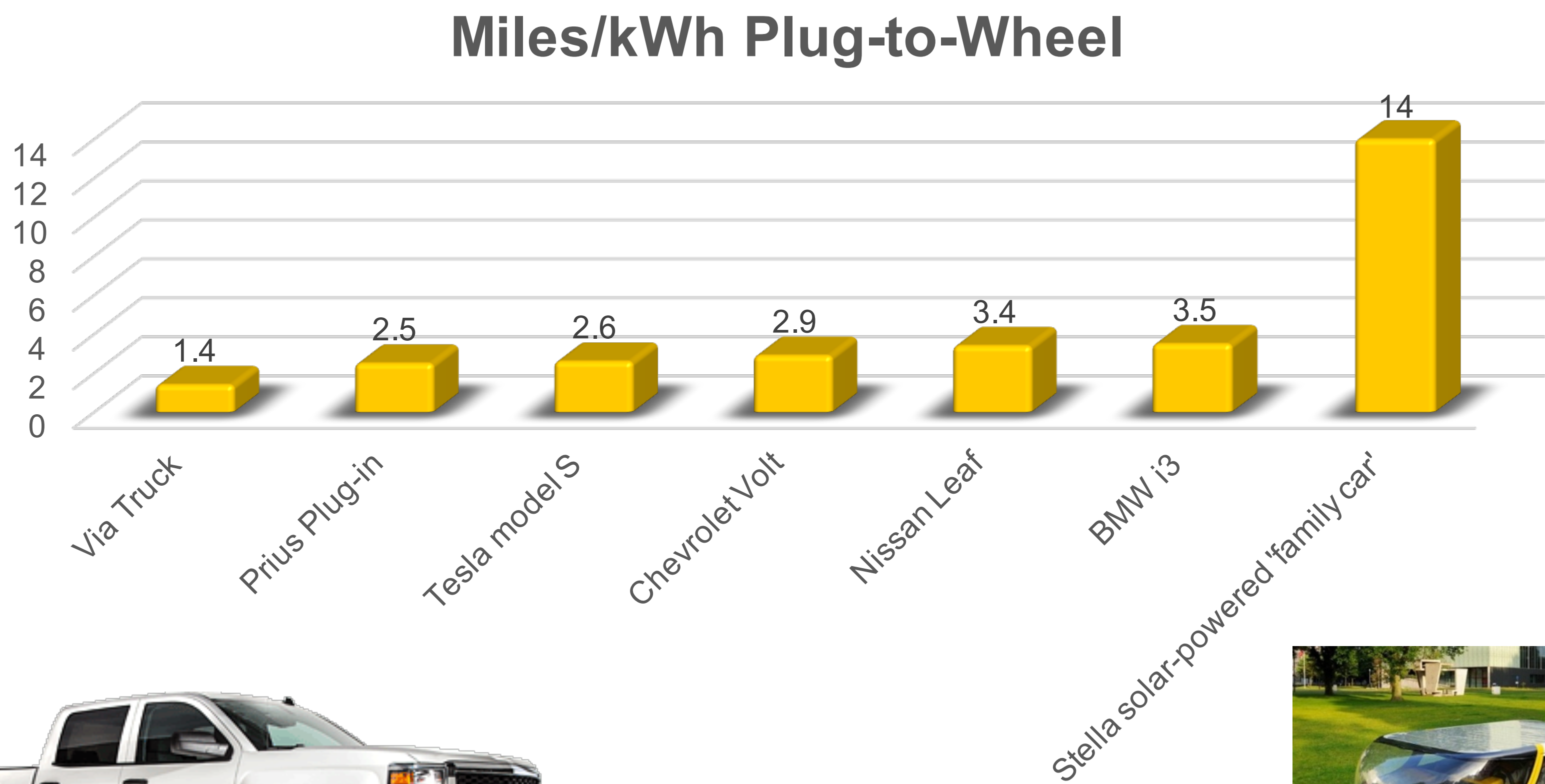
The good news:

All this potential energy comes back on the downhill leg!

SPEED: HASTE IS WASTE



IS A SIGNIFICANT EFFICIENCY IMPROVEMENT REALISTIC?



VIA truck EREV
190kW motor, 3000kg

10x efficiency gap

Stella experimental:
14kW motor, 380kg

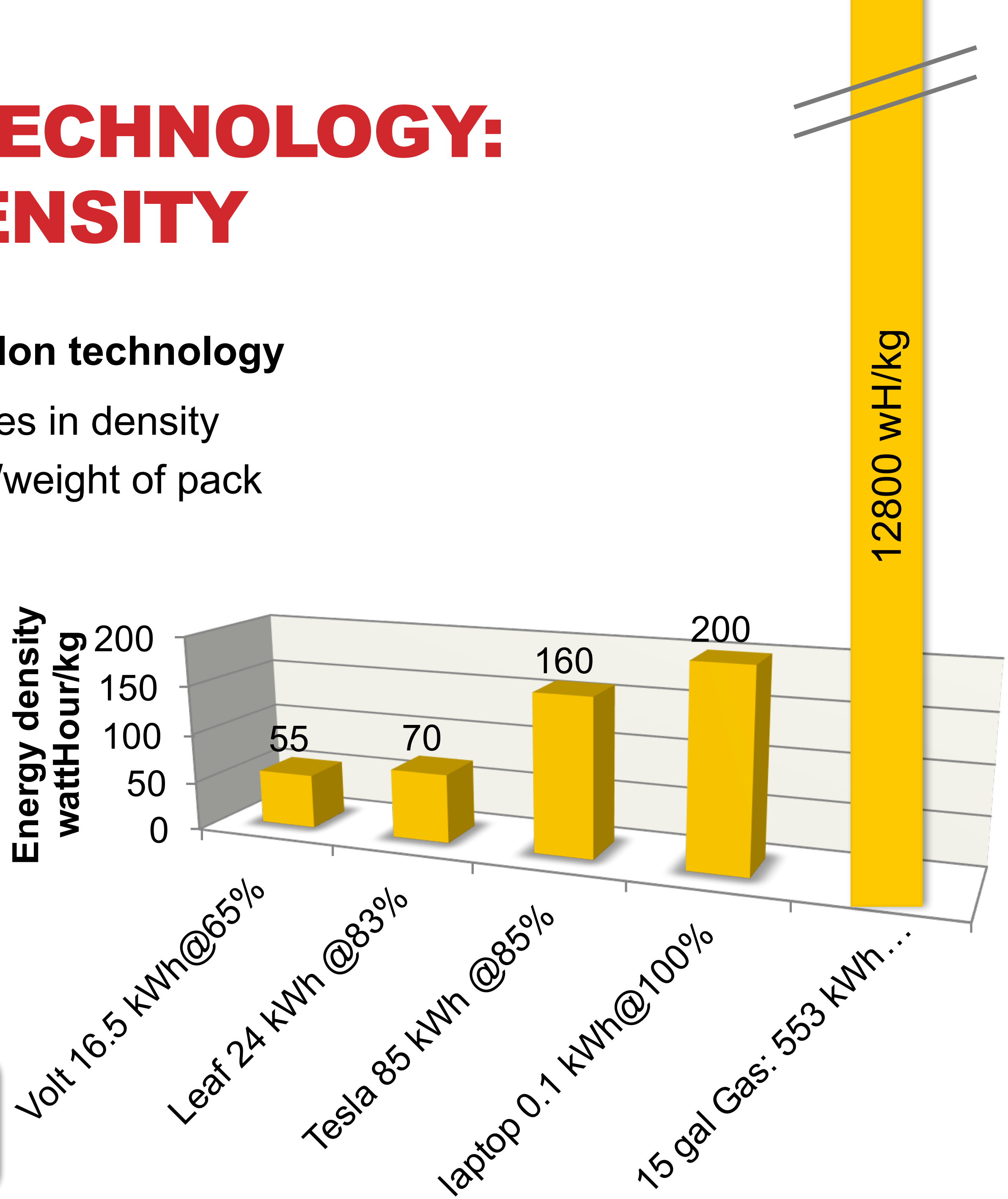
BATTERY TECHNOLOGY: ENERGY DENSITY

All EVs use advanced Li-Ion technology

- Yet there are differences in density
- Density = usable kWh/weight of pack

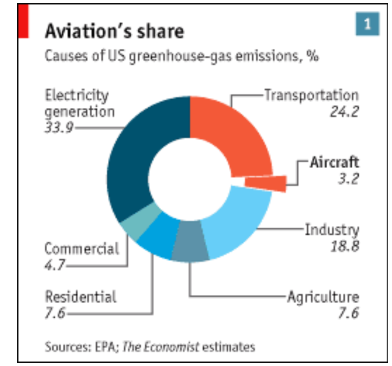
Differences:

- Charge window at Volt is only 65%, while Tesla uses 85%
- Extent of cooling/heating equipment.

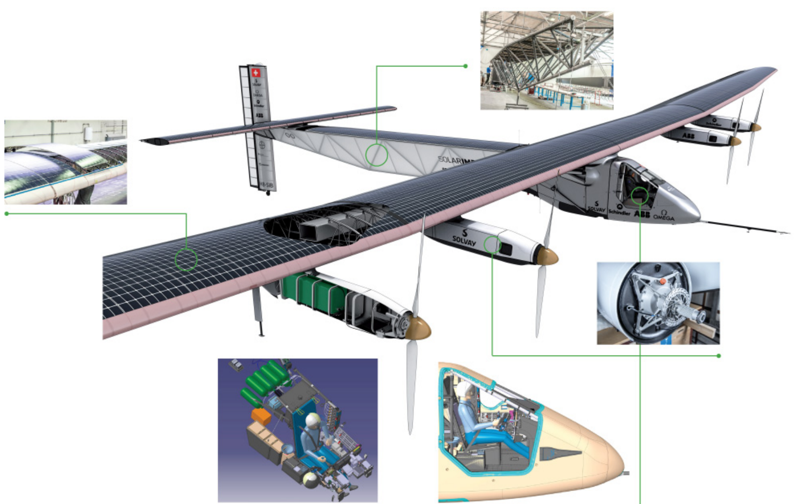


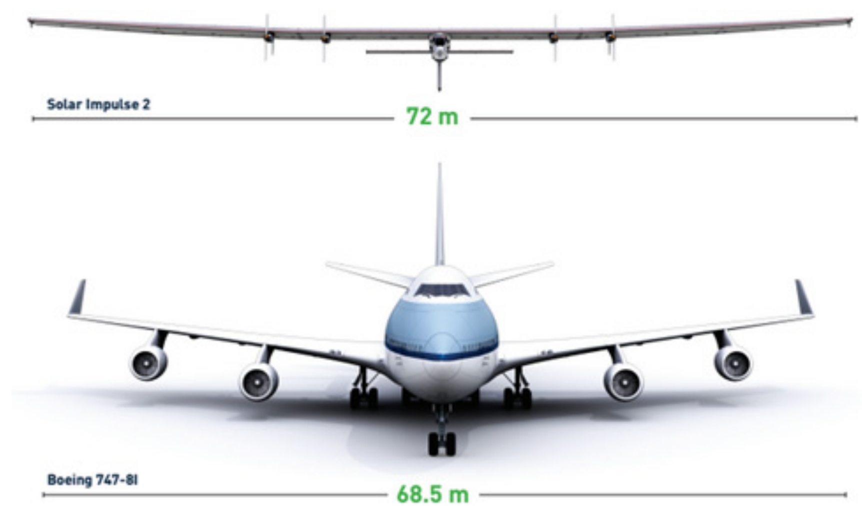
Charge window and battery temperature control affect battery wear!

WILL ELECTRICALLY POWERED AIRPLANES EVER BE FEASIBLE?

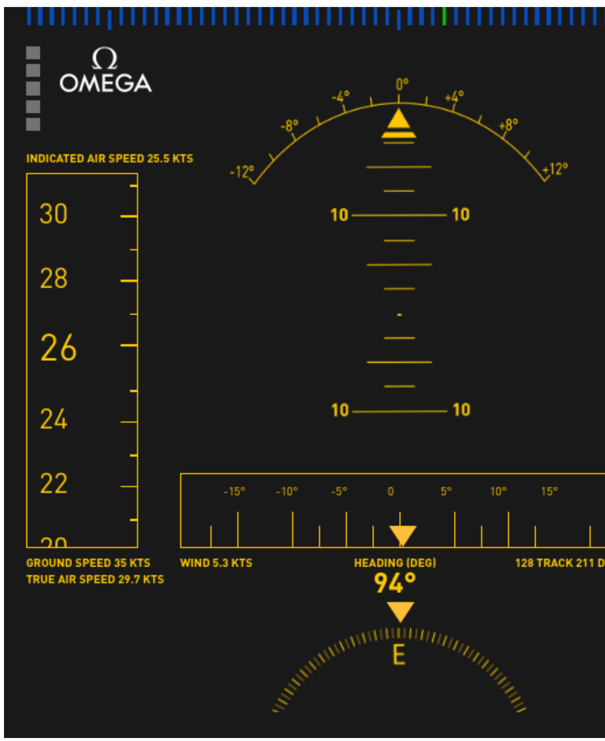


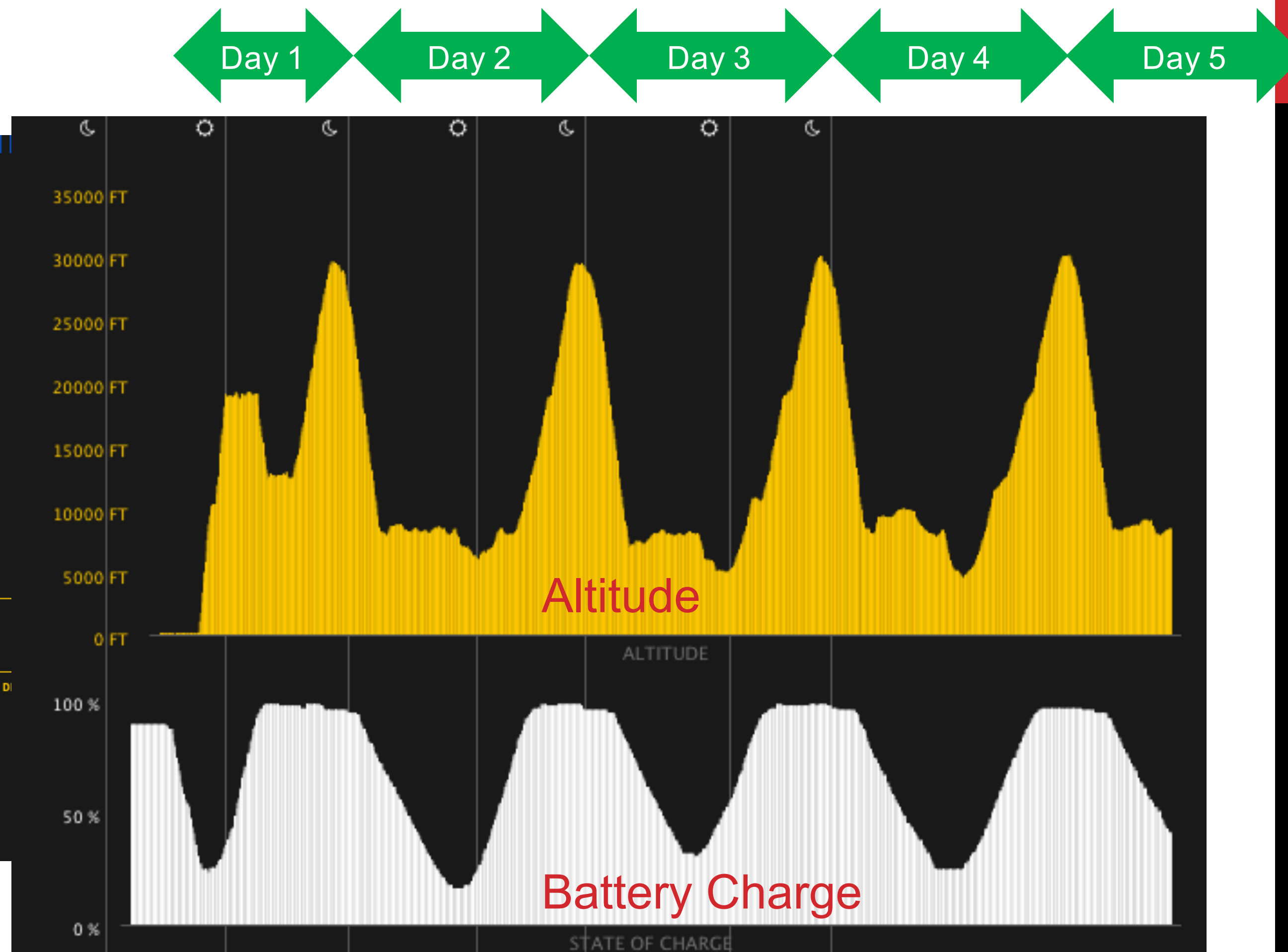
- **Solar Impulse:**
  - 30kW max power, 7kW sustained
  - 84kWh batteries, 450kg
  - 45kW peak solar cells
  - Huge wingspan (!!)





SOLAR IMPULSE ELECTRIC FLIGHT





26 knots speed…

Fried the batteries during Japan to Hawaii trip.

Day Strategy:
  Charge battery full then
  Climb as high as possible

Night Strategy:
  Glide down to 8000ft
  Then run on battery

ENGINEERING IMPLICATIONS BY VEHICLE TYPE

- **Plug-in Hybrid: 12-18 miles EV range**
  - 4.4kWh @77% = **3.4kWh** usable
  - At 12000 miles = **365 full cycles/year**
  - Should last 8 years/ 3000 cycles.

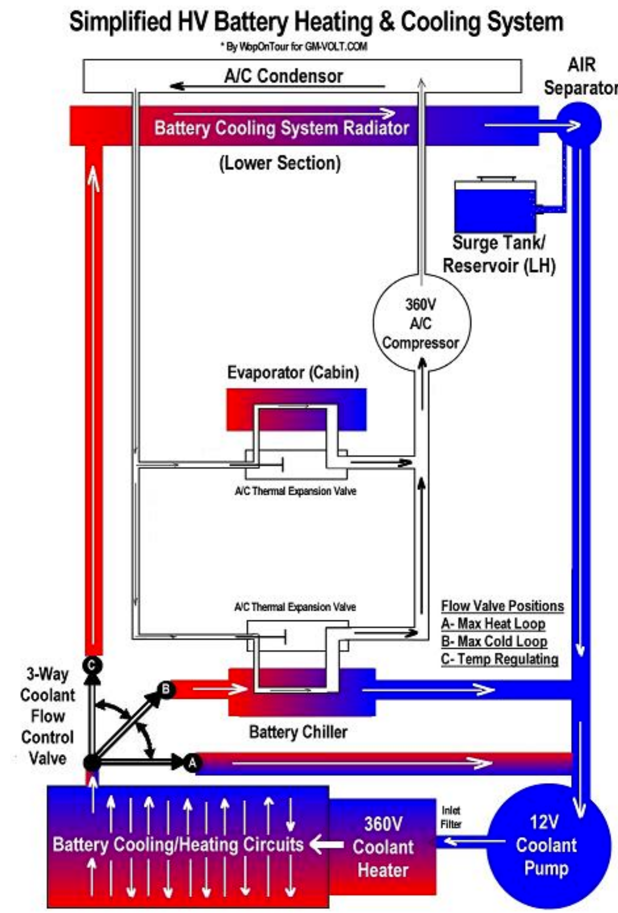
- **Extended Range EV: 38 miles EV range**
  - 16.5kWh @ 65% = **10.5kWh** usable
  - At 12000 miles/year = **315 full cycles/year**
  - Guaranteed to 3000 cycles (8 years), likely more

- **Commuter EV: 75 miles EV range**
  - 24kWh @ 83% = **20kWh** usable
  - At 12000 miles/year = **160 full cycles/year**
  - So aging 1000 cycles = 6 year

- **Full EV: 250 miles EV range:**
  - 85kWh @ 85% = **72 kWh** usable
  - At 12000miles/year = **48 full cycles/year**
  - So aging 1000 cycles: 20 years, 7x fewer than Volt

MAKING THE BATTERY LAST FOR 10 YEARS

- **Control 'depth of charge'**
  - Charge window affects lifetime very non-linearly
  - So trade-off energy density vs lifespan
- **High temperature is *very* detrimental**
  - Active liquid cooling above 30C using air conditioner: Volt, Tesla, BMW i3
  - Energy load of compressor: 0.5-2 kW
  - Nissan Leaf uses cheaper air cooling
- **Current density during charge and discharge**
  - Typical generation and re-generation currents are ~100A (~40kW).
  - In Tesla 85kWh that is 1.4A/cell
  - In Volt that is 33A per cell (20x)
  - Driving style affect lifetime and internal losses as well.



Gm-volt.com

POPULAR EV BATTERY TYPES

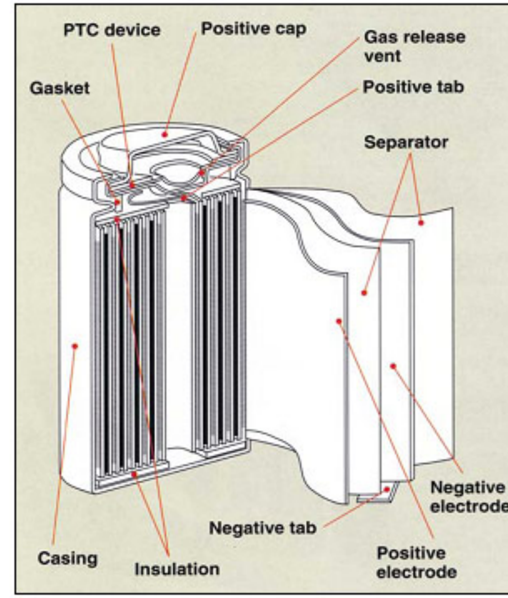
	Cell Maker	Chemistry	Capacity	Configuration	Voltage	Weight	Volume	Ener dens	Spec Ener	Used in:	
		Anode/Cathode	Ah		V	Kg	liter	Wh/liter	Wh/kg	Company	Model
1	AESC	G/LMO-NCA	33	Pouch	3.75	0.80	0.40	309	155	Nissan	Leaf
2	LG Chem	G/NMC-LMO	36	Pouch	3.75	0.86	0.49	275	157	Renault	Zoe
3	Li-Tec	G/NMC	52	Pouch	3.65	1.25	0.60	316	152	Daimler	Smart
4	Li Energy Japan	G/LMO-NMC	50	Prismatic	3.7	1.70	0.85	218	109	Mitsubishi	i-MiEV
5	Samsung	G/NMC-LMO	64	Prismatic	3.7	1.80	0.97	243	132	Fiat	500
6	Lishen Tianjin	G-LFP	16	Prismatic	3.25	0.45	0.23	226	116	Coda	EV
7	Toshiba	LTO-NMC	20	Prismatic	2.3	0.52	0.23	200	89	Honda	Fit
8	Panasonic	G/NCA	3.1	Cylindrical	3.6	0.048	0.018	630	233	Tesla	Model S

Panasonic 18650
Cylindrical cell (Tesla)

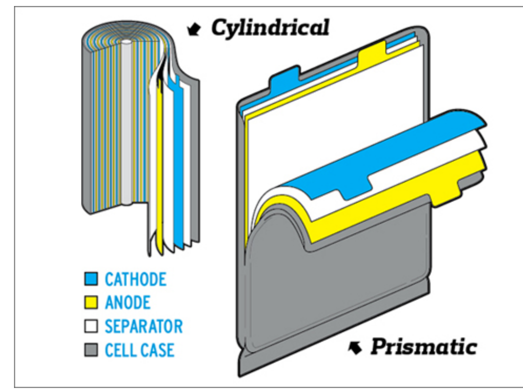
BATTERY FORM FACTORS

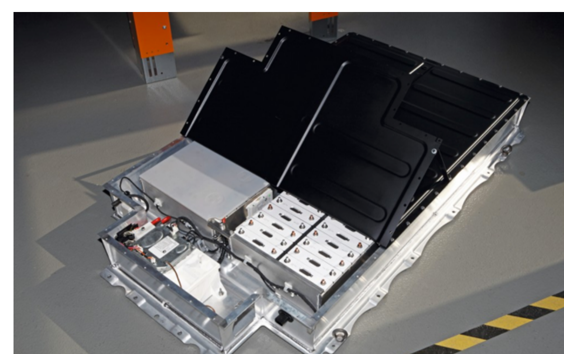
- **Cylindrical: Tesla**
  - More expensive
  - Less fire hazard
  - Flat pack shape
  - 12Wh/cell

Panasonic 18650 Cylindrical



- **Pouch/prismatic: Volt, Leaf, BMW i3, B787**
  - More cost-effective
  - Adaptable shape
  - More compact and less weight overhead
  - Needs thermal management
  - Thermal/Fire issue

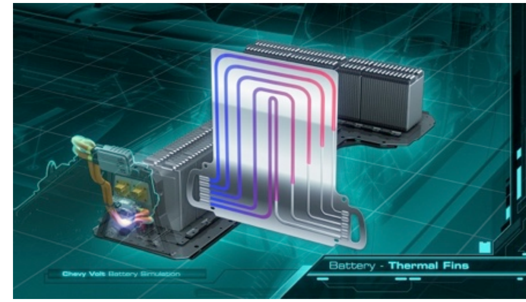


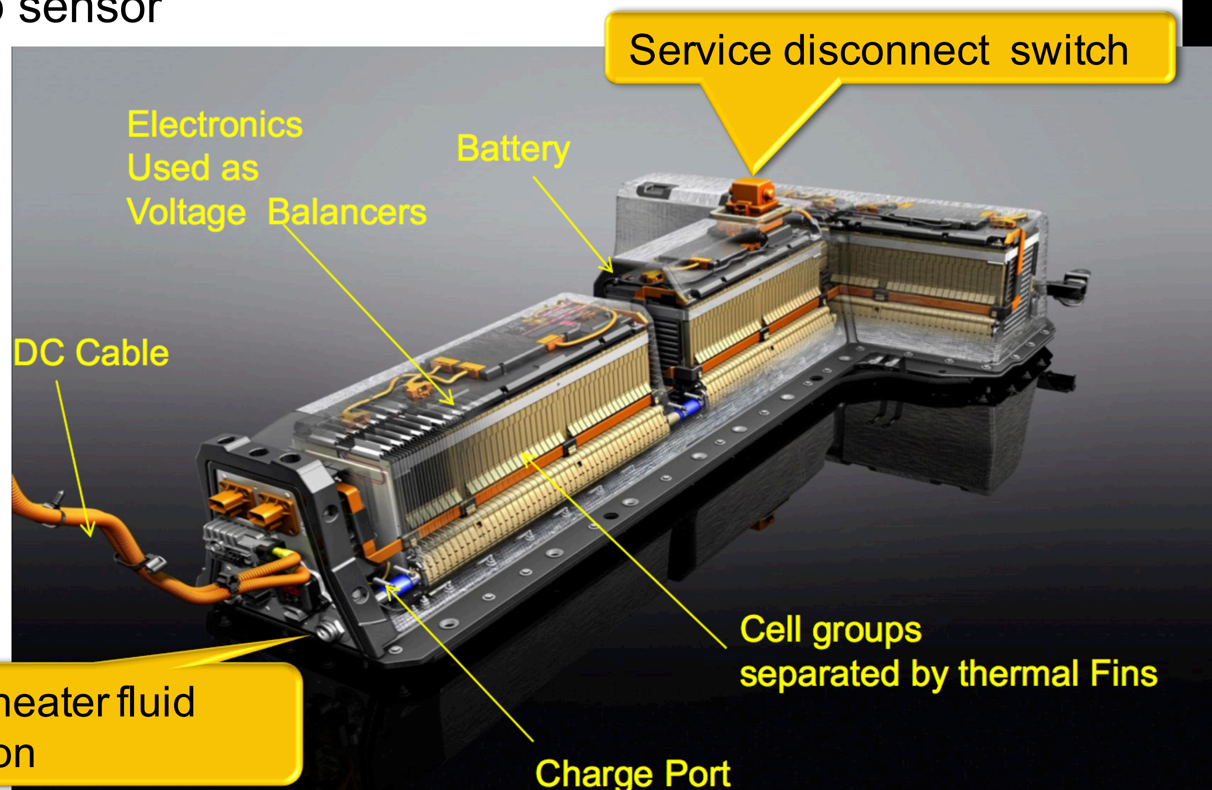


BMW i3 battery pack

VOLT 16.5KWH BATTERY PACK

- **T-shaped arrangement:**
  - Series of 96 cell groups (360V)
  - Each cell groups:
    - 3 pouch cells parallel
    - Liquid cool fin
    - Voltage + Temp sensor
    - Balancer
- **2kW heater**
- **1.5kW Cooler**
- **Cells replaceable.**

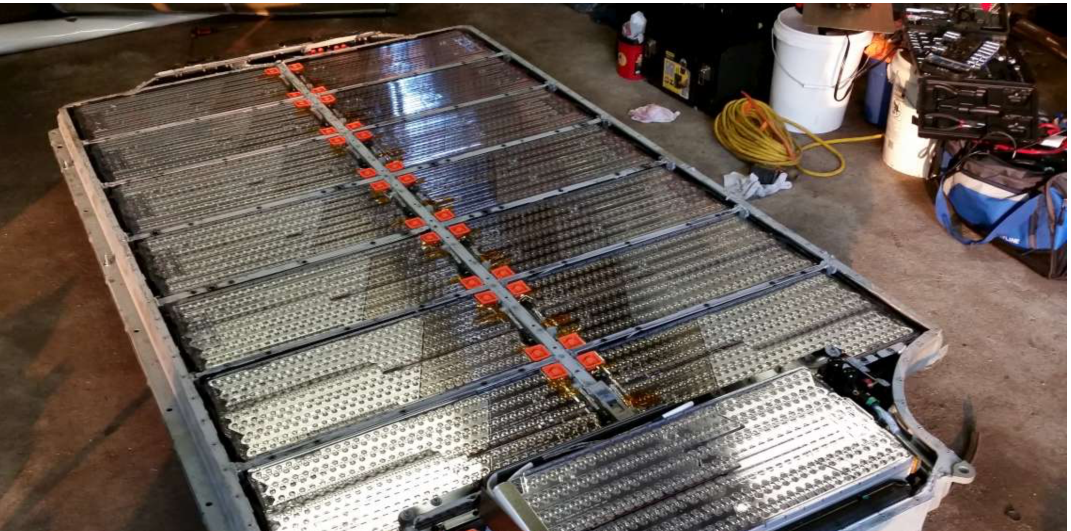




TESLA BATTERY LAYOUT

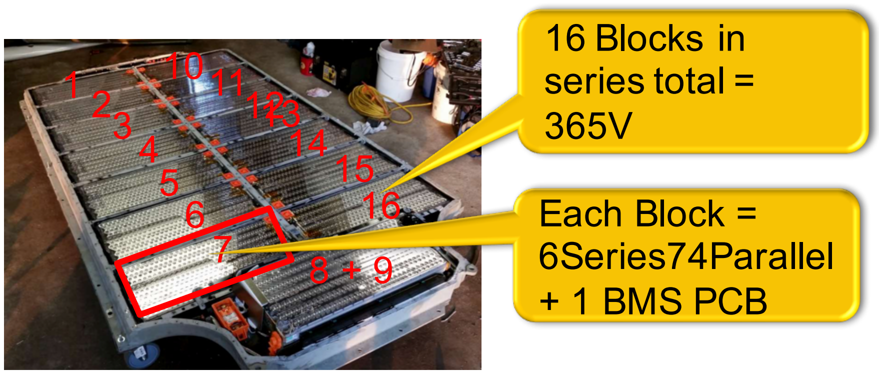
Total capacity	85kWh
Number of 18650 cells (Panasonic)	7104
# of cells in parallel per group	74
# of groups in series	96
Voltage	364V
Max current	~950A
Cooling/heating	Liquid
Battery cell balancing	Yes

Each cell is 11Wh (roughly 1/4 of laptop battery)

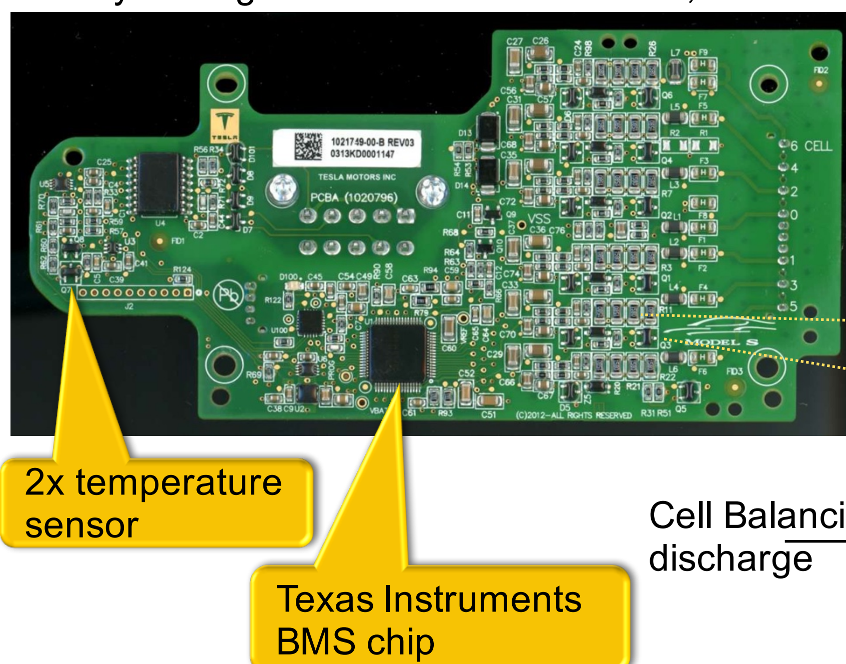


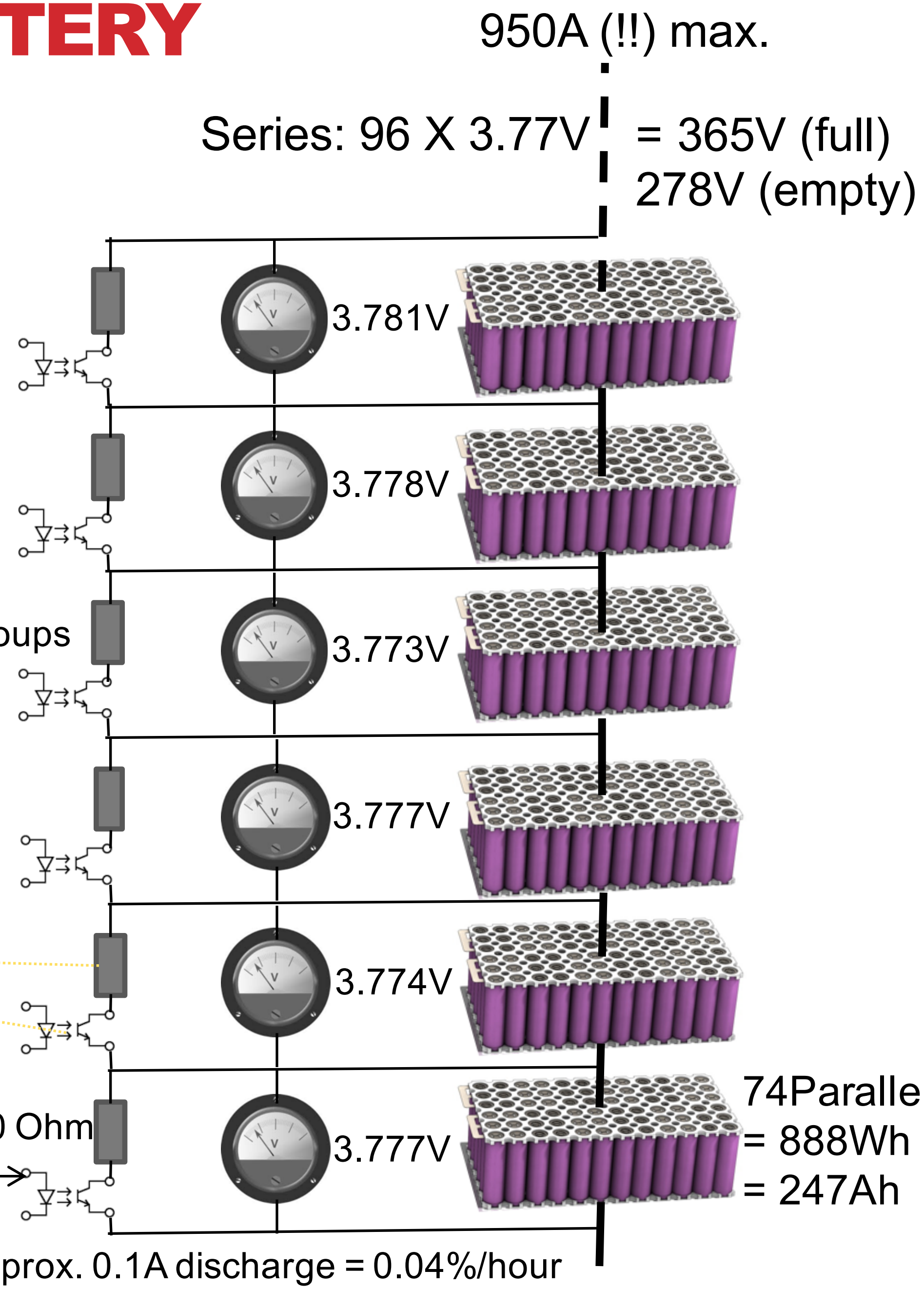
Aluminum strip profile with coolant/heater fluid

SERIES-PARALLEL BATTERY STRUCTURE



Battery Management PCB for each block, serves 6 P groups

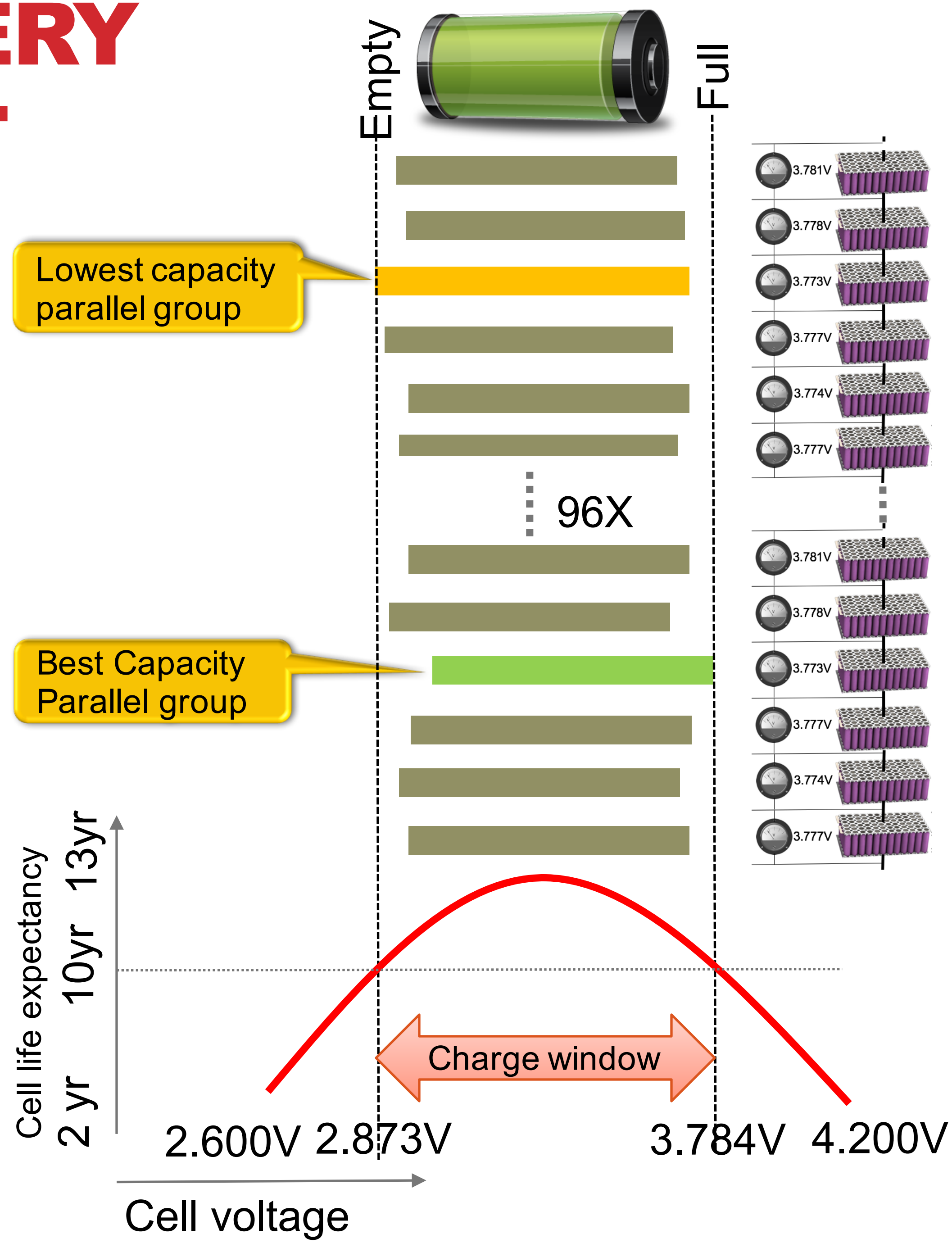




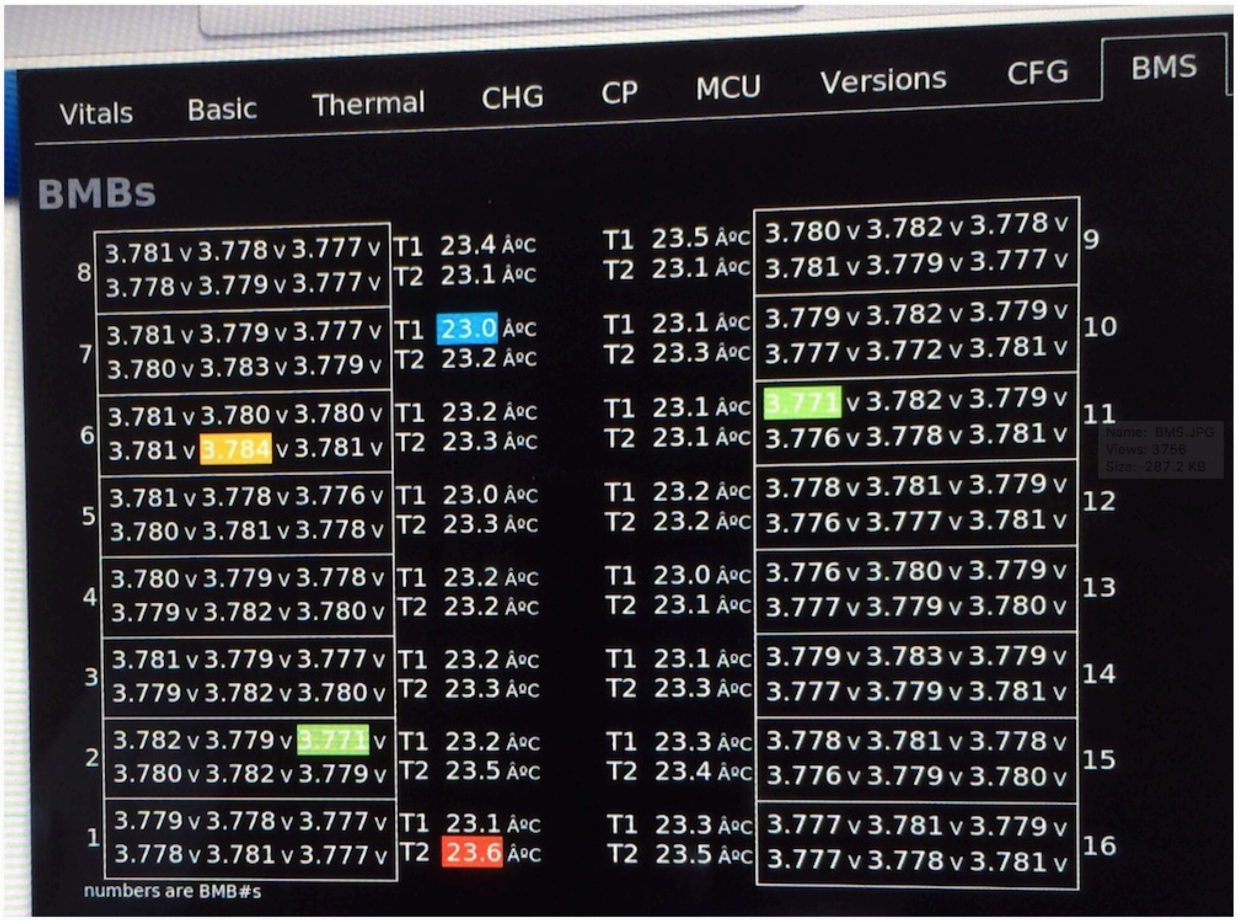
ACTIVE BATTERY MANAGEMENT

The difference between the worst and
the best P-Groups determines capacity!

Solution: Balance by selectively
discharging the best groups



'SECRET' TESLA SERVICE MODE FOR BATTERY MANAGEMENT



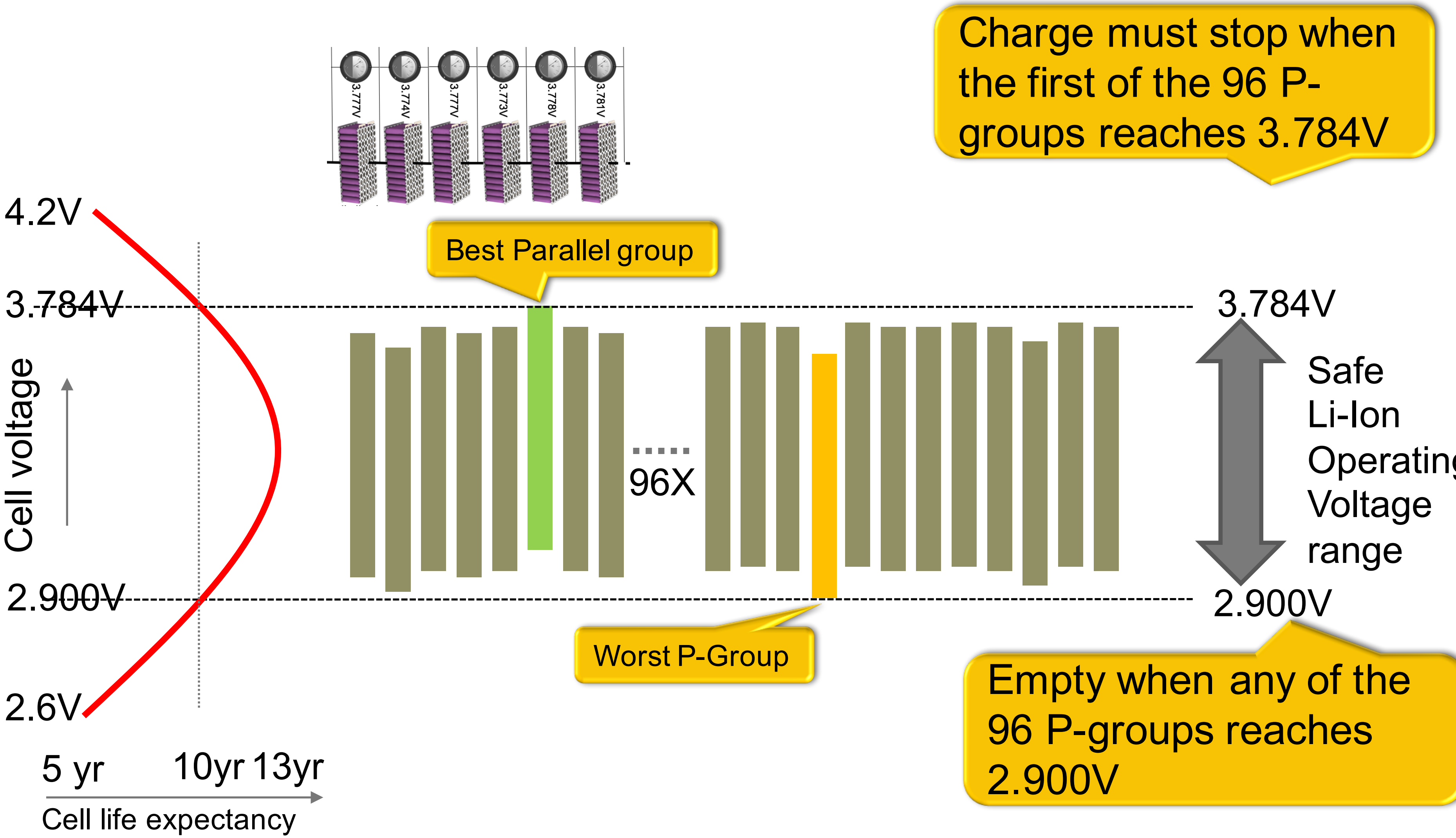
Highest voltage = 3.784V
Lowest voltage = 3.771V

Surprise: Just 0.3% max. imbalance!

Likely the randomization of cells over parallel groups of 74 each results is very equal aging of cells

Temperature within 0.6 C.
Uniform temperature results in uniform aging

ACTIVE BATTERY MANAGEMENT



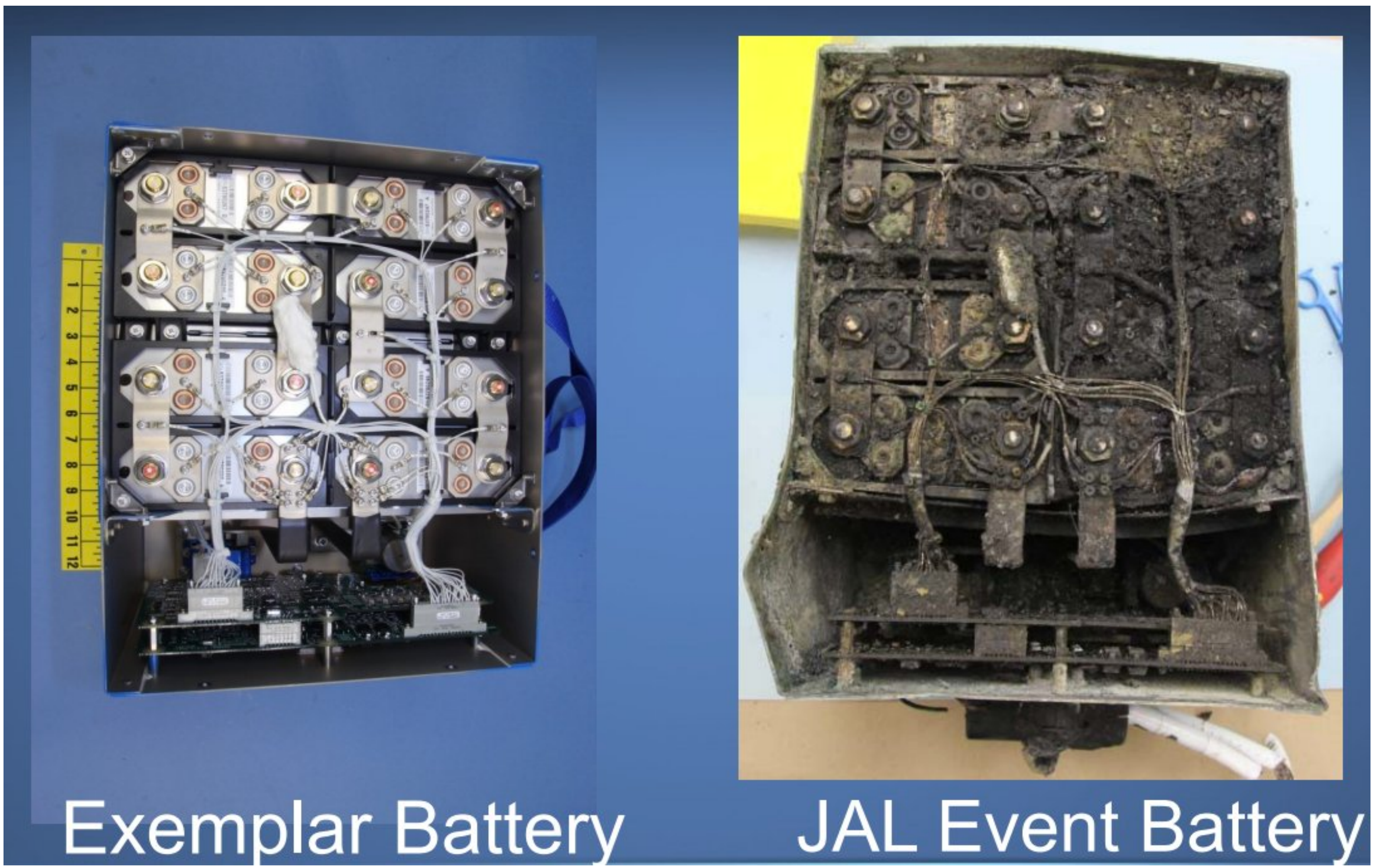
The difference between the worst and the best P-Groups determines capacity!

Solution: Balance by selectively discharging the best groups

LI-ION BATTERY SAFETY

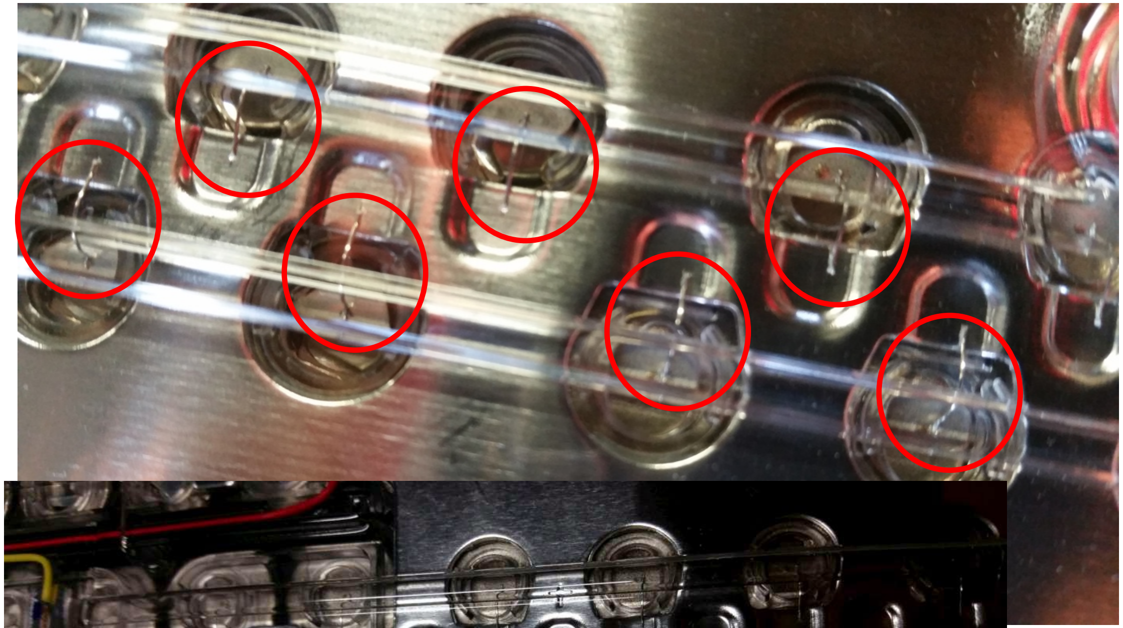
High energy density = inherently dangerous

2013 Boeing 787 Dreamliner uncontained battery fire



TESLA'S SOLUTION

Cylindrical cells are inherently safer due to isolation.



Electric fuse wire per cell prevents fire due to catastrophic short-circuit

Max current per cell is 12A so 15A fuse would make sense.

REALISTIC PREDICTIONS

- **CO_2 emissions of Electric Grid reduce by 1% per year**
  - Large time constants ☹
- **EV efficiency (in miles/kWh) will hardly improve.**
  - Physics is a bitch,
  - People like less efficient SuV style
- **Batteries will continue steady incremental improvements**
  - Lower cost, but barely lower weight
  - 200 Miles at reasonable cost soon feasible
- **EV cost will drop steadily:**
  - Feasible without taxpayer subsidy.
- **Workplace EV charging will be commonplace.**
  - 80 Charging spots at Synopsys, all in use!

ELECTRIC VEHICLES: WHAT'S IS IN IT FOR THE EDA FOLKS?

- **Designing the Electric drivetrain is a multi-faceted optimization problem:**
  - Design space exploration tools
  - Modeling of systems: Charger, Battery, Inverter, Control, Motor, modes, etc.
  - Simulation and tuning of the system
- **Hardware-software co-optimization**
  - Apply EDA design methods to mechanical CAD
- **Software Verification & Correctness**
- **Security**

THANKS!

Questions?