Green(er) Cars & Trucks

John C. Bean

Outline

Energy spent moving Cars & Trucks

"Greener" vehicles mitigating the impact of internal combustion engines (ICEs):

- Improving ICE fuel/air mixing, injection & spark ignition
- Using gasoline ICEs more effectively:
  - Improved transmissions, including Dual Clutch & Continuously Variable (CVTs)
  - Combined electric motor / ICE drives => Hybrid Electric Vehicles (HEVs)
- Storing (rather than dissipating) kinetic energy when vehicles slow or stop
  - Kinetic Energy Recovery Systems (KERs) or Regenerative Braking Systems

"Green" electric vehicles

- Powered by a not yet Green Grid => "Well-to-Wheel" / Lifecycle Energy & GHG analyses
- Green Grid + Battery Plug-in Electric Vehicles
  - Challenges & possible benefits for the Grid
    - Including one weirdly plausible Grid-vehicle synergy: "Vehicle-to-Grid (V2G)"
- Green Grid + Combined Hydrogen Fuel Cell / Battery Vehicles
- Impacts of Autonomous Vehicles

(Written / Revised: December 2020)

Car & Truck Acronyms:

4WD = Four wheel drive

ATDC = (degrees) After Top Dead Center

AV = Autonomous Vehicle

BEV = Battery Electric Vehicle = PEV

BTDC = (degrees) Before Top Dead Center

CD = Cylinder Deactivation

CGI = Charged Gasoline Injection = FSI

CV = Conventional Vehicle (diesel or gas ICE)

CVT = Continuously Variable Transmission

Diesel = my term for a Diesel ICE

diesel = my term for diesel fuel

DOHC = Dual Over Head Camshaft

e-Motor = Electric Motor

EV = Electric Vehicle (e.g., PEV or FCEV)

FC = Fuel Cell

FCEV = Fuel Cell Electric Vehicle

FSI = Fuel Stratified Injection = CGI

GDI = Gasoline Direct Injection = SIDI

GHG = Greenhouse Gas

ICE = Internal Combustion Engine = Diesel or SI-ICE

KERS = Kinetic Energy Recover System

HEV = Hybrid Electric Vehicle

MPFi = Multi Port Fuel Injection = PFI

NG = Natural Gas

MPG = Miles per Gallon => 2.35 Liters per km

OHC = Over Head Camshaft (SOHC or DOHC)

OHV = Over Head Valve (OHC, SOHC, or DOHC)

PEV = Plug-in Electric Vehicle (a.k.a. EV & BEV)

PFI = Port Fuel Injection = MPFi

PHEV = Plug-in Hybrid gasoline Electric Vehicle

PTDI = Petroleum Turbocharged Direct Injection

RPM = Revolutions per Minute

SIDI = Spark Ignited Direct Injection = GDI

SI-ICE = Spark Ignition ICE = gasoline ICE

SOHC = Single Over Head Camshaft

TDC = Top Dead Center (see also ATDC & BTDC)

TtW = **T2W** = Tank to Wheel energy / GHG analysis

VVT = Variable Valve Timing

WtW = **W2W** = Well to Wheel energy / GHG analysis

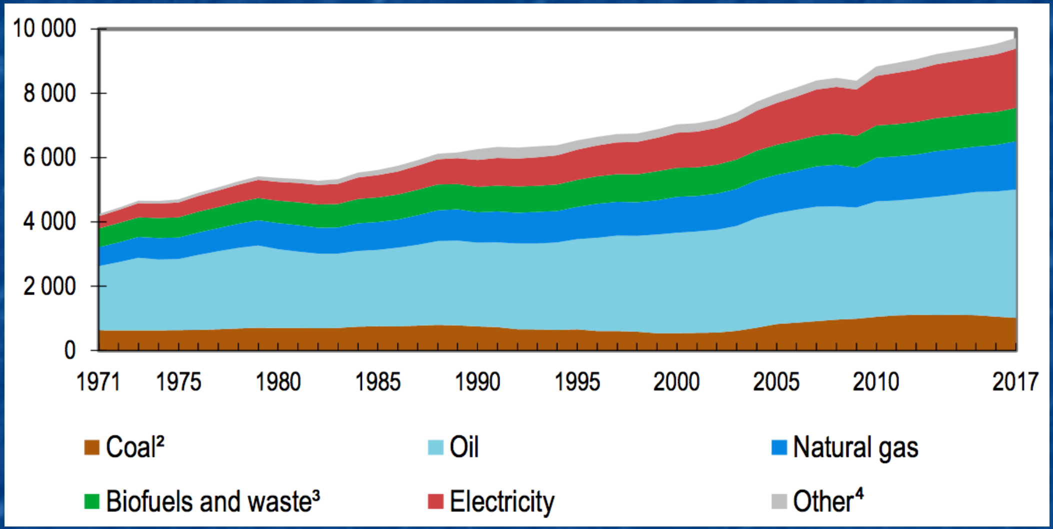
WtT = **W2T** = Well to Tank energy / GHG analysis

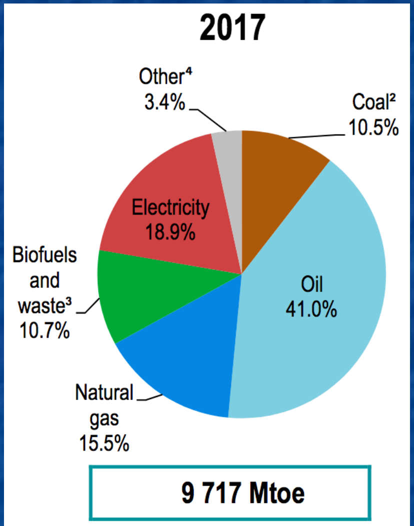
ZEV = Zero (GHG) Emission Vehicle (BEV or FCEV)

Why is Car & Truck energy use particularly important?

First, because it is the second largest contributor to overall human energy use:

International Energy Agency (IEA) plot of **annual world energy consumption:**





The figure's units are MTOe = Million Tonnes Oil equivalent

Its conversion to metric units is 1 MTOe = 11.63 TW-h (T = Tera = 10^{12})

From those figures, making that metric conversion for the final year of 2017:

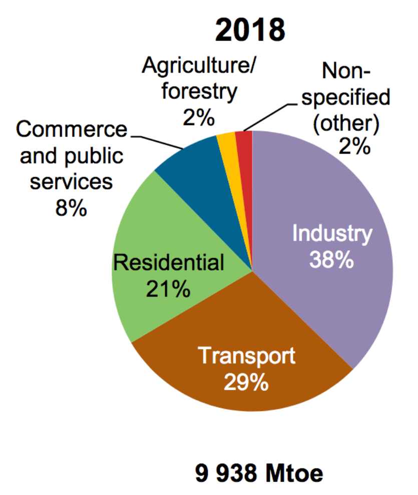
Total World Energy Consumption = 9717 MTOe => **113,000 TW-h**

Total Electrical Energy Consumption = (18.9%) (9717 MTOe) => **21,357 TW-h**

1) Page 34 in: https://webstore.iea.org/key-world-energy-statistics-2019

What part of the total energy was used by Cars & Trucks?

Pertaining to that question, the same IEA report provided data for only 2018:



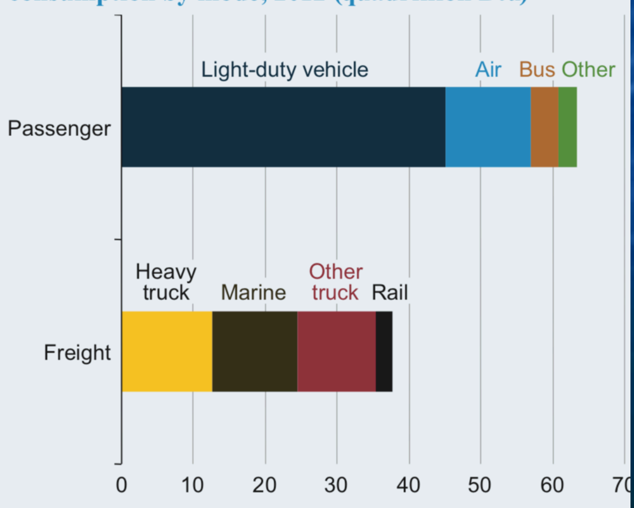
Total Energy Consumption = 9,938 MTOe => **115,580 TW-h**

Of which 29% was used for transport:

Total Transport Energy = 2,853 MTOe => **33,180 TW-h**

The U.S. Energy Information Administration (EIA) broke down Transport Energy as: [1]

Figure 8-8. World transportation energy consumption by mode, 2012 (quadrillion Btu)



Light duty vehicles (cars & light trucks) = 44%

Heavy trucks = 13%   Other trucks = 12%

Car & Truck total = 69% of Total Transport Energy

Combining that with the IEA value given above:

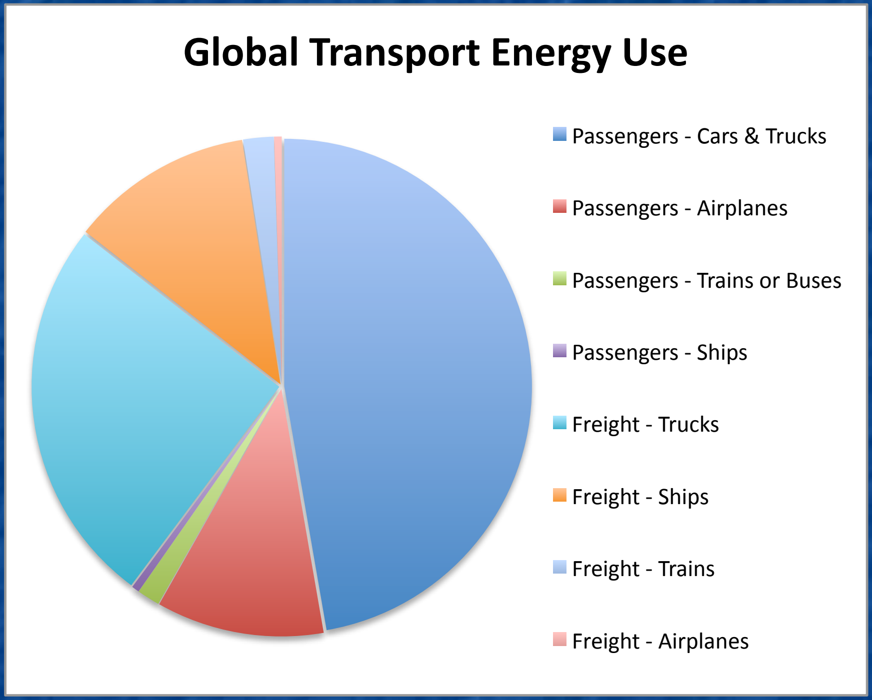
Cars & Trucks = (.69)(33,180 TW-h) => **22,890 TW-h**

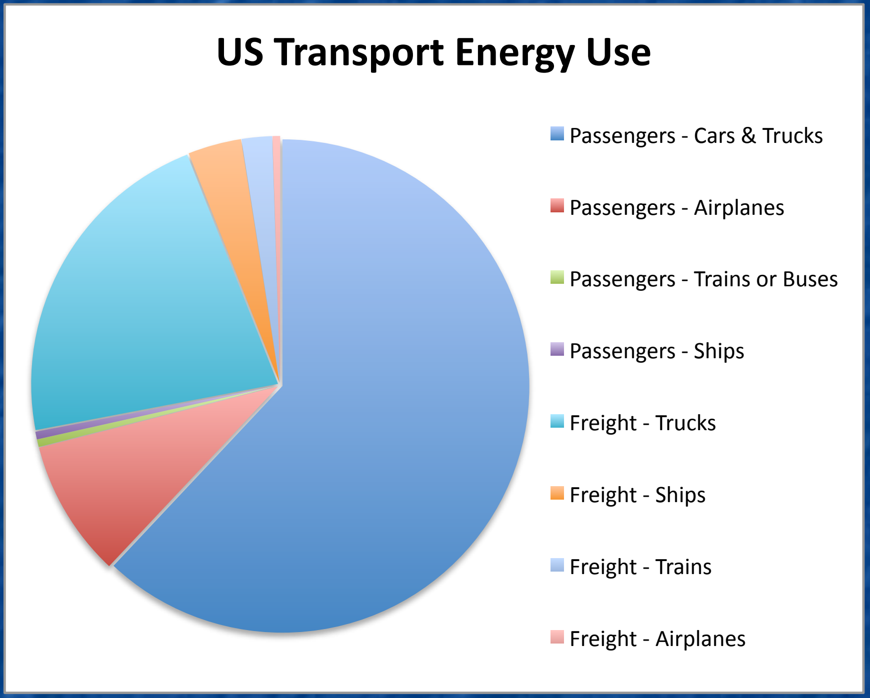
1) Page 131 in: https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf

The Car & Truck share of Transport Energy is even larger in the U.S.

From my note set **Energy Consumption in Transportation** (pptx / pdf / key),

the large **blue slices** of these pie charts depict Car & Truck energy use:





The second reason Car & Truck energy use is particularly important:

Because so much of that energy use is based upon OUR personal decisions:

From the IEA (above), 44% of World Transport Energy = "Light Cars & Trucks"

Which is to say: cars & pick-up trucks that we have personally chosen,

or vehicles chosen mostly by local business owners

So we can't just push responsibility off onto far distant corporations & governments

We (personally & locally) largely created this problem

Giving us the means & responsibility for dealing with this problem

From Walt Kelly's now iconic cartoon on the occasion of the 2nd World Earth Day in 1971 (Post Hall Syndicate)

*To which your very **personal & local** response might well be:*

"But I'm already fixing things:

I drive (or will likely soon buy) a **Hybrid Electric Vehicle (HEV)**

And, when "they" get the range & number of charging stations high enough

I'll happily move up to an all-electric **Plug-in Electric Vehicle (PEV)**

Problem Solved (or, at least I'll have personally done my part)!"

But it's not that simple:

PEVs will only be truly green when the Grid **charging** them is also green

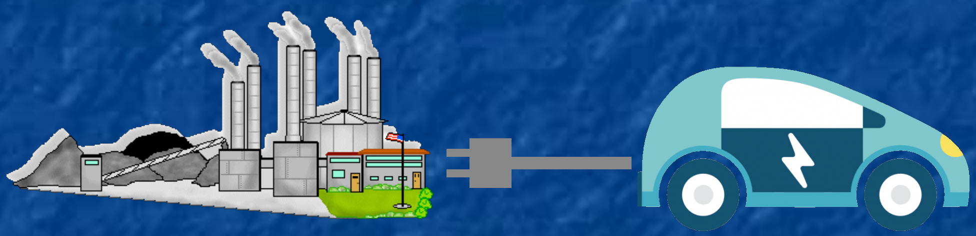
If it isn't, you'll just be shifting your Greenhouse Gas (GHG) emissions

from your car's tailpipe to your power plant's smokestack

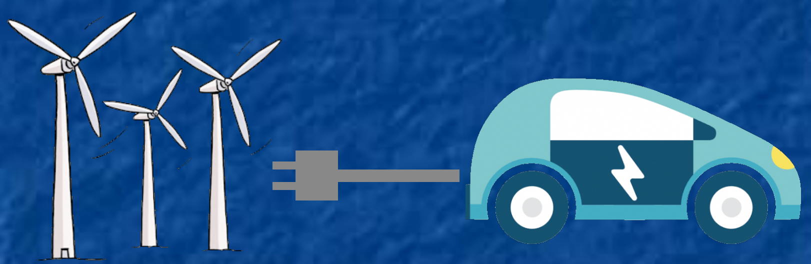
And to **charge** all those green PEVs, a green Grid will need a lot more capacity

But how difficult can those changes be? Let's try for some quick estimates:

Challenge #1: Cleaning up the Electric Power Grid



Today



Tomorrow

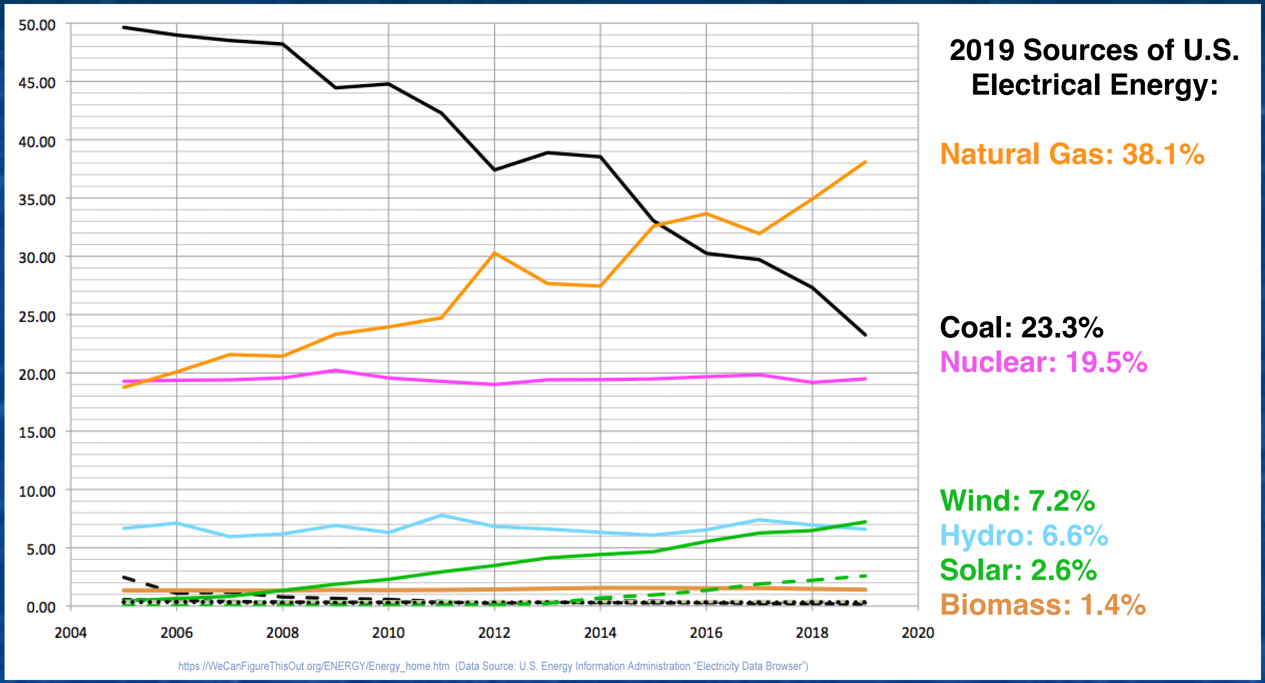
http://clipart-library.com/clipart/419820.htm

http://clipart-library.com/wind-turbine-clipart.html

https://www.autoloans.ca/blog/are-you-ready-to-drive-an-electric-vehicle/

*How dirty **is** today's Electric Power Grid?*

From my note set: **U.S. Energy Production and Consumption** (pptx / pdf / key):



Despite recent dramatic gains by wind & solar power, the U.S. electrical Grid,

along with most other worldwide electrical Grids, is **FAR from Green**

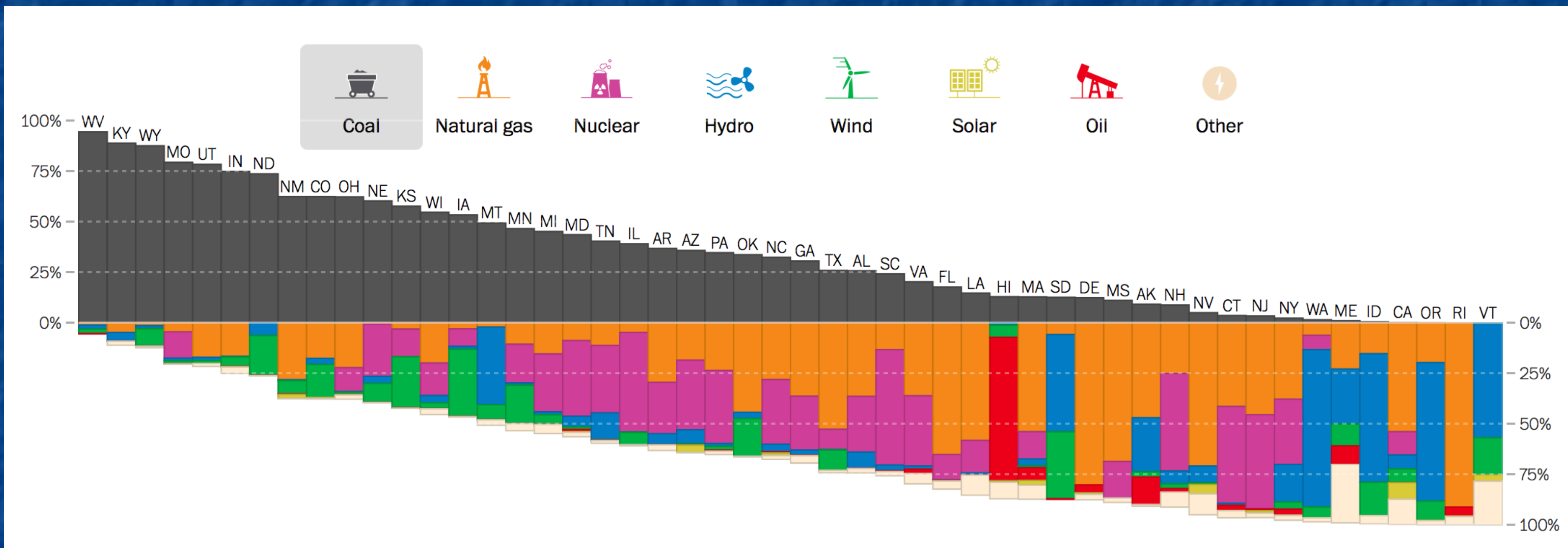
As seen in my compilation of U.S. Energy Information Administration data above,

over 61% of our power comes from fossil-fueled natural gas & coal power plants

Another 26% comes from nuclear & hydro power plants many consider almost as bad

And in many parts of the U.S. electrical power is downright filthy:

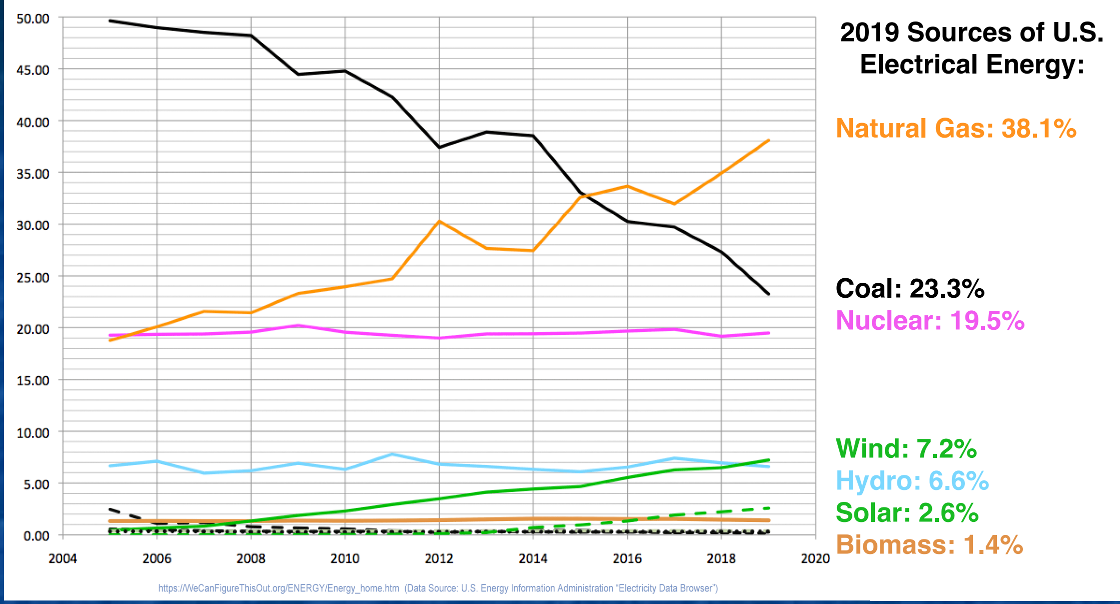
This 2017 Washington Post figure depicted state-by-state electrical power sources: [1]



West Virginia
Utah
Ohio
Idaho
Maryland
Pennsylvania
Texas
Virginia
Massachusetts
New Hampshire
Washington
California
Vermont

1) http://www.washingtonpost.com/graphics/national/power-plants/

How much will green / desirable electrical energy sources have to grow?



Eliminating fossil-fuel natural gas (38.1%) & coal (23.3%) will require remaining sources

to grow in total capacity by a factor of 100 / (100 - 38.1 - 23.3) => **2.5 X**

Eliminating fossil-fuels & nuclear (19.5%) will require remaining sources

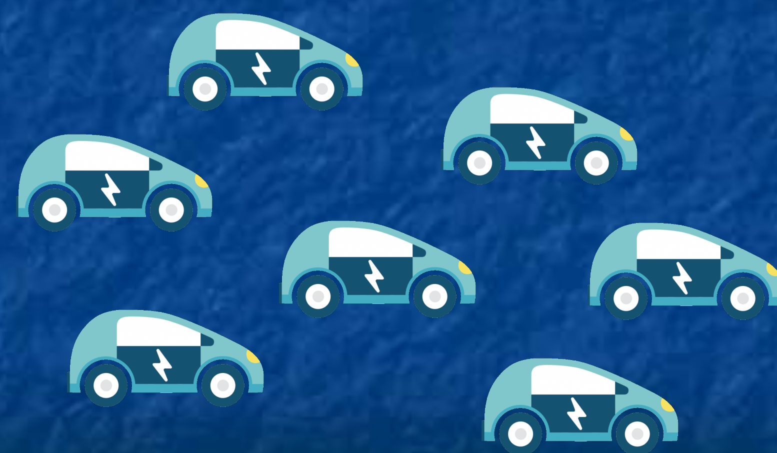
to grow in total capacity by a factor of 100 / (100 - 38.1 - 23.3 - 19.5) => **5.2 X**

Eliminating fossil fuels & nuclear & hydro (6.6%) will require remaining sources

to grow in total capacity by a factor of 100 / (100 - 38.1 - 23.3 - 19.5 - 6.6) => **8 X**

Challenge #2: Increasing the Grid's Capacity

Today



Tomorrow

To charge tomorrow's PEVs, how much will the Grid have to grow?

Today Cars & Trucks are almost 100% fossil-fueled, with that chemical energy

being converted to kinetic (motion) energy by **Internal Combustion Engine (ICEs)**

With that kinetic energy then transmitted to the vehicle's wheels via a "Drivetrain"

generally consisting of at least one transmission, driveshaft and differential

Assume (for a few slides) that energy conversion & transfer

is comparably efficient for today's ICEs and tomorrow's PEVs:

The PEVs completely replacing those fossil-fueled Cars & Trucks would then require

ADDED Grid electrical energy equaling the former fossil-fuel vehicle energy

which, from nine slides ago, we identified as **22,890 TW-h**

But, from ten slides ago, the world's electrical Grids **now** produce **21,357 TW-h**

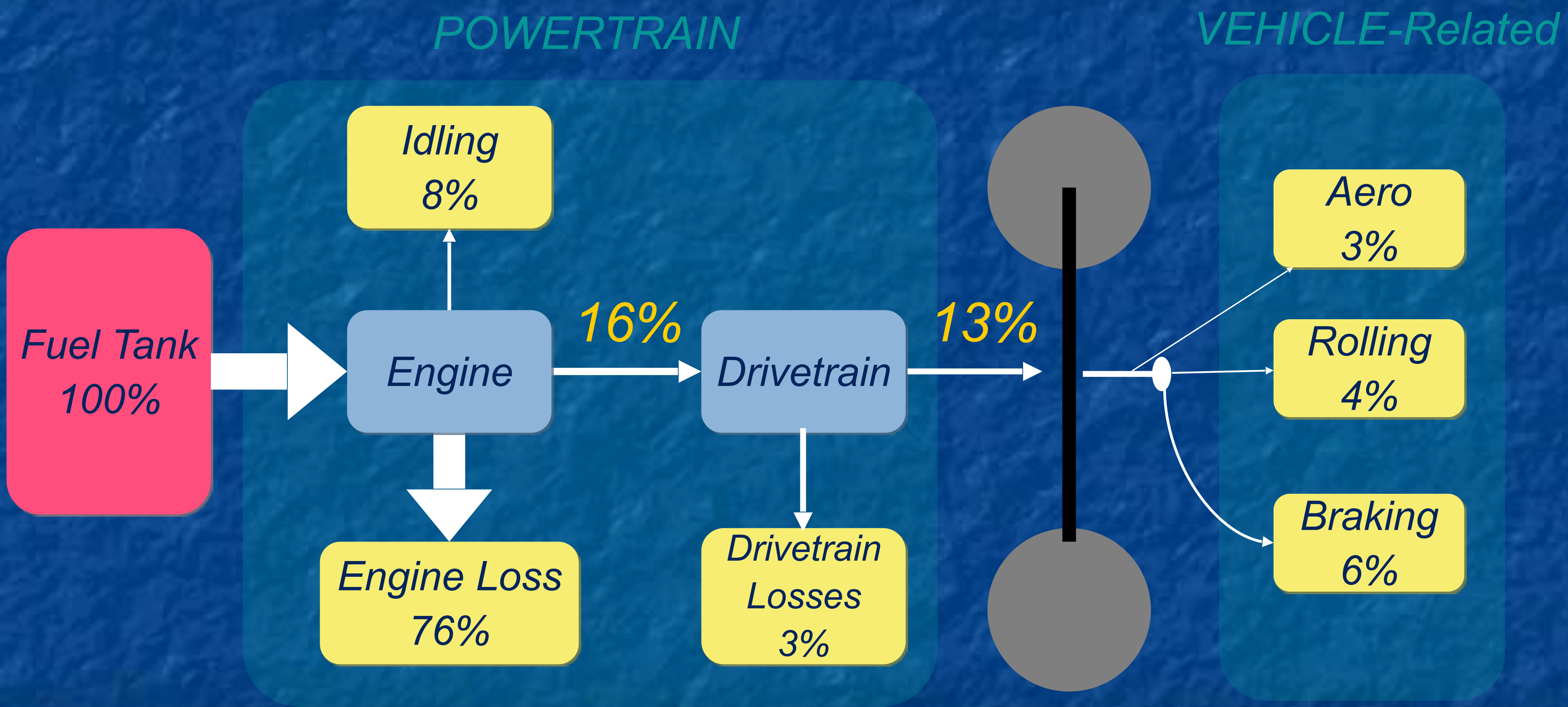
Added PEV-charging energy would thus exceed Today's TOTAL Grid energy

Suggesting that electric Grid capacity would have to more than DOUBLE

*But are ICE & electric vehicle efficiencies **ACTUALLY** comparable?*

MIT's Dan Lauber generated this analysis of energy flow in a 2005 ICE Toyota Camry

For stop and go city driving (**PgDn** to animate):



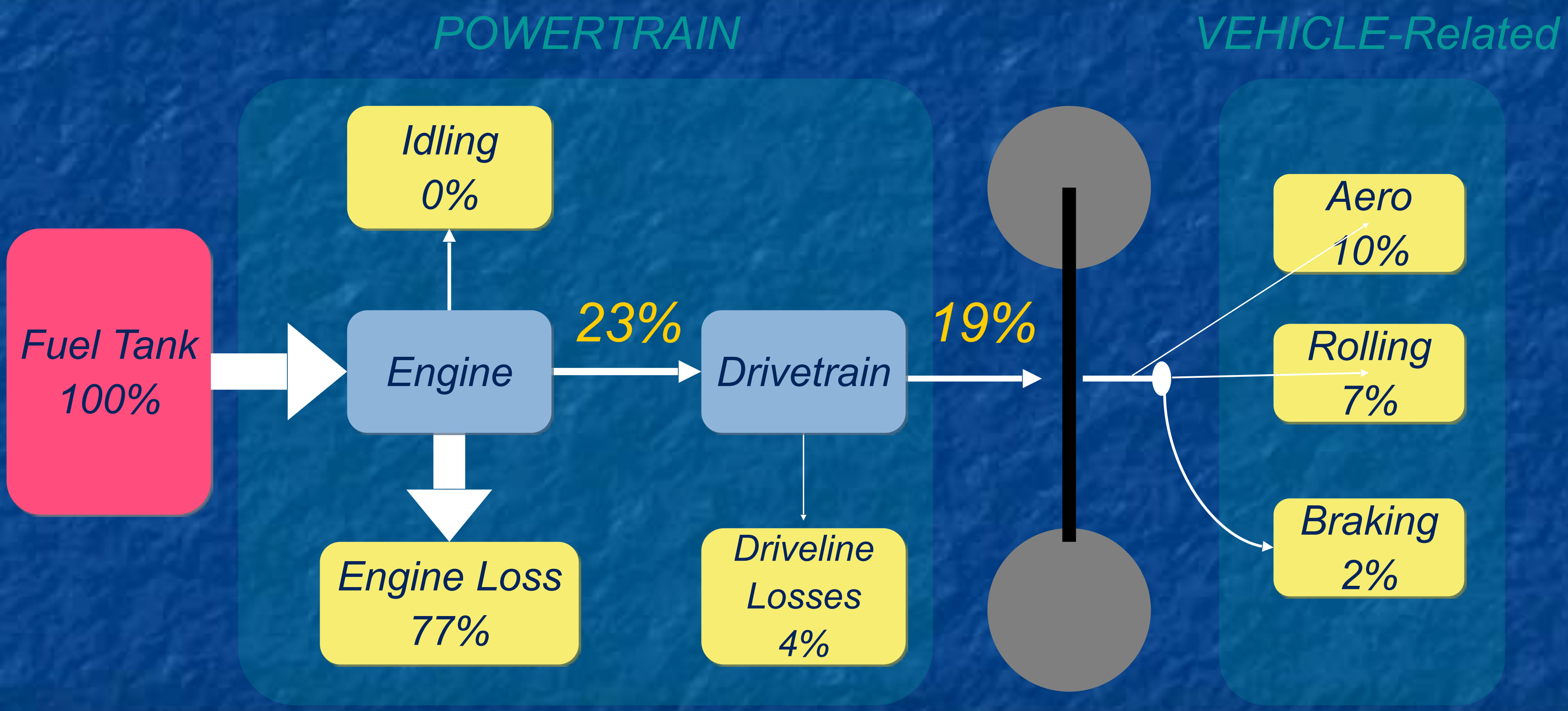
Fossil fuel chemical energy ultimately transferred to the wheels: 13%

Dominant loss: 76% of energy going into heating the ICE & its exhaust gases

http://www.slidefinder.net/e/electric_vehicles_101_introduction_dan/evs101-11-13-09%28web%29/10697203

Compared to the same ICE vehicle in *steadily moving highway driving:*

(**PgDn** to animate):



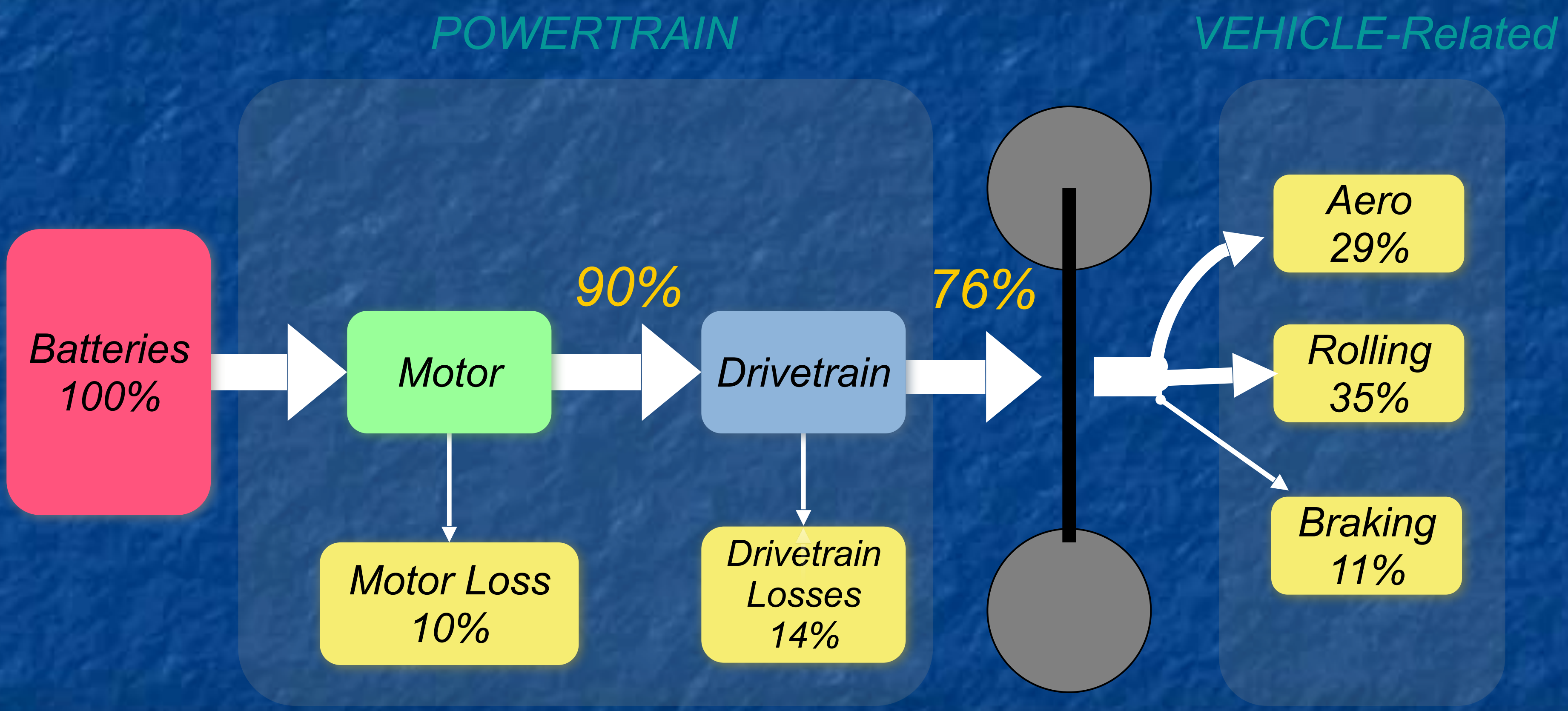
Fossil fuel chemical energy ultimately transferred to the wheels: 19%

Dominant loss: 77% of energy going into heating the ICE & its exhaust gases

http://www.slidefinder.net/e/electric_vehicles_101_introduction_dan/evs101-11-13-09%28web%29/10697203

Compared to a Plug-in Electric Vehicle in steadily moving highway driving:

(**PgDn** to animate):



Battery chemical energy ultimately transferred to the wheels: 76%

Minor losses: Electric Motor & Drivetrain

http://www.slidefinder.net/e/electric_vehicles_101_introduction_dan/evs101-11-13-09%28web%29/10697203

But those 2009 PEV numbers are in need of revision:

For one, the battery should not be labeled as the beginning 100% PEV energy source

A PEV's energy source is in fact Grid electrical energy (via its power plug)

But then, even good **batteries loose ~ 10%** of electrical energy put into them

Second, an added **Power Control System** must direct electricity within the vehicle

Power FROM the battery must varied to change the PEV's speed

Power INTO the battery must be carefully controlled to avoid recharging damage

Power FROM motors can be recaptured when stopping, but only if it's routed thru

a rapid storage device (e.g., a capacitor) before trickling back into the battery

But **power controllers also loose ~ 10%** of the passing electricity (as heat)

Finally, even **electric motors loose ~ 10%** of their input energy (again, as heat)

Giving a **cumulative PEV efficiency of about (~ 0.9)(~ 0.9)(~ 0.9) ~ 70-75%**

At least if the large mechanical "drivetrain" losses could be eliminated

And in PEVs they CAN be, by just eliminating most of the drivetrain:

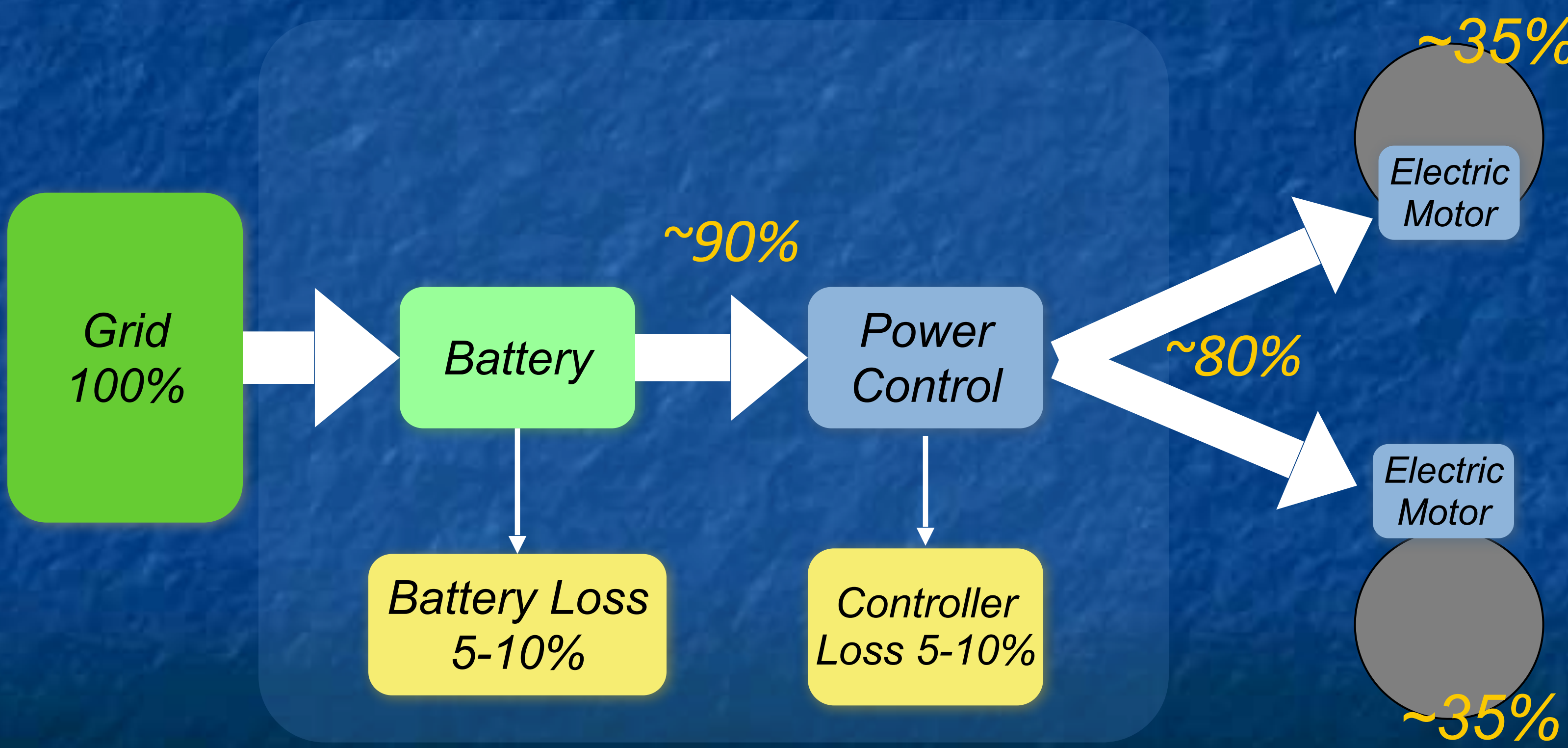
Properly identifying the ***Grid (not battery) as the energy source:***

Here instead is **my** PEV ADDING necessary (but energy-consuming) Power Control,

but ELIMINATING most of the energy-consuming Drivetrain

by connecting that Power Control to motors DIRECTLY driving each wheel

For steadily moving highway driving (**PgDn**):



Grid electrical energy ultimately transferred to the wheels: ~ 70-75%

Revising our estimate of added Grid capacity required for new PEVs:

For much better accuracy, we will later delve into **"Well-to-Wheel" vehicle efficiency studies**

But for now let's base our revision upon the above quick comparison of ICE's & PEVS:

In the earlier slides we found that annually:

Today's electrical Grids have a total capacity of **21,357 TW-h**

Today's ICE Cars & Trucks consume **22,890 TW-h** of fossil-fuel energy

The latter amount would have to be ADDED to the former if future Grids were to power

PEVs with energy conversion efficiencies comparable to today's ICE vehicles

Corresponding to a (22,289 + 21,357) / 21,357 => **2X Grid expansion**

But we've now seen that PEVs might be ~ 4X as efficient (~75% vs. ICE's 13-19 => ~ 16%)

Which reduces the necessary increase in Grid capacity to ~ 22,980 / 4 ~ **5,700 TW-h**

Corresponding to a (5,700 + 21,357) / 21,357 => ~ **1.3 X Grid expansion**

Which WILL be a heck of a lot easier

But which must still be compounded with the need to CLEAN UP those Grids:

Because a truly Green PEV must be powered by a similarly Green Grid

To green the U.S. Grid, we considered three different Green Grid scenarios:

1) Close fossil-fuel power plants => Other plants must expand by 2.5 X

2) Close fossil-fuel & nuclear power plants => Other plants must expand by 5.2 X

3) Close fossil-fuel & nuclear & hydro plants => Other plants must expand by 8 X

Compounding those with a 1.3 X expansion needed to replace ICEs with PEVs:

1) **No fossil fuels** => 1.3 x 2.5 = **3.3 X expansion** of remaining power sources

2) **No fossil fuels or nukes** => 1.3 x 5.2 = **6.8 X expansion** of remaining sources

3) **No fossil, nukes or hydro** => 1.3 x 8 = **10.4 X expansion** of remaining sources

Given the recent & surprisingly rapid decline in coal, and rise of wind & solar power,

over the span of a couple of decades completing scenario #1 seems **possible**

But (at least to me) also completing the no-nuke scenario #2 seems **unlikely**

And completing the no-nuke & no-hydro scenario #3 seems **very unlikely**

Electric Cars & Trucks alone are thus nowhere near a complete solution

PEVs are the easy part in that we already have most of the necessary technology,

and (with enough willpower) could fully implement it within just a handful of years

But even if the necessary PEV-charging infrastructure could be added just as quickly,

such a rapid PEV conversion could have limited positive, or even negative impact

Negative impact if the local Grid (still ~ today's Grid) lacked the necessary capacity,

or if that capacity produced energy dirtier that that of the ICE vehicles displaced

The more complete & environmentally sound solution may thus be to:

- Emphasize the likely long & difficult process of expanding our green Grid energy
- Continue PEV development & deployment, but at a pace consistent with our ongoing expansion of green Grid energy AND vehicle-charging infrastructure
- In that interim, implement technologies mitigating the impact of remaining ICEs

Which motivates the two major remaining sections of this note set:

Greener Cars & Trucks: That mitigate the impact of remaining ICE vehicles by:

Using ICE's with increased efficiency & reduced emissions

Operating ICE's only as they are most efficient & clean by combining them

with better transmissions OR electric motors (=> **Hybrid Electric Vehicles**)

Recovering and reusing energy now wasted as heat during vehicle braking

Green Cars & Trucks: PEVs that, as noted above, are themselves straightforward

But for which effective integration with a still-greening Grid

will require often complex decisions about timing and location

That integration will also require development of a massive charging infrastructure

including both daytime commercial plus nighttime home-charging stations,

with the latter actually offering a way to **accelerate** greening of the Grid

All of which may not be free of unintended consequences, such as the

negative environmental impacts of at least today's PEV batteries

Energy / Power Consumption of IDEAL Cars & Trucks

Before moving on, we need one more bit of useful background:

We discussed how much energy today's Cars & Trucks **STORE** onboard,

and what fraction of that energy ultimately makes it to those vehicles' wheels

But we never figured how much energy a vehicle of a certain size, shape & mass

NEEDS at its wheels to move in a certain way (slow vs. fast, steady vs. stop & go)

That information will strongly affect the design and use of future vehicles

Accurate answers are a lot of work, but approximate answers are surprisingly easy

All we've got to do is resurrect a bit high school science

Specifically: Sir Isaac Newton's laws of motion

Easy, at least, if we cheat a little by considering only the **biggest** moving things:

the car (as a single unit) and the air (as uniformly moving volumes)

By neglecting smaller moving things (e.g., atoms or gas molecules) we ignore heating

But the resulting predictions are still accurate enough to be very, very useful

Physics MODEL 1: Stop-and-Go Vehicle [1]

Assume vehicle moves a distance **L**, at velocity v_{max}, stops, then repeats this cycle

At the start of each cycle, fuel energy is transformed into vehicle kinetic energy of:

$$E_{vehicle\_kinetic} = ½\, M_{vehicle}\, v_{max}^{\ 2}$$

As in all of these models, energy put into air heating is neglected

But if vehicle never goes very fast, energy put into moving blocks of air is **also** small

Leaving the above vehicle kinetic energy as the major expenditure of energy

That energy (almost alone) carries the vehicle a distance L, yielding:

$$\textbf{Energy per distance}_{stop\_go} = M_{vehicle}\, v_{max}^{\ 2} / 2\,L$$

OR, the rate of energy consumption while the vehicle is moving = Δ E / Δtime = Power

Over moving part of cycle: $\Delta E = ½\, M_{vehicle}\, v_{max}^2$ $\Delta time = L / v_{max}$ yielding:

$$\textbf{Power}_{stop\_go} = M_{vehicle}\, v_{max}^3 / 2\,L$$

This model approximates **Car & Truck city driving**

1) This and models that follow build upon David J.C. McKay's chapters "Cars II" (link) & "Planes II" (link),

Physics MODEL 2: Steadily Moving Vehicle

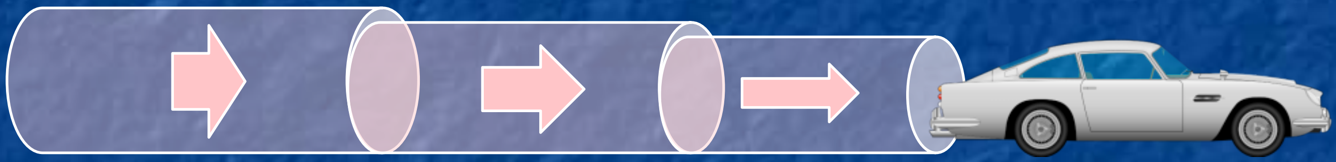
Which is mostly what is going on during long trips:

Then, the interval between accelerations is **vastly** stretched out

Diluting the kinetic energy investment during acceleration described by MODEL 1

The dominant energy loss then becomes the loss due to the "drag" of air

That is, the vehicle accelerates & drags along a volume of air at almost its own speed



That moving air thereby acquires its own kinetic energy (and gradually spreads out)

But while the energy going into moving those **blocks** of air is now accounted for,

energy going into **air friction / heating** is still neglected

which is again a better approximation for lower speeds of travel

This model will approximate **Car & Truck highway driving**

Car image from: www.clipartlord.com/category/transportation-clip-art/

The analysis:

Consider a cylinder of air that WAS stationary in front of the vehicle

but is now being dragged along behind it at a nearly the vehicle's speed

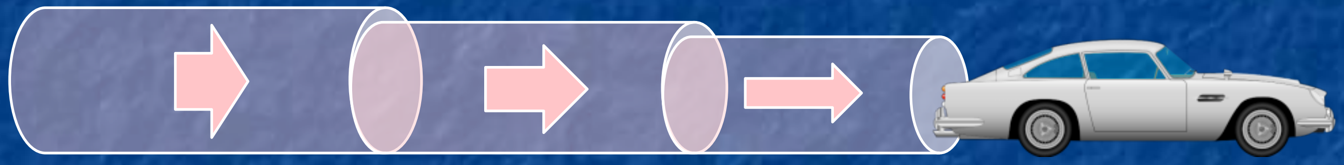
The cross-section of that air cylinder will depend upon the car's streamlining

Better streamlining => Less air accelerated => Smaller cylinder cross-section (A):

$$\text{Area}_{air} = c_{drag}\ \text{Area}_{vehicle}$$

That is, the air's cross section = c_{drag} x (vehicle's frontal cross-section area)

With c_{drag} likely being < 1 and decreasing with better and better streamlining



Then, over a time interval t, the volume of accelerated air = A_{air} x (v_{steady} x t)

with that accelerated volume now moving at ~ vehicle's velocity = v_{steady}

Energy gained by the trailing cylinder of air:

For **air of mass density ρ_{air},** we can then calculate its gained kinetic energy:

$$E_{air\_kinetic} = E_{drag} = ½ M_{air}\ v_{steady}^2 = ½ (\rho_{air} \text{ x volume of air }) v_{steady}^2$$

But from above, volume of air = A_{air} x (v_{steady} x t) = $c_{drag}\ A_{vehicle}\ v_{steady}\ t$ and thus:

$$E_{drag} = ½ \rho_{air} (A_{air}\ v_{steady}\ t)\ v_{steady}^2 \Rightarrow ½ \rho_{air}\ c_{drag}\ A_{car}\ t\ v_{steady}^3$$

Dividing that by distance (v_{steady} x t) gives the energy expended per distance:

$$\textbf{Energy per distance}_{steady} = ½ \rho_{air}\ c_{drag}\ A_{vehicle}\ v_{steady}^2$$

Or dividing it by time gives the power used while moving:

$$\textbf{Power}_{steady} = ½ \rho_{air}\ c_{drag}\ A_{vehicle}\ v_{steady}^3$$

Takeaways from those Physics Models:

Common to both stop & go and steadily-moving vehicle models:

Energy per distance traveled is **proportional to vehicle speed squared**

Power (energy per time) is **proportional to vehicle speed cubed**

Particular to lower speed stop & go city travel:

Energy / Power use is mostly due kinetic energy put into the vehicle's motion,

which is then thrown away (heating the brakes) every time the vehicle stops

That Energy / Power is **proportional to the vehicle's mass**

But that Energy / Power is **unaffected by the vehicle's size and shape**

Particular to higher speed steadily moving highway travel:

Energy / Power use is mostly due to kinetic energy put into a trailing volume of air

That Energy / Power is proportional to that air's mass, and thus to the air's volume,

which is **strongly affected by the vehicle's frontal area and shape**

But that Energy / Power is **unaffected by the vehicle's mass and length**

Part I:

GREENer Cars & Trucks

For more than 50 years we've been trying to clean up ICE's

As motivated by news about auto-pollution, illustrated by pictures such as those below

But the highlighted cities have changed, from LA in the 1950-70's,

to Beijing early in this century, to Dehli in the last couple of years

Lack of recent focus on LA suggests its **ICE vehicles are now much less polluting**

While new reporting about Beijing and Dehli could be explained by either:

Recent vast increases in the number of ICE vehicles being used and/or

ICE vehicles that are still using older, far from state-of-the-art, technology

In different parts of the world, ALL THREE explanations turn out to be correct

https://timeline.com/la-smog-pollution-4ca4bc0cc95d

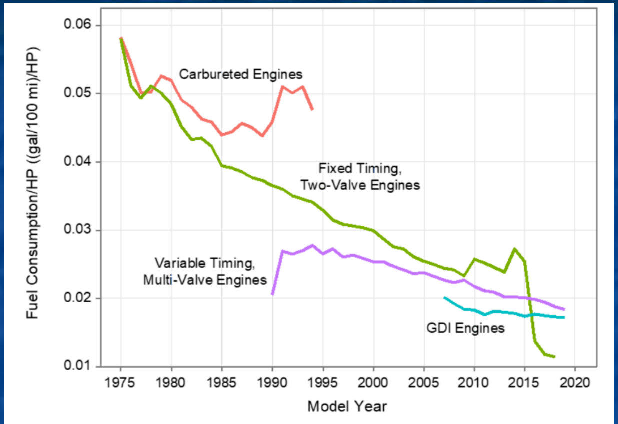
https://www.chinadaily.com.cn/china/2015-04/01/content_19973373.htm

https://www.dw.com/en/new-delhi-schools-closed-as-air-pollution-worsens/a-51235841

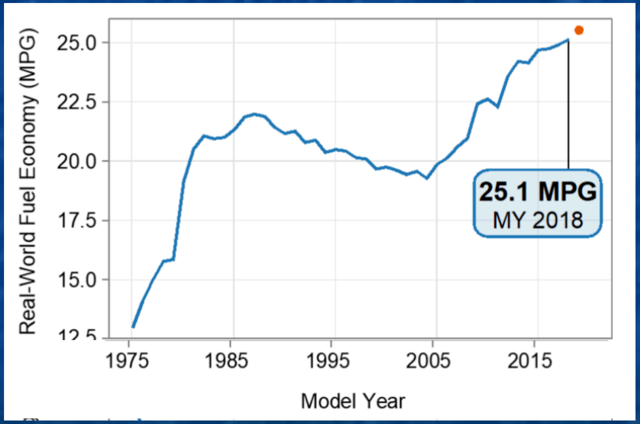
Improvements in state-of-the-art ICE technology are evident in these figures:

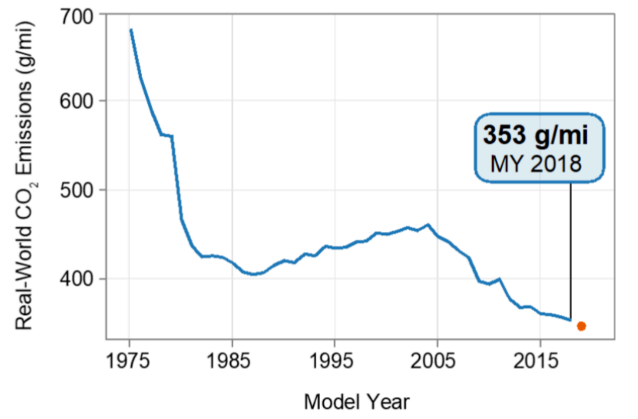
From the U.S. Environmental Protection Agency's "2019 Automotive Trends Report" [1]

ICE Fuel Consumption per Horsepower:



Leading to these trends in U.S. ICE auto mileage and emissions:





WHEN we mandated improvement (gas crises of 70/80's + prior U.S. administration)

there WAS phenomenal growth in ICE fuel economy and decline in emissions

1) Pages 46 & 5 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

But has ICE technology now reached its limit? Experts say no:

Government experts: Including those who developed new fuel mileage standards

mandating a further **doubling** of U.S. vehicle mileage (**to as much as 54.5 mpg**) [1]

Auto industry experts: Who'd bitterly labeled 1970-90's standards as "unachievable,"

but who now see opportunity in mandates applied fairly to all competitors, and thus

stood smiling behind the President as he signed new 2012 standards into law [2]

Emissions-driven ICE innovation will thus likely continue into a 6th or 7th decade

But laboratory innovation and real-world implementation are very different things:

The developed world is still implementing ICE technologies invented 1990-2000

While the developing world is adopting technologies invented 1970-1980

And the undeveloped is still using technology virtually unchanged since 1950-1970

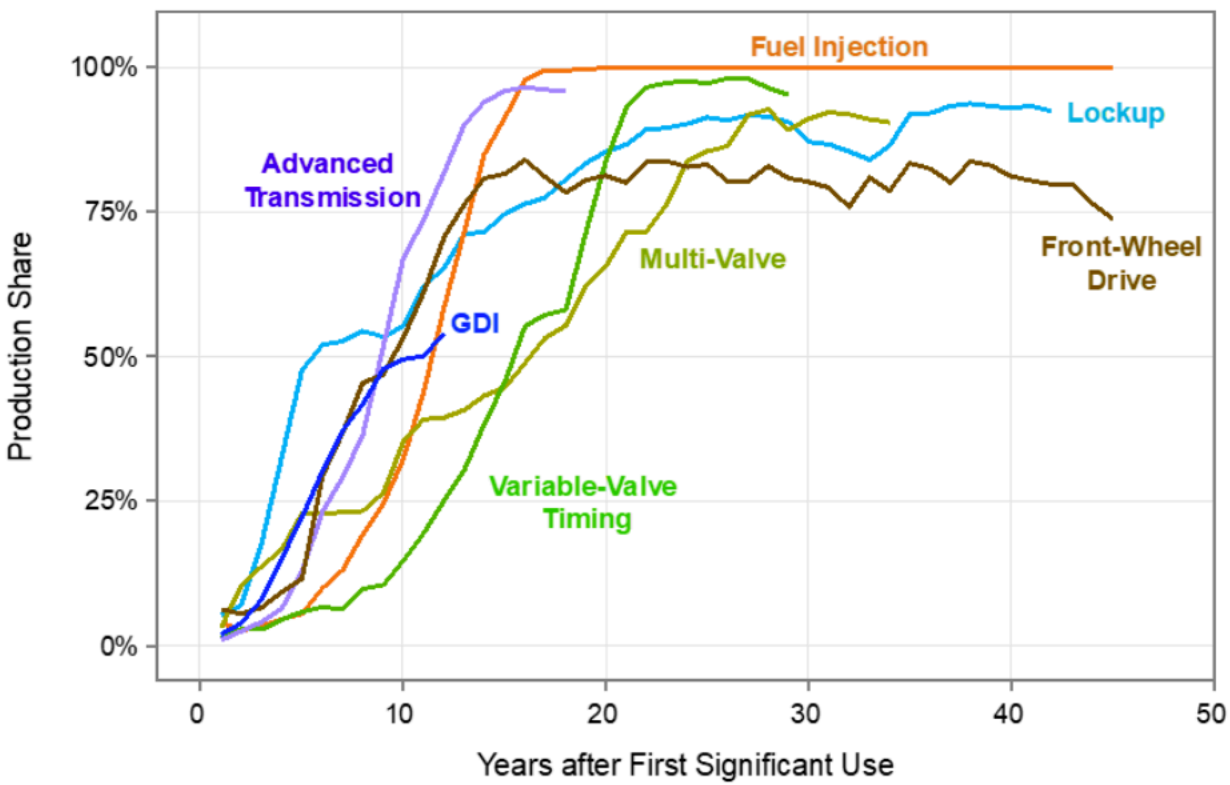
Technologies developed 1970 onward are thus STILL leading-edge . . . somewhere

Which is WHY I will shortly try to describe that full span of ICE technology

1) https://www.ucsusa.org/resources/brief-history-us-fuel-efficiency
2) https://obamawhitehouse.archives.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic-545-MPG-fuel-efficiency-standard

This EPA figure documents the slow rate of U.S. ICE technology introduction: [1]

Figure 4.22. Industry-Wide Car Technology Penetration after First Significant Use



Page 66 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

*How might ICE vehicles now evolve (over their likely **final** decades)?*

This note set's Resources webpage identifies 100+ sources discussing ICE innovations

But most cover only a single would-be technology innovation, and many were

obviously strongly influenced by that technology's developer or manufacturer

A search on the broader question asked in this slide's title was far less productive

Yielding only a handful of media articles (NPR [1] and two Scientific American [2, 3])

And a pair of government-backed studies (EPA [4] & U.S. National Academies [5])

The government-backed studies were much longer and much, much more detailed

But, confirming its "Automotive Trends" title, the EPA report looked mostly backward

It did, however, provide the figures used in the last three slides

It also provided the following figure about technologies under investigation,

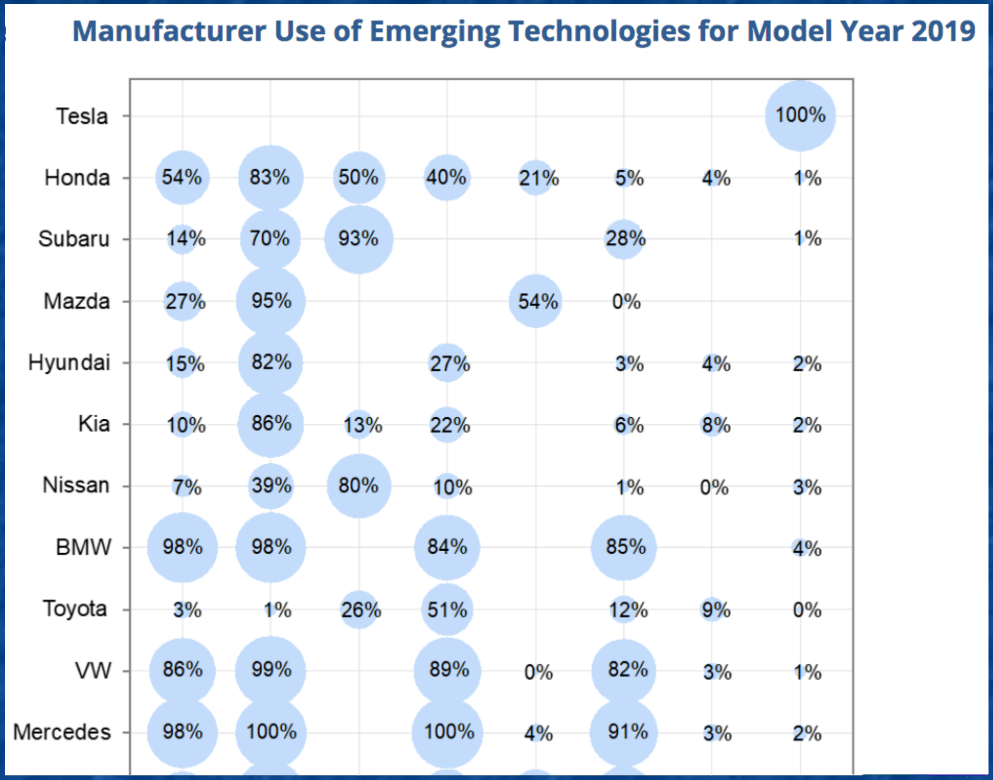
and the subsequent figure about introduction dates for some of those technologies:

1) https://www.npr.org/transcripts/104315952 2) https://www.scientificamerican.com/article/how-automakers-can-meet-new-fuel/
3) https://www.scientificamerican.com/article/why-automakers-keep-beating-government-standards/
4) https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf
5) https://www.nap.edu/catalog/21744/cost-effectiveness-and-deployment-of-fuel-economy-technologies-for-light-duty-vehicles

List of 2019 "emerging technologies" used by by various manufacturers:

From the U.S. EPA's **2019 Automotive Trends Report** [1]

"Engine technologies such as turbocharged engines (Turbo) and gasoline direct injection (GDI) allow for more efficient engine design and operation. Cylinder deactivation (CD) allows for only using part of the engine when less power is needed, and stop/start can turn off the engine entirely when the vehicle is stopped to save fuel. Hybrid vehicles use a larger battery to recapture braking energy and provide power when necessary, allowing for a smaller, more efficiently-operated engine. Transmissions that have seven or more speeds (gears), and continuously variable transmissions (CVTs), allow the engine to more frequently operate near its peak efficiency, providing more efficient average engine operation and a reduction in fuel usage."



1) Page 38 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

Chronology of technology adoption by various manufacturers: [1]

But this table is a bit misleading:

Most of its "technologies" are actually a whole **class of technology,** which encompasses many different forms and generations, each of distinctly different effectiveness.

For instance: In the U.S. only the most primitive form of fuel injection was widely introduced by 1990 (as indicated by this figure).

But in fact, introduction of more sophisticated and more effective forms of fuel injection continues right up to the present day.

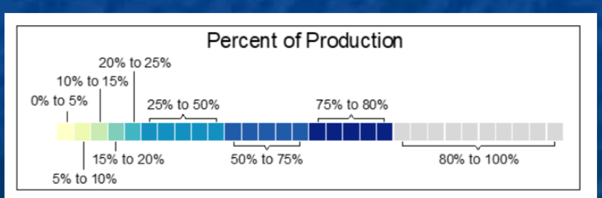
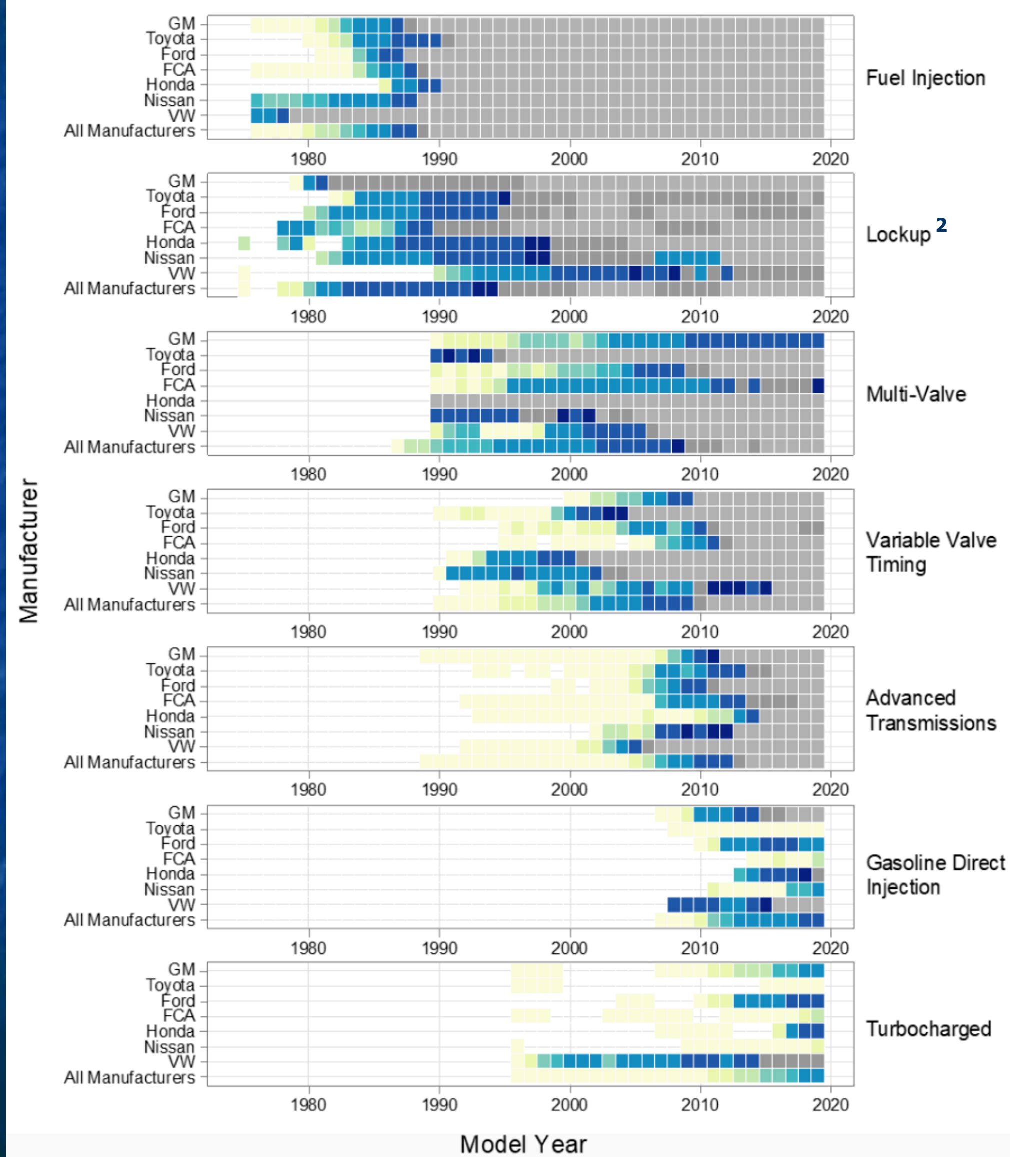


Figure 4.23. Manufacturer Specific Technology Adoption over Time for Key Technologies



1) Page 68 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

2) LOCKUP = holding an automatic transmission in a certain gear to reduce fuel consumption

The other government-backed report was from the National Academies [1]

It was entitled:

"Cost, Effectiveness, and Deployment of Fuel EconomyTechnologies for Light-Duty Vehicles"

Running to 479 pages, that report was not only exhaustive but exhausting

Particularly frustrating was its obsession with detail at the expense of perspective:

For instance, in chapter 2, its analysis of fuel consumption extended to the minor roles played by oils, water pumps, cooling fans & alternators (p. 47)

And in cost-analyzing one technology, it got down to the $1.00 cost of "oil-drillings" (?), the $1.79 cost of wires & wire connectors, and the $1.80 cost of a larger fuel pump (p. 50)

And when the report **did** finally get to the point of presenting its summary of:

"Estimated Fuel Consumption Reduction Effectiveness of SI Engine Technologies"

That summary spanned seven pages of single-spaced text tables (pp. 90-96), making identification of the **most** promising & rapidly **impactful** technologies **very** difficult

1) https://www.nap.edu/catalog/21744/cost-effectiveness-and-deployment-of-fuel-economy-technologies-for-light-duty-vehicles

Finally, returning the media's answer to "How might ICE vehicles now evolve?"

Those answers came from three overview articles, from NPR [1] & Scientific American [2, 3]

I decided to tally the number of times they mentioned any technology

Those mentions were (as indicated by the references):

- More efficient ICE engines (via a variety of possible sub-technologies) [1, 2, 3]
- Lighter vehicles [1, 2, 3]
- Gas engine + electric motor vehicles (a.k.a. Hybrid Electric Vehicles) [1, 2, 3]
- More efficient transmissions [1, 3]
- More aerodynamically vehicles [1]
- Smaller vehicles [2]
- Diesel powered cars [1]
- More efficient climate control systems [3]

1) https://www.npr.org/transcripts/104315952 2) https://www.scientificamerican.com/article/how-automakers-can-meet-new-fuel/
3) https://www.scientificamerican.com/article/why-automakers-keep-beating-government-standards/

By merging together the answers from all of those sources

Then adding impressions gained from those 100+ Resources webpage sources

It appears that the most promising paths towards Greener Cars & Trucks are:

At the top of the list: **Improved Internal Combustion Engines (ICEs)**

This note set's next section thus focuses on the many forms that may take

Closely related, and thus next down the list: **More effective USE of ICEs**

Leading to a section about **alternate transmissions** and **Hybrid Electric Vehicles**

Also closely related is the possibility of **Diesel powered cars**, which will be discussed

in an introductory section about ICEs and a later section about Diesel emissions

Finally, the **preceding** section about **Physics** modeling of vehicle motion energy

prompts a group of options receiving both direct & indirect attention:

lighter, smaller, and more aerodynamic vehicles

1) https://www.npr.org/transcripts/104315952 2) https://www.scientificamerican.com/article/how-automakers-can-meet-new-fuel/
3) https://www.scientificamerican.com/article/why-automakers-keep-beating-government-standards/

But responses to those final options are controversial (especially in the U.S.)

For stop & go vehicle travel our Physics-based model concluded:

Energy / Power use is mostly due **kinetic energy** put into the vehicle's motion

which is then lost (heating the brakes) every time the vehicle stops

That Energy / Power is **proportional to the vehicle's mass**

Vehicle weight reduction has thus been, and is still being, aggressively pursued

To date: By replacing much of the vehicle body & engine steel with **aluminum**

In the future (inspired by aircraft): By replacing metals with **fiber composites**

But weight reduction affects strength, ultimately compromising **crash survivability**

Hence the approach of **reducing vehicle weight by reducing vehicle size**

Which runs absolutely contrary to mainstream buying preferences of U.S. consumers

Leading to the alternative of developing **Kinetic Energy Recovery Systems**

Which are thus covered in another upcoming section of this note set

1) https://www.npr.org/transcripts/104315952 2) https://www.scientificamerican.com/article/how-automakers-can-meet-new-fuel/
3) https://www.scientificamerican.com/article/why-automakers-keep-beating-government-standards/

Our other Physics model prompted the remaining option of streamlining:

For higher speed steadily-moving highway travel that Physics model concluded:

Energy / Power goes mostly into the kinetic energy of a trailing volume of air

That Energy / Power is proportional to that air's mass, and thus to the air's volume,

which is **strongly affected by the vehicle's frontal area and shape**

Specifically: $\textbf{Energy per distance}_{steady} = \frac{1}{2}\, \rho_{air}\, c_{drag}\, A_{vehicle}\, v_{steady}^{2}$

$\textbf{Power}_{steady} = \frac{1}{2}\, \rho_{air}\, c_{drag}\, A_{vehicle}\, v_{steady}^{3}$

One option is thus to shrink the vehicle's frontal area ($A_{vehicle}$)

But (again especially in the U.S.) larger, not smaller, vehicles are strongly favored

A second option (opposed pretty much worldwide) is reducing vehicle speed (v_{steady})

A third option is reducing air density (ρ_{air}), as inside Elon Musk's proposed Hyperloop

Leaving only the option of shrinking the vehicle's drag coefficient (c_{drag}) via streamlining

1) https://www.npr.org/transcripts/104315952 2) https://www.scientificamerican.com/article/how-automakers-can-meet-new-fuel/
3) https://www.scientificamerican.com/article/why-automakers-keep-beating-government-standards/

But we've already approached the practical limits of streamlining:

	c_{drag}:
Honda Insight	0.25
Prius	0.26
Renault 25	0.28
Honda Civic	0.31
Volkswagen Polo	0.32
Peugeot 206	0.33
Ford Siesta	0.34
Audi TT	0.35
Honda Civic	0.36
Citroen 2CV	0.51

For modern cars (unlike the Citroen 2CV):

Streamlining => diminishing returns

- Somewhat boxy Polo: $c_{drag} = 0.32$
- Teardrop shaped Insight: $c_{drag} = 0.25$
- Total reduction is only ~ 20%

Stronger improvement would require:

- Much longer (and hence heavier) cars
- Or much lower cars (as used in racing)
  - With more difficult entry & exit AND
  - Much less passenger / cargo space

Thus moving onward to a discussion of:

GREENer Cars & Trucks:

Improving Internal Combustion Engines

(ICE Basics / Diesel vs. Gas / Fuel-Air Mix / Timing / Turbocharged Small ICEs)

ICE Basics: *The classic "4-stroke" Engine*

Piston within cylinder is tied by **connecting rod** to rotating (wheel-driving) **crankshaft**

Crankshaft is connected via a **timing belt** to one or two **camshaft(s)** (not shown)

Cams (bumps) on camshaft(s) open one of **two types of valve** in the cylinder roof

Stroke 1: Piston falls, cam opens left valve(s), air OR fuel + air mixture is drawn inward

Stroke 2: Valve closes, rising piston compresses and heats air or fuel + air mixture

End of Stroke 2: If not already added, fuel is then injected

Compressed fuel + air mixture is then ignited

vastly increasing its temperature & pressure

Stroke 3: High pressure drives piston back downward

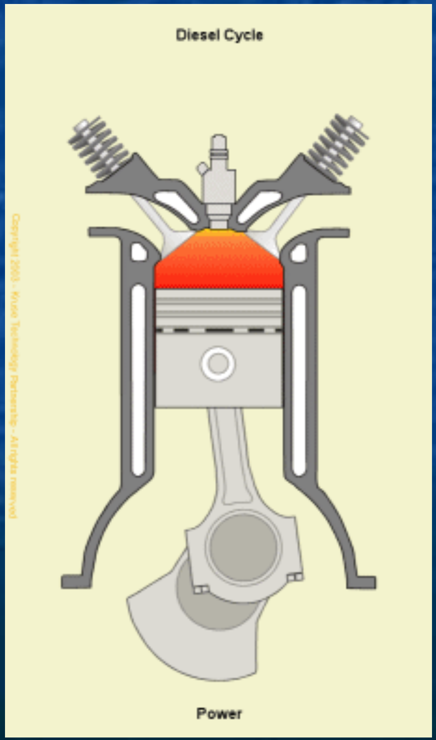
Stroke 4: Piston rises as cam on camshaft opens right valve(s)

allowing hot high-pressure exhaust gases to exit

Near top of piston's stroke, the exhaust valve(s) closes

Back to Cycle #1, repeat as wanted or until fuel is gone

(PgDn to animate)



Animated gif: http://www.kruse-ltc.com/Diesel/diesel_animation.html

Labeled parts of a ***gasoline Spark Ignition Internal Combustion Engine (SI-ICE)***:

(***PgDn*** to animate)

Intake Valve (1 or 2)
driven up & down by one cam

Spark Plug

Exhaust Valve (1 or 2)
driven up & down by other cam

Carburetor
mixing fuel with air

Exhaust Pipe

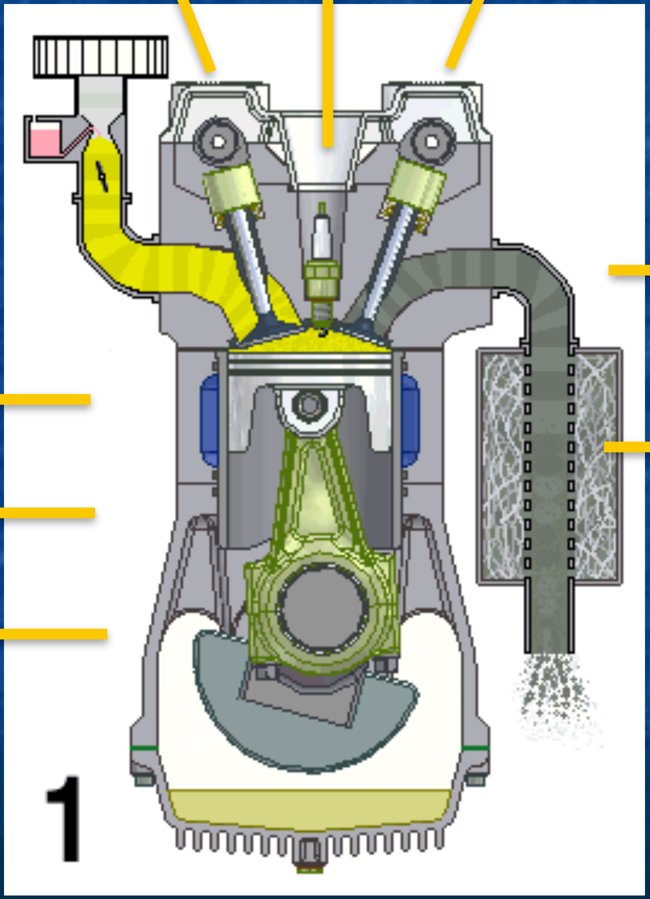
Piston

Exhaust Muffler

Connecting Rod

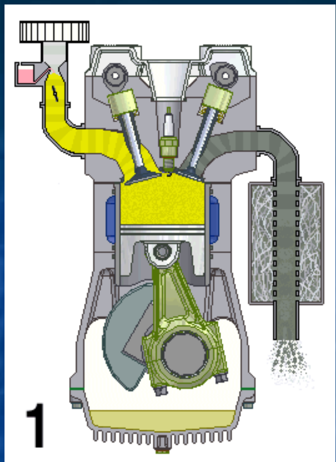
Engine Crankshaft

Stroke # =

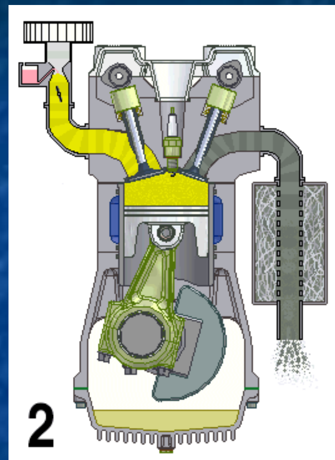


https://commons.wikimedia.org/wiki/File:4-Stroke-Engine-with-airflows_numbers.gif

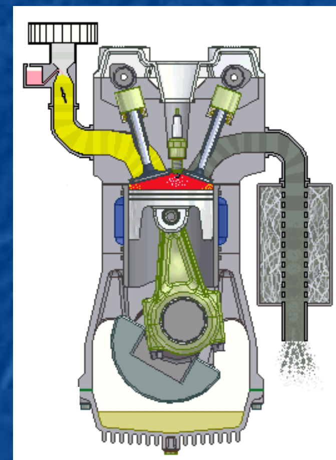
In stop action:



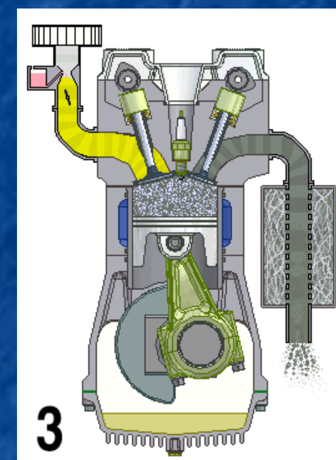
Downstroke:
Fuel + Air Intake
via open left valve(s)



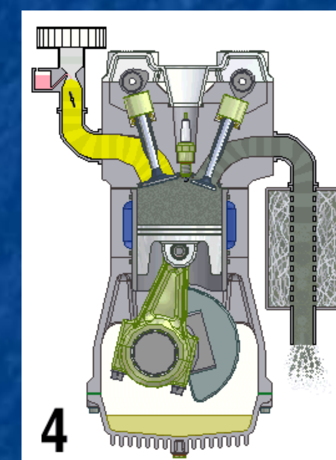
Upstroke:
Fuel + Air
Compression



Fuel + Air Ignition
caused by spark plug



Downstroke:
Combustion Gas
Expansion



Upstroke:
Combustion Gas
Exhausting
via open right valve(s)

← *All valves closed* →

From: https://commons.wikimedia.org/wiki/File:4-Stroke-Engine-with-airflows_numbers.gif

Finally, paying attention to the valves and what is driving them:

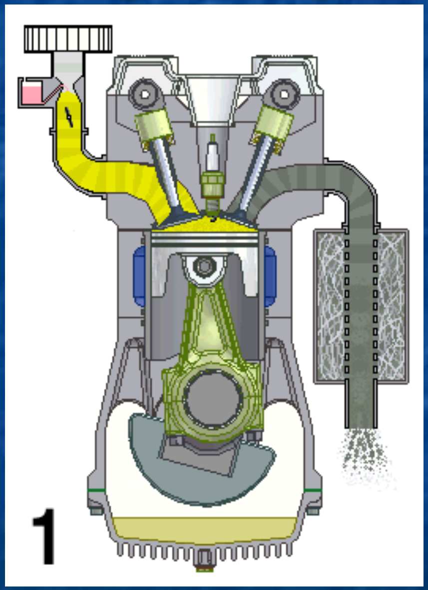
They're opened & closed by **cams** (bumps) on one or two **camshafts** atop the engine

Which are rotated by a **timing belt** connected to the **crankshaft** low in the engine

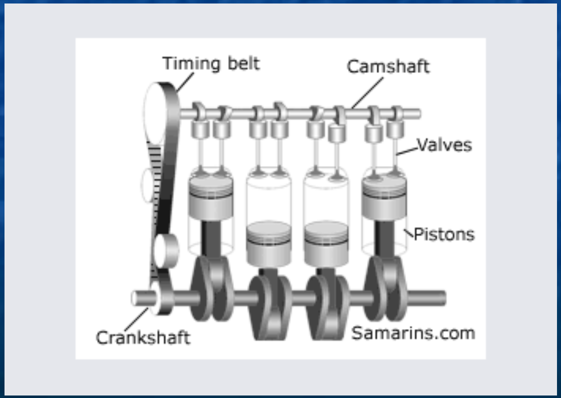
(**PgDn** repeatedly to start animations)

Intake Valve(s)
driven up & down by camshaft

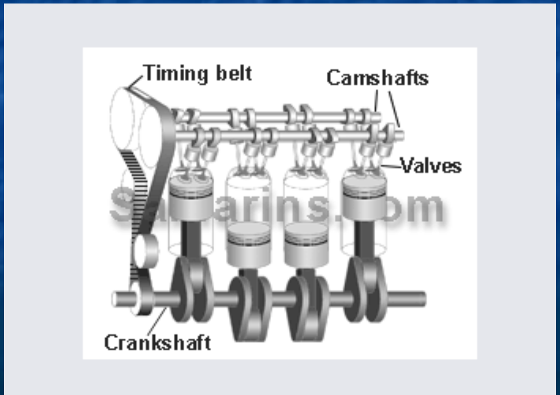
Exhaust Valve(s)
driven up & down by camshaft



X-ray side view of entire
Over Head Valve (OHV) Engine with
Single Over Head Camshaft (SOHC)
(two valves per cylinder)



X-ray side view of entire
Over Head Valve (OHV) Engine with
Dual Over Head Camshaft (DOHC)
(four valves per cylinder)



Top: https://commons.wikimedia.org/wiki/File:4-Stroke-Engine-with-airflows_numbers.gif
Bottom: https://www.samarins.com/glossary/dohc.html

Diesel vs. Gas: Where and when fuel is added:

Classic Gasoline SI-ICEs:

Outside of the cylinder, gasoline mist / vapor is first mixed with air,

that **mixture** is then drawn into the cylinder (during stroke 1)

Engine speed is varied by changing the mixture's fuel / air ratio

AND by varying exactly **when** that fuel + air mixture is spark-ignited

Diesel ICEs:

After air is drawn in and compressed by the rising piston (end of stroke 2),

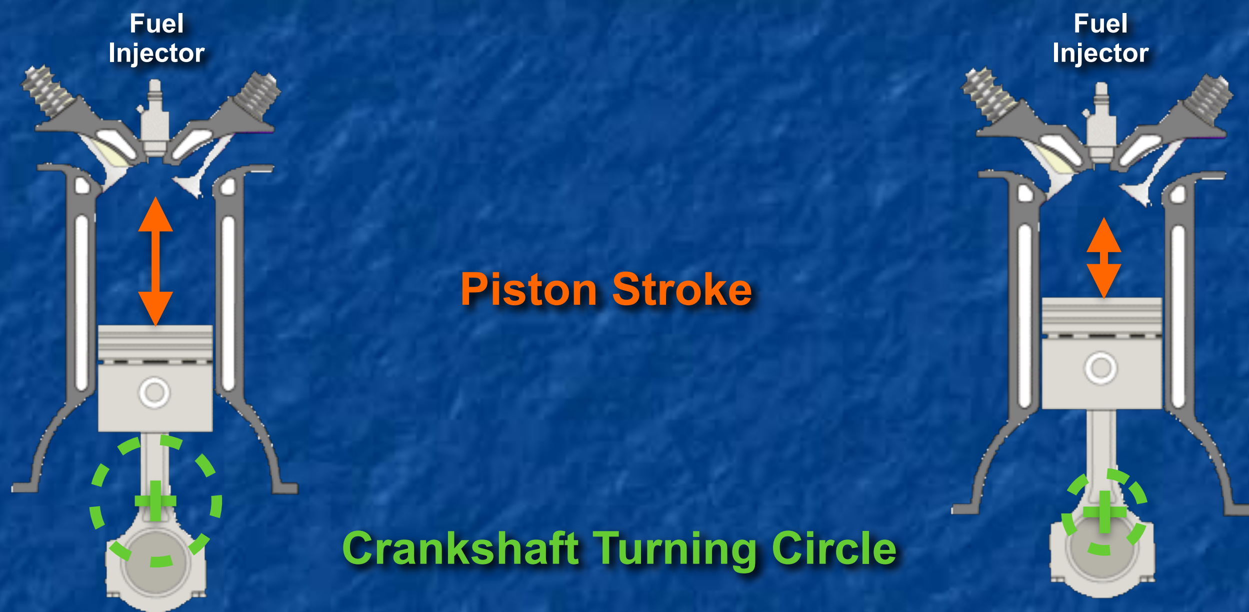
pure diesel fuel is injected into that compressed / heated air within the cylinder

Engine speed is varied by changing **only** the amount of fuel injected

Diesel vs. Gas: *How fuel is ignited:*

Diesels change the rotating point where the **connecting rod** attaches to the **camshaft**

Large circle => Long piston stroke: Small circle => Short piston stroke:



Long => high **compression ratio** (max / min volume) => Much more air compression

Diesel engines thus compress air by 14-25 times (vs. ~10 times in gasoline ICEs) [1, 2]

More air compression => More heating => Air temperatures at or above 500ºC [1]

Hot enough that many injected fuels almost immediately **auto-ignite**, including

less-refined fuels such as standard diesel, biofuels & used cooking oil

1) https://www.explainthatstuff.com/diesel-engines.html 2) https://en.wikipedia.org/wiki/Diesel_engine

*But **both** types of ICE are still **"Thermal Engines"***

So called because when input energy creates temperatures differences within them,

those differences can be used to induce motion (thermal energy => kinetic energy)

Thermal Engine conversion efficiencies are modeled by the **Carnot Cycle** [1]

Which predicts energy conversion efficiencies of: $(T_{max} - T_{min}) / T_{max}$

Where T_{max} & T_{min} are highest and lowest temperatures within the engine

For all ICEs, $T_{min} \sim T_{incoming\ air} \sim T_{ambient\ air}$ (in the absence of added technologies) [2]

But the higher compression within Diesel engines drives up T_{max} in a number of ways:

Stronger compression heats the pre-combustion air to much higher temperatures

Stronger compression increases the O_2 available, thereby intensifying combustion

Leading the Carnot formula to correctly predict much more efficient Diesel operation:

Diesel efficiencies = 40-45% vs. Gasoline Si-ICEs efficiencies ≤ 20%

Doubling Diesel fuel mileage . . . possibly halving GHG output? (more about that later)

*1) For further discussion about the Carnot Cycle, see my note set: **Fossil Fuels** (pptx / pdf / key)*

*2) Such as: **TURBOCHARGING** (which heats incoming air) or **INTERCOOLING** (which then tries to cool it back down)*

*Apparent bottom lines: Diesels are **FAR** more efficient and **FAR** simpler:*

To control their speed (power and GHG emissions) gasoline SI-ICEs must:

- Vary the fuel to air ratio of the mixture drawn into the cylinder

  Which was once done by finicky but cheap mechanical "carburetors"

  but is now increasingly done by injection devices

  controlled by less finicky but expensive & complex control electronics

- Vary the exact timing and intensity of the electronic pulse sent to the spark plug

  As once done by finicky but cheap mechanical "distributors & ignition coils"

  but now done by less finicky but expensive & complex electronic ignitions

To control their speed Diesels must instead:

- Vary the amount of fuel injected into the already compressed cylinder air

PERIOD

Diesels' greater simplicity => Enhanced reliability => Lower operating costs

*But then along came **Dieselgate:***

Which was a scandal revealing **massive fraud** in emissions testing of Diesel engines [1]

During emission tests, cars were typically operated in non-real-life modes,

such as at constant speed, or in one particular stop & go cycle

Which simplified testing, making it both more reproducible & automatable

But like all of today's cars, diesel cars have considerable onboard computer power

and a **Volkswagen cabal** recognized that those computers could be

programmed to recognize **when** the vehicle was being emissions tested

And further programmed to then **temporarily** reduce the vehicle's emissions,

by altering fuel use in ways which would degrade real-world driving performance,

but likely remain undetected by automated emissions-testing equipment

Convicted in both German and U.S. courts, **Volkswagen / Audi** has since paid:

"$33.3 billion in fines, penalties, financial settlements and (diesel) buyback costs" [1]

Testing by **Volvo, Renault, Jeep, Hyundai, Citroen & Fiat** has also been questioned

1) https://en.wikipedia.org/wiki/Volkswagen_emissions_scandal

So what IS the truth about Diesel engines' environmental friendliness?

Industry sources (now considerably lacking in credibility) claim that use of Diesels

has massively reduced worldwide vehicle CO_2 emissions [1]

The basic science suggests this should be possible for at least an idealized Diesel:

From my note set about **Fossil Fuels** (pptx / pdf / key):

Diesel's molecules are 8-21 C atoms long, gasoline's 4-12 C atoms long

Meaning that, per molecule, diesel packs ~ twice the C of gasoline

But tighter molecular packing ultimately gives diesel up to 20% higher mass density [2]

Suggesting ~ 20% more C per volume of diesel fuel => Estimate of CO_2 output:

(1.2 x higher C / vol) (0.5 vol burned /distance) => 0.6 CO_2 produced per distance

But back out in the real world, non-industry sources report much poorer results

From the **International Council on Clean Transportation**'s lab + on-road study: [3]

"gasoline vehicle(s) can have the same or lower CO_2 emissions than a comparable diesel"

1) https://www.smmt.co.uk/2015/03/smmt-puts-record-straight-on-diesel-cars-with-new-nationwide-consumer-campaign/
2) https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html
3) https://theicct.org/publications/fact-sheet-gasoline-vs-diesel-car-co2-emission

Further, Diesels emit more particulates & organics, including mutagens:

From a study posted on the U.S. National Institutes of Health website: [1]

	Light-duty diesel vehicle	Light-duty gasolne vehicle w/ catalytic converter
GAS PHASE EMISSIONS in mg / km:		
Benzene	15	8
Carbon monoxide	79	7625
Formaldehyde	13	3
Nitrogen oxides	794	1469
Propylene	-	11
Toluene	-	20
GAS PHASE PAHs & PAH DERIVATIVES in μg / km:		
Anthracene	1313	38
Fluoranthene	188	4
	569	-
2-Nitrofluorene	56	-
Pyrene	238	6
	706	-
PARTICLATE PHASE PAHs & PAH DERIVATIVES in μg/km:		
Anthracene	66	2
Benzo[a]pyrene	8	0.3
	0.6	0.1–1
Benzo[a]pyrene (contd)	-	0.06
	-	2
	21	1
Benzo[e]pyrene	9	0.3
Fluoranthene	140	3
	427	-
	583	-
2-Nitrofluorene	61	-
1-Nitropyrene	7	<0.06
	3	0.1
	5	0.1
Pyrene	178	4
	530	-
	178	6
	24	16
Total PAH	125–625	
OTHER EMISSIONS:		
Total particulate phase in mg/km	246	11
Total extractable matter in mg/km	124	6
MUTAGENICITY:		
TA98 (without activation) in rev/km	595 000	30 000
TA98 (with activation) in rev/km	240 000 - 320 000	30 000
PAH = Polycyclic Aromatic Hydrogarbon		

Reasons why Diesel exhaust is SO much richer in unhealthful particulates & organics?

Greater complexity of diesel fuel molecules + ultra-fast & thus incomplete combustion

*1) My Excel table above is abstracted from Table III in the study: **Diesel and Gasoline Exhausts . . .***
As downloaded from the U.S. National Institutes of Health website at: https://www.ncbi.nlm.nih.gov/books/NBK531294/

Others echo this concern about the unique character of Diesel emissions

For instance, in the European Environmental Agency's report: "Air Quality in Europe" [1]

Putting this all together, my takeaway is that:

Higher conversion efficiency means **simple diesel engines** can use less fuel,

reducing their output of the primary hydrocarbon combustion products CO_2 & H_2O

But reductions have been effectively matched in **complex modern gasoline engines**,

which exploit their more numerous ways of fine-tuning combustion

Diesels have thus lost their strong theoretical advantage in primary GHG emissions,

and attention has turned to their secondary emissions which,

while they may have a lower long term global warming impact,

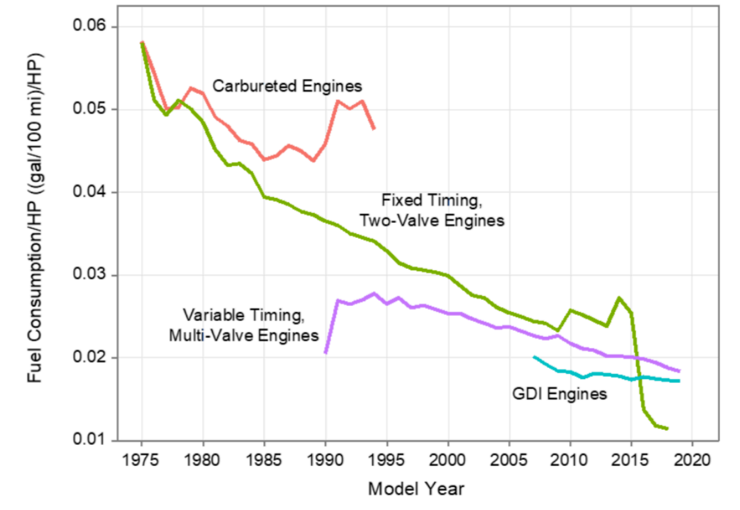
could well have a more immediate human health (and biosphere) impact

I will thus now focus on the possible improvement of ONLY gasoline ICEs

1) See, for instance pages 15, 18 & 84 in: https://www.eea.europa.eu/publications/air-quality-in-europe-2016

*How **might** SI-ICEs be markedly improved . . . **within just 5-10 years**?*

This earlier "EPA Automotive Trends Report" figure provides some cryptic hints: [1]



1) Page 46 in: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YVFS.pdf

Improvements suggested by that figure involve either:

Better control of HOW & WHERE fuel and air get mixed

Better control of WHEN the fuel air mix enters the cylinder

OR of WHEN air, then fuel, separately enter the chamber

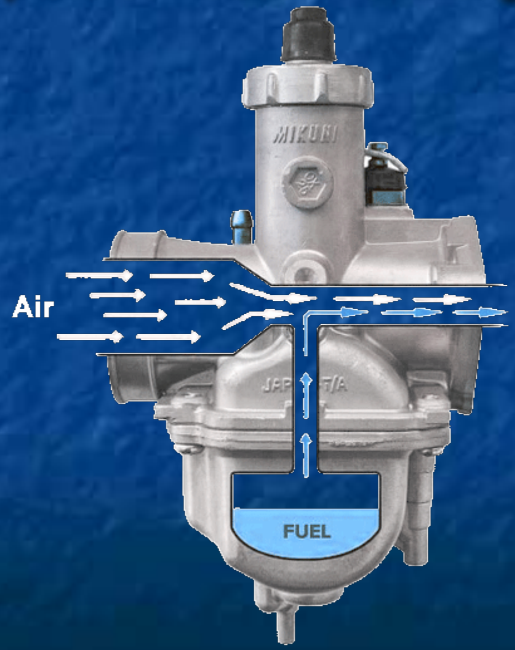
OR of WHEN, however it got into there, the resulting mix is ignited

Fuel-Air Mix: *What IS a fuel injector & how is it used?*

Fuel Injectors are all about creating a fast & cleanly burning fuel + air mixture:

This was originally done by **Carburetors** inside of which (via the Venturi effect) passing air sucked gasoline out of a reservoir forming a stream of droplets

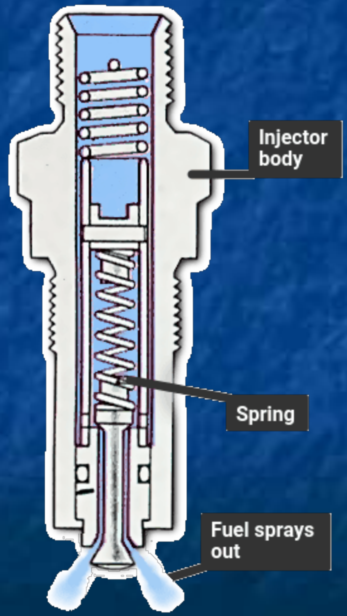
Which **was** a fuel + air mixture, but a crude one that did not facilitate rapid and complete combustion of that gasoline



Derived from: https://www.revzilla.com/common-tread/how-does-a-carburetor-work

Fuel pumps instead supply **Fuel Injectors** with high-pressure gasoline

That pressurized fuel then sprays out of the Injector via a carefully designed "atomizing" nozzle. The result is a very fine mist of fuel in air, which can burn much more quickly and completely



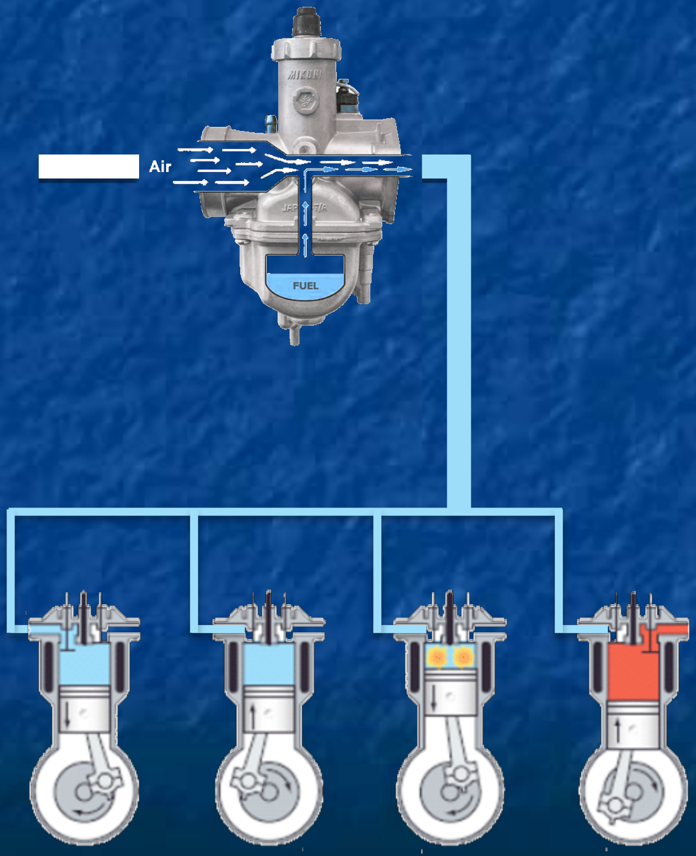
Derived from: https://www.howacarworks.com/basics/how-a-fuel-injection-system-works

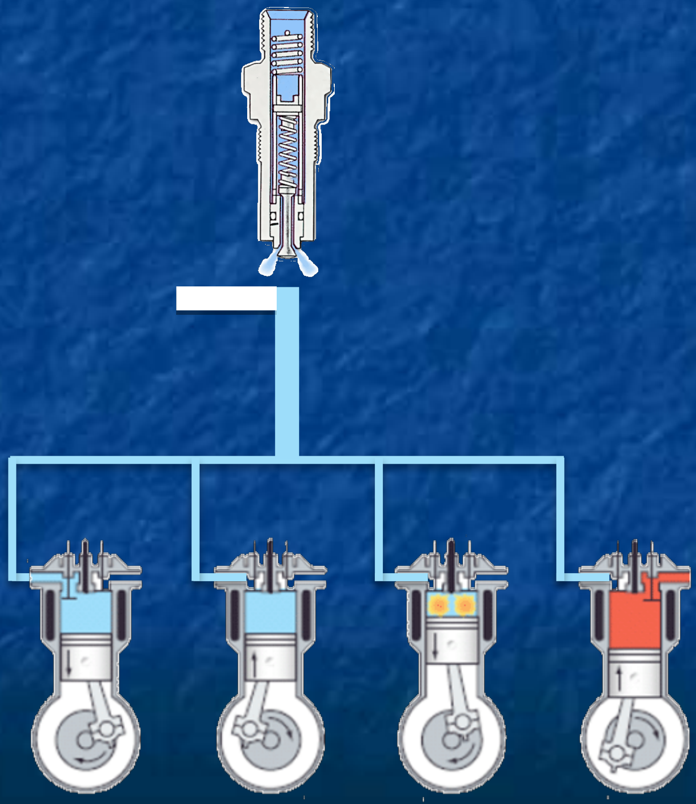
But Fuel Injectors have been used in all sorts of different ways:

Classic gasoline ICEs had a single Carburetor mixing together fuel and air,

which was then drawn by opening intake valves into one cylinder after another

1980's vintage cars simply replaced that **single** Carburetor with a **single** Fuel Injector:





Parts of figure derived from: https://engihub.com/diesel-engine-working/

But as they pass down pipes, ultra-fine fuel droplets tend to coalesce

Forming fewer larger droplets, undercutting the advantage of Fuel Injectors,

which is to create a more quickly and completely burning fuel + air mixture

Later cars thus incorporated one Fuel Injector per ICE engine cylinder,

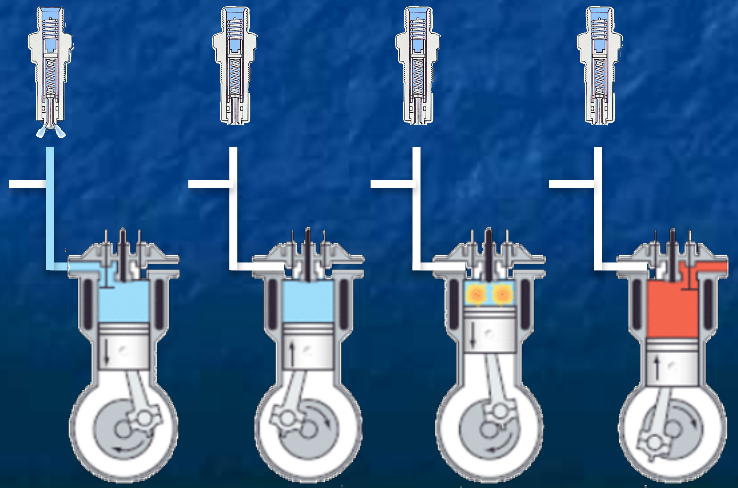
with that injector injecting fuel into the air pipe just outside of the cylinder

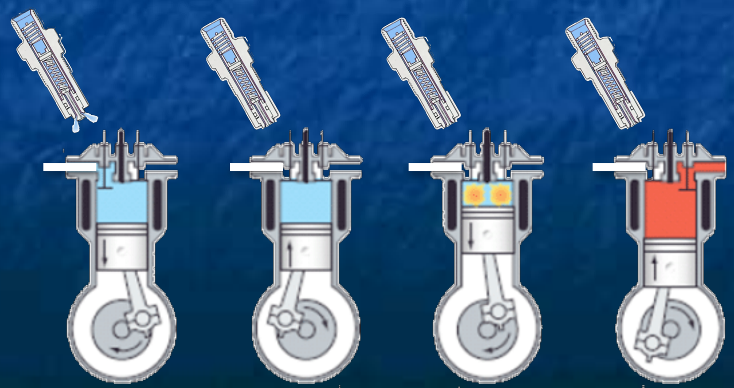
(with the subsequent intake valve(s) still controlling admission of the fuel + air)

While in the most recent cars, injectors shoot **directly** into each cylinder, giving them

FULL control of the **fuel's** injection (with the intake valves then controlling only **air**)

This is the Gasoline Direct Injection (GDI) referred to in earlier figures

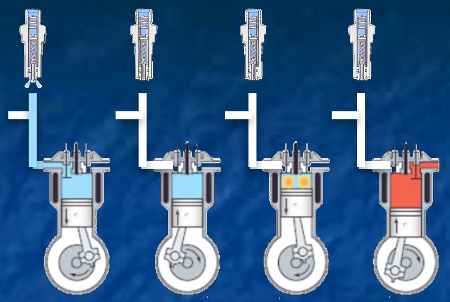




The full alphabet soup of Fuel Injection gets even more confusing:

MPFi = Multi Port Fuel Ignition

also called just: =



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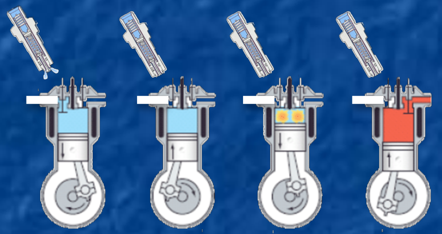
PFI = Port Fuel Injection

GDI = Gasoline Direct Injection

also called: =



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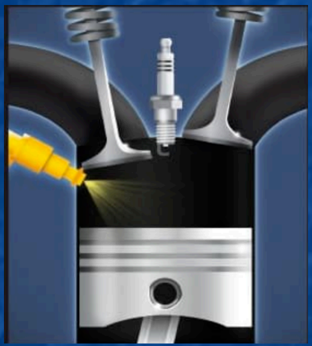


SIDI = Spark Ignited Direct Injection

FSI = Fuel Stratified Injection = **CGI** = Charged Gasoline Injection

Injector & intake valve(s) are designed such that **near the spark plug** fuel air mix is "richer" in fuel (and thus more readily ignited)

But such that fuel mix lower down is "leaner" (i.e., having an excess of air / oxygen) promoting more complete & cleaner combustion

Figures:
Right top/middle: https://autoportal.com/articles/what-is-gdi-fsi-cgi-sidi-direct-injection-6965.html
Right bottom: https://automobile.fandom.com/wiki/Fuel_Stratified_Injection

But the important takeaways about Fuel Injection are that:

In the most advanced SI-ICEs, gasoline is now injected **directly** into the cylinder,

just as diesel fuel is injected directly into the cylinders of Diesel Engines

But Fuel Injected gasoline SI-ICE's still require the use of spark plug ignition

While Diesel engines instead rely upon auto-ignition,

as enabled by their cylinder's greater compression and thus higher air heating which,

for their more combustible diesel fuels, enables auto-ignition

But in gasoline SI-ICEs, Fuel Injection DOEs enhance fuel vaporization,

especially when that injection is directly into the cylinders,

which also allows for sophisticated fuel-saving / pollution-reduction strategies

such as non-uniform "stratified" fuel-air mixtures

However:

This improved control of HOW & WHERE is only half of what's really needed

The other half is better control of WHEN:

Timing: Essential for proper ICE operation, especially in gasoline ICE's:

Viewed in slow motion, ICE timing seems easy (PgDn):

During full downward Stroke 1: Keep the inlet valve(s) open

Allowing fuel + air mix to enter

During full upward Stroke 2: Keep all valves closed

Compressing fuel + air mix

At Top of Piston Travel: Fire Spark Plug

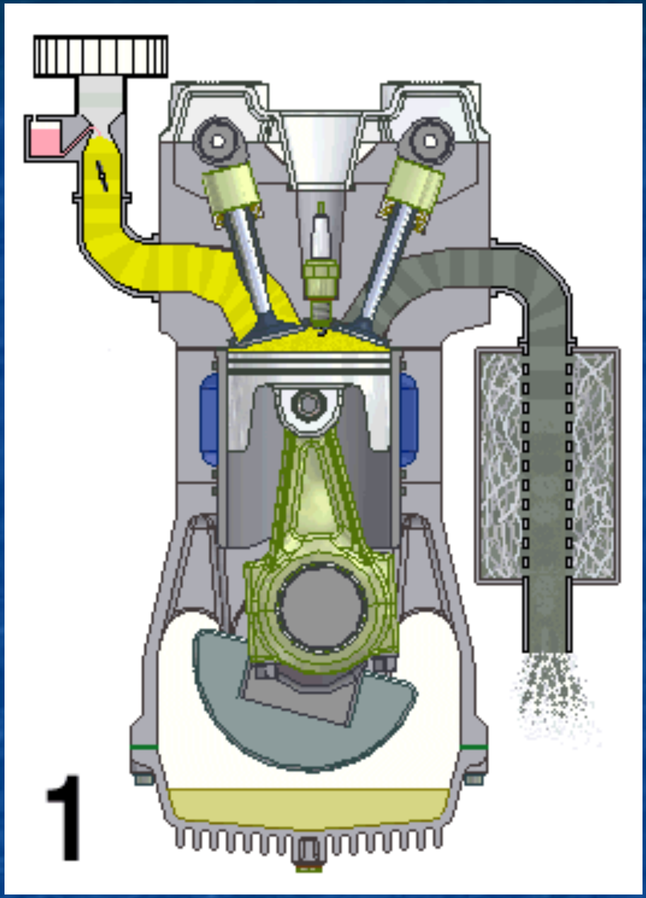
Igniting fully compressed fuel + air mix

During full downward Stroke 3: Keep all valves closed

While hot combustion gases expand

During full upward Stroke 4: Open exhaust valve(s)

Expelling combustion gases



But as we drive, our gasoline ICE's speed can range from about 700 to 7,000 RPM

Meaning that one engine rotation lasts only 85 to 8.5 milliseconds

And that the full two-rotation 4-Stroke cycle lasts only 170 to 17 milliseconds

https://commons.wikimedia.org/wiki/File:4-Stroke-Engine-with-airflows_numbers.gif

On millisecond time scales, critical things occur slowly within an ICE:

During Stroke 1, **starting & stopping inward air + gas flow takes milliseconds**

Gas molecules travel at a finite speeds, meaning they have finite momentum

But, barring infinite force, Newton says neither can change instantaneously

Between Strokes 2 & 3, **fully igniting the compressed air + gas takes milliseconds**

Because the spark plug's spark can only excite nearby fuel and O_2 molecules

and that excitation must then be passed molecule-to-molecule outward

During Stroke 4, **starting & stopping outward exhaust gas flow takes milliseconds**

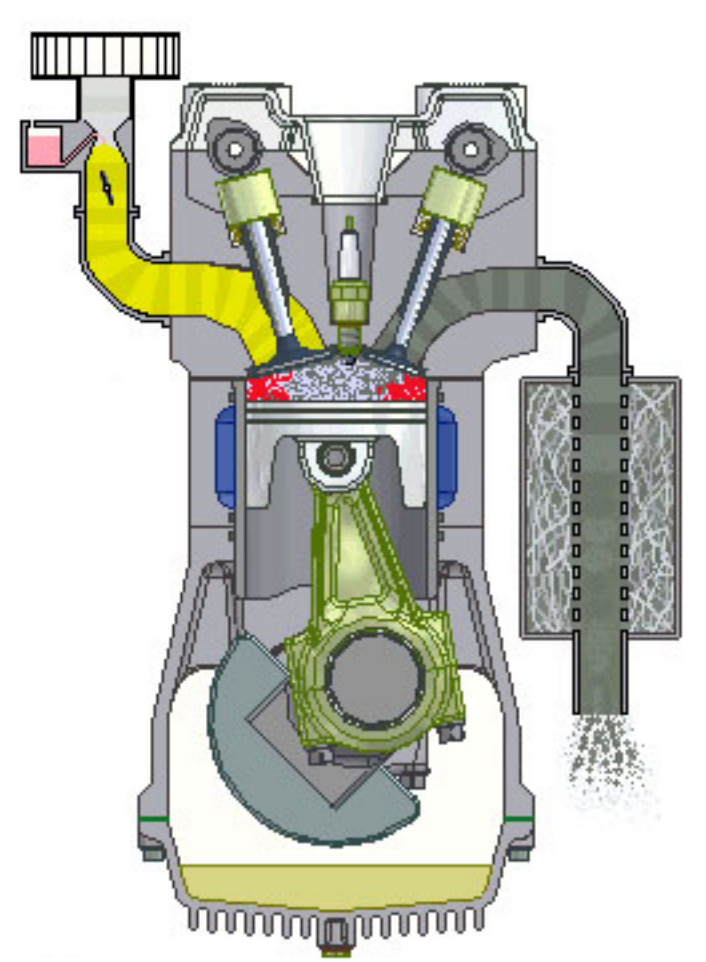
For same reason Stroke 1 air + gas molecules couldn't respond instantaneously

All three of those processes thus need to be given a HEAD START

Getting head starts right STRONGLY AFFECTS ICE EFFICIENCY & EMISSIONS

*The earlier ICE animation portrayed one of those **HEAD STARTS**:*

Here are its seven animation frames, from late in Stroke 2 to early in Stroke 3 (**PgDn**):



45º

Stroke 3: End of Combustion

- 45º : Piston rising, fuel + air compressing

- 30º : Piston rising, fuel + air compressing

- 15º : Spark plug fires

0º : Small local pocket of combustion

15º : Spreading pocket of combustion

30º : Nearly complete central combustion

45º : Final outer edge combustion

https://commons.wikimedia.org/wiki/File:4-Stroke-Engine-with-airflows_numbers.gif

Real life fuel + air combustion takes about 3 milliseconds [1]

As determined by the chemistry & physics governing hydrocarbon + O_2 ignition,

followed by that of heat spreading outward through a highly compressed gas

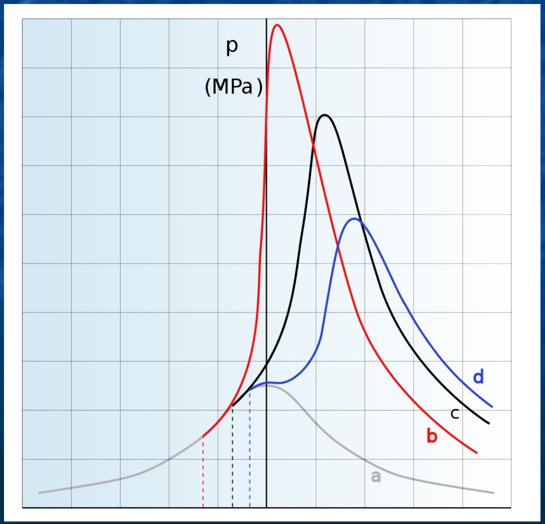
During those ~ 3 milliseconds, pressure inside the cylinder rises and falls,

as depicted in these curves which differ in the amount of spark plug Head Start [2]

Of these curves, "c" is optimum in that it maximizes the product of pressure x duration

and that combustion cycle thus drives the piston downward most strongly

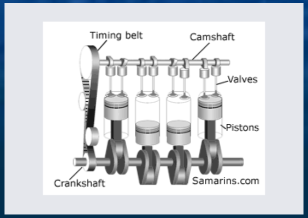
That curve's dashed beginning marks where in time the spark plug should be sparked



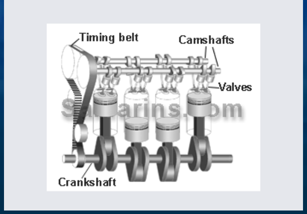
One Head Start problem seemingly solved! Not quite:

Because in classic ICEs timing is not based on time

Timing is instead based on the engine rotation angle:



(**PgDn** twice)



1) See the excellent video at: https://carbiketech.com/ignition-timing/ 2) https://en.wikipedia.org/wiki/Ignition_timing

Well, just convert timing to rotation angle via the engine's speed!

For instance, at 6000 RPM ICEs rotate 360º in 1/100 Second => 36º per mS

Thus, if the spark plug needs to fire ~ 1 mS before the piston reaches cylinder top,

its firing should be **advanced** to about 36º **before top dead center (BTDC)**

But that was **not** what the animation depicted - it showed 15º before top dead center

Yes, because ICEs turn at anywhere from about 700 to 7,000 RPM

Making the animation's spark firing at 15º before top dead center

consistent with a ~ 1 mS advance for an engine turning at 2,500 RPM

MY POINT: While rotational mechanics was indeed used to set ICE timing,

that timing was then BUILT-IN to the ICE's gears, belts, camshafts & cams

Those were chosen to OPTIMIZE efficiency & emissions at ONE SPEED

But diverging from that speed, operation became increasingly SUB-OPTIMAL [1]

1) An historical exception: As ICE's speed up, the suction of air into their cylinders increases, and that increasing partial vacuum was used to **slightly advance** the sparking charge sent from a mechanical "ignition distributor"

*It's easy to see why **timing of the spark** is hyper-critical:*

Spark too early and combustion will fight against the upward piston motion of Stroke 2

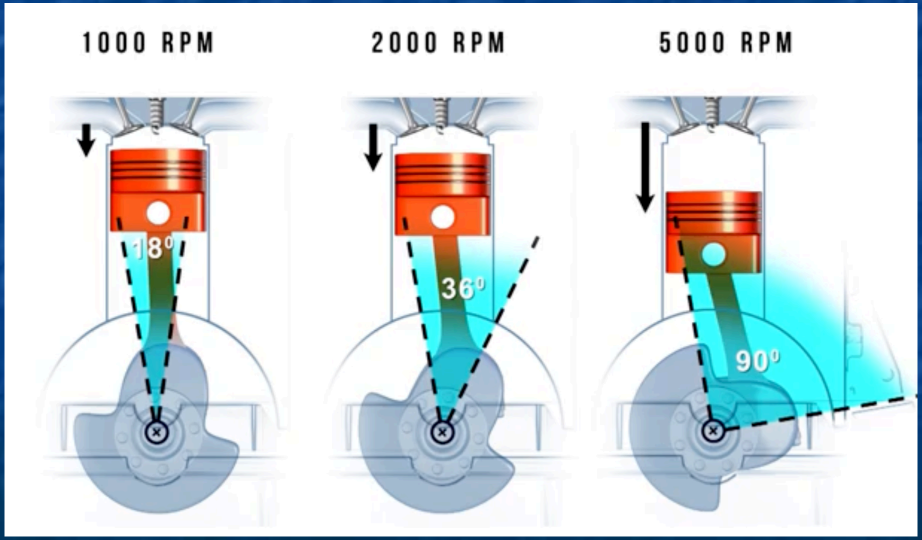
Spark too late and combustion might continue past the end of downward Stroke 3

allowing still expanding gas to escapes though Stroke 4's open exhaust valve(s)

But the timing of the intake & exhaust valves is similarly hyper-critical

Depending on the speed at which the ICE is rotating,

look how **far** it rotates while completing 3 mS of fuel-air combustion:



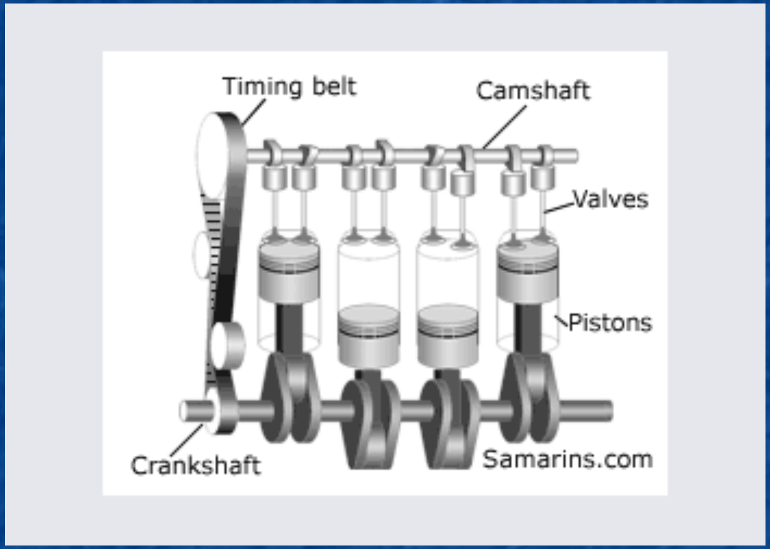
From the video at: https://carbiketech.com/ignition-timing/

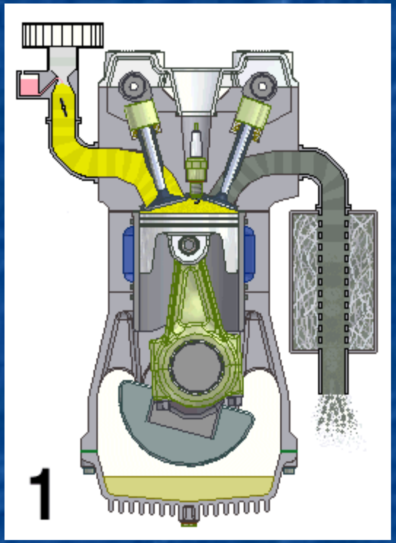
Radical changes in ignition span call for similarly aggressive changes in valve timing

*But to this day, **valve timing** is STILL controlled mechanically*

Making it one of few ICE features that has hardly changed in fifty years:

An ICE's crankshaft turns timing belt turning camshaft(s) opening valves (**PgDn**):





Emissions could be reduced by what's labeled **Variable Valve Timing (VVT)**

Which has thus far been pursued by making the mechanics even **more** complex

The reviews I found on VVT development had virtually no explanatory illustrations [1, 2]

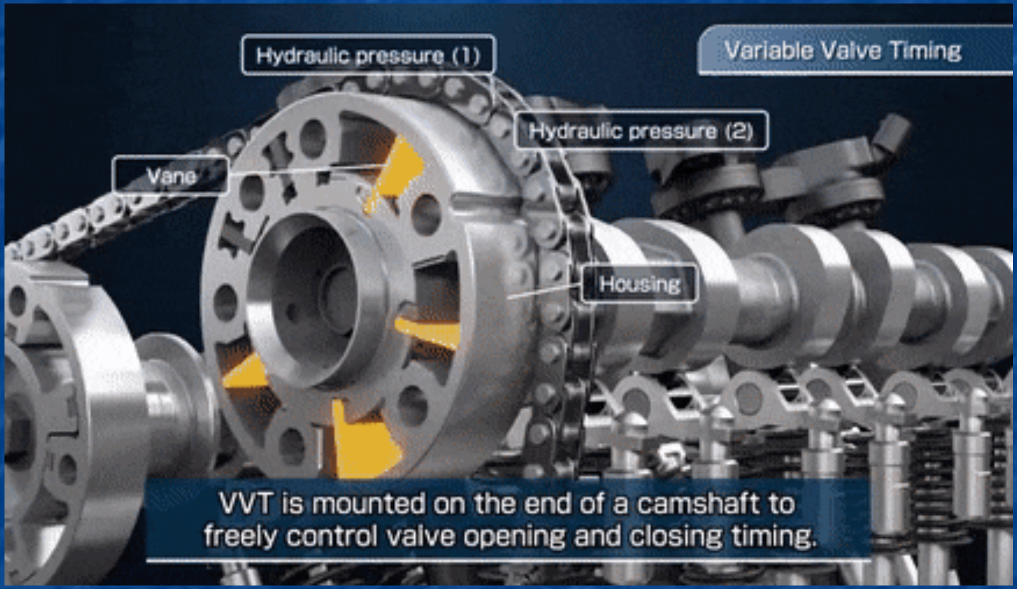
Leading me to instead gather figures from throughout the Internet =>

1) https://en.wikipedia.org/wiki/Variable_valve_timing   2) https://en.wikipedia.org/wiki/Camless_piston_engine

*One **VVT** goal is to adjust the "phasing" of the camshafts:* [1]

That is the equivalent of somehow removing and then reinstalling the timing belt such that it engages the gear on the camshaft a few teeth earlier or later

That effect can be produced by redesigning that gear, so that when oil is driven into it an internal vane attached to the camshaft slightly shifts its rotation (**PgDn**):



The obvious challenge of this approach is getting the controlling hydraulic oil reliably in and out of that rapidly rotating assembly (i.e., w/o it leaking away)

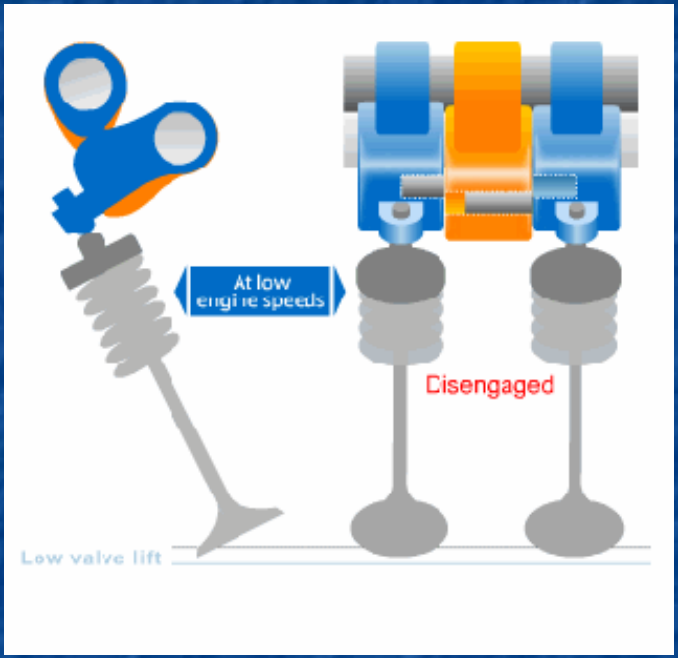
*1) Without source attribution, this animated gif is widely posted. I identify it as being derived from a YouTube video from Japan's **Aisin Group** about their VVT technology: https://www.youtube.com/watch?v=0EzBGIO8Y2U)*

Instead, sliding pins might select between alternate secondary cams [1]

Which, because of their different shapes, would open & close valves differently,

changing how long they are open and/or how widely they are open (**PgDn**):

Rotating camshaft with primary cams



Rocking secondary cams

Elegantly, here while the camshaft and its cams are still a rapidly rotating assembly,

secondary cams are not part of that assembly, with pivot points fixed to the engine

Their simple rocking makes sliding the controlling pins **hugely** simpler (**PgDn** again)

*1) Again without source attribution, this animated gif is widely posted. I could not identify its source, but it depicts **Honda**'s "VTEC" version of VVT technology as described & depicted at: https://global.honda/heritage/episodes/1989vtecengine.html*

The obvious (but perhaps still too expensive?) alternative:

Completely eliminating the timing belt, camshaft and cams,

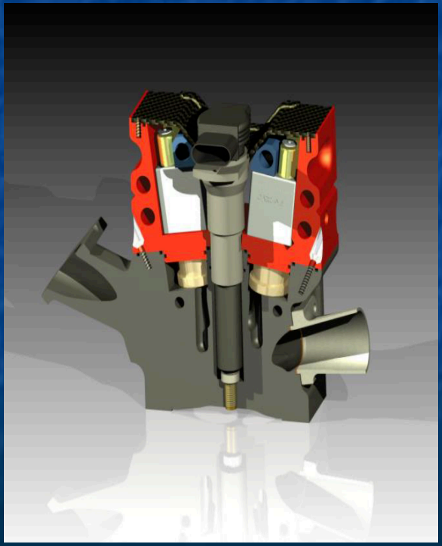
putting in their place cylinder-by-cylinder,

completely fixed-in-position,

pneumatically or electronically-actuated valves

This has been proposed by a company variously called "FreeValve" or "Cargine" [1]

Which at one point posted a PowerPoint presentation depicting their valve:



This (or an equivalent technology) would be as revolutionary as the earlier replacement of Carburetors by GDI Fuel Injection in that, under complete electronic control, valve timing and duration of opening could be arbitrarily and immediately varied to accommodate the ICE's current operating speed / mode

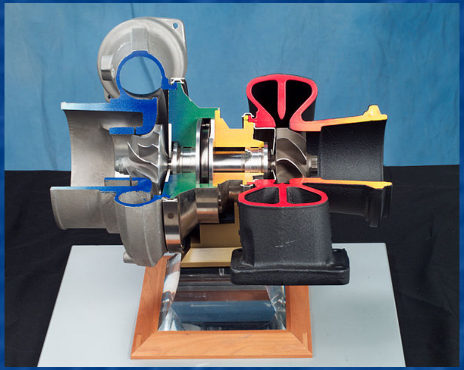
1) https://www.freevalve.com/

Finally: *ICE's can steal technology from gas-guzzling / GHG-spewing supercars*

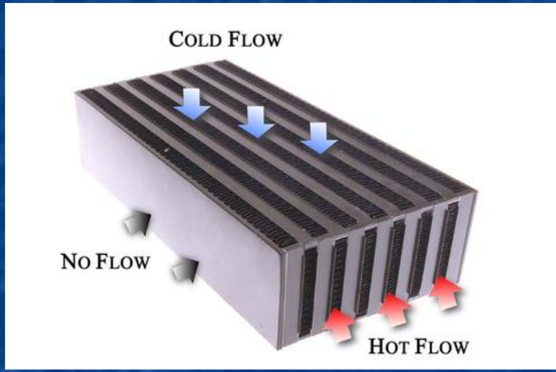
Specifically, a technology applied to the incoming air: **Turbocharging + Intercooling**

These were developed to enhance large engine performance (GHGs be damned!):

Turbocharger = Air Compressor



Intercooler = Heat Exchanger



THE IDEA: If the air ENTERING the engine were denser,

after heating it by combustion it would try to expand more

pushing the pistons downward more strongly => More ICE power per fuel consumed

ITS IMPLEMENTATION: Incoming air is densified by compressing it = Turbocharger's job

But compressing that air also heats it, inhibiting its fuller compression

That's corrected by cooling the hot air leaving the Turbocharger = Intercooler's job

Figure: https://en.wikipedia.org/wiki/Turbocharger

Figure https://burnsstainless.com/blogs/articles-1/air-to-water-intercooler-tech-101-what-it-does-and-what-you-need

Turbocharger = Air Compressor

Air can be compressed by pistons (as inside bicycle pumps)

Air can also be compressed by spinning "turbine" blades (as inside jet engines)

To achieve required speed, electric motors most often drive turbine compressors

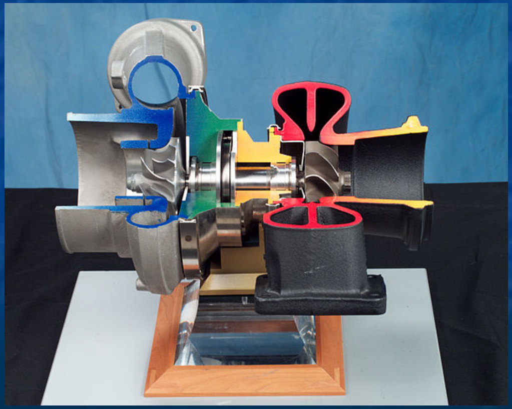
But hot ICE engine compartments are neither electric motor or generator friendly

Turbochargers thus consist of two interconnected turbines (but no electric motor):

High pressure gas is piped into the red turbine, spinning it, then exiting to the right

A connecting shaft makes the blue turbine spin, drawing air in from the left

The blue turbine compresses that air, expelling it from the top/left port



Source of high pressure gas driving the red turbine? The ICE's own exhaust!

Intercooler = Heat exchanger

A heat exchanger forces a gas or fluid at temperature T_{hot}

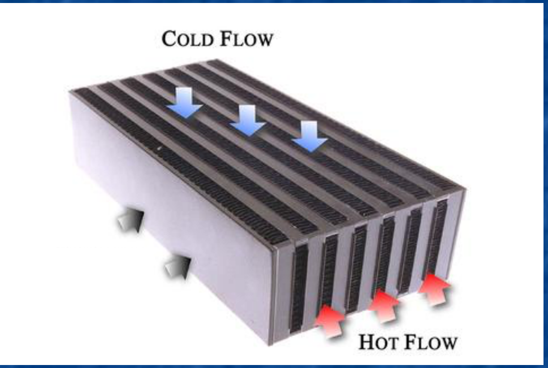
into intimate contact with another gas or fluid at T_{cold}

By "intimate contact" I mean that, while they are not allowed to mix,

they are separated by only very thin metal walls that easily conduct heat

Further, that wall area is maximized via a zigzagging / interleaved flow pattern

An example? Your car's radiator in which air flows past zigzagging water pipes



The result? The hot gas/fluid gets cooler and the cold gas/fluid gets warmer

The **Intercooler's hot** gas is the partially compressed air exiting the Turbocharger

Its **cold** gas / fluid is either ambient air OR water coming from the car's radiator

(but using ambient air, Intercoolers must be larger, sometimes too large for smaller cars)

Putting those together, you get this:

As carefully labeled in the left static figure, or fuzzily animated on the right (**PgDn**): [1]

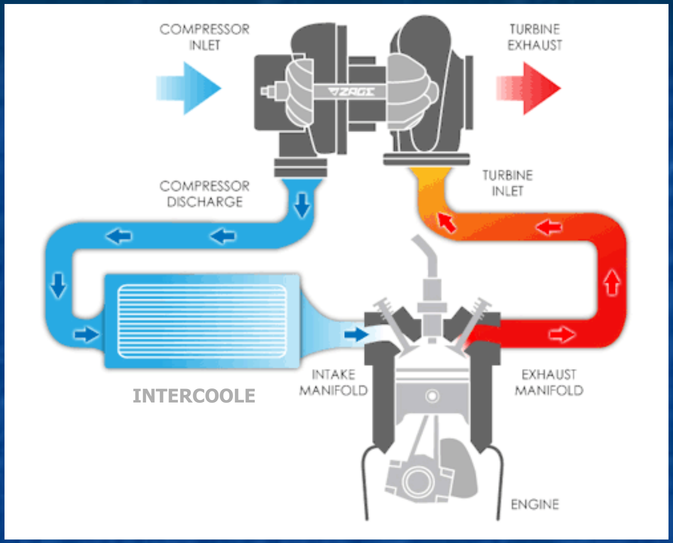


Figure derived from: https://thecraftychemist.tumblr.com/post/60928536051/how-a-turbo-system-works-engine-power-is

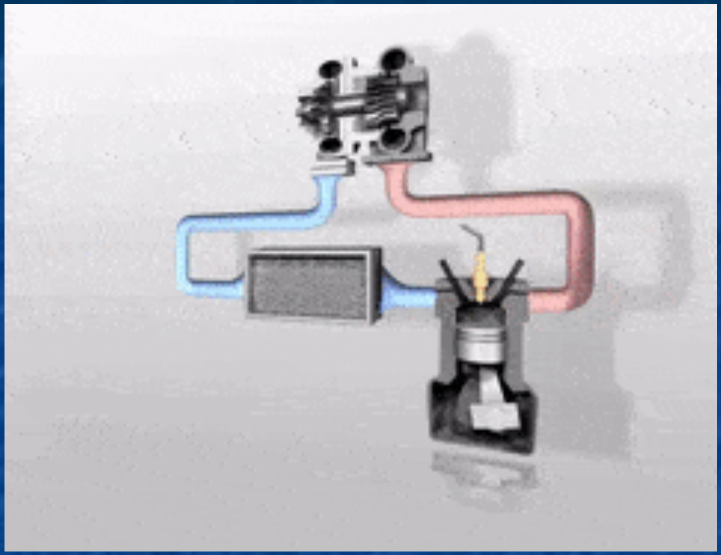


Figure https://makeagif.com/gif/how-a-turbo-works-6sQhnA

Via Turbocharging + Intercooling:

Small / underpowered, but fuel-efficient & low emission ICEs can acquire enough power to be used, while retaining most of their economy & cleanliness

"Most" because, **contrary to many accounts, Turbocharging has an energy cost:**

It impedes Stroke 4 exhaust & needs bigger water pump (w/ water-cooled intercooler)

1) On the right is yet another widely posted but unattributed animated gif. I identified it as the conversion of a short clip from a product video posted by BTNturbo.com at: https://www.btnturbo.com/turbotech/turboworks.aspx

Best known example of such a Petroleum Turbocharged Direct Injection (PTDI)?

Ford's EcoBoost Engine

According to a Ford corporate webpage, that engine is now used in models including: [1]

Fiesta	Fusion	Mustang	Escape	Edge
Flex	Explorer	F-150	EcoSport	Expedition

Wikipedia reports that: [2]

"(EcoBoost achieves) **30% better fuel economy and 50% lower GHG emissions"**

"(Ford) sees the EcoBoost technology as **less costly and more versatile than further developing or expanding the use of hybrid and diesel engine technologies"**

Popular Mechanics ran ran appreciative story entitled: [3]

"Why the 3.5 EcoBoost Is the Best Ford F-150 Engine"

But reliability issues were noted in an advisory from a used car marketing company: [4]

"Everything You Need to Know About Ford EcoBoost Engine Problems" [4]

Has new technology become so complex that it's now degrading ICE reliability?

1) https://www.ford.com/powertrains/ecoboost/ *2) https://en.wikipedia.org/wiki/Ford_EcoBoost_engine*
3) https://www.popularmechanics.com/cars/trucks/a29149378/2019-ford-f-150-review/
4) https://www.cashcarsbuyer.com/ford-ecoboost-engine-problems/

A final untended consequence of Ford's use of smaller turbocharged engines:

As reported in the 21 January 2015 business section of the Washington Post [1]

“America’s best-selling cars and trucks are built on lies: The rise of fake engine noise”

“Stomp on the gas of a new Ford Mustang or F-150 an you’ll hear a throaty rumble – the same style of roar that Americans have associated with auto power and performance for decades. It’s a sham.”

YES: Fearing customers might shun more efficient (and thus quieter) vehicles, Ford has now created artificial engine noises and is secretly piping them in through the vehicle’s hi-fi speakers!

1) http://www.washingtonpost.com/business/economy/americas-best-selling-cars-and-trucks-are-built-on-lies-the-rise-of-fake-engine-noise/2015/01/21/6db09a10-a0ba-11e4-b146-577832eafcb4_story.html

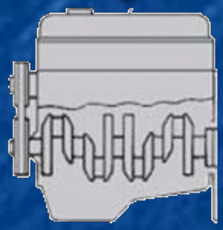
GREENer Cars & Trucks:

Using ICEs More Effectively

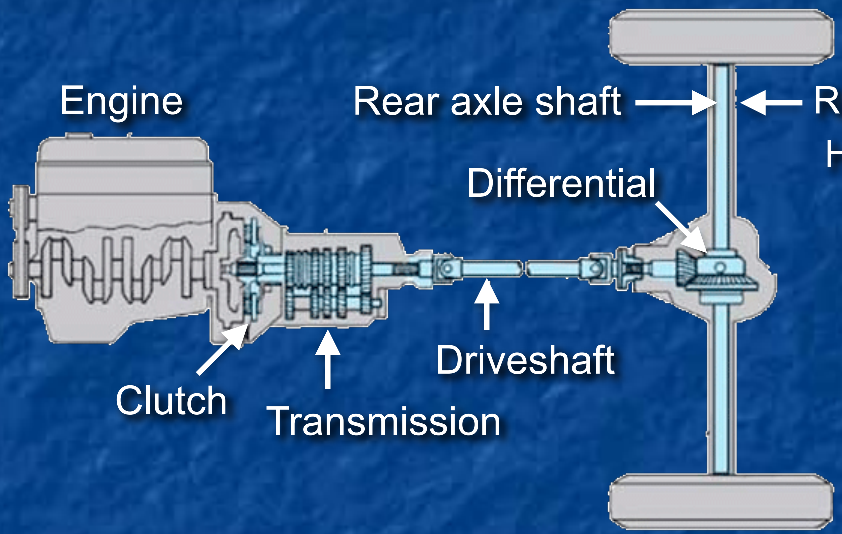
(Power Bands / Transmissions / Hybrid Electric Vehicles)

Using Internal Combustion Engines more effectively:

The previous section was about making cleaner and more efficient ICE's:



The section is instead about using an ICE to power a vehicle in the cleanest and most efficient manner:



There's a LOT OF COMPLEXITY separating an ICE from the wheels it drives

That includes a **Clutch**, **Transmission**, **Driveshaft** and **Differential**

Which, together, are called a **Drivetrain** or **Driveline** [1]

That complexity can come at a steep cost, in both money and energy

1) POWERTRAIN = ENGINE + DRIVETRAIN / DRIVELINE

Figure adapted from: https://www.drivespark.com/off-beat/car-drivetrain-systems-explained-022723.html

The Differential performs an essential function, but in a simple / clever way:

As explained by the static figure on the left:

The engine's green driveshaft turns a yellow crown gear that is attached to a red cage

In the sides of that cage are two small opposing green gears

Through the cage's ends come two blue gears attached via blue shafts to the wheels

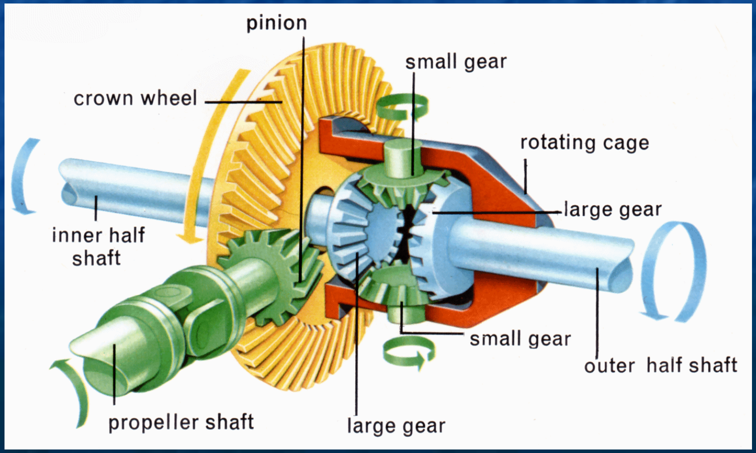
Driving straight, the green gears don't turn, while the blue gears just rotate **with** the cage

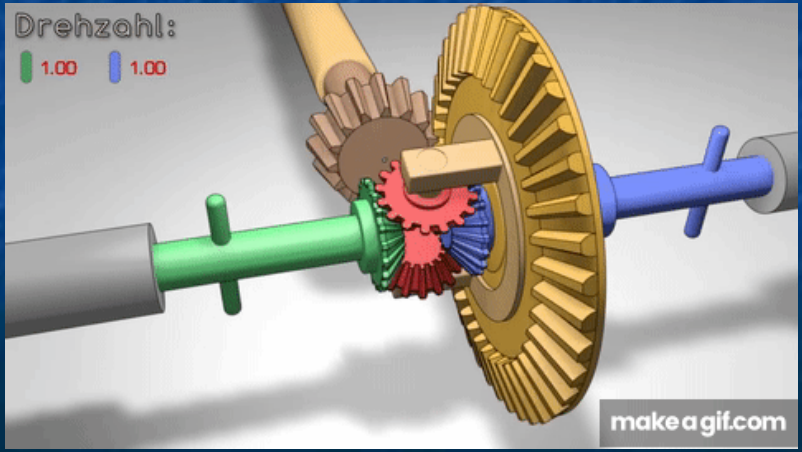
But while the vehicle turns, the outer wheel tries to turn faster than the inner wheel

That's allowed because the outer wheel's shaft starts turning faster than the cage

which, via the green gears, turns the other wheel's shaft slower than the cage

(**PgDn** to play the differently colored animation at right)





http://www.mrclutchnw.com/services/differential-rebuilding/

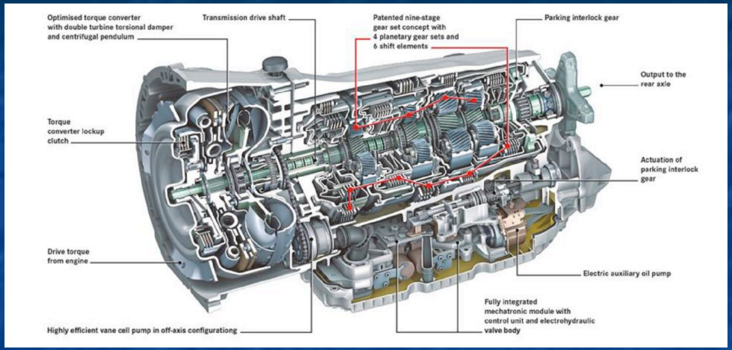
https://makeagif.com/i/nhTd99

But Clutches and Transmissions are anything BUT simple

Clutches disconnect engines, allowing **Transmissions** to transform themselves

<= Gearbox

Clutch & Transmission =>



Gearboxes are collections of meshed gears, with input and output shafts

Their input shaft speed / output shaft speed = a fixed ratio, determined by the gears

This is also called a "1-speed gearbox," despite all sorts of speeds being possible

It is only the **ratio** of those shaft rotational speeds that has a single fixed value

Transmissions = multiple choice Gearboxes with added gears that can be moved

such that a subset meshes to produce alternate ratios of input-speed / output-speed

But each ratio is (again) confusingly labeled as a possible transmission "speed"

ICE vehicle transmissions have 3, 4, 5, 7 or more "speeds" (i.e., input / output ratios)

Why do ICE vehicles require transmissions with so many alternate "speeds?"

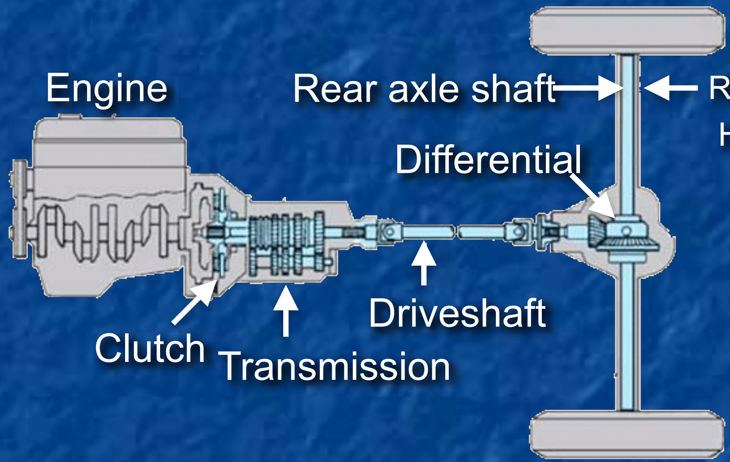
Especially given that:

A typical **Clutch** might have **dozens of moving parts**

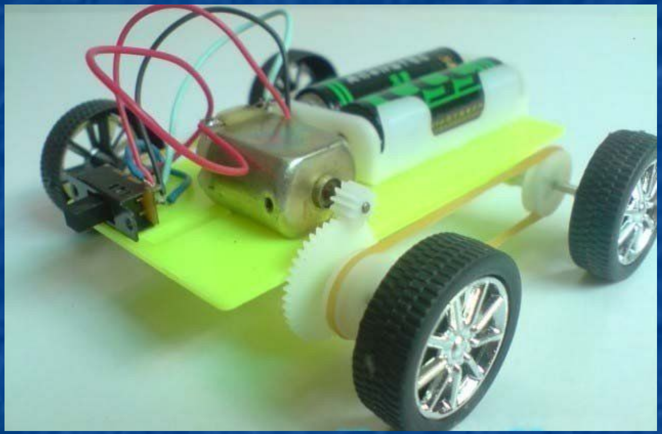
While a typical **Transmission** has **hundreds & hundreds of moving parts**

Vs. a simple pair of gears (i.e., a simple gearbox) which serves TOY cars so very well:

Moving them effectively and efficiently over their **entire range of speeds**



vs.



Simple gearboxes ALSO allow full-sized Plug-in Electric Vehicles (PEVs)

to move effectively and efficiently over their entire range of speeds,

BECAUSE of the unique power & torque characteristics of electric motors:

Photo from: https://www.pinterest.com/pin/275704808415430219/

Motor & Engine Torque and Power Curves:

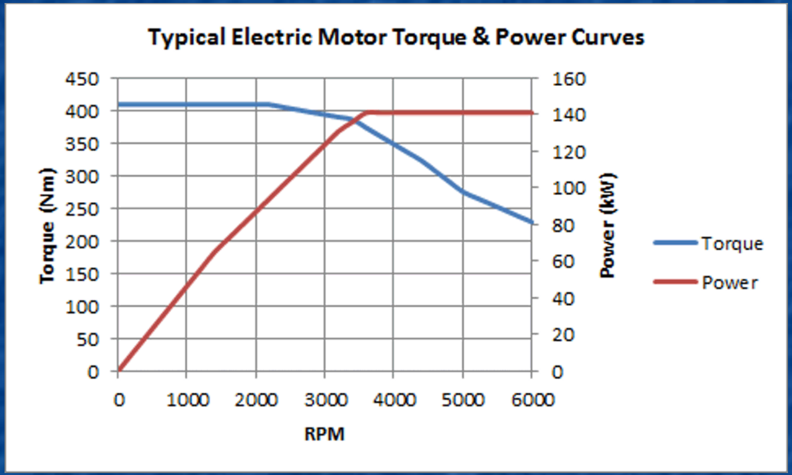
These, also called **Torque Bands** & **Power Bands**, describe the

Maximum Torque & **Maximum** Power that can be delivered at a specific RPM

A lightly loaded electric motor transfers from its battery far less than $\mathbf{Power_{max}}$

But as the load increases, more power is transferred, and the motor **maintains** speed

Only as it approaches $Power_{max}$ does the motor begin to bog down, loosing speed



https://theconversation.com/heres-why-electric-cars-have-plenty-of-grunt-oomph-and-torque-115356

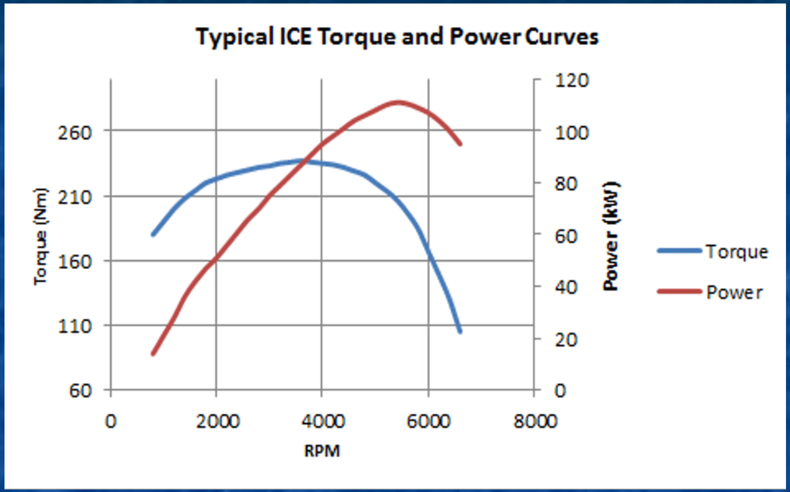
But the most remarkable thing about electric motors?

Electric motors deliver high torque starting at even low speeds

And with a fixed gearbox can push **toy cars & PEVs** over their **FULL SPEED RANGE**

But Internal Combustion Engines behave very differently:

Their Torque limits fall off sharply at both LOW and HIGH rotational speeds:



https://theconversation.com/heres-why-electric-cars-have-plenty-of-grunt-oomph-and-torque-115356

Thus, to produce high torque (which is essential for strong acceleration)

this particular ICE would have to be turning at ~ **1750-5000 RPM**

The car would hardly accelerate (or stall out) if you tried starting well below 1750 RPM

Which is why you instead first "rev" an ICE before manually engaging 1st gear

And in any gear, if you "over-revved" (to over 5000 RPM) acceleration would fall off

That's a VERY narrow effective speed range: spanning a ratio of only ~ 3 to 1

Figure derived from: https://theconversation.com/heres-why-electric-cars-have-plenty-of-grunt-oomph-and-torque-115356

WHY *are ICE's* ***so very poor*** *at low & high speeds?*

An **electric motor** rotating at very low speeds maintains Torque

by just sucking more Power from its battery (i.e., by drawing more current)

But at **low speeds** the bursts of combustion inside an **ICE** are fewer and farther apart,

being mechanically limited to one combustion per two now very slow revolutions

And power can only be mildly increased by adding more fuel per combustion,

because combustion intensity is soon limited by the O_2 available within the cylinder

Whereas at **very high speeds** an **ICE** effectively begins to "trip over its own feet"

Because engine strokes then occur so quickly that

a diminishing amount of air flows into the cylinder during Stroke 1

and combustion can continue through Stroke 3 and right on into Stroke 4

allowing its late power to blow straight out of open exhaust valve(s)

What are the consequences?

Well, we expect our ICE to power our vehicle from about 1 mph to at least 75 mph

Which is to say, for at least a 75X range in vehicle speed

But the ICE has strong power and torque over a rotational speed range of only ~ 3X

Let's see: 3 x 3 x 3 x 3 = 81, which is just a bit above 75

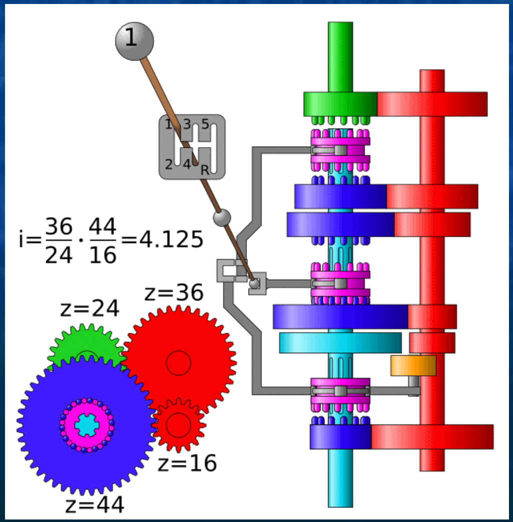
So to accelerate through our desired 1 to 75 mph vehicle speed range,

while keeping the ICE within its most effective 1 to 3 rotational speed range,

our ICE vehicle is going to need to switch between four different gear ratios

Or, for better performance (keeping the ICE **very near peak** operation), 5 gear ratios

Leading to the common
ICE Manual Transmission
("i" = net gear ratio):



(**PgDn** to animate)

https://imgur.com/r/gifs/GWNN3D3

*But how might we **now** use ICEs even **more** effectively?*

By using the ICE over an even narrower range of speed!

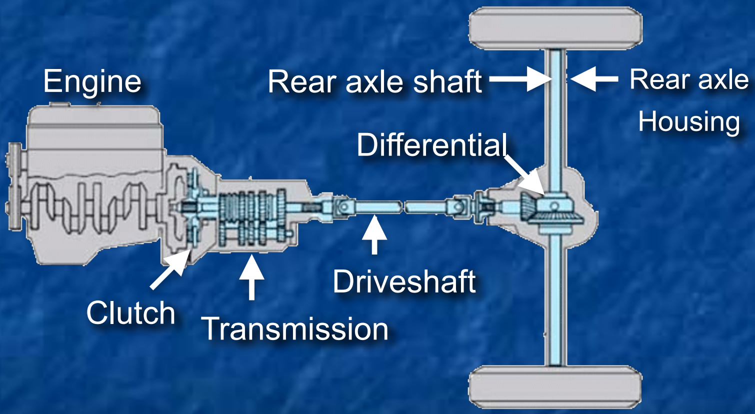
Speeds that, based on the peaks of its Torque, Power & Fuel Efficiency curves

allow for the most efficient yet customer-acceptable vehicle operation

Which could be done in a number of different ways:

Solution #1) ADD GEARS => more gear ratios => more transmission "speeds"

That is, make at least the Transmission even MORE complex



But while big rig drivers may (grudgingly?) endure "ten speed" manual transmissions

To achieve car-like acceleration, **frantic** repeated shifting would be required

Automatic transmissions would relieve the stress . . . but operate slowly

Shifting between too many gear combinations can thus become unacceptable slow

Leading to **Solution #2: Dual Clutch Automatic Transmissions** [1-3]

Which have been described in words as acting like two different transmissions

One with, perhaps, 5 possible gear ratios

One with 5 **different** gear ratios **falling between those** of the other transmission

The Dual Clutch Transmission would **alternate between those two transmissions**

inserting one into the drivetrain, while the idle one changed to its next gear ratio

and so on and so on, moving through all ten of the possible gear ratios

Which would be an absurd suggestion if the transmissions **were indeed** separate

In fact, they are very cleverly merged into one very complex transmission

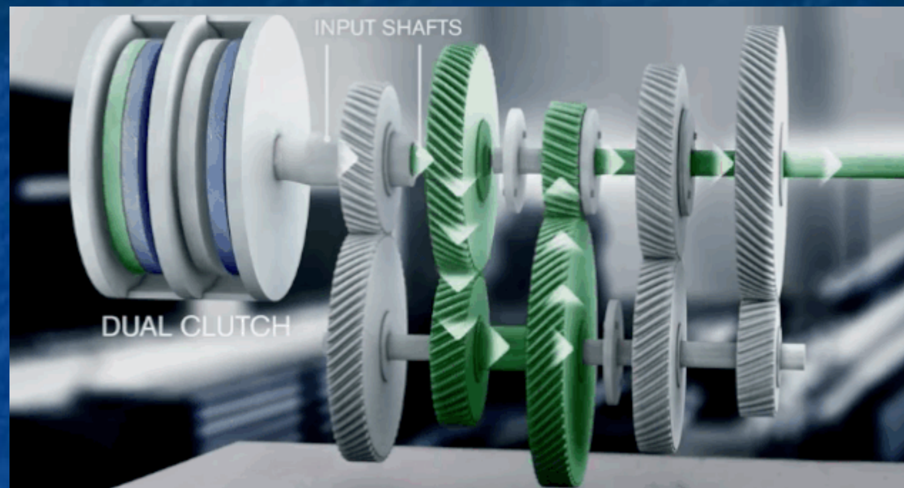
So clever that I've yet to find a really good detailed description

But I have found a supposedly accurate (if simplified) animation:

1) *https://www.matfoundrygroup.com/News%20and%20Blog/Whats_a_Dual_Clutch_Transmission_and_How_Does_it_Work*
2) *https://www.carfax.com/blog/what-is-a-dual-clutch-transmission*
3) *https://www.faistgroup.com/news/how-dual-clutch-transmissions-work/*

Animation of the inside of a Dual Clutch Automatic Transmission:

At left, two clutches, alternately engaging two driveshafts (a rod & its surrounding tube)



(**PgDn** to animate)

My slowed down and non-repeating version of: https://imgur.com/lONRIUE

My corresponding incomplete attempt at figuring out how those thin disks alternately tie different gearshafts together, or different segments of the same shaft together:

Solution #3: A Continuously Variable Transmission (CVT)

Which, instead of having lots of immutable multi-tooth gears,

uses a belt linking together what amounts to two strangely variable pulleys

Because here each pulley consists of two opposing cones, with a variable separation

A stiff belt rides between those cones at a diameter that accommodates its width

Then, as one set of cones increases separation, the other decreases separation

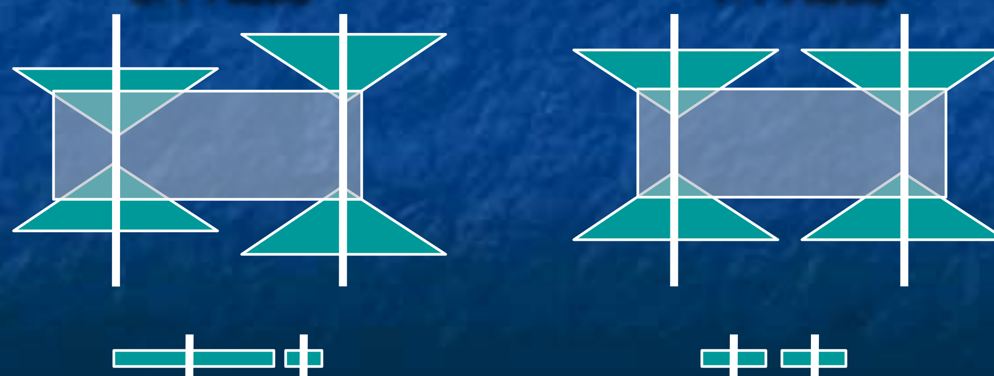
The effect is that of meshing two gears of variable diameters,

allowing the simple CVT to effectively mimic ALL gear ratios within its range

The ICE can thus rotate at a near single optimum speed for ALL vehicle speeds

5:1 Ratio

1:1 Ratio



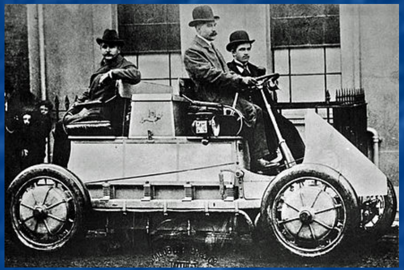
Gear equivalents at bottom

http://nissanaltimaaustin.com/altimas-cvt-keeps-moving/

Solution #4: Hybrid Electric Vehicles (HEVs)

We tend to think of HEVs as being a new idea, and one that's applied to only cars

But HEVs are far from new, as seen in these early 1900's photos:



https://www.wikiwand.com/en/Hybrid_electric_vehicle

http://www.columbusrailroads.com/orm%20pc%20set%202.htm/

And HEVs come in ever increasing varieties, as seen in these modern examples:

https://www.leonardodrs.com/news/electric-and-hybrid-marine-world-expo/

https://www.wisegeek.com/what-is-a-diesel-electric-locomotive.htm

https://www.wartsila.com/marine/build/power-systems/electric-propulsion/electric-propulsion-systems

https://www.maritime-executive.com/editorials/a-future-for-hybrid-and-battery-electric-wing-ships

Why are HEVs such an old idea?   Why are there so many kinds of HEV?

ICE FACTOIDS:

Super-energy-packed fossil-fuels allow ICEs to run seemingly for ever

But their low-speed performance is lousy!

ELECTRIC MOTOR FACTOIDS:

Electric motors work well & super-efficiently at all sorts of speeds

But when powered by batteries they stop running way too soon!

Which, respectively, have long inspired these HEV solutions:

Solution #1: **Supplement ICEs with e-Motors to help them out at low speeds**

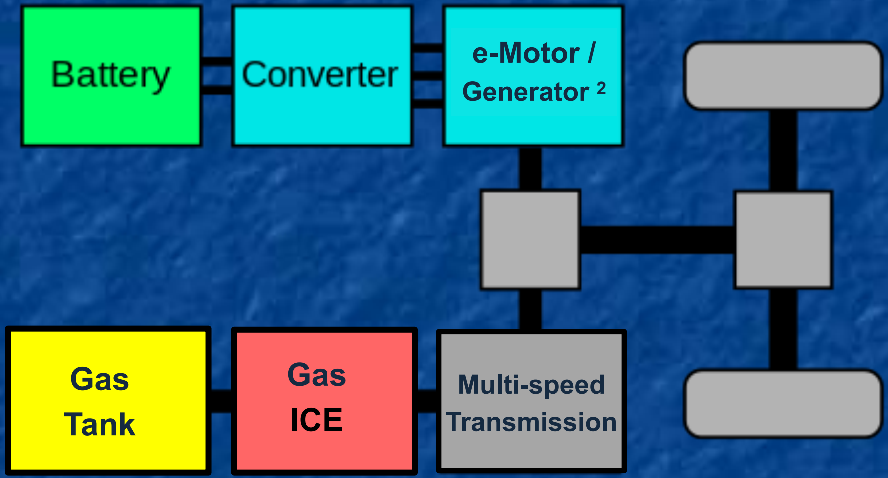
Solution #2: **Keep e-Motors running w/ electricity from ICE-driven Generators**

For #1 (e-Motor helping out ICE) a **Parallel Hybrid** configuration is used: [1]

TOP battery-powered electric motor/generator [2] system is active during:

STARTING: Electric motor helping out the ICE which is weak a low speeds

STOPPING: Power from wheels => generator => capacitor => battery [3]



BOTTOM gasoline-powered ICE is active during:

STARTING: Per above, working **WITH** the electric motor

CRUISING: Working **ALONE** to drive wheels because it's efficient at higher speeds

AND driving e-motor (now acting as a generator) [2] to recharge battery

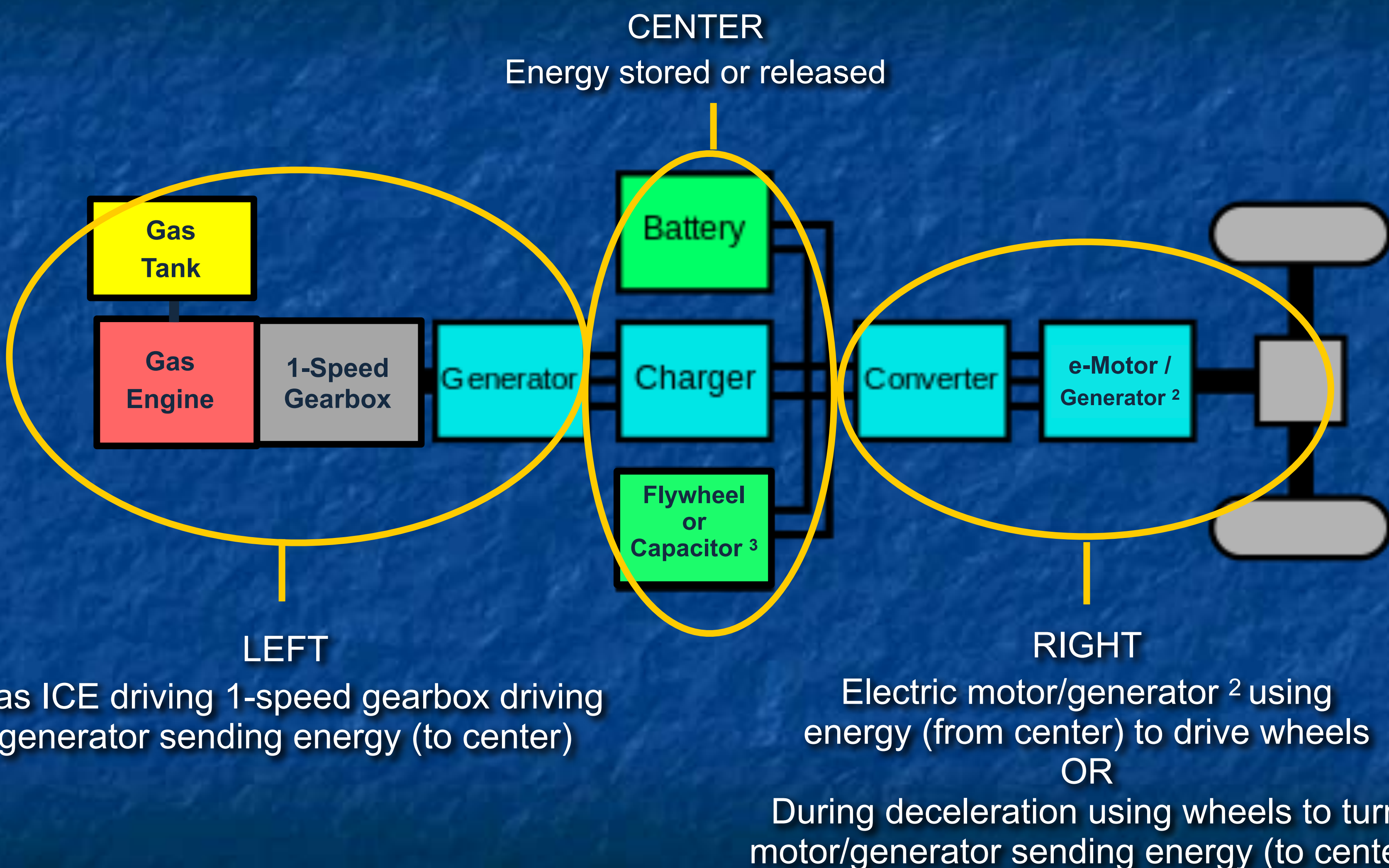
!) This is my modified version of a figure at: https://en.m.wikipedia.org/wiki/Hybrid_vehicle_drivetrain

2) More about this electric motor <=> electric generator duality in a few slides

3) More about this "Regenerative Braking" in just a few slides

For #2 (ICE extending e-Motor range) a **Series Hybrid** configuration is used: [1]

Gas ICE drives a generator, charging a battery, feeding an e-Motor, turning the wheels:

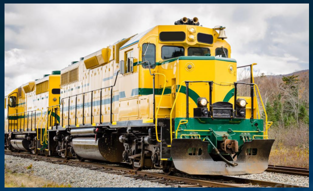


1) This is my modified version of a figure at: https://en.m.wikipedia.org/wiki/Hybrid_vehicle_drivetrain

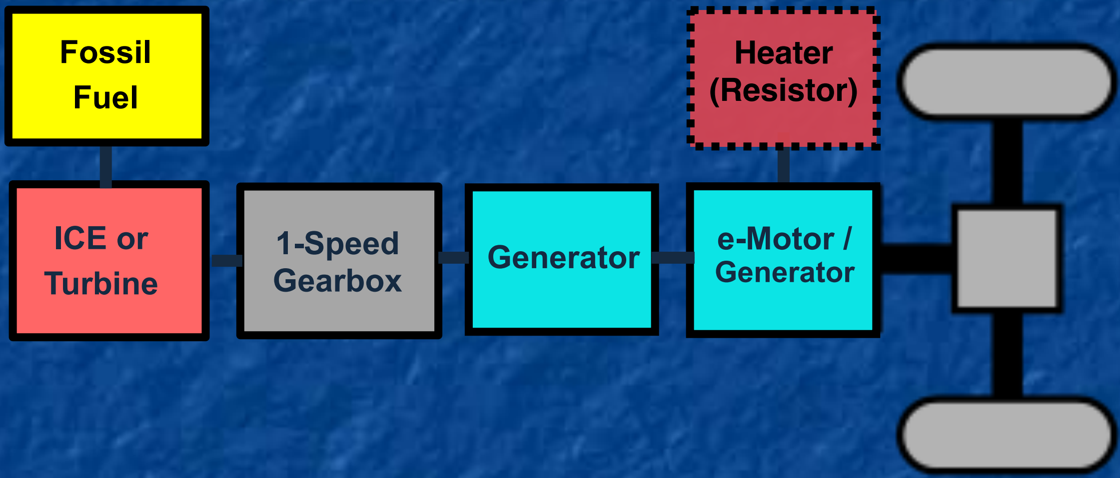
2) More about this electric motor <=> electric generator duality in a few slides

3) More about how Flywheels & Capacitors are used in Regenerative Braking in just a few slides

Or for really BIG vehicles, omit the batteries:



Yielding what's simply called a **Diesel-Electric** or **Gas-Electric** or **Turbine-Electric**



Most of the time **Ships** & **Freight Trains** move at an nearly constant moderate speed,

allowing ICE to turn at efficient mid-range speed, driving generator, powering e-Motor

During brief gradual accelerations, the ICE is pushed to less efficient higher speeds

During decelerations, ships either disconnect everything or do acceleration in reverse

While trains apply heat-producing & wasting brakes (w/ e-Motor electrically disconnected)

OR w/ e-Motor electrically connected, send its generated power out to heater atop engine

But in supercars to people's cars many more configurations are being tried:

All exploiting the fact that, when turned, e-Motors become electrical Generators

Ferrari LaFerrari: **1 e-Motor** placed between **1 ICE** / 7-speed transmission & rear wheels
Driven by ICE or wheels, the e-Motor charges batteries
Powered by batteries the e-Motor drives rear wheels

Jaguar C-X75: **2 Diesel gas turbines** drive **2 e-Motors** charging batteries
Powered by batteries **4 more e-Motors** (one per wheel) directly drive the wheels

BMW i3: **1 ICE** drives **1st e-Motor** charging batteries
Powered by batteries **2nd e-Motor** drives rear wheels

Honda Accord: LOW SPEED: **1 ICE** drives **1st e-Motor** charging batteries
Powered by batteries **2nd e-Motor** drives wheels
HIGH SPEED: **ICE** drives wheels via 1-speed gearbox

Le Ferrari: http://auto.ferrari.com/en_EN/sports-cars-models/car-range/laferrari/
Jaguar C-X75: http://en.m.wikipedia.org/wiki/Jaguar_C-X75
BMW i3: http://en.m.wikipedia.org/wiki/BMW_i3
Honda Accord: http://www.greencarreports.com/news/1087518_2014-honda-accord-hybrid-has-no-transmission-how-it-works

GREENer Cars & Trucks:

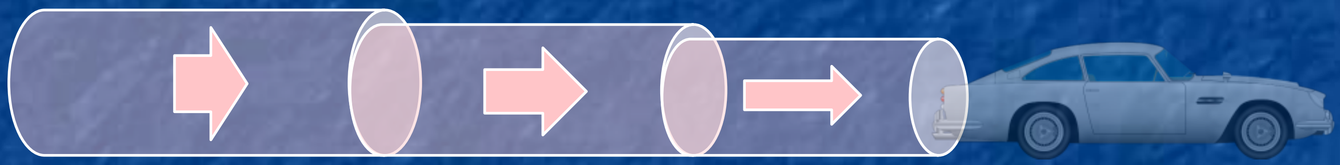
Storing CURRENT Kinetic Energy for LATER Motion

(Kinetic Energy Recovery Systems / Regenerative Braking)

From Physics models: Wheel Energy => Kinetic Energy of some other thing

For **steady highway driving** that "other thing" was air drawn along by the vehicle

Unfortunately, there's **NO WAY** to recapture & reuse that air's Kinetic Energy (KE)



But for **stop & go city driving** that "other thing" was the vehicle itself

And there **ARE** ways of recapturing & reusing most of the vehicle's Kinetic Energy

Vehicle Kinetic Energy is recaptured by what are called either:

Kinetic Energy Recovery Systems (KERS) or **Regenerative Braking Systems**

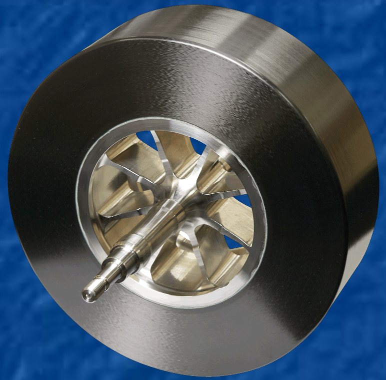
KERS generally (but not always) refers to KE recapture within a **mechanical device**

Regenerative Braking generally (but not always) to KE recapture in an **electronic device**

ICE vehicles are largely mechanical devices

Which makes it easier to recapture their KE in **other** mechanical devices => KERS

The other mechanical device is usually an extremely big, massive & strong **flywheel** [1, 2]



The flywheel has be **extremely strong** because in a KERS, to slow the vehicle,

rather than just applying the brakes (which throw away vehicle KE as waste heat),

vehicle wheels are decoupled from the ICE's transmission

and recoupled (via a gear box) to spin a flywheel up to ~ 50,000 RPM

When the vehicle wants to restart, the gearing is changed so that the ICE & flywheel

work together (the flywheel slowing as its KE is transferred back to the vehicle)

Figure & 1) https://ricardo.com/news-and-media/news-and-press/breakthrough-in-ricardo-kinergy-%E2%80%98second-generation
2) https://en.wikipedia.org/wiki/Kinetic_energy_recovery_system

You've likely heard about the use of flywheel KERS for diesel city buses

Such as these London city buses where KERS cut fuel consumption by 20%: [1]

But KERS development was actually driven by the **sudden need** to increase fuel mileage in vehicles such as this: [2]

"Sudden need?" Yes:

Formula 1 Racing was born as a vrroom-vroom macho celebration of powerful ICEs

And partially justified by its claim that racing would further ICE development

But by the early 2000's auto industry sponsors were cultivating Green corporate images,

which were being undermined by continued participation in this gas-guzzling sport

Hence, beginning in 2009, stringent Formula 1 fuel restrictions were introduced [2] making

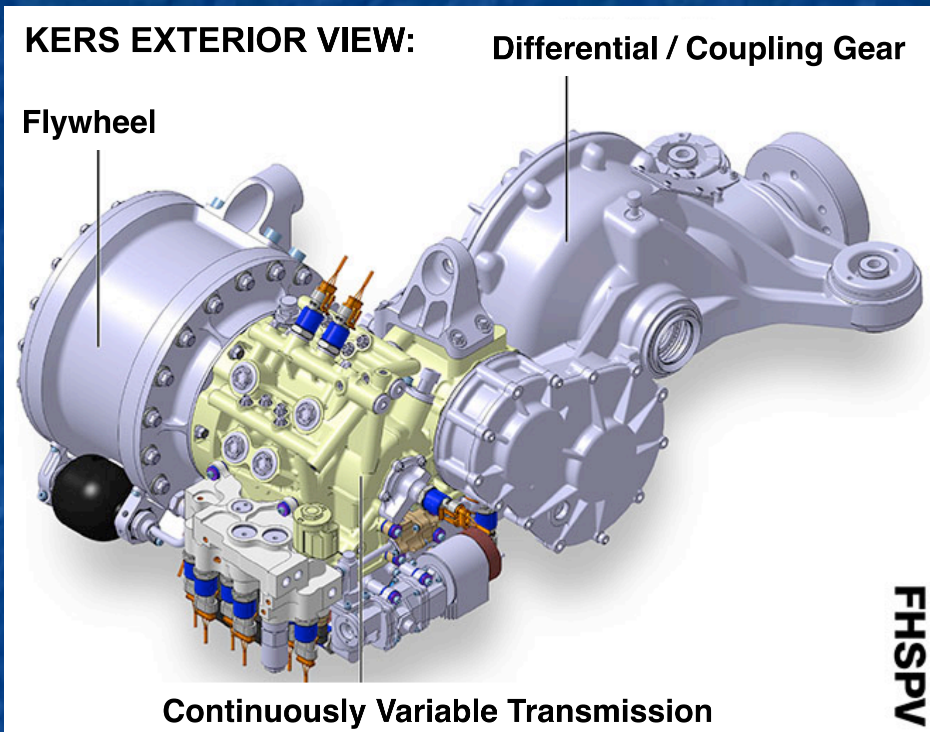
it imperative that cars NOT throw away energy braking into every curve => KERS

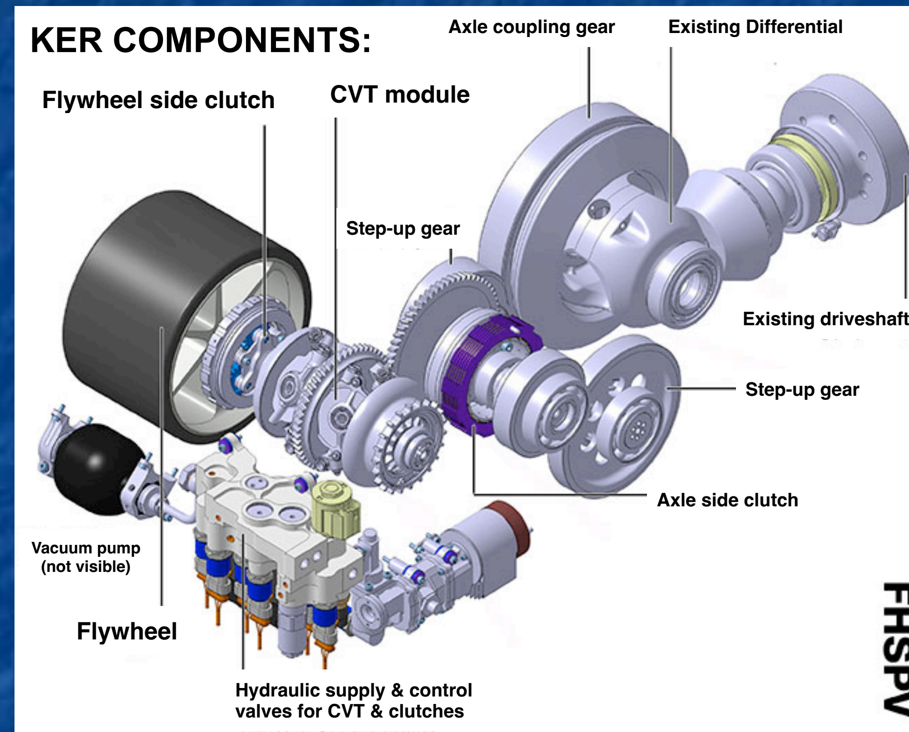
1) https://www.wired.com/2014/07/f1-kers-london-buses/ 2) https://en.wikipedia.org/wiki/Kinetic_energy_recovery_system

Leading, over the last decade, to KERS showing up in luxury ICE cars:

Pictured here, for example,

is a flywheel-based KERS system developed for Jaguar's cars:





But as with the earlier example of Turbocharged + Intercooled ICE's

KERS technology adds a lot of complexity to already very complex ICE vehicles

Stimulating the search for alternate, much simpler, Kinetic Energy capture schemes

My version (captions enlarged) from: https://www.wired.com/2010/10/flywheel-hybrid-system-for-premium-vehicles/

The prime alternative? Dual use of any available Electric Motors

By this I mean exploiting another very unique characteristic of e-Motors:

If supplied with electrical power they produce mechanical power = A Motor

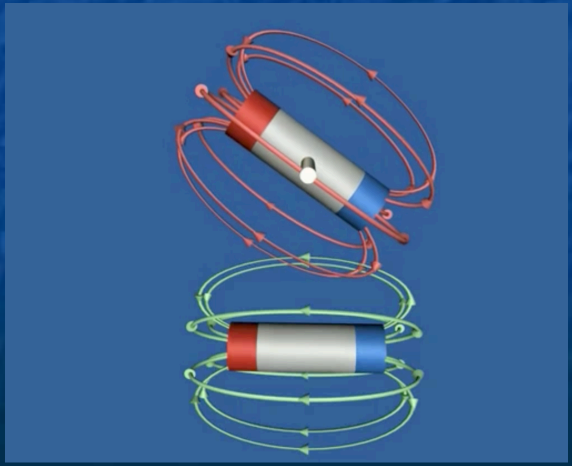
If driven by mechanical power, they produce electrical power = A Generator

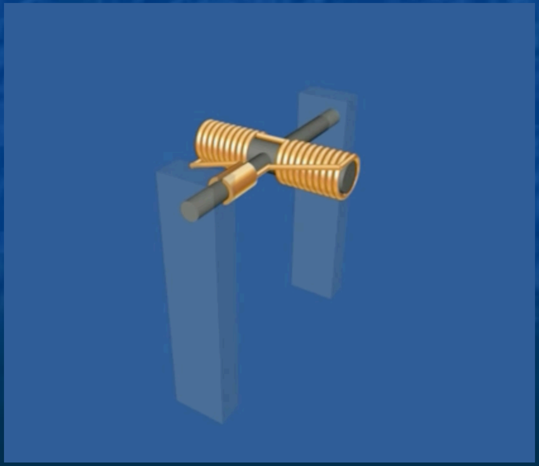
The science behind this uniquely reversible behavior is the subject of my note sets:

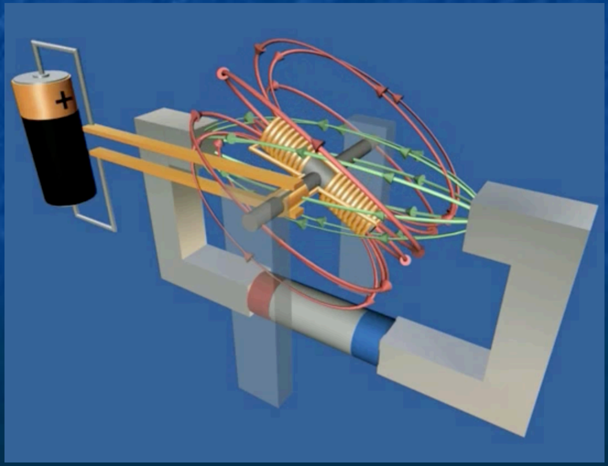
Electric & Magnetic Fields (pptx / pdf / key) **Magnetic Induction** (pptx /pdf / key)

And my animated explanation of how e-Motors work is a complete WCFTO Virtual Lab:

AC & DC Electric Motors







The idea is to repurpose the e-Motor that had been pushing the car

And instead, when you want to slow or stop, use the car to push the motor which,

then acting as an e-Generator, can be used to recharge your car's Batteries

But, contrary to popular accounts, that alone will not work - because of time scales:

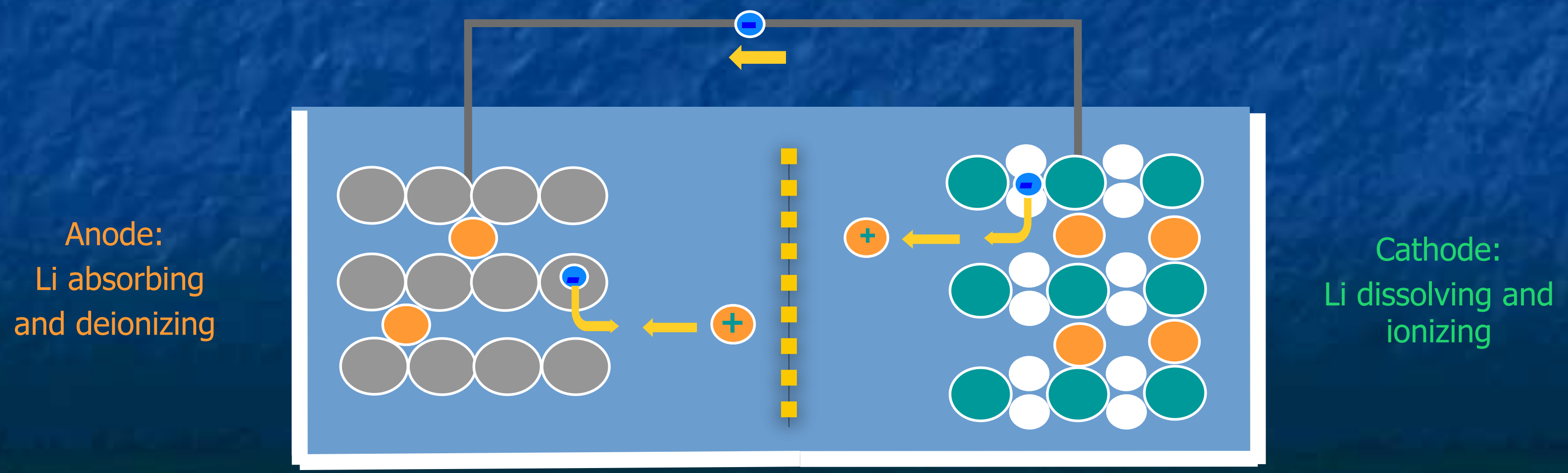
Slowing or stopping cars takes from a few seconds to perhaps half a minute

But even quick-charging a battery takes from a fraction of an hour to hours

Batteries can't move atoms & ions fast enough to accept a slowing car's energy

From my note set **Batteries & Fuel Cells** (pptx / pdf / key),

the atom-by-atom rearrangement going on within a charging Li-ion battery:



A temporary energy storage device is needed ***between*** *e-Generator & Battery*

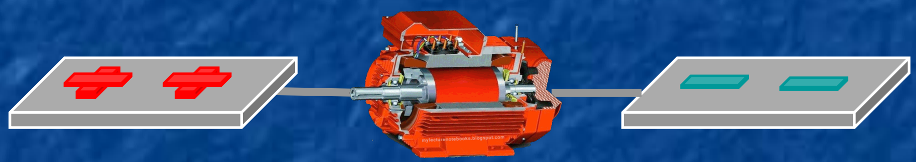
A device that can quickly accept energy generated as a car briefly decelerates or stops

then gradually send that energy onward at a rate that the Battery can accept

Imagine trying to store energy by pumping electrons from one metal plate to another

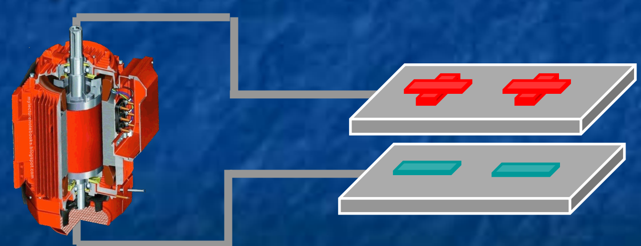
THIS wouldn't work: Because accumulating net - - charges repel each other fiercely

And + charges left behind suck back that - charge just as fiercely



But THIS COULD if the two plates were ~ as close as the + + and - - charge spacings

Because + + and - - charge repulsions would then be balanced by + - charge attractions



This is a simple **Capacitor**, which CAN store & expel charge energy VERY quickly

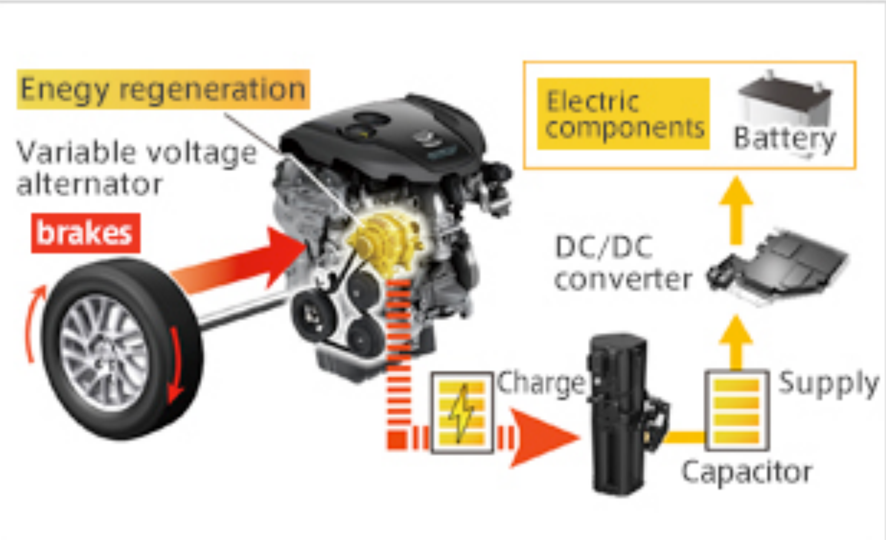
(even if the amount of charge, and thus charge energy, is very limited)

Capacitor => ***Supercapacitor*** *if its plates are mere atoms apart*

Which, with e-Motor / e-Generator + Battery allows for **Regenerative Braking:**

When car is slowing or stopping
the wheels turn the **e-Generator**
which charges the **Capacitor**
which gradually recharges the **Battery**

When the car is cruising
Capacitor charging of **Battery** continues
OR (not shown in figure):
the **Battery** can power the **e-Motor**
helping the **ICE** to power the wheels
(= **HEV** configuration discussed earlier)



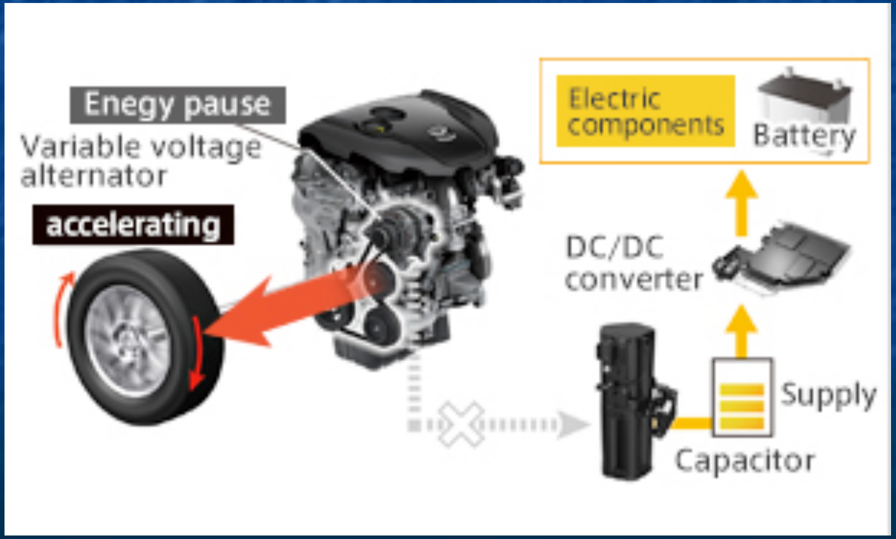


Figure of MAZDA "i-ELOOP system from: https://www.mazda.com/en/innovation/technology/env/i-eloop/

*Regenerative Braking **really** is just about that simple:*

The essential ingredient is a handy **e-Motor / e-Generator** (along with its **Batteries**)

The **Capacitor** is easy (and more effective Supercapacitors are being developed)

And the **electronic components** consist primarily of simple electrical circuits which

ensure that electrical power moves in desirable directions, at desirable times

(For electrically inclined readers, I've included papers about the required circuit operation + circuit examples HERE in this note set's Resources webpage)

Making electronic Regenerative Braking a LOT simpler than mechanical KERS

But, of course, if you want to make things even simpler,

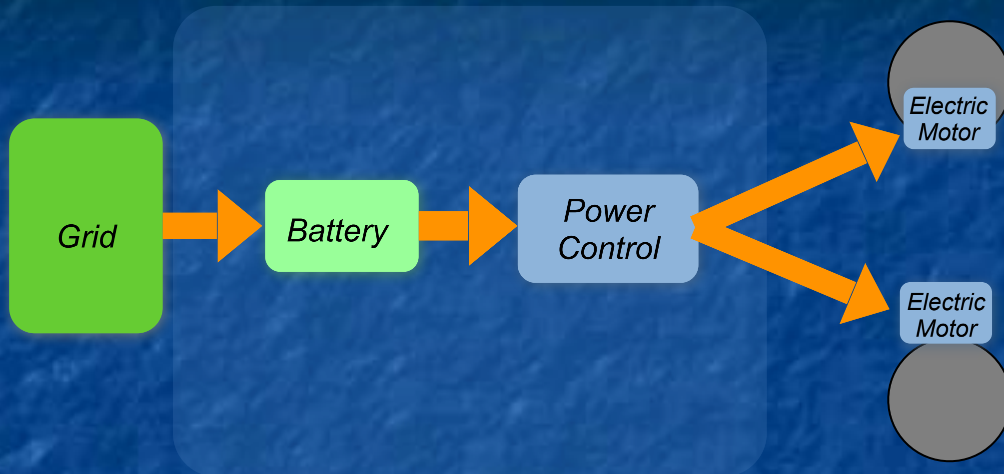
there IS the option of just eliminating the ICE, taking you all the way to:

Part II:

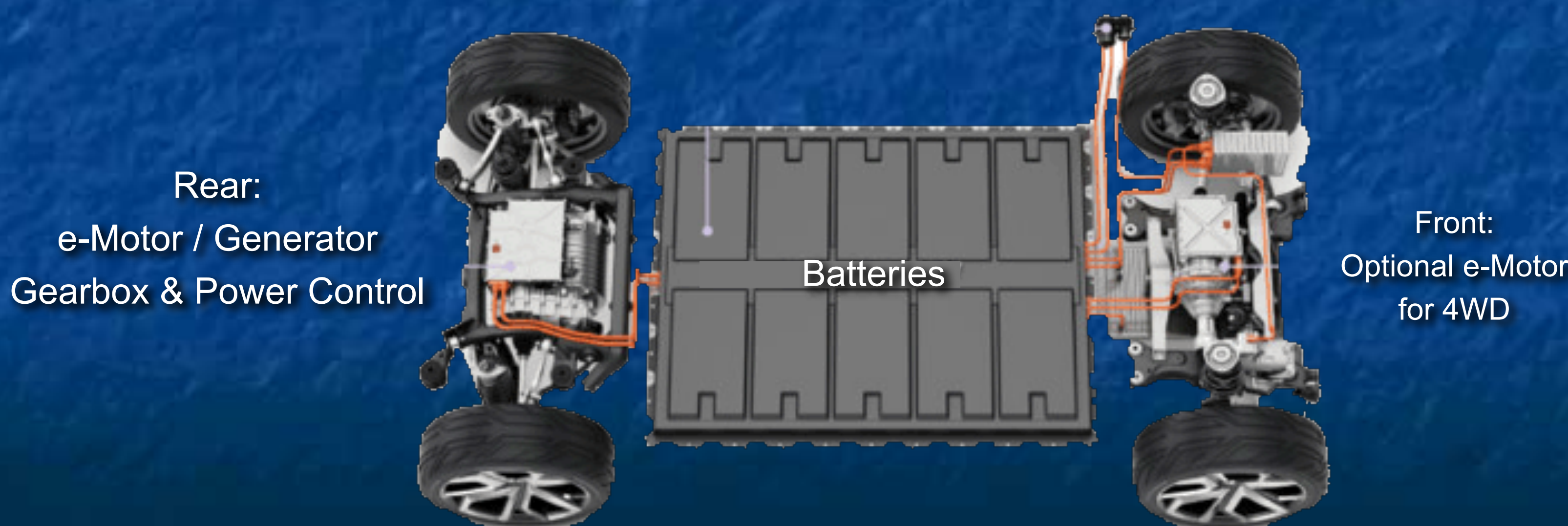
GREEN Cars & Trucks

Green Plug-in Electric Vehicle Basics:

Earlier I suggested a PEV might be this simple:



Which looks **awfully close** to a "PEV concept" released by Volkswagen:



Adapted from: https://evreporter.com/ev-powertrain-components/

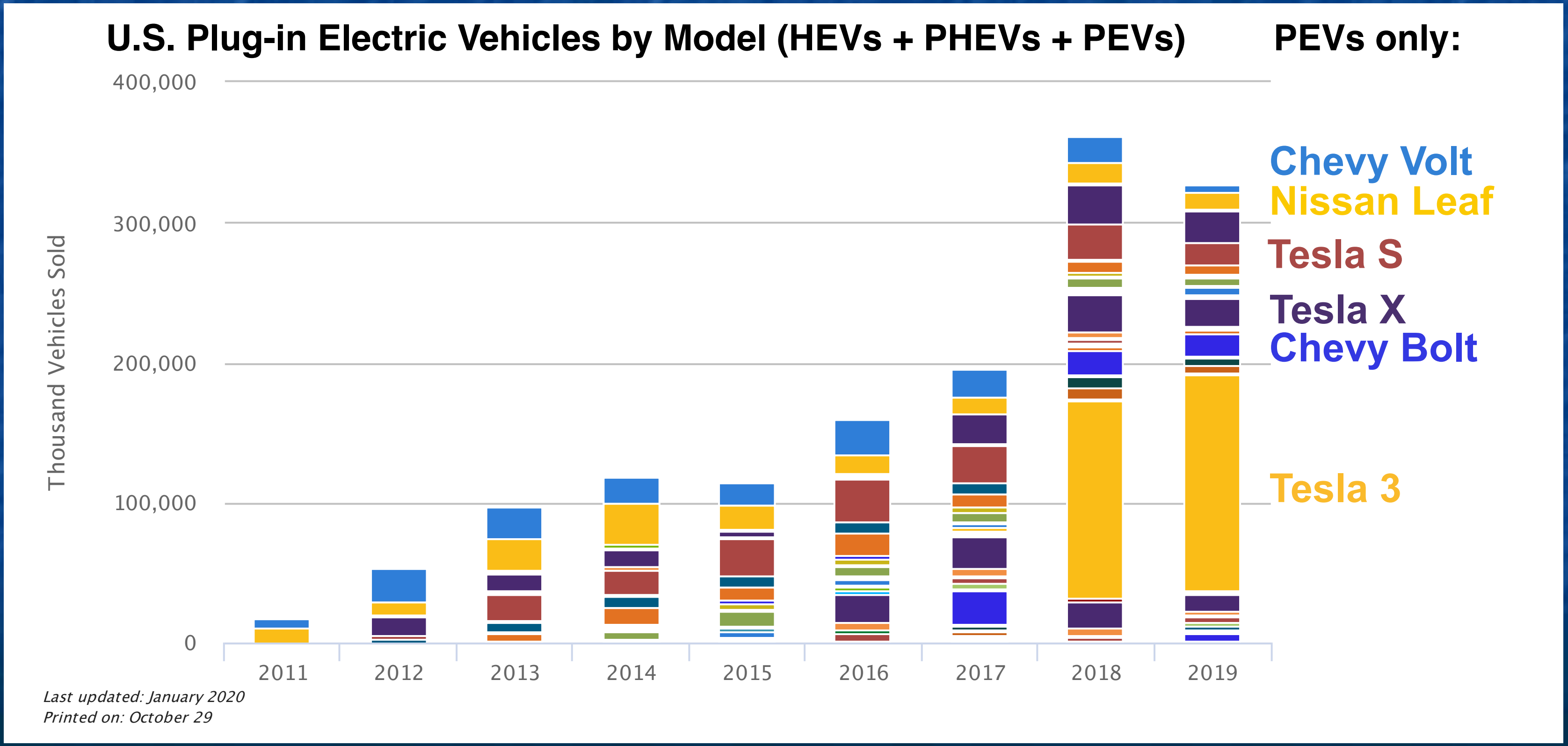
But moving beyond "concept" and into reality:

What is now the best-selling PEV in the U.S.?

From a listing posted by the U.S. DOE's "Alternative Fuels Data Center" [1]

a figure in which I've labeled the major 2019 PEVs:

The winner apparently is . . . the Tesla Model 3

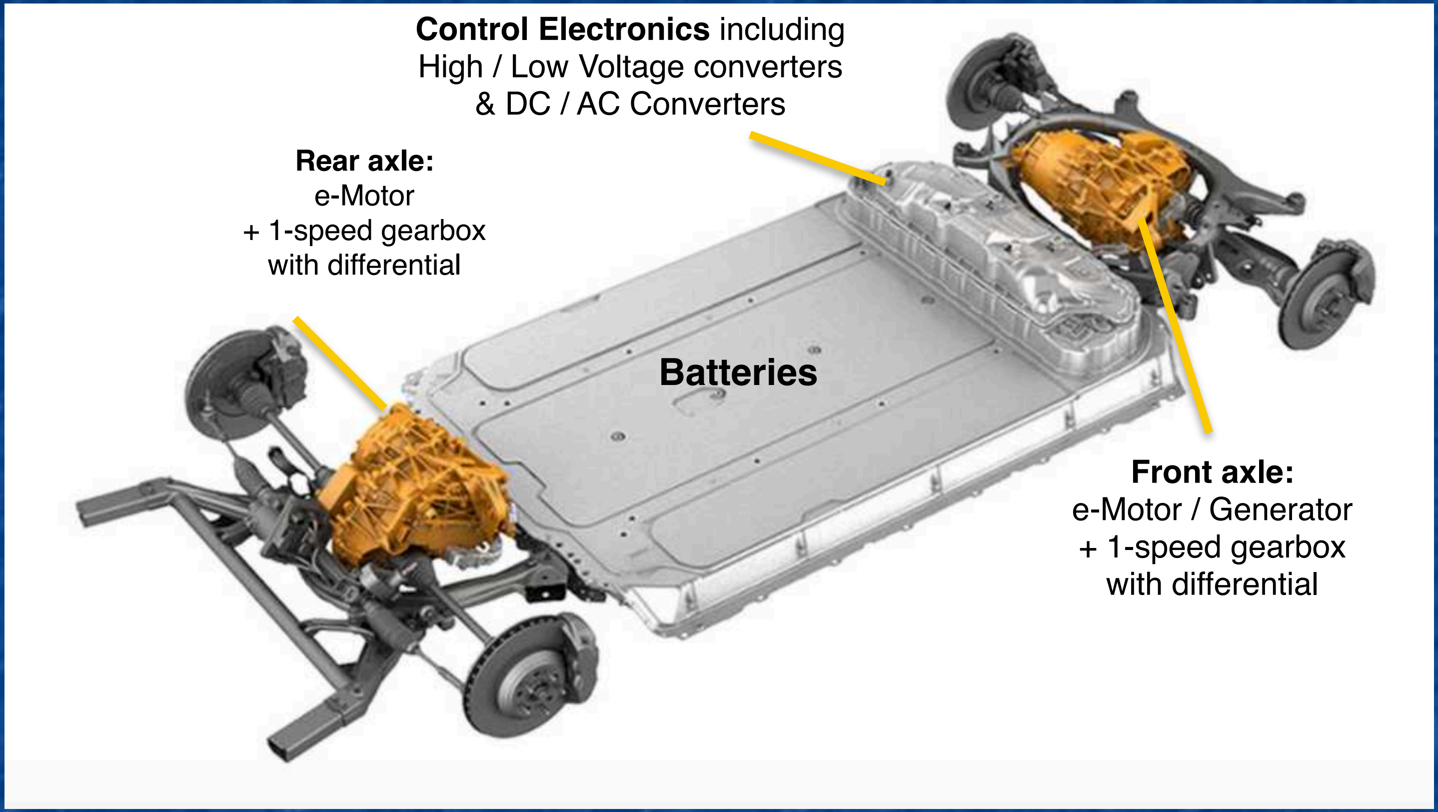


This is my re-captioned version of a figure listed at: https://afdc.energy.gov/data/

Link to the unmodified figure: https://afdc.energy.gov/data/10567

THIS is a diagram of what's inside such a Tesla Model 3

Which was unlabeled, compelling me to dig into other sources to sort out the details:



My captions added to figure from: https://insideevs.com/news/360161/16-percent-batteries-model-3/

A closer look at the front axle e-Motor / Generator + gearbox + differential:

Tesla has integrated these with the steering, suspension, brakes & tire mounts

The resulting monolithic assembly is installed at the front of the Model 3 PEV by ONLY:

tightening 4 bolts + connecting electrical cables, steering wheel, and brake lines [1]

e-Motor / Generator

+ 1-speed gearbox with differential

Suspension / Steering

Disc Brake

Tire mount

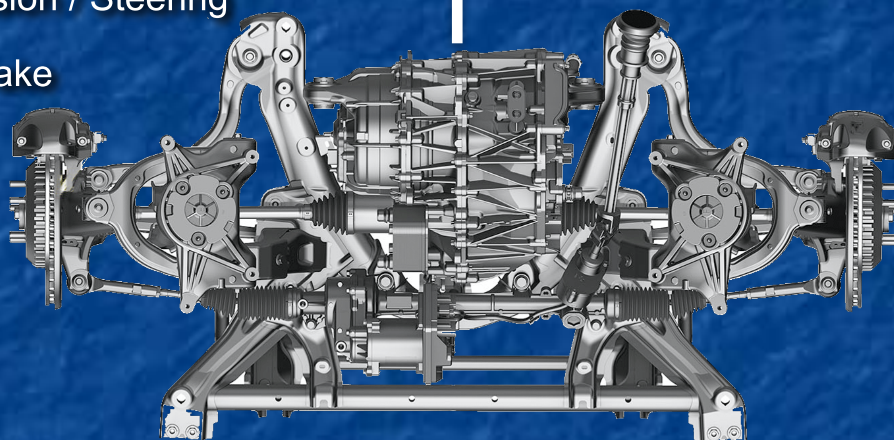


Figure derived from: https://www.autocar.co.uk/car-news/industry/secret-tech-behind-tesla-model-3

1) Tesla service and owner blogs report that in the M3 electronic connections have NOT YET replaced traditional mechanical steering linkage and hydraulic brake lines (but I could find no Tesla confirmation of this)

Surprisingly, you can now even buy one on eBay (this one was offered at $14,999):

The simplification, compared to a modern ICE vehicle, is stunning!

As stated on the homepage of one of Germany's Fraunhofer Institutes: [1]

> **"Vehicle complexity decreases sharply whenever the combustion engine is replaced by an electric powertrain.**
>
> **Whereas a car fitted with a combustion engine consists of some 1400 moving parts, those with an electric powertrain have only approximately 210.**
>
> **An eight-cylinder (ICE) engine is made up of around 1200 parts, each of which requires fitting; in contrast, an electric engine has only 17.**
>
> **Consequently, there have been considerable changes in the range of system parts and components needed. New suppliers and smaller vehicle manufacturers suddenly find themselves in an environment in which they can compete with large, established OEMs due to the reduction in vehicle complexity."**

Given that simplicity almost always yields lower operating & repair costs

and that PEVs' have 3-4 times the intrinsic energy efficiency,

the eventual displacement of ICE vehicles by PEVs seems inevitable

1) https://www.ipt.fraunhofer.de/en/trends/future-powertrain.html

Non-Green Grid + Green PEVs:

When & where will it make GHG sense?

("Well-to-Wheel" & Vehicle Life Cycle Analyses)

*Answers to that question are **not** clear cut:*

As suggested by these news articles:

2009 IEEE Spectrum: **How Green is My Plug-in?** [1]

2013 IEEE Spectrum: **Unclean at Any Speed: Electric Cars Don't Solve the Automobile's Environmental Problems** [2]

2013 BBC News: **How Environmentally Friendly are Electric Cars?** [3]

2016 Scientific American: **Electric Cars ar Not Necessarily Clean** [4]

Doubts raised by the IEEE (Institute of Electrical & Electronic Engineers)

are particular noteworthy in that this international professional society

has almost a half million members, likely including

most of the engineers designing today's PEVs

as well as those operating many of the world's electrical Grids [5]

1) http://aboutme.samexent.com/classes/spring09/ee4940/Plugin1.pdf
2) https://spectrum.ieee.org/energy/renewables/unclean-at-any-speed
3) http://www.bbc.co.uk/news/magazine-22001356?print=true
4) https://www.scientificamerican.com/article/electric-cars-are-not-necessarily-clean/
5) DISCLOSURE: I am an IEEE member / Fellow

*Solid answers require **Well-to-Wheel** (WtW / W2W) analyses that evaluate:*

The COMPLETE transfer of energy from the energy source to a vehicle's wheels

OR the COMPLETE greenhouse gas (GHG) emission **due** to that energy transfer

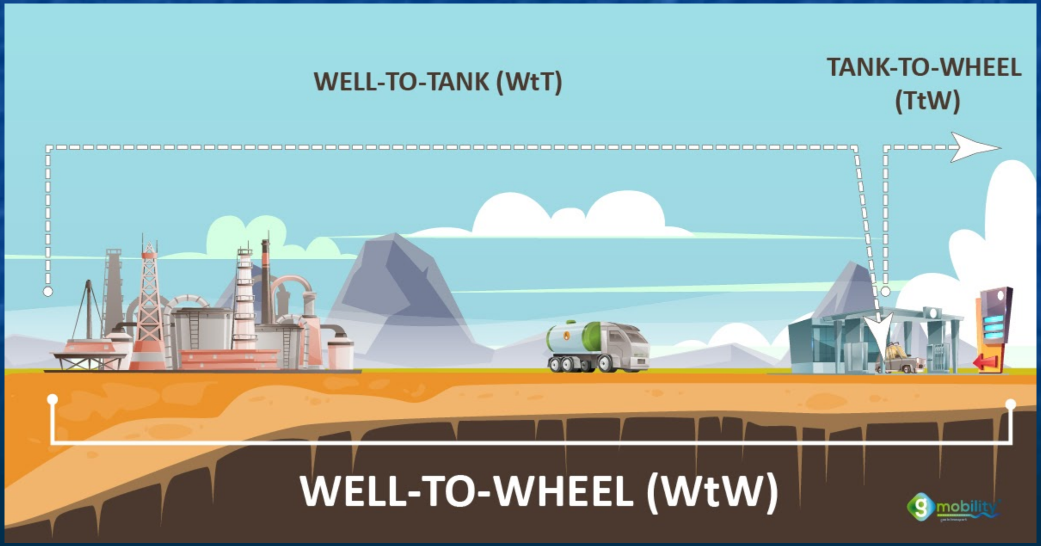
These can be subdivided as: **Well-to-Wheel = Well-to-Tank + Tank-to-Wheel**

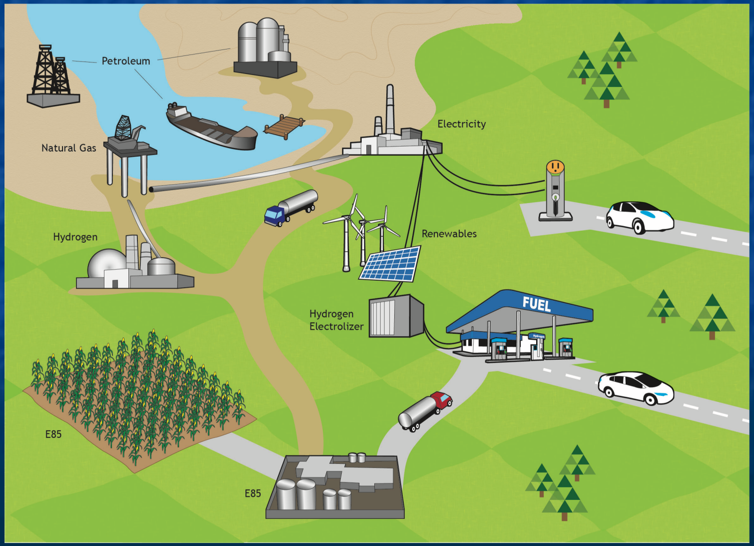
Those terms were originally chosen to describe fossil-fueled vehicles,

but they are now also applied to hybrid and all-electric vehicles:

"Well" = **Oil or gas well, coal mine, nuclear or hydro plant, wind or solar farm . . .**

"Tank" => **Vehicle's fossil-fuel tank / electric battery / fuel cell . . .**



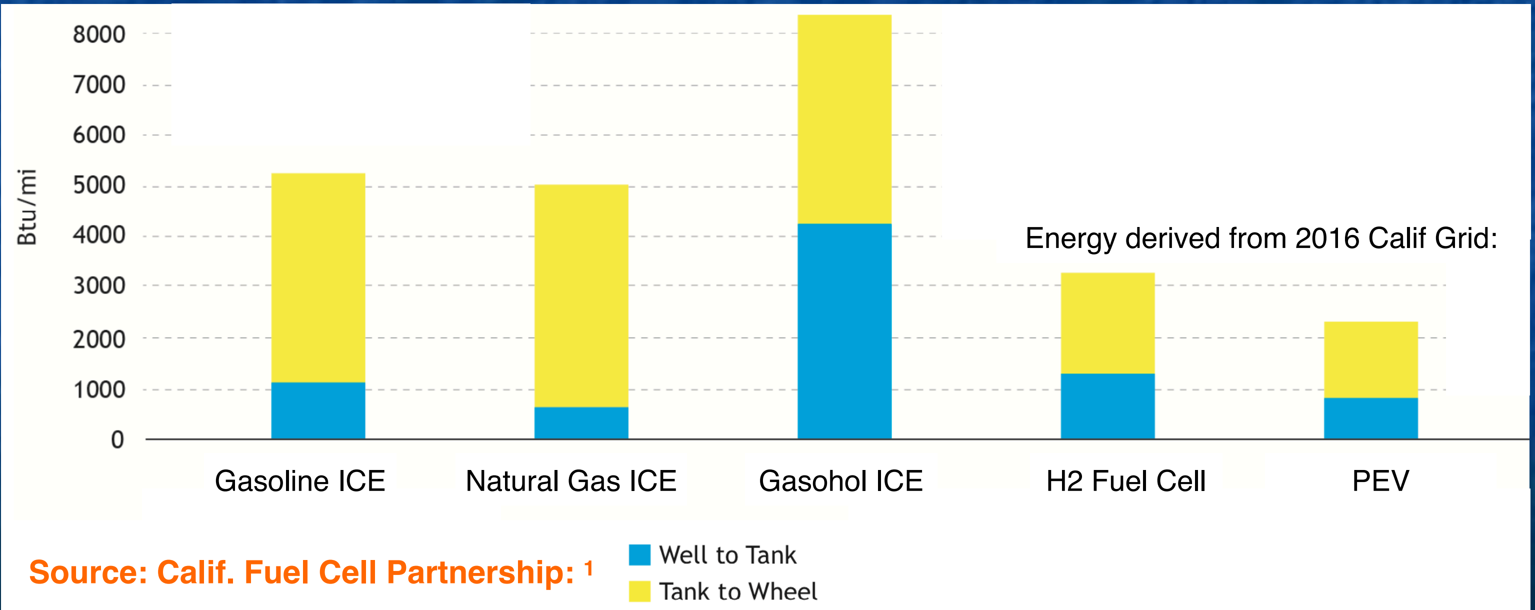


https://gmobility.eu/what-is-well-to-wheel/

https://cafcp.org/sites/default/files/W2W-2016.pdf

*An Example: Calif. Well-to-Wheel **Energy / mile traveled** for alternately fueled vehicles:*

	Well-to-Tank:	**Tank-to-Wheel:**
Gas & NG ICEs:	Drilling + Refinery + Transport energy from well to refinery to gas station	ICE energy losses as heat ICE drivetrain & braking losses Vehicle drag losses
Gasohol ICE's:	Gasoline 85%: Energies above Alcohol 15%: Farm chemical, irrigation, machinery energies + fermentation & distillation energies	ICE energy losses as heat ICE drivetrain & braking losses Vehicle drag losses
Fuel Cell & PEV:	Energy drawn from Calif. power plants	Small e-Motor / gearbox / control losses Reduced braking losses Vehicle drag losses

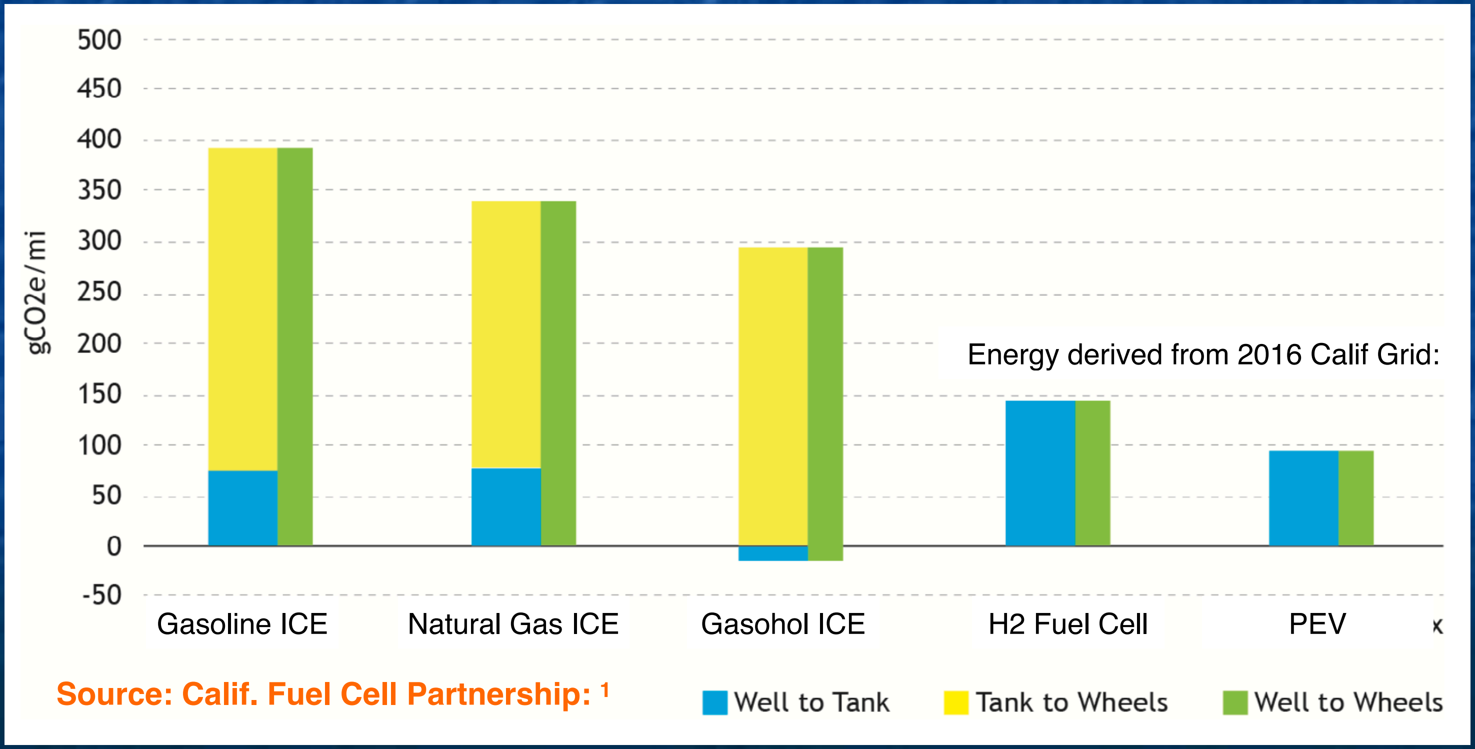


Source: Calif. Fuel Cell Partnership: [1]

1) My cleaned up and relabeled version of figure in: https://cafcp.org/sites/default/files/W2W-2016.pdf

*Continued: Calif. Well-to-Wheel analysis of **GHG emissions** for alternately fueled vehicles:*

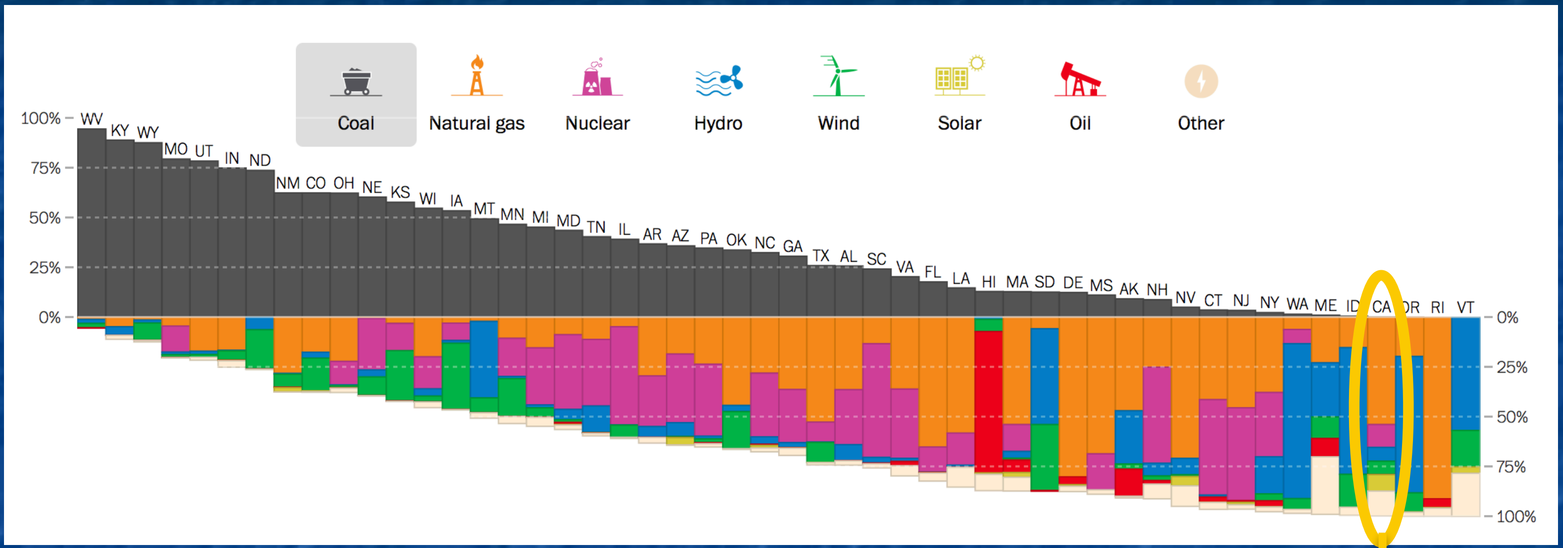
	Well-to-Tank:	**Tank-to-Wheel:**
Gas & NG ICEs:	Drilling GHGs + Refinery GHGs + pipeline/truck GHGs moving fuel from well to refinery to gas station	Gasoline & NG combustion gases
Gasohol ICE's:	Slight net negative due to corn carbon capture	Gasohol combustion gases
Fuel Cell & PEV:	Due to fossil fuel combusted at California's natural gas burning power plants (Ca coal plants ~ 0)	Zero in-vehicle GHG emission

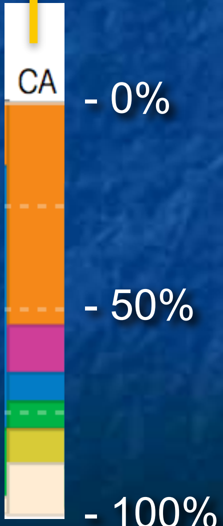


1) My relabeled version of figure in: https://cafcp.org/sites/default/files/W2W-2016.pdf

But California's Grid was already Greener than most in the U.S.:

The 2017 Washington Post figure used earlier: [1]





55% Natural Gas Power (w/ GHG's 20-40% less than Coal Power): [2]

45% Low life cycle GHG Nuclear, Hydro, Wind, Solar + Other Power:

1) http://www.washingtonpost.com/graphics/national/power-plants/

2) See my note set ***Fossil Fuels*** *(pptx / pdf / key)*

Making that an atypical case, from a possibly biased source

To really answer my question of :

Non-GREEN Grid + Green PEVs: When & where will it make GHG sense?

We need Well-to-Wheel analyses for a wider range of locations

We need Well-to-Wheel analyses from supposedly neutral sources

Including refereed scientific journals, governmental and NGO sources

We need to consider more than Well-to-Wheel's production-to-consumption time frame

considering, instead, Energy consumed & GHG emissions over entire **Life Cycles**,

from gathering of raw materials through to final full disposal or recycling

I have identified seven analyses apparently meeting those criteria, spanning 2012-20

Links and cached copies are given HERE on this note set's Resources webpage

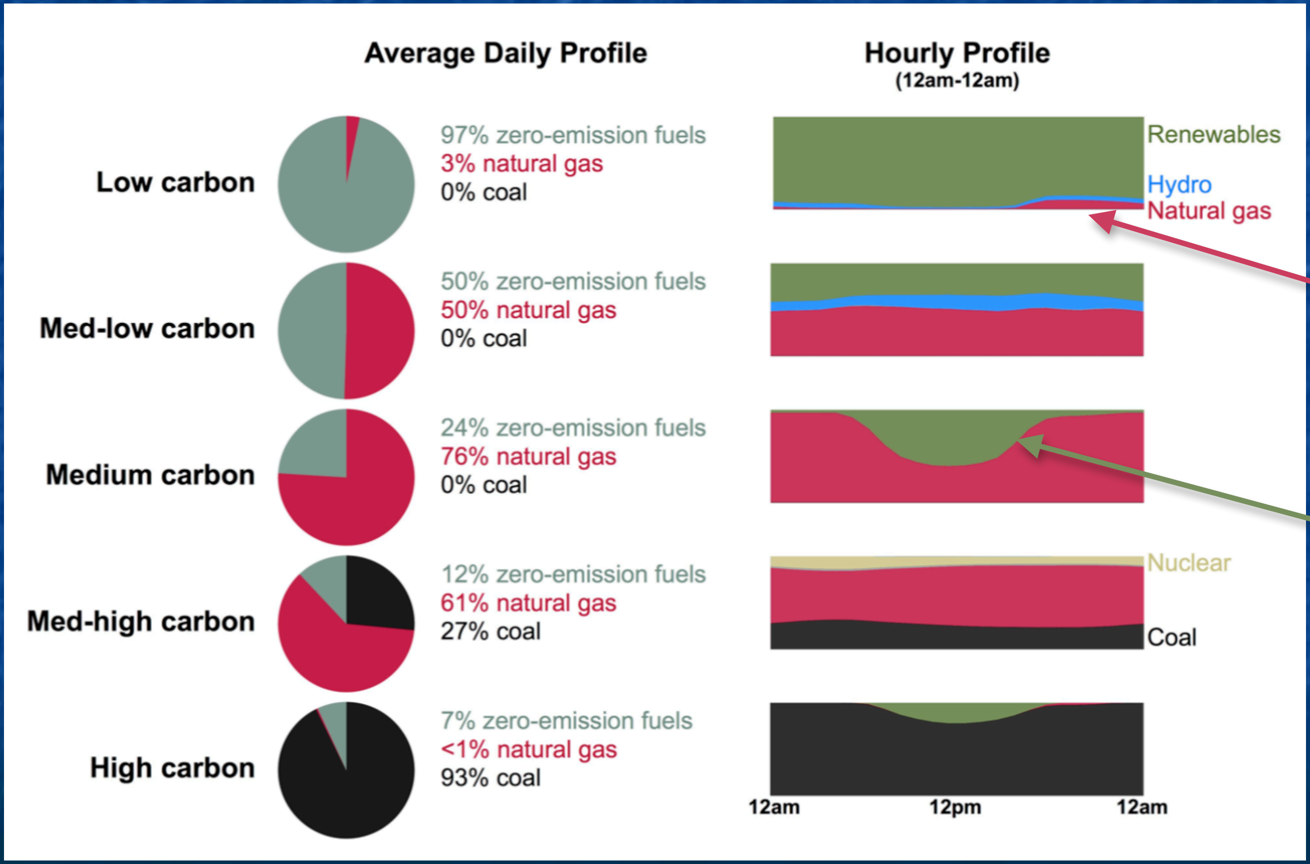
Looking to those sources for answers about when & where PEVs make GHG sense:

From a 2016 U.S. National Renewable Energy Lab study [1]

Which modeled conventional ICE vehicles, PEVs, and PHEVs,

with the latter two types drawing their electric power from a range of Grid types

(roughly equivalent to today's cleanest to dirtiest U.S. power grids)



Presumably:

Evening only "Peaking" NG power Plants

Midday Solar Plants & Late midday Wind Plants

1) https://afdc.energy.gov/files/u/publication/ev_emissions_impact.pdf

With power delivered via alternate BEV / PHEV charging locations, times, and levels:

	Scenario Name	Where can you charge?	When can you charge?	Charging Technology/Speed
H1	Home L1	Only at home	Anytime	Level 1
H2	Home L2	Only at home	Anytime	Level 2
TR	Time Restricted	Only at home	Midnight-1 p.m. only	Level 2
WP	Workplace	At Home & work	Anytime	Level 2

Per the preceding slide, different scenarios draw on a different mix of power plants

TR is the least likely to draw from natural gas plants used only in the evenings

(which, while cleaner than coal plants, are dirtier than renewables & nuclear)

And, as discussed in more detail later in this note set:

Level 1 electric charging stations use standard 110V x 15 Amps home circuit

Level 2 electric charging stations use heavy duty 230V x 30 Amps home circuit

But U.S. homes are NOT now built with such a spare 230V x 30 Amp circuit

Leading to a range of possible vehicle GHG emissions: [1]

Using a Low Carbon Grid:

ICEs: High GHG emissions

PEVs: GHGs ~ 1/3 that of ICEs

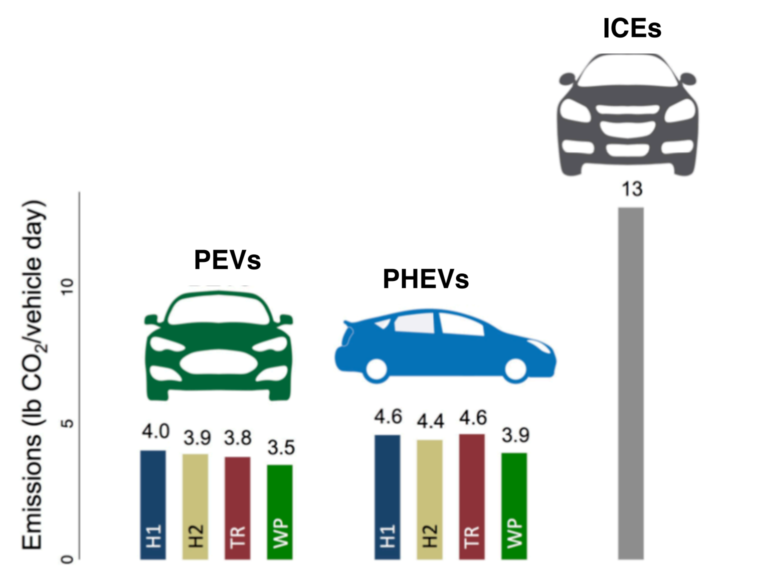
PHEVs: GHGs ~ 1/3 that of ICEs

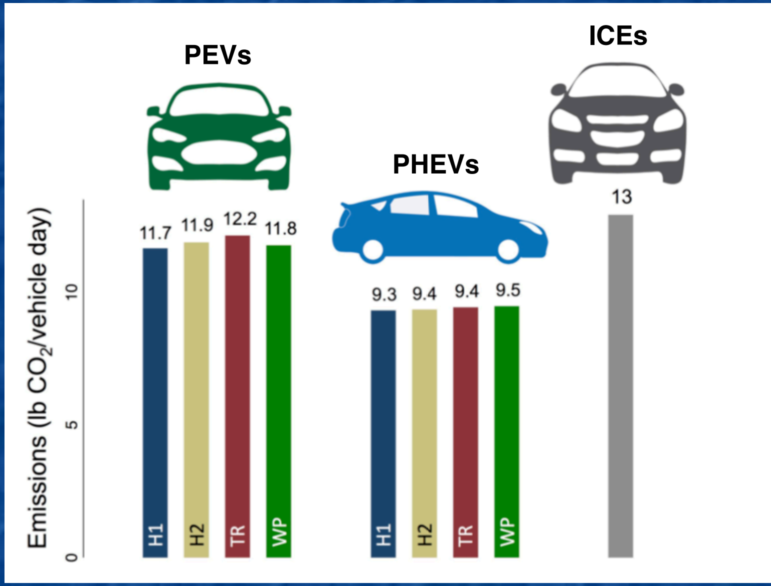
Using a High Carbon Grid:

ICEs: High GHG emissions

PEVs: GHGs ~ 92% that of ICEs

PHEVs: GHGs ~ 73% that of ICEs





Drawing from a High Carbon Grid:

PEV emissions are virtually identical to those from a fossil-fueled ICE

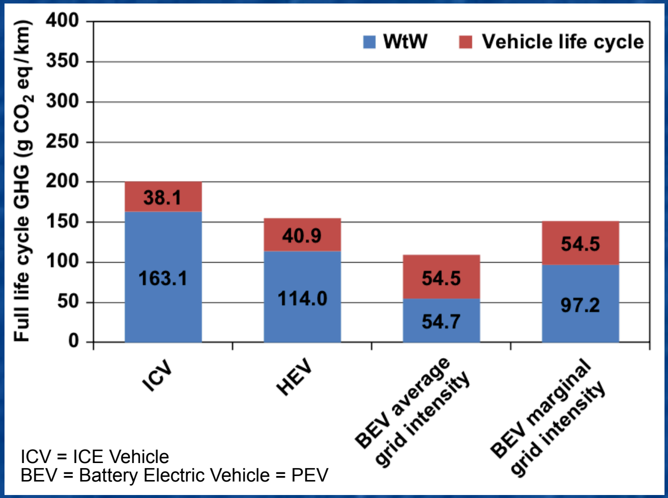
and PHEV emissions are only slightly lower

1) I've changed acronyms to be consistent with those used in this note set

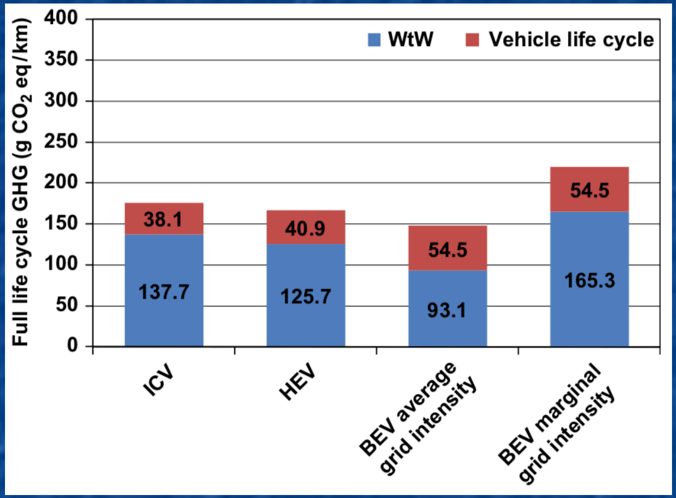
From a journal analysis pertaining to 2012 U.K. & California Grids: [1]

United Kingdom GHG emissions: Well-to-Wheel + full Life Cycle:

Low speed & light load urban driving



Higher speed & load non-urban driving



"BEV marginal grid intensity" = "incremental electricity that must be brought on stream to meet the additional demand from BEVs"

Which this study argues is a better indicator of true GHG impact

Urban driving: ICE vehicle GHGs are ~ 30% higher than HEV & PEV (BEV) GHGs

Non-urban driving: ICE vehicle GHGs are ~ equal to HEV GHGs

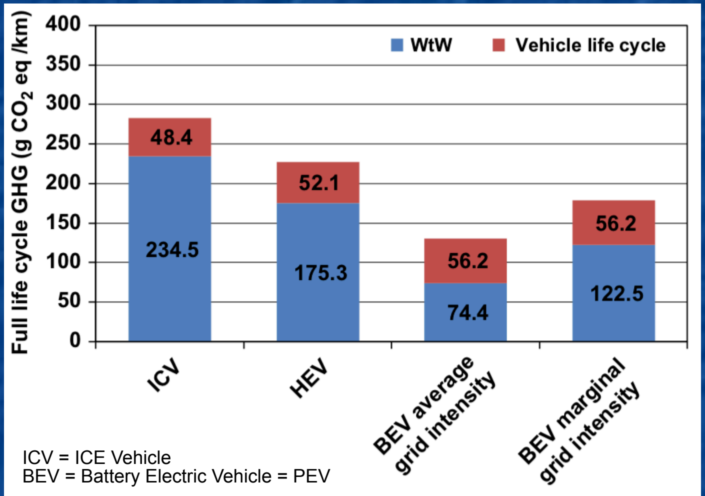
ICE vehicle GHGs are ~ 25% lower than PEV (BEV) GHGs (!)

1) *https://kundoc.com/pdf-a-new-comparison-between-the-life-cycle-greenhouse-gas-emissions-of-battery-elec.html*

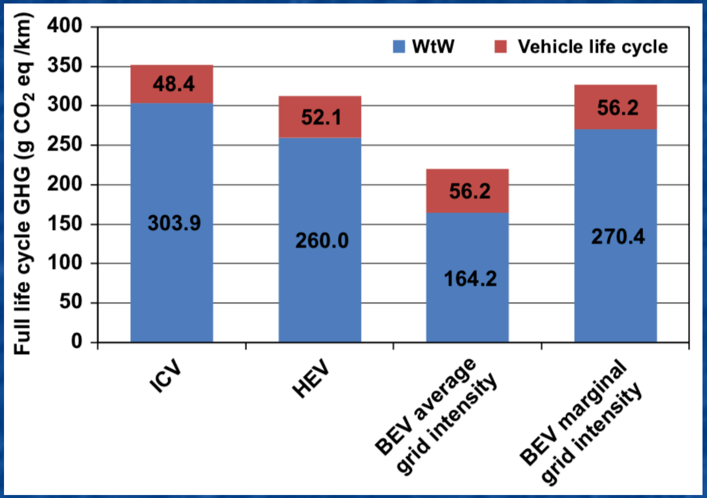
From that same 2012 journal analysis: [1]

California GHG emissions: Well-to-Wheel + full Life Cycle:

Low speed & light load urban driving



Higher speed & load non-urban driving



Again based on BEV marginal grid intensities:

Urban driving: **ICE vehicle GHGs are ~ 30% higher** than HEV GHGs

ICE vehicle GHGs are ~ 60% higher than PEV (BEV) GHGs

Suburban driving: **ICE vehicle GHGs are ~ 14% higher** than HEV GHGs

ICE vehicle GHGs are ~ 8% higher than PEV (BEV) GHGs

1) https://kundoc.com/pdf-a-new-comparison-between-the-life-cycle-greenhouse-gas-emissions-of-battery-elec.html

What was going on there?

UK urban driving: ICE vehicles ~ 30% dirtier than both Hybrids & PEVs

UK non-urban driving: ICE vehicles as clean as Hybrids & 25% cleaner than PEVs

Explanation for UK urban vs. suburban driving difference?

Gasoline ICE "fuel economy" increases markedly for highway (vs. city) driving

CA urban driving: ICE vehicles ~ 30% dirtier than Hybrids, 60% dirtier than PEVs

CA non-urban driving: ICE vehicles 14% dirtier than Hybrids, 8% dirtier than PEVs

Explanation for CA vs. UK PEV differences?

California Grid is significantly GREENER than UK Grid (zero vs. significant coal power)

which makes PEVs charged from the CA Grid much cleaner

Explanation for CA vs. UK suburban ICE vs. HEV difference?

Higher speed CA suburban driving (freeways) depressing ICE vehicle fuel economy?

From a 2015 Union of Concerned Scientists study comes this strange map:

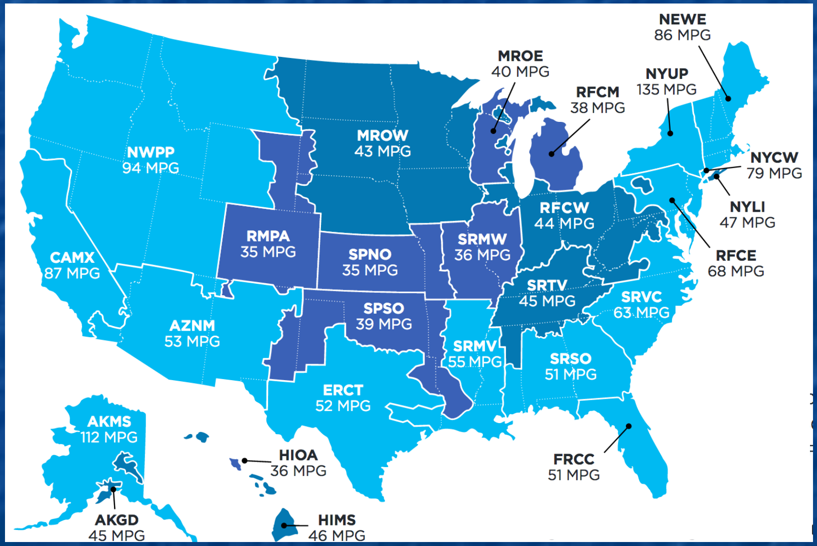
By U.S. region, taking into account the GREENESS of that region's Grid,

its colors and MPG numbers refer to the

city/highway fuel economy a gasoline ICE vehicle must achieve to match

the GHG output of a PEV charged from that region's electrical Grid

Greener Grid => Greener PEV => Higher mileage required from GHG-matching ICE



ICE's fuel economy to be cleaner than PEV:

Hydro-powered Northwest: > 94 MPG

NG + zero-GHG powered California: > 87 MPG

Mix powered South: > 50-63 MPG

Partly coal-powered upper Midwest: > 43 MPG

Heavily coal powered central states: > 35 MPG

In darker regions MOST gasoline HEVs are still cleaner than PEVs

In darker regions MORE fuel efficient gasoline ICEs are even cleaner than PEVs

1) https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf

From a 2016 journal publication comes a different type of GHG emission map: [1]

Which compares GHGs from three PEV models (identified vertically near left margin)

versus Prius gasoline HEV or Mazda gasoline ICE w/ regenerative braking [2]

Blue = Where PEV is cleaner

Intensity => PEV advantage

Red = Where Gasoline vehicle is cleaner

Intensity => PEV disadvantage

Prius gasoline HEV:

Cleaner than or about as clean as all PEVs ANYWHERE across U.S. Grid

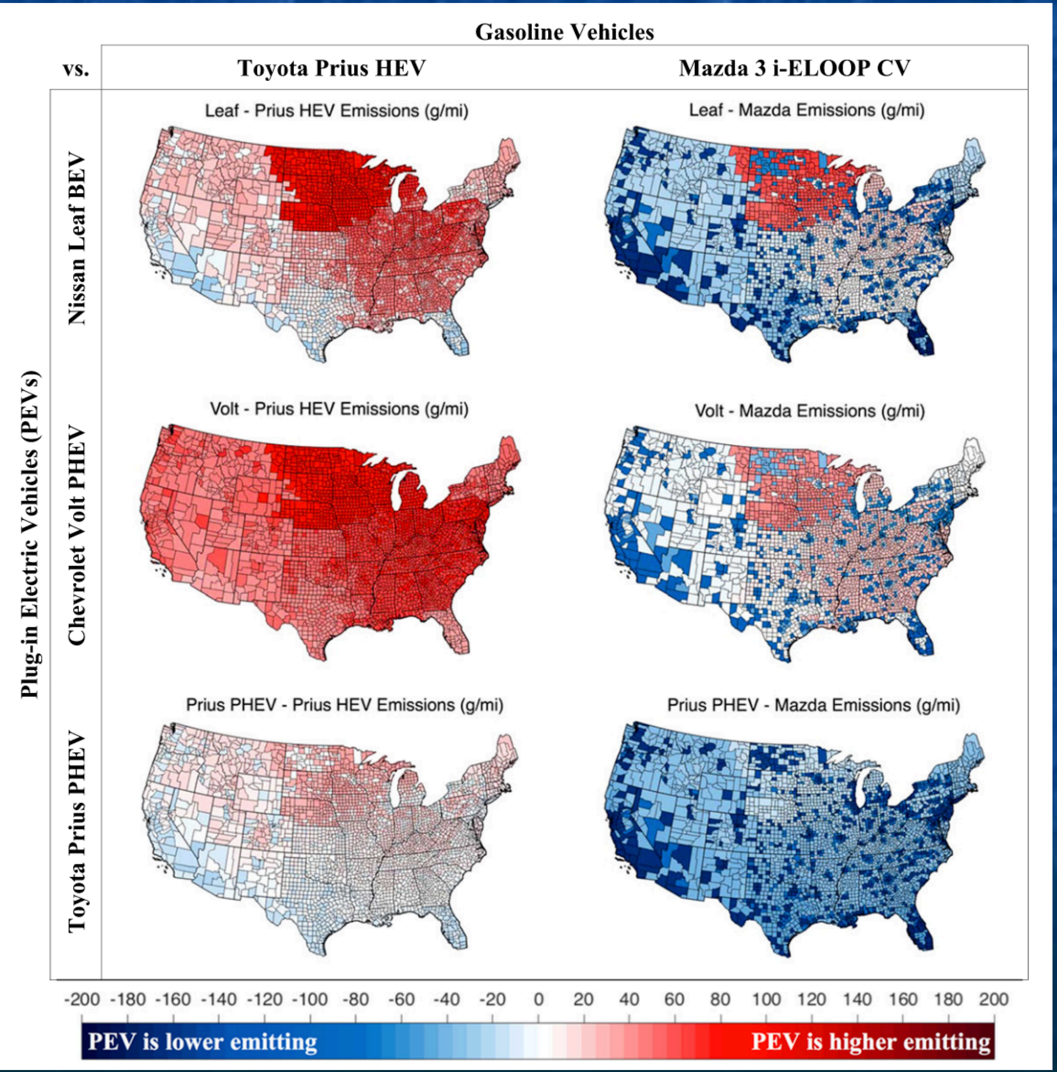
Mazda gas ICE + regenerative braking:

Cleaner than Leaf in upper Midwest

Cleaner than Volt in Midwest & East

1) https://iopscience.iop.org/article/10.1088/1748-9326/11/4/044007?platform=hootsuite

2) By coincidence, this Mazda was exactly the vehicle I used earlier in my explanation of regenerative braking



A final 2020 study spanned most of the world: [1]

It opened by asking the essentially my question:

"Could electrification policies backfire
by promoting their diffusion before electricity is decarbonized?" [1]

The study then estimated the country-by-country GHG-emission impact of
replacing a gasoline ICE vehicle with a PEV in 2015, or at various future dates,

Likely future GHG improvement in PEV and ICE vehicles was also accounted for

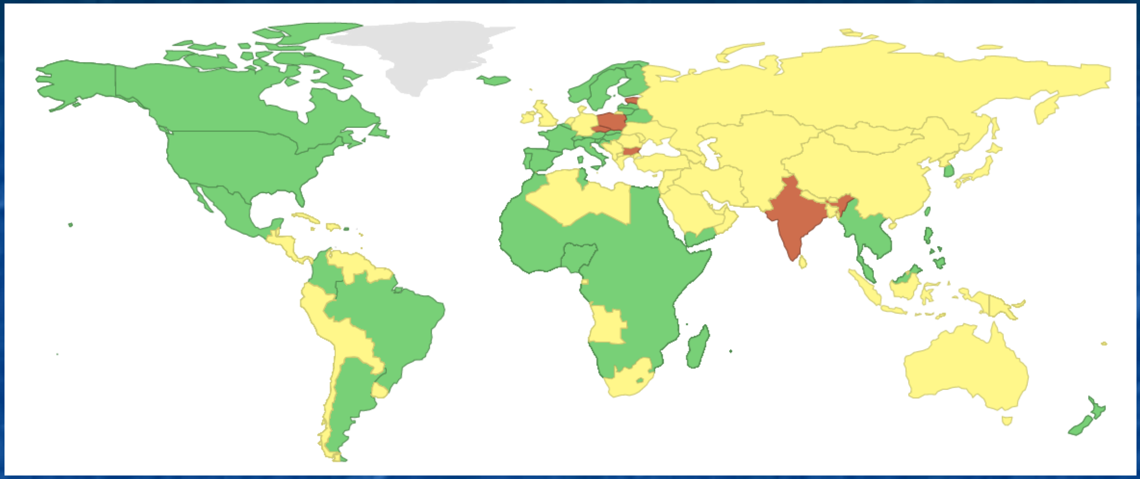
But for each country, the GHG cleanliness of its Grid was averaged over that country
This study therefore lacks information on where in a large country (e.g., the U.S.)
PEV replacement of gasoline ICE vehicles makes the most or least sense

With many alternate scenarios + consideration of **both** vehicle & heating electrification
this paper demands extensive and extended study,
so let me here focus on its more immediately vehicle-relevant findings:

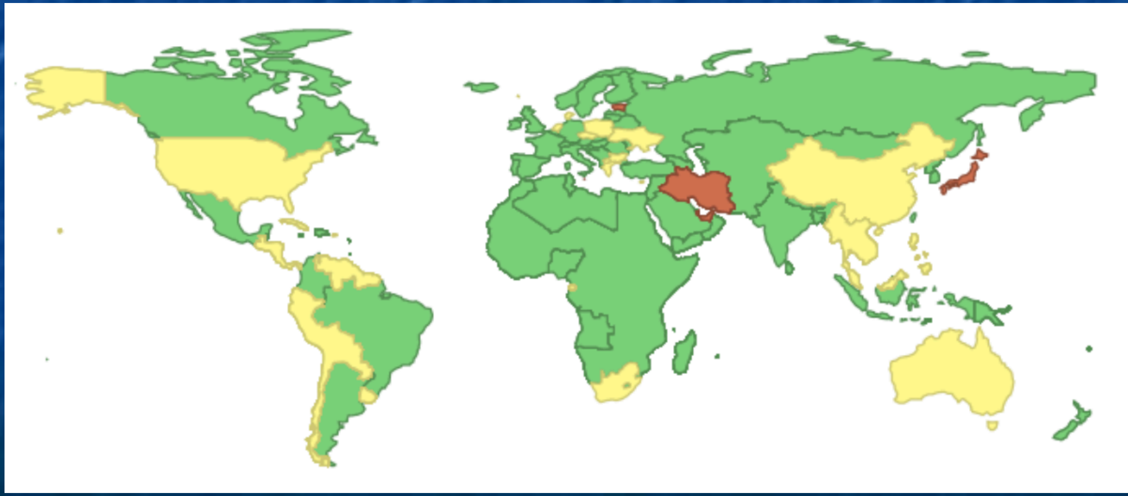
1) https://www.researchgate.net/publication/340127420_Net_emission_reductions_from_electric_cars_and_heat_pumps_in_59_world_regions_over_time

Predicted country-by-country GHG impact of replacing ICE vehicle with PEV:

For PEV replacing gasoline ICE vehicle in 2015:



For PEV replacing gasoline ICE vehicle in 2030:



Where Grid-powered PEV is "almost always" cleaner than the ICE it replaces

Where **on average** Grid-powered PEV is cleaner than the ICE it replaces

Where **on average** Grid-powered PEV is dirtier than the ICE it replaces

PEV advantage **lessens** in the U.S. by 2030?

Yes, **because** our ICE's were predicted to get cleaner faster than our Grid!

Non-GREEN Grid + Green PEVs: When & where will it make GHG sense?

Together, these **Well-to-Wheel** and **Life Cycle** studies support the ambivalence of earlier IEEE, BBC & Scientific American articles concerning vehicle electrification

Specifically, there appears to be a strong scientific consensus that:

1) **PEVs do not now reduce GHG** emissions in areas with dirtier electrical grids

With "dirtier" being pretty much synonymous with heavy use of coal power

2) Even **where** replacement of conventional ICE vehicles by PEVs **does** reduce GHGs:

Regenerative-braking-enhanced ICE vehicles can **match** PEV GHG reductions

While **gasoline HEVs** are ***reported*** [1] to **better** PEV GHG reductions

3) The advantage of PEVs strengthens when & where the Grid becomes GREENer

1) See next slide

*Based on finding #2, the best interim choice **appears** to be driving HEVs*

HOWEVER: Reported HEV fuel economy & emissions have long been questioned:

Consumer Reports (2013): [1]

"(reported fuel economy) can be far higher than many drivers will actually get.

And the largest differences involve some of the most fuel-efficient cars, **particularly hybrids**"

Car and Driver Magazine (2013): [2]

"Why is the EPA so bad at estimating hybrid Fuel Economy?"

Time Magazine (2013): [3]

"Your (hybrid) car won't get the mileage posted on the window"

Consumer Reports (2014): [4]

"Ford cuts mpg ratings on hybrids, again"

USA Today (2014): [5]

"Honda Accord Hybrid mileage way off"

Magnitude of the reported HEV fuel economy overstatements? About 20-25% [2, 4]

1) https://www.consumerreports.org/cro/magazine/2013/08/the-mpg-gap/index.htm

2) http://www.caranddriver.com/features/why-is-the-epa-so-bad-at-estimating-hybrid-fuel-economy-feature

3) http://business.time.com/2013/09/10/your-car-wont-get-the-mileage-posted-on-the-window-and-maybe-thats-ok/

4) http://www.consumerreports.org/cro/news/2014/06/ford-revises-c-max-fusion-mkz-hybrid-fiesta-fuel-economy-ratings/index.htm

5) http://www.usatoday.com/story/money/cars/2014/05/29/consumer-reports-honda-accord-hybrid-mpg-rating/9724733/

Then, in the summer of 2020, very much larger errors were reported for PHEVs

As reported online and in the press:

Plug-in Hybrids are a 'Wolf in Sheep's Clothing' - BBC & CNBC [1, 2]

The Plug-in Hybrid Con - TransportEnvironment.org [3]

Real-World (PHEV) CO2 Emissions 2-4X Higher - GreenCarCongress.com [4]

The articles correctly reported GHG emissions 2-4X higher than in standardized tests,

even if the news agencies misidentified the originating data source, which was the

Fraunhofer Institute / International Council on Clean Transportation (ICCT) study:

Real-World Usage of Plug-in Hybrid Electric Vehicles
Fuel Consumption, Electric Driving and CO2 Emissions [5]

How could official evaluations chronically **overstate** HEV fuel economy by 20-25% ?

How can official evaluations now **understate** Plug-in HEV GHG emissions by 50-75% ?

Because HEVs vacillate between GHG-emitting ICEs & zero-GHG e-motors

1) https://www.bbc.com/news/science-environment-54170207
2) https://www.cnbc.com/2020/09/17/study-claims-plug-in-hybrid-emissions-are-higher-than-thought-.html
3) https://www.transportenvironment.org/sites/te/files/publications/2020_09_UK_briefing_The_plug-in_hybrid_con.pdf
4) https://www.greencarcongress.com/2020/09/20200928-isi.html
5) https://theicct.org/publications/phev-real-world-usage-sept2020

Accuracy requires figuring out how much time HEVs spend using ICE vs e-Motors

For a standard HEV that depends upon not only the car's programming

but also upon the particular driving style of the vehicle's operator:

- Faster acceleration is more likely to demand **joint** ICE & e-Motor power
- Rapid braking can result in **less complete** regenerative energy capture

But it gets much more complicated for a Plug-in HEV:

For shorter journeys:

A PHEV departing with fully-charged batteries may make little or no use of its ICE

But departing with incompletely-charged batteries, use of its ICE may be unavoidable

For long journeys it's also much more likely that a PHEV will have to switch to its ICE

In China, Germany, Netherlands, Norway, US & Canada, Fraunhofer / ICCT found

unexpectedly heavy incompletely-charged + long-distance use of PHEVs

All of which brings into question the interim advantage of both HEVs & PHEVs

Growing a future GREEN Grid:

Our obvious challenge: Fully greening (de-carbonizing) the Grid

Which will require expansion of low-GHG power [1] alternatives which now include

(in the order of their present day power contribution to the U.S. Grid):

Nuclear (19.5%), **Wind** (7.2%), **Hydro** (6.8%), **Solar** (2.8%),

Biomass (1.4%) **Geothermal** (<1%)

Bearing in mind our earlier estimate that net expansion of at least 3.3X will be required,

those technologies (plus other candidates) can be explored in one or more note sets

listed (and outlined) on the WeCanFigureThisOut.org Energy homepage

But what about NON-OBVIOUS challenges to fully greening our Grid?

Some have to do with our general use of the Grid

Some have to do with how PEVs will use the Grid

1) By "low-GHG power" I recognize that when properly evaluated over its full life cycle, NO TECHNOLOGY IS ZERO GHG

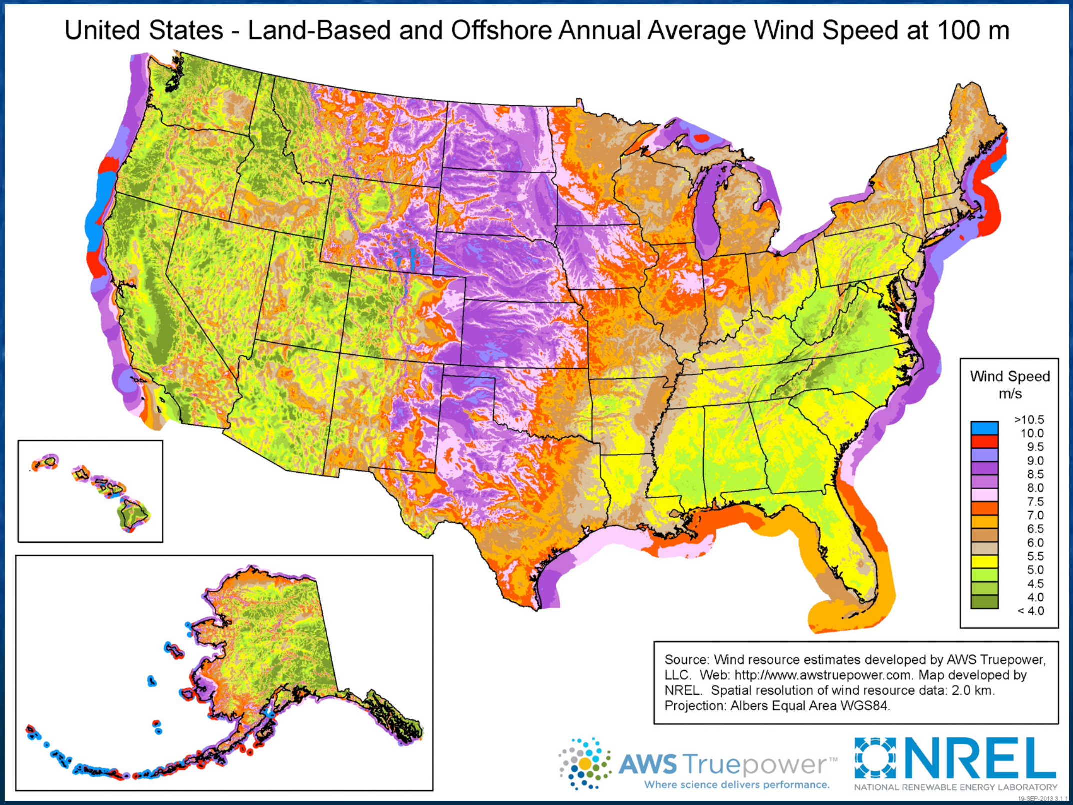
General challenges to the Grid: Where & When we use power

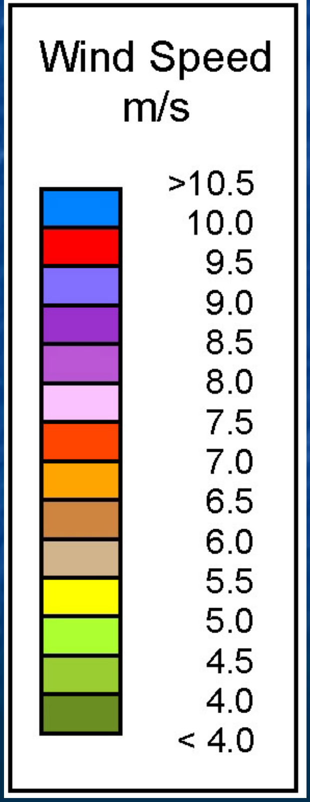
WHERE we'll use GREEN power is mostly FAR from WHERE it's produced

Fast wind carries VASTLY more energy, because its power varies as (wind speed) **cubed**

Where then do we get fast winds (and will Wind Farms be **vastly** more productive)?

From my note set **Wind Power I** (pptx / pdf / key):



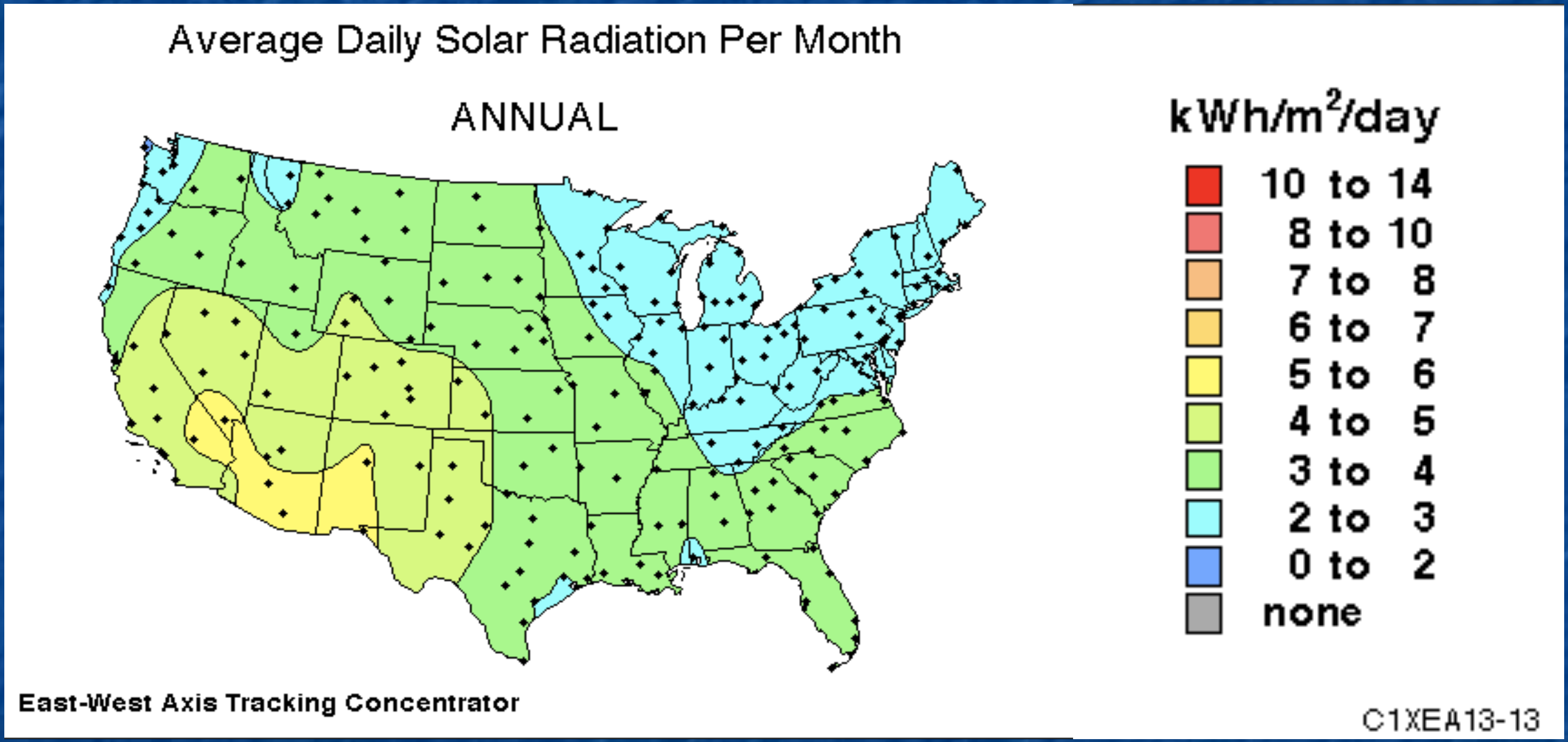


www.nrel.gov/gis/wind.html

Similarly: Where do we get the most annual sunlight?

As required to make Solar Photovoltaic Power Plants most productive

From my note set **Solar Power I - Today's PV** (pptx / pdf / key):

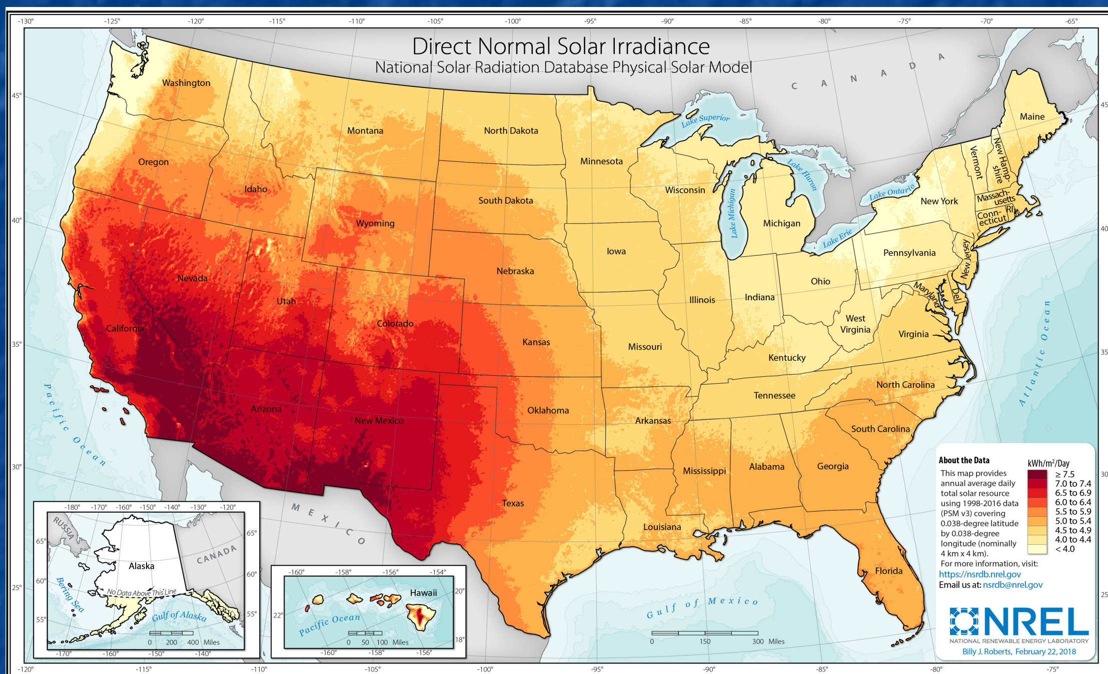


http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/

*And where do we get the most **direct** (non cloud-scattered) sunlight?*

Which is far more efficiently concentrated by the mirrors of Solar Thermal Power Plants

From my note set **Solar Thermal Power / Heat Storage** (pptx / pdf / key):



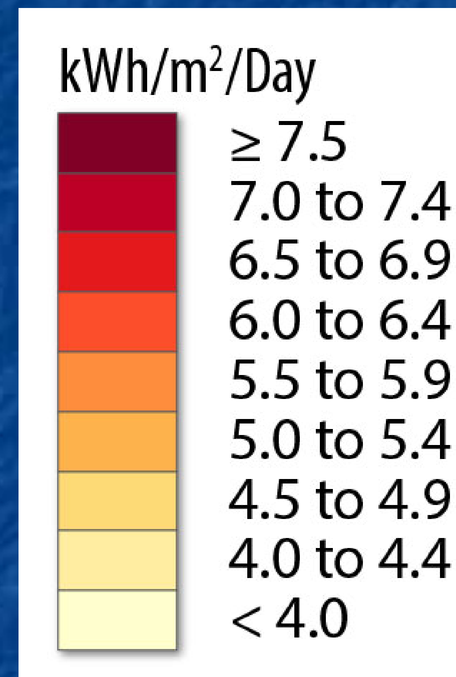
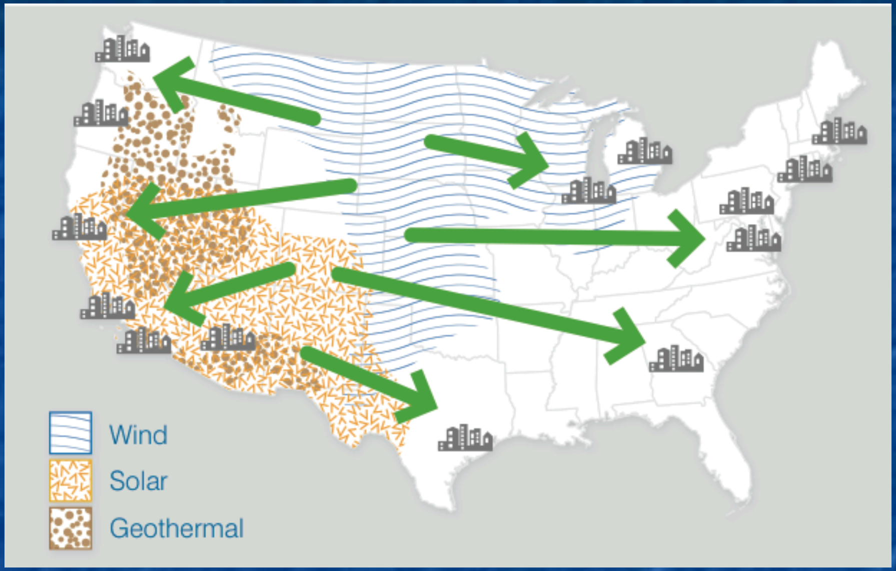


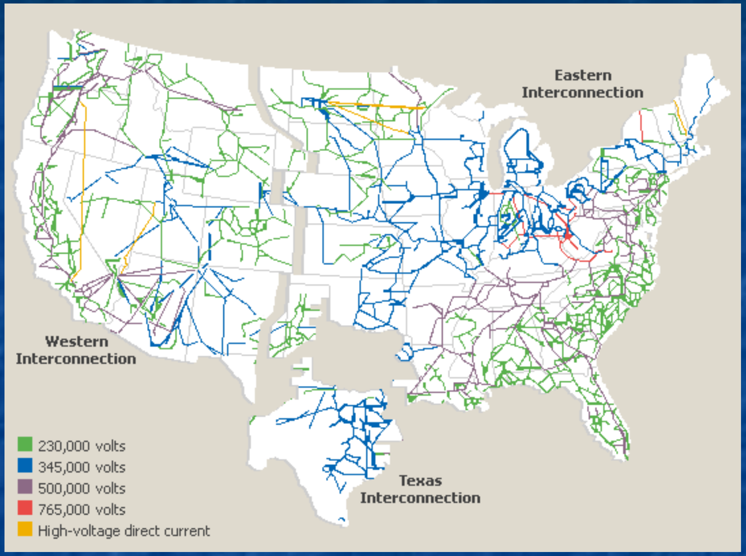
Figure: https://www.nrel.gov/gis/assets/pdfs/solar_dni_2018_01.pdf

Further, to transport that Green energy from source to consumer . . .

We'll need a Grid able to this:



And not today's fragmented this:



The challenge lies not only in the fragmentation of today's U.S. Grid, it's also in Grid technology that cannot now efficiently send power over long distances

These problems, and their potential solutions are discussed in my note sets:

A Generic Power Plant & Grid (pptx / pdf / key)

A Renewable Distributed Grid (pptx / pdf / key)

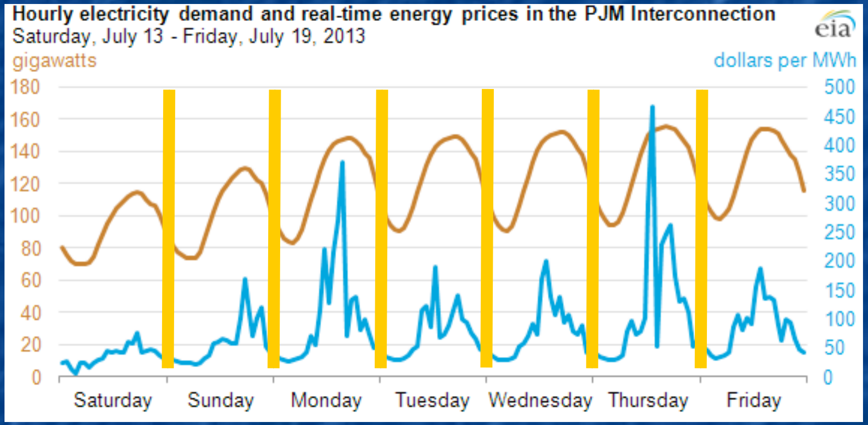
http://www.awea.org/files/filedownloads/pdfs/greenpowersuperhighways.pdf

http://www.geni.org/globalenergy/library/national_energy_grid/united-states-of-america/americannationalelectricitygrid.shtml

*But even **with** a much improved Grid:*
*WHEN green power is mostly produced is **not** WHEN we mostly want it*

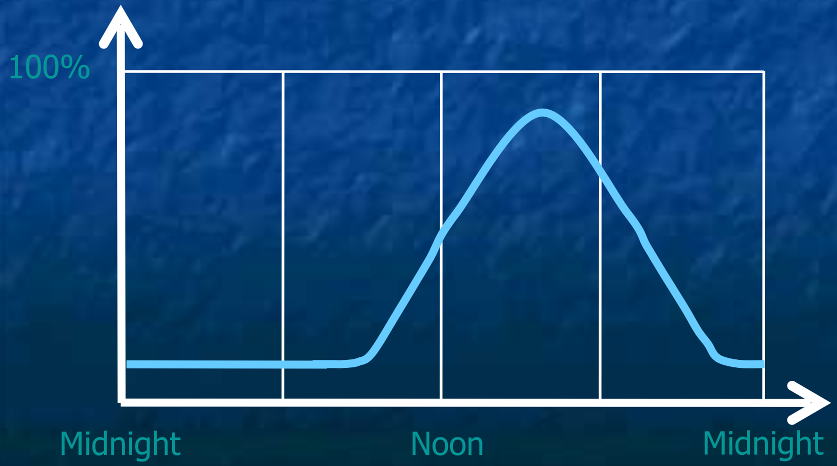
As discussed in my note set **Power Cycles and Energy Storage** (pptx / pdf / key),

When we mostly **use** power is early evening:

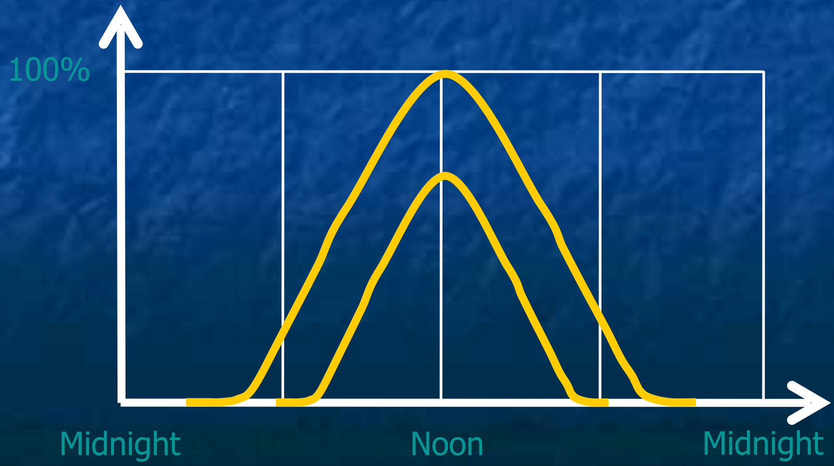


www.eia.gov/todayinenergy/detail.cfm?id=12711

But we mostly **get** wind power late afternoon:

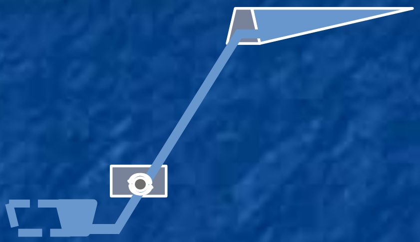


And mostly **get** solar power midday:

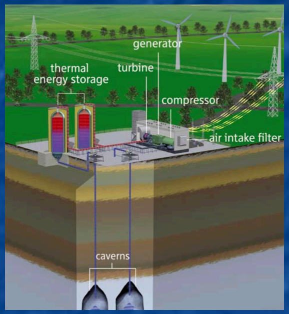


*A GREEN Grid will thus **also** require vast short-term **energy storage***

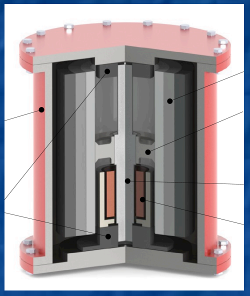
Via technologies either still unproven or still grossly lacking in necessary capacity: [1]



Pumped Storage Hydro (PSH)
(the **only** proven technology)

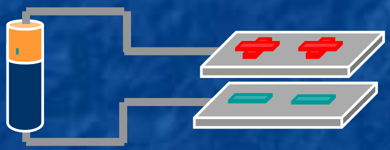


Compressed Air Storage
(CAES)

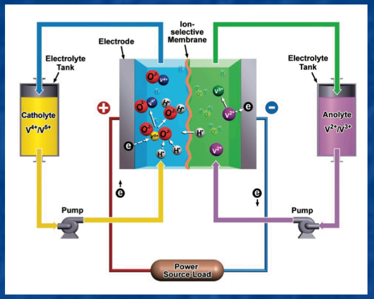


Flywheels

Fuel Cells



Super Capacitors



Super Batteries

Technologies that, today, at least DOUBLE the cost of the delivered power [2]

*1) Figures from my note set: **Power Cycles and Energy Storage** (pptx / pdf / key)*

*2) As documented in my note set: **Power Plant Economics** (pptx / pdf / key)*

The preceding seven slides were a grossly compressed explanation of WHY

this note set has focused so strongly on the TRANSITION to PEVs + Green Power

and why I believe that complete transition could take decades

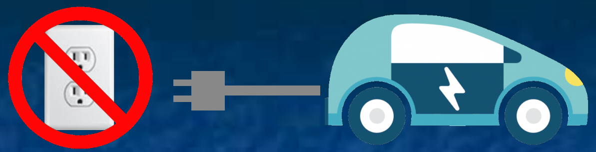
If not for that concern, this note set would have covered only

PEVs & FCEVs, and their necessary charging infrastructures

(and this note set would likely have been about 1/5 as long!)

GREEN Grid + GREEN Plug-in Electric Vehicles

PEV challenges *to the Grid: Charging infrastructure / Energy Storage*



Vehicle charging time = Vehicle battery capacity / charging station's power output

Tesla Supercharger [1] stations have a power output 75 kW at each vehicle outlet

For an 85 kW-h Tesla Model S, that resulted in a full charge time of ~ **75 minutes** [1]

For a Nissan Leaf, with only 30 kW-h of batteries,[2] full charge time should be ~ **27 min**

Most power outlets in U.S. homes can supply up to 1.65 kW (110V x 15 Amps)

Via a voltage converter, one outlet could thus charge the Nissan Leaf in:

27 minutes x (75 kW / 1.65 KW) = **20.5 hours**

TOTAL power to U.S. homes is typically 240V at 100-200 Amps => 24-48 kW

Even if 100% of a home's power could be safely fed to a single outlet, charging

1 Nissan Leaf would take: 27 minutes x 75 kW / (24-48 KW) = **0.7 to 1.4 hours**

"We're gonna need a bigger ~~boat~~ outlet"

1) https://en.wikipedia.org/wiki/Tesla_Supercharger *2) https://batteryuniversity.com/learn/article/electric_vehicle_ev*

Because even 48 minutes is a heck of a lot longer than a gas station visit!

We'll thus want to build charging stations where vehicles **already sit for hours**

The U.S. Idaho National Lab evaluated where vehicles park [1]

And assuming I've correctly interpreted their very strangely presented findings:

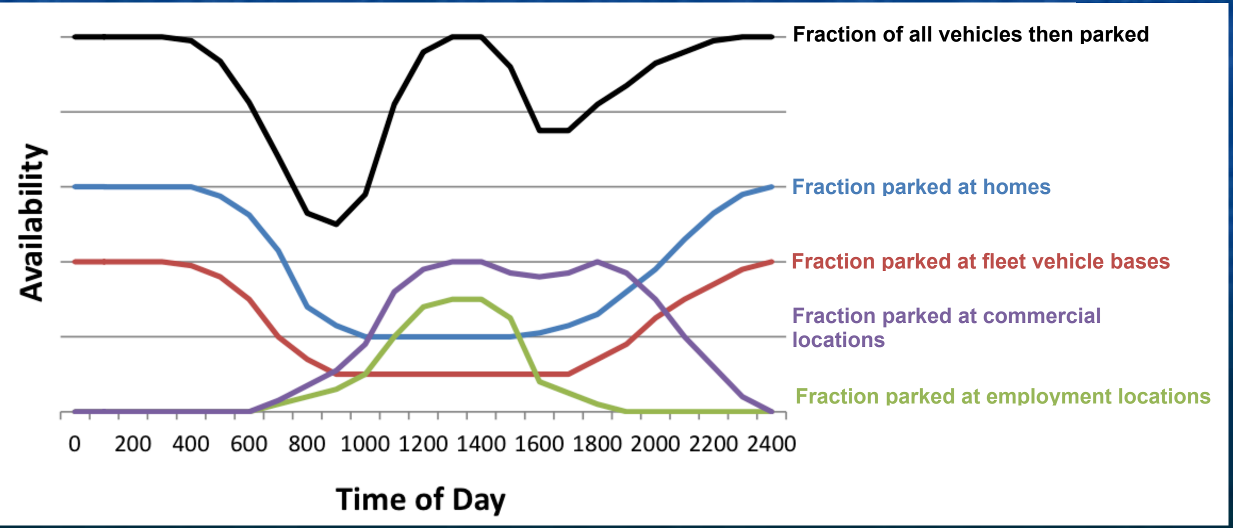
60% park **overnight at homes** (blue) + 30% park **midday at employers** (green)

Apparently allowing for charging of almost 90% of our personal PEVs

40% park **overnight at "fleet" vehicle home bases** (red)

40% park **midday in commercial lots** (malls, theaters, doctor's offices . . .) (purple)

Allowing for charging of the ~ 10% of personal PEVs **not** charged at home or work?



1) https://www.energy.gov/sites/prod/files/2014/02/f8/v2g_power_flow_rpt.pdf

Figure: My relabeled version of Figure 19, page 26, in the report above

Suggesting four types of PEV charging locations:

Fleet vehicle home base parking lots

High power likely nearby + security allowing for simple charging outlets

Personal home garages

Medium power nearby but new wiring & outlets required

Apartment complex parking lots

Medium high power nearby, user identification & billing **likely** to be an issue

Workplace and commercial parking lots

Medium to high power nearby, user identification & billing **certain** to be an issue

Fleet vehicle home base charging seems almost trivial:

Fence in overnight parking lots and/or add guards and/or add CCTV security

Then just wire up enough high capacity outlets,

ready to charge up any vehicle arriving with a compatible cord/plug

Next easiest (in concept if not cost): Personal Home Garages

Inside such a garage, security & billing are done deals, leaving only choices of wiring & outlets

A standard 110V x 15 Amps outlet is labeled a **Level 1** electric vehicle charging station [1]

With its ~ 1.6 kW max power flow, a Leaf PEV would charge in an unacceptable 20 hours

A **Level 2** electric vehicle charging station would instead use 230V x 30 Amps [1]

Most homes now have only one or two 230V x 30 Amp circuits (for dryers & ovens)

New 230V x 30 Amp circuit(s) would have to be run from breaker box to garage

Requiring a licensed electrician to burrow new power lines through walls, ceilings . . .

With the resulting ~ 7 KW max power flow, a Leaf PEV should fully charge in ~ 4.5 hours

Level 3 electric vehicle charging stations are proposed at 480V x 400 Amp capacity [1]

At ~ 192 kW max power flow, a Leaf PEV might fully charge in ~ 1.5 hours

But that, alone, is 4X the power **ever** consumed by whole large modern homes

Based on time + power: **Level 2** home charging seems the only acceptable alternative

1) https://www.yumpu.com/en/document/view/44916420/tom-king-clean-energy-speakers-series

What about the likely up front cost to the homeowner?

According to a different 2008 U.S. Idaho National Lab report, on average: [1]

Cost of adding 1 new Level 1 (110V / 15 Amp) charging outlet to a garage = $878

Level 1 Residential	Labor	Material	Permits	Total
EVSE (charge cord)	- -	$250	- -	$250
Residential circuit installation (20A branch circuit, 120 VAC/1-Phase)	$300	$131	$85	$516
Administration costs	$60	$43	$9	$112
Total Level 1 Cost	$360	$4 24	$94	$878

Cost of adding 1 new Level 2 (230V / 30 Amp) charging outlet to a garage = $2,146

Level 2 Residential	Labor	Material	Permits	Total
EVSE (32 A wall box)	- -	$650	- -	$650
EVSE (charge cord)	- -	$200	- -	$200
Residential circuit installation(40A branch circuit, 240 VAC/1-Phase)	$455	$470	$155	$1,080
Administration costs	$91	$94	$31	$216
Total Level 2 Cost	$546	$1,414	$186	$2,146

But as a DIYer who recently ran a new power line through my home's walls, ceilings . . .

I must point out that the boxes above do **not** seem to include the costs of

putting walls, ceilings . . . back together and then restoring their paint & finishes!

That, plus report's age => My prediction of costs at least twice those stated above

1) Page 31 in: http://www.electrictechnologycenter.com/pdf/phevInfrastructureReport08.pdf

Bringing us to charging sites in open parking lots:

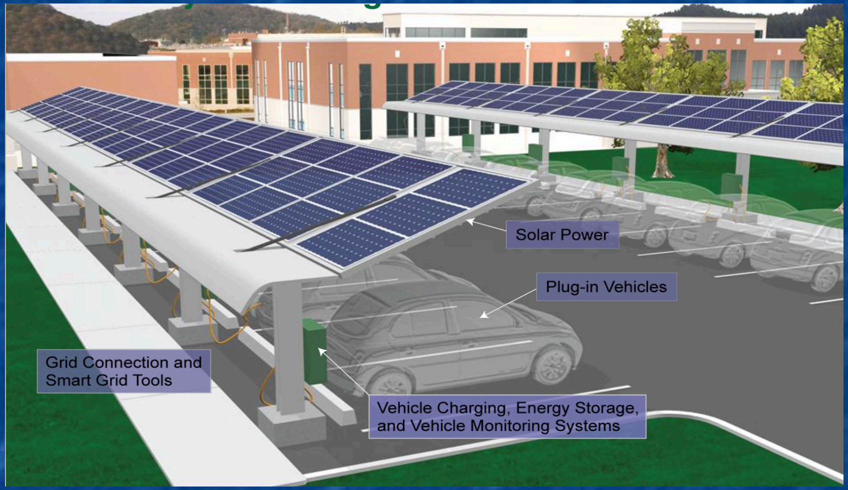
In such commercial / semi-commercial locations, large power lines are likely nearby

And before or after lot construction, wiring could be easily slot-trenched underground

But plug-in outlets would have to withstand weather, accidental damage & vandalism

And any sort of outlet would have to facilitate proper identification & billing of users

One fanciful suggestion looked like this:



https://www.yumpu.com/en/document/view/44916420/tom-king-clean-energy-speakers-series

"Fanciful" because pictured ~3 m^2 of solar cells per car would (at best) deliver ~ 0.6 kW [1]

allowing a 30 kW-h Nissan Leaf to fully recharge after **50 hours (of midday sun!)**

1) See my note set: ***Solar Power I - Today's PV*** *(pptx / pdf / key):*

*Here is a much **less** fanciful suggestion:*

Stick with power from likely distant Green Grid power plants

DO NOT use conventional outlets susceptible to weather, damage & vandalism

DO USE buried magnetic induction coils coupling to coils in the floor of cars

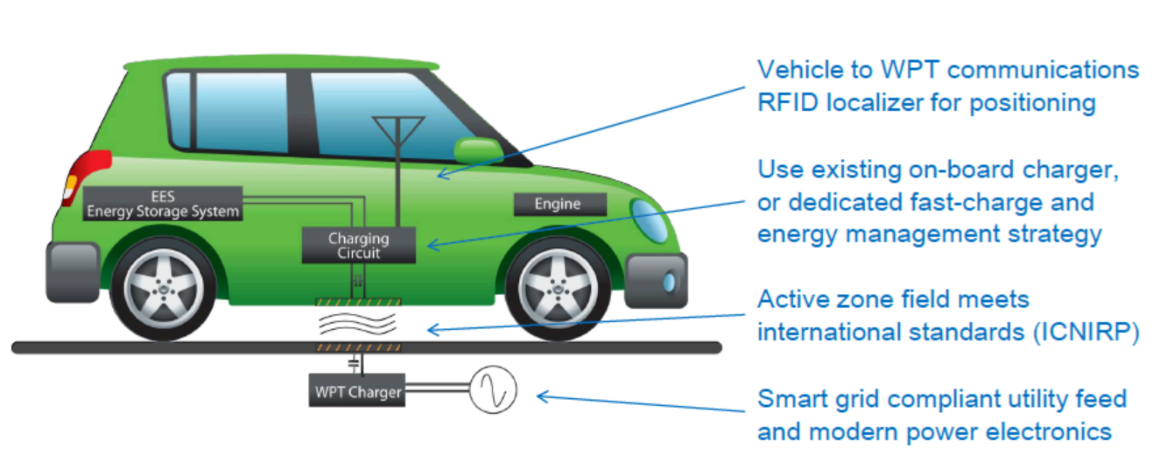
= Essentially a scaled up version of your electric toothbrush and its charger

ADD to that a buried short-range Bluetooth-like transmitter/receiver

Linking to your car's computer, negotiating quantity & billing for power received

If thief tried to steal power by slipping his own power-receiving coil under your car

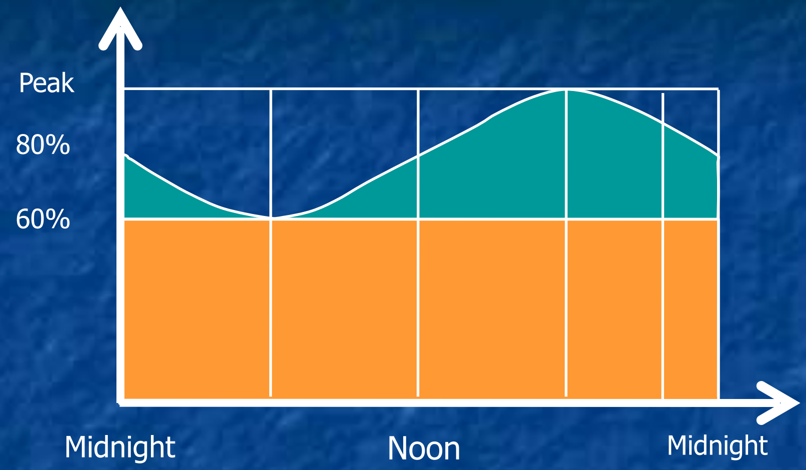
smart charger & car could detect power send/receive discrepancy, cutting it off!



1) https://www.yumpu.com/en/document/view/44916420/tom-king-clean-energy-speakers-series

But how will massive use of PEV's affect the Grid?

Today (with few PEVs), our use of Grid power peaks strongly in the early evenings:



Power companies deal with this by running two different types of power plant:

"Base plants" boil water into steam, driving turbine generators (e.g., coal & nuclear)

Before producing power, these plants must consume lots of energy heating up

Then, if turned off, as they cool back down their latent heat energy is wasted

Such steam-based Base plants thus want to **STAY** on, running near capacity

"Dispatchable plants" deal with the evening peak by **ONLY** then turning on

Effects of today's Base + Dispatchable power plant model:

Base plants maximize efficiency by near-constant & high-level power production

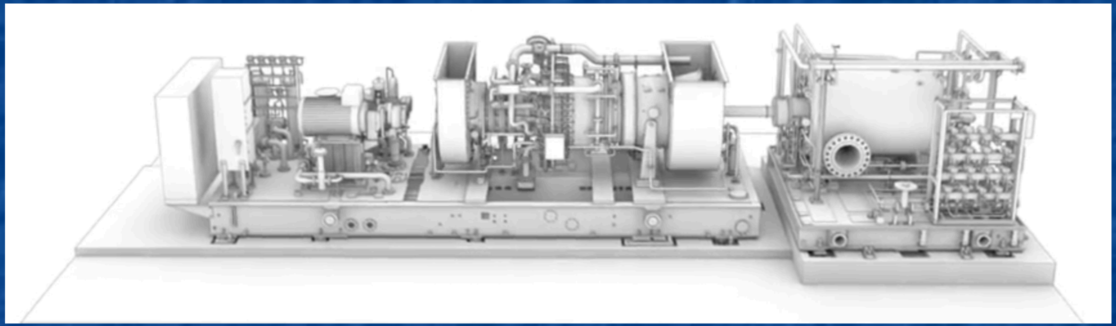
Their full-time high-power output helps justify purchase of clean technologies

Dispatchable plants plants may instead be used for as little as a few hours per day

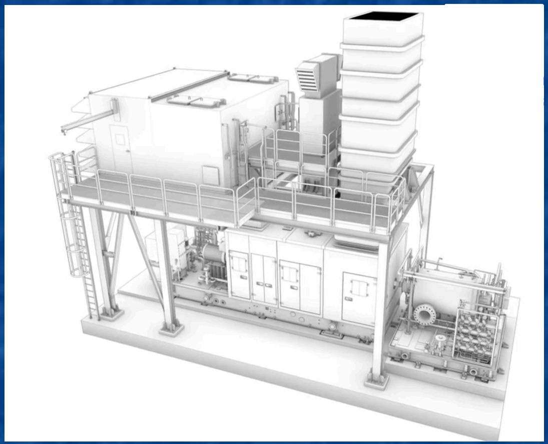
This drives power companies towards use of very low purchase price plants

Today's favorite: "Open-cycle" gas turbine (OCGT) power plants, which are this simple: [1]

Insides of an OCGT power plant:



Entire plant (for scale, note the guardrails):



But simplicity also makes OCGT's the dirtiest users of natural gas:

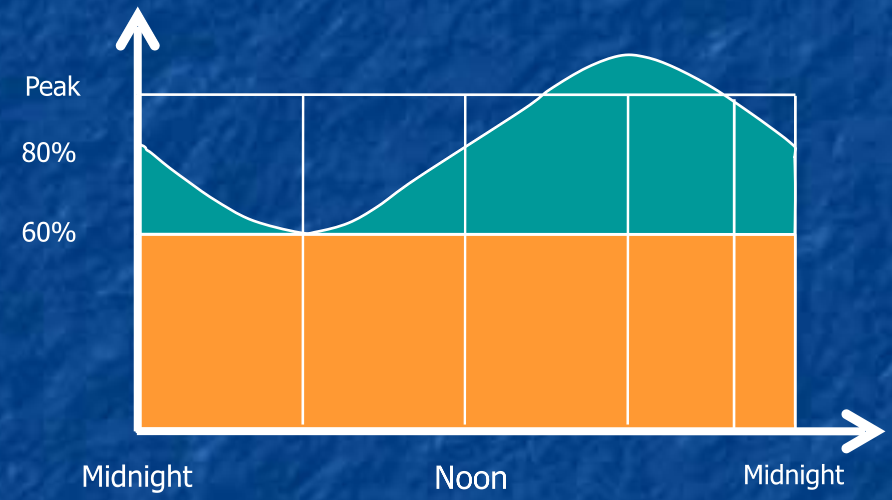
OCGT GHG emissions are only ~ 20% lower than those of coal power plants [1]

*1) For details see my note set: **Fossil-Fuel Power Plants** (pptx / pdf / key)*

Effect of adding PEVs to such a Base + Dispatchable power plant model?

PEV use will make things even worse because, arriving home in the evening,

most people will immediately plug-in their PEV, ADDING to peak power demand:



According to circa 2011 U.S. Oak Ridge National Lab models, from 2020 to 2030:

Without PEVs, U.S. evening peak power demand might grow by 45 GW

While with heavy use of PEVs & Level 1 chargers, it might instead grow by 155 GW

But what if we could instead "Shave the peak?" [2]

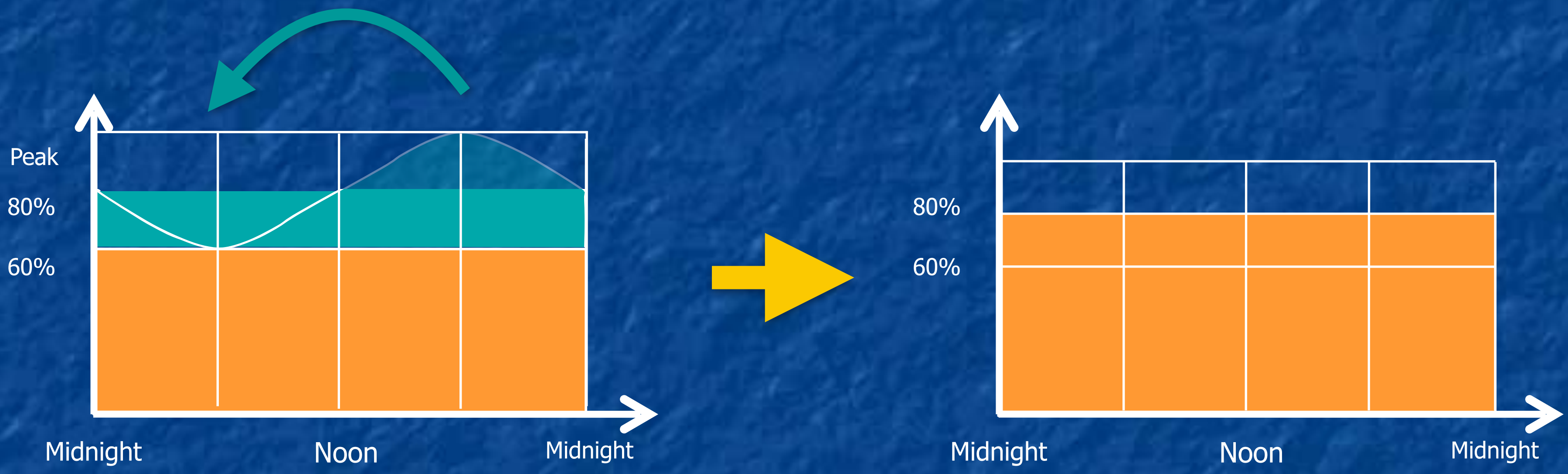
1) https://www.yumpu.com/en/document/view/44916420/tom-king-clean-energy-speakers-series

2) page 6 in: https://www.fueleconomy.gov/feg/topten.jsp?year=2020&action=MyMpg

Thereby transferring most of the evening demand to post-midnight hours:

If 100% successful, the daily power demand cycle would be flattened, allowing more

efficient, economical, and clean **Base power plants** to handle ~ all the demand



As noted earlier, this WOULD require large-scale Grid energy storage:

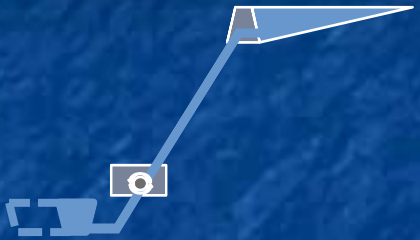
Storing part of the power produced post midnight - but not then needed,

so that it could instead be used the following evening

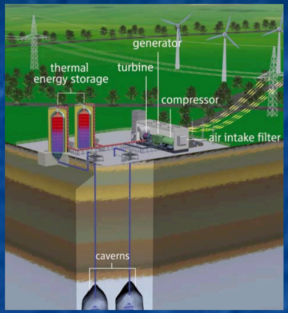
But in a **new scenario** this storage would be added by the massed batteries of PEVs:

Leading to this new option's name: ***Vehicle-to-Grid (or just V2G)***

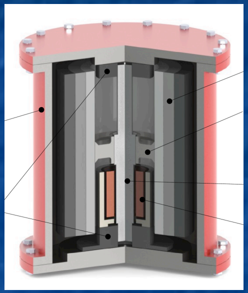
Which, in reality, would probably only **supplement** other forms of Grid energy storage:



Pumped Storage Hydro

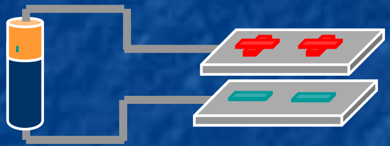


Compressed Air Storage

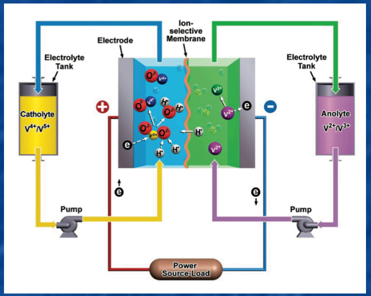


Flywheels

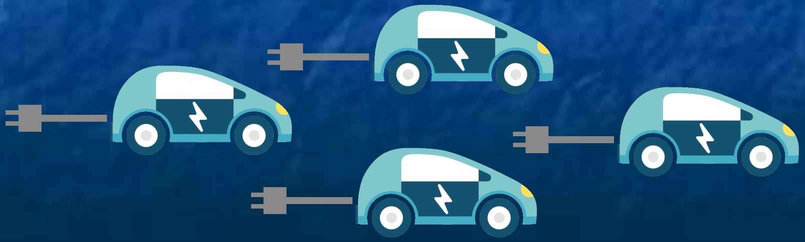
Fuel Cells



Super Capacitors

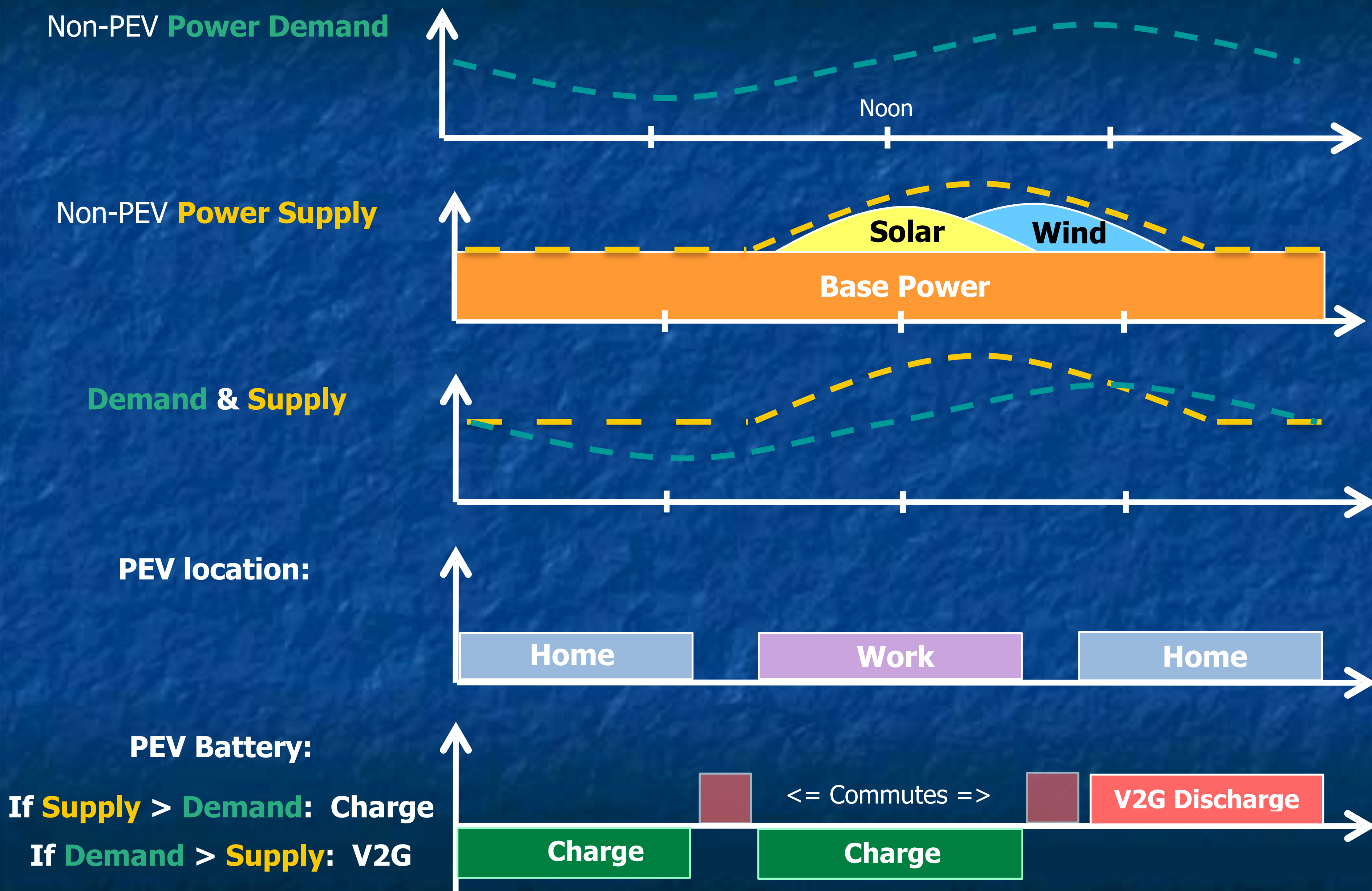


Super Batteries



+ Lots & Lots of PEVs

How V2G could help balance supply & demand in a future Green Grid:



For V2G to work:

PEV battery capacity would have to exceed that needed for the daily commute

Probably already the case as most owners demand not only a safety reserve,

but also enough capacity for longer-distance weekend / holiday excursions

Arriving at home, car owner would not want Grid to fully drain battery during evening

Car might be programmed to stop V2G if reserve fell below a certain level:

For instance, retaining enough reserve to allow short local pre-midnight trips

With an override option to disallow V2G discharge on special evenings

Instead of being based solely on time-of-day, default & override options, V2G might also

be based the price being charged for power at that time

which, reflecting demand, already rises sharply in evenings at many locations

All of which would require smart cars and/or smart Grids

with the latter being the topic of my note set **Smart Grids** (pptx / pdf / key)

But that's all in the future - How do we get there?

Studies addressing that question are cited HERE on this note set's Resources webpage

They discuss alternate political, economic & social strategies that could stimulate growth of the necessary PEV charging & Grid support infrastructures

These four studies were particularly comprehensive:

- 2013: Electric Vehicle Grid Integration in the US Europe and China - International Council on Clean Transportation
- 2015: Overcoming Barriers to Deployment of Plug-in Electric Vehicles, U.S. National Academies,
- 2017: Integrating Electric Vehicles within U.S. and European Efficiency Regulations, International Council on Clean Transportation
- 2020: Global EV Outlook - Entering the Decade of Electric Drive? International Energy Agency

But I'm going to leave deeper investigation of such strategies to the reader

Partially because strategies & requirements vary sharply from country to country

Partially because they also change with the political environment, as in the U.S. where support became obstruction from one administration to the next (raising doubts about the relevancy and value of older studies)

GREEN Grid + GREEN Hydrogen Fuel Cell / Battery Vehicles

Hydrogen Fuel Cells

Batteries depend upon the "electrochemical" transfer of electrons between atoms

Those transfers can be reversed, allowing for battery discharging **and** recharging,

even if, in real life, recharging is practical for only certain types of battery

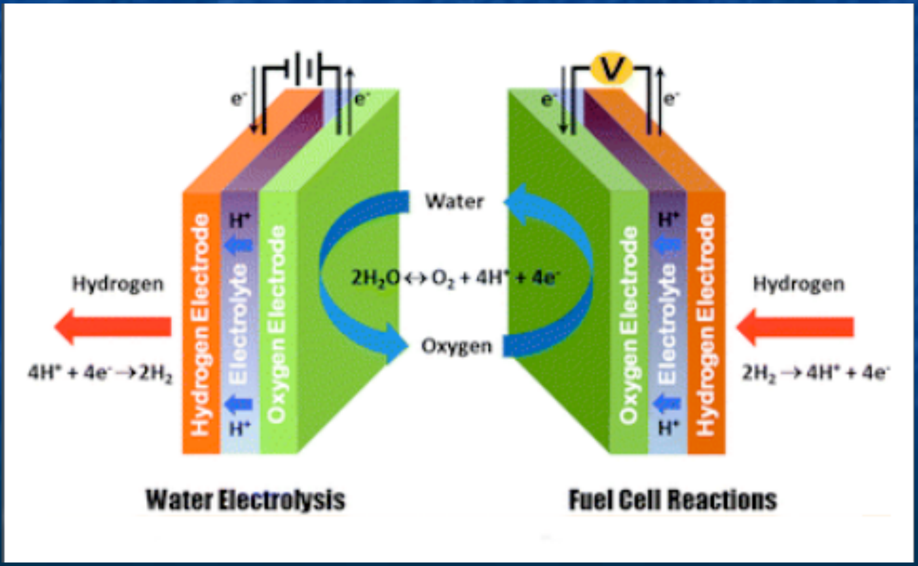
Fuel Cells share all of those qualities, leading to figures such as this one (from MIT) [1]

which depicts reversible **Hydrogen Fuel Cell** action based upon

the reversible electrically-driven decomposition of water:

At Left:

Supplied with electricity
the structure
produces H_2 gas



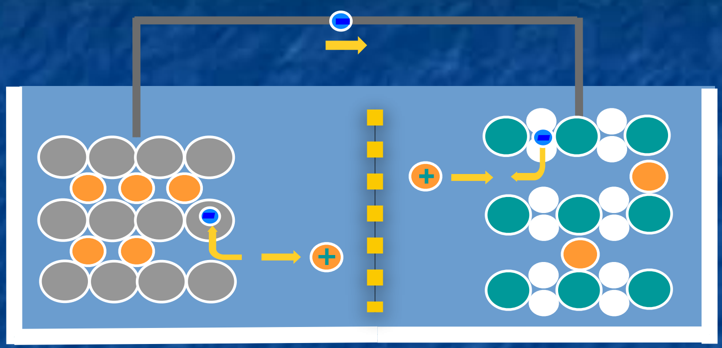
At Right:

Supplied with H_2 gas
the structure
produces electricity

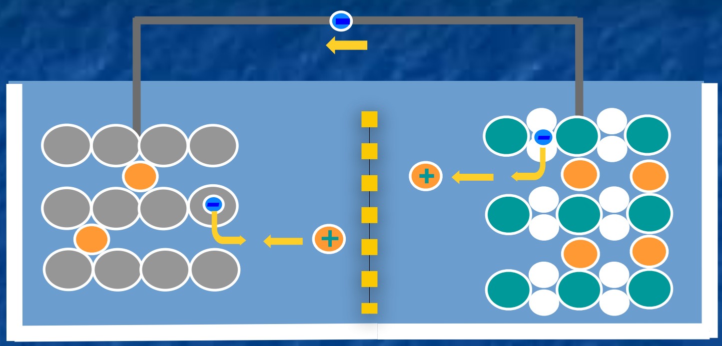
1) https://cees-www.mit.edu/index.php/item/29-reversible-fuel-electrolysis-cells.html

That parallels the reversible action within a Li-Ion Battery:

As depicted in my note set **Batteries & Fuel Cells** (pptx / pdf / key):



Discharge



Recharge

But that is a FALSE parallel: Simple Hydrogen Fuel Cells are NOT reversible

Because, unlike most batteries, simple H_2 Fuel Cells are **NOT closed systems**

During electric **charging** they expel hydrogen gas **TO** somewhere else

During electric **discharging** they draw in hydrogen gas **FROM** somewhere else

And those very different actions call for very different structures:

Hydrogen-producing Electrolysis Cell vs. hydrogen-consuming Fuel Cell

Electrolysis Cell:

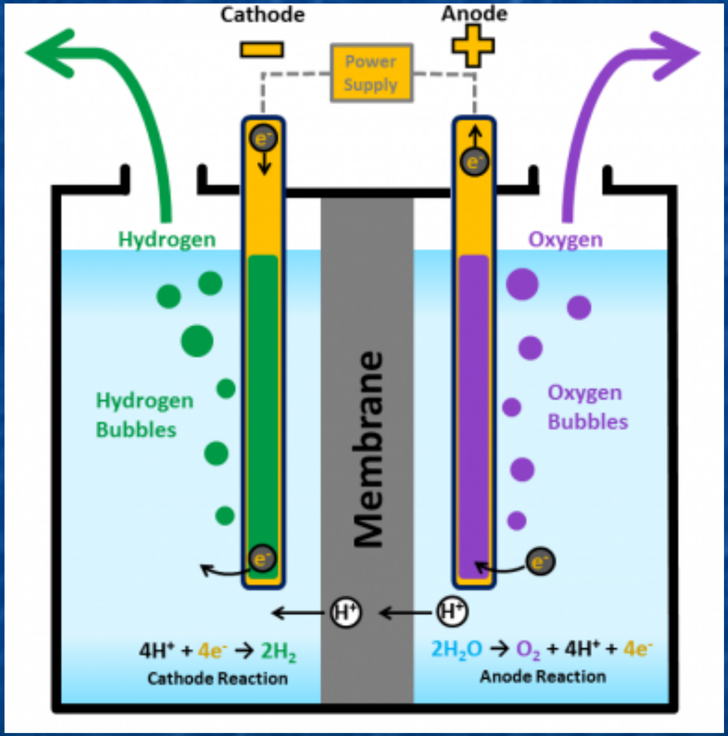
Reactions consuming **liquid** water

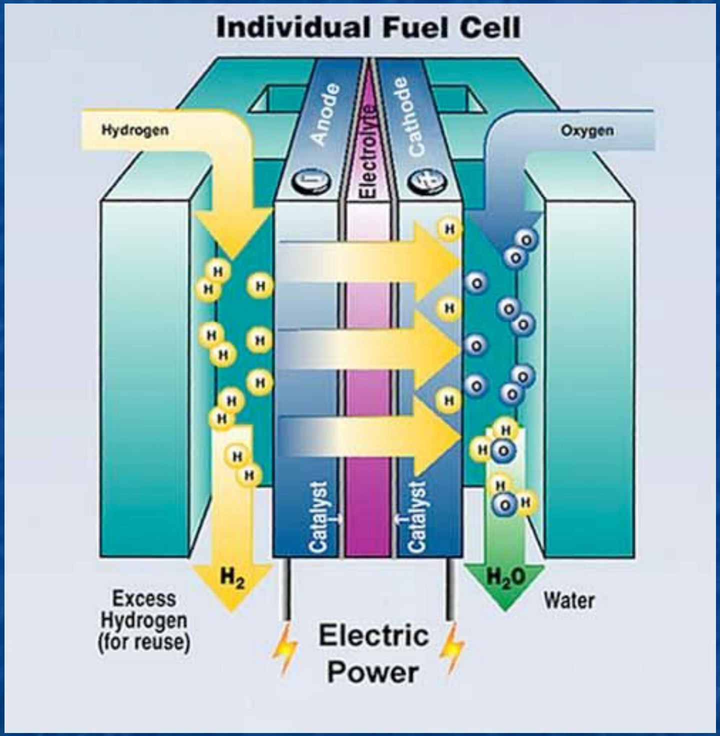
and releasing H_2 & O_2 **gases** [1]

Fuel Cell:

Reactions consuming **gaseous** H_2 and O_2

and releasing H_2O vapor (**gas**) [2, 3]





Left figure: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

Right figure: https://www.betterworldsolutions.eu/more-efficient-production-of-hydrogen-is-possible-says-stanford/

1) http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/electrol.html

2) https://en.wikipedia.org/wiki/Fuel_cell 3) https://www.energy.gov/eere/fuelcells/types-fuel-cells

To make a H_2 Fuel Cell reversible, it must become a "closed system"

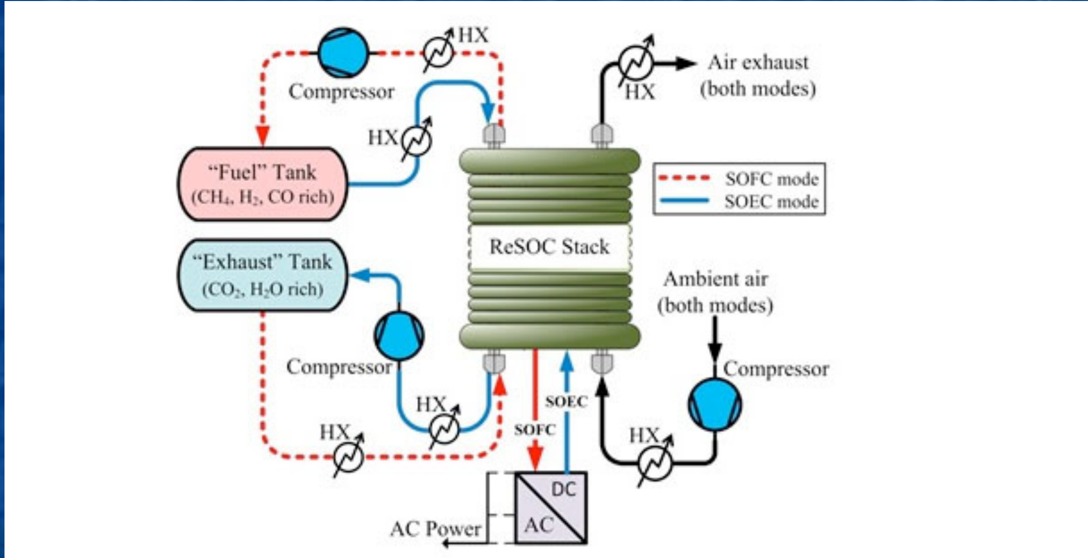
Where no chemicals are allowed to enter or leave,

and where gases can be transformed into liquids (via pumps & compressors)

This yields distinctly **non-simple reversible Hydrogen Fuel Cell SYSTEMS**,

generally based upon either Proton Exchange Membrane (PEM) cells, [1, 2]

or as depicted here, Solid Oxide Cells (SOCs) => "Re(versible) SOC" [3]



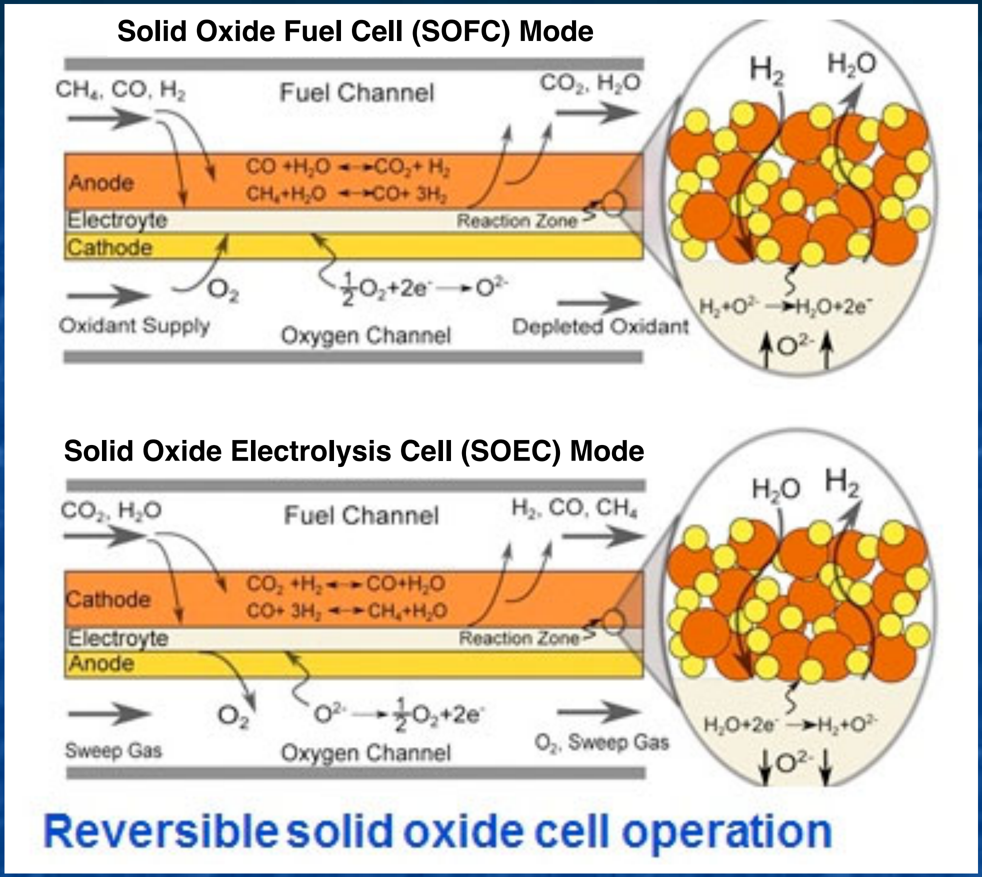
Simplified schematic of a ReSOC electrical energy storage system

Figure from: https://aes.mines.edu/design-and-analysis-of-reversible-solid-oxide-cells-for-electrical-energy-storage/

*Imagine how complex the full **non-simplified** system must be!*

1) hhttps://en.wikipedia.org/wiki/Regenerative_fuel_cell 2) https://www.altenergy.org/renewables/regenerative-fuel-cells.html
3) https://www.electrochem.org/dl/interface/wtr/wtr13/wtr13_p055_062.pdf

*Further, to operate in both modes, **atomic structures** must also be very complex:*



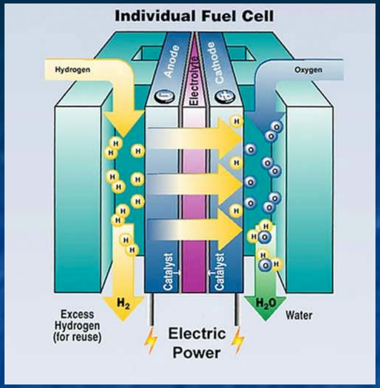
Such system & cell complexity IS being being contemplated for

large, stationary, reversible **Grid energy storage**, as depicted earlier:

But (at least for now) it is **far too complex for use in vehicles**

Upper labels added to:: https://aes.mines.edu/design-and-analysis-of-reversible-solid-oxide-cells-for-electrical-energy-storage/

Vehicles instead use "simple" ***non-reversible*** *H_2 Fuel Cells:*



Those Fuel Cells are NOT drop-in replacements for Batteries:

Batteries are "fueled" electrically, by plugging them in for recharging

Simple Fuel Cells are fueled by H_2 gas (from "somewhere else") + O_2 from air

Fuel Cell Electric Vehicles are thus really **Hydrogen Fueled Electric Vehicles**

But complicating FCEVs even further:

1) **Fuel Cells don't "like" to vary their power output - which vehicles require**

2) **Regenerative Braking = Energy recovery, which simple Fuel Cells can't do**

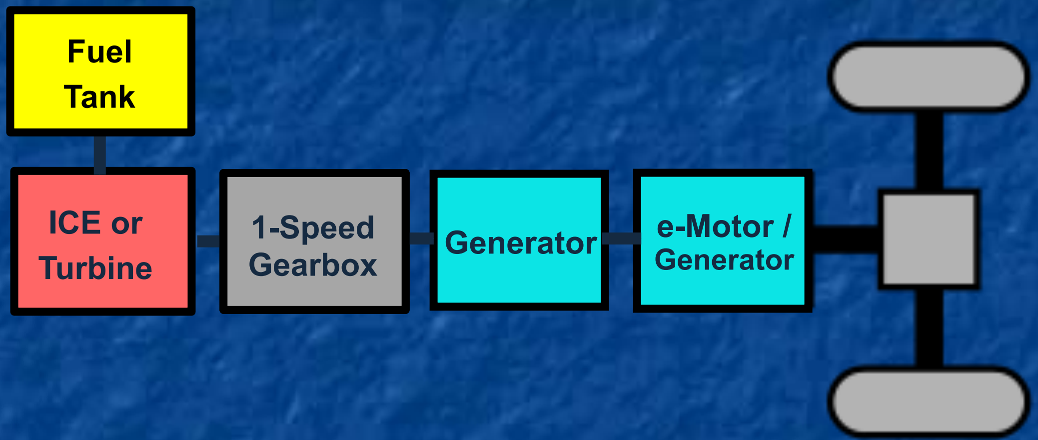
To solve both problems, **FCEVs MUST HAVE BATTERIES**, meaning FCEVs are really:

Hydrogen Fuel Cell Battery Electric Vehicles (HFCBEVs?)

FCEVs thus end up resembling earlier Diesel-Electric Hybrid Vehicles

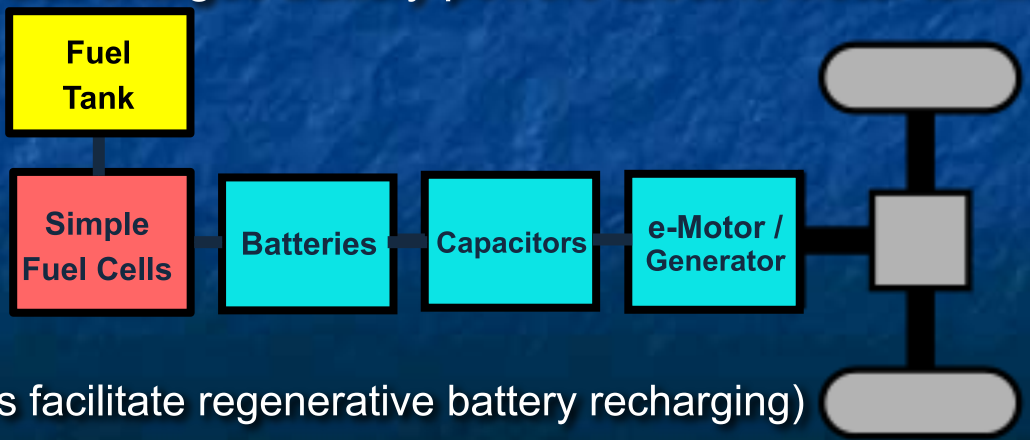
Diesel-Electric Hybrid Vehicles:

Diesel Generator powers Electric Motor turning wheels



(Hydrogen) Fuel Cell (Battery) Electric Vehicles:

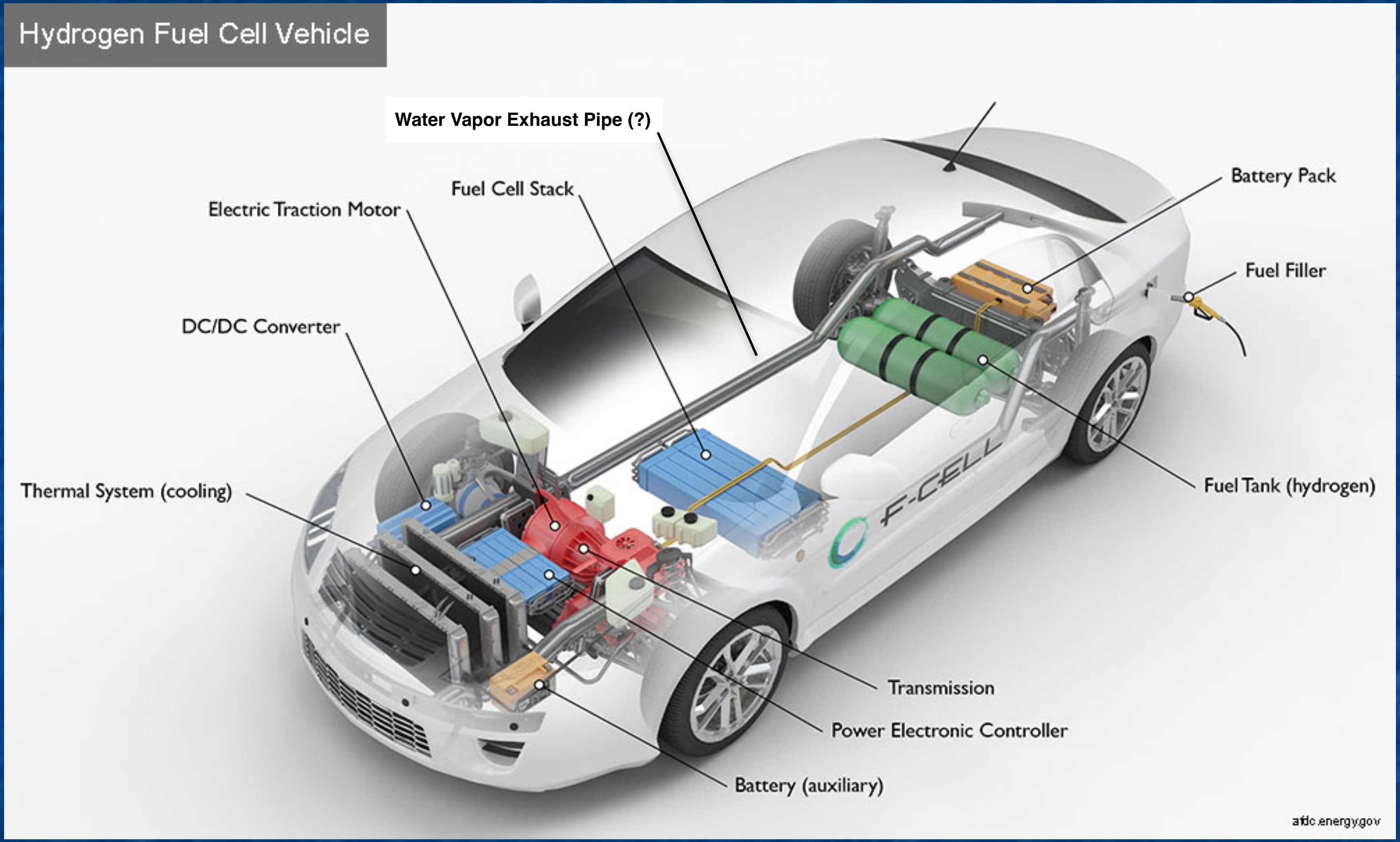
Hydrogen Fuel Cell charges Battery powers Electric Motor turning wheels



(Capacitors facilitate regenerative battery recharging)

Or as more commonly depicted:

From the U.S. Department of Energy's Alternative Fuels Data Website [1]



Not shown: Capacitors needed to rapidly capture Regenerative Braking energy

and then pass it on, more slowly, to recharge the batteries

1) One label added to: https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work

A quick comparison to Plug-in Battery Electric Vehicles?

Fuel Cell Vehicle Pros:

Charging Time: In contrast to the hours needed to recharge PEVs, FCEV tanks can be filled with H_2 in minutes because, aside from engaging a H_2-tight coupling, the process is virtually identical to that we now use to add gasoline

Vehicle Weight: While FCEVs retain batteries, they need far fewer than PEVs

And the Fuel Cells largely replacing those heavy batteries are considerably lighter

That means lighter FCEVs need less energy (1/2 **m** v^2) to accelerate which remains important because Regenerative Braking systems cannot fully recapture (and thus conserve) kinetic energy during stop-and-go driving

Fuel Cell Vehicle Cons:

Low Fuel Cell Efficiencies:

As discussed earlier, Batteries can return up to ~ **90%** of the energy put into them

leading to PEV "Tank-to-Wheel" vehicle energy efficiencies of up to ~ 75%

Fuel Cells return far less of the energy put into them: [1]

H_2 Fuel Cell Type:	Alkaline	Proton Exchange Membrane	Solid Oxide
Return Efficiency:	**62%**	**30-50%**	**55-60%**

Poisoning of Key Types of Hydrogen Fuel Cells:

In today's particularly well-developed & commonly used Alkaline Fuel Cells,

trace CO_2 in the fuel gases reacts to "poison" cathode surface reactions,

requiring use of purified O_2 (rather than O_2 drawn from unpurified air)

Plus two potentially crippling Cons:

High Energy Input & GHG Output of Today's Hydrogen Production Process

Absence of a Hydrogen Distribution Infrastructure

From an exceptionally comprehensive Wikipedia webpage: https://en.wikipedia.org/wiki/Fuel_cell

Hydrogen Production:

Today, 95-97% of our H_2 [1, 2] comes from a process hiding behind the vague name:

Steam Reforming [2]

"hiding" because a far more descriptive name is **Steam Reforming of Methane**

which at least hints at its underlying reactions (and problems):

$CH_4 + H_2O$ (steam) => $CO + 3\ H_2$ $\Delta H = -206$ kJ / mole

$CO + H_2O$ (steam) => $CO_2 + H_2$ $\Delta H = -41$ kJ / mole

Combined: **$CH_4 + 2\ H_2O$ (steam) => $CO_2 + 4H_2$** $\Delta H = -247$ kJ / mole

Production of supposedly "clean" H_2 is thus both energy & GHG intensive

Begging the question of how the **other** 3-5% of today's H_2 is produced?

The answer: Mostly via the same water electrolysis process discussed a little earlier:

$2\ H_2O$ (liquid) <=> $2\ H_2$ (gas) + O_2 (gas)

Which is still **energy-intensive** and, while it **directly emits no GHG's**,

indirectly emits GHG's if the required electricity comes from a still **non-Green Grid**

Resurrecting familiar questions about when & where FCEVs become cleaner than ICEs

1) https://en.wikipedia.org/wiki/Fuel_cell *2) https://en.wikipedia.org/wiki/Hydrogen_production*

*Answers again call for full **FCEV "Well-to-Wheel" Energy & GHG Analyses***

But recall that: Well-to-Wheel = Well-to-Tank + Tank-to Wheel

Eliminating "Well" GHG emissions requires **Electrolysis** powered by a Green Grid

But how would that H_2 then get from that "Well" to the vehicle's tank?

The futuristic scenario is that of H_2 completely replacing methane natural gas

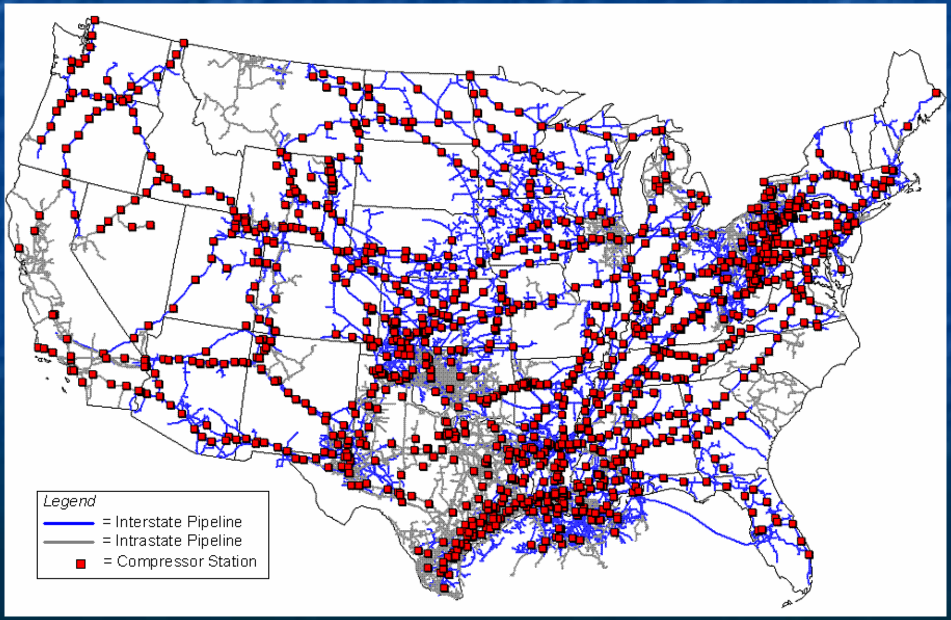
Allowing it to travel through mostly existing pipelines from far-distant "wells,"

with those "wells" then being huge industrialized Water Electrolysis Plants

Existing U.S.

Natural Gas

Pipeline Network:



http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/images/compressorMap.gif

*But that would likely require **complete** North American CH_4 to H_2 conversion*

Which presents **huge** challenges and complexities, as elaborated

in my separate full note set: **A Hydrogen Economy?** (pptx / pdf /key)

A simpler & nearer-term scenario is building smaller local hydrogen depots roughly equivalent to today's gasoline stations

As supplied by trucked-in hydrogen, or by hydrogen electrolyzed on-site from H2O

This scenario **is** being tested, at least on a small scale, in California

Building such a "start from scratch" infrastructure has proven challenging, [1, 2]

as has been noted in press with titles such as:

"Costs Check Growth of Fuel-Cell Infrastructure" [3]

"Why We Still Can't Deliver on the Promise of Hydrogen Cars" [4]

"California's 'Hydrogen Highway' Never Happened - Could 2020 Change That?" [5]

1) https://cleantechnica.com/2018/09/14/a-look-at-hydrogen-fueling-infrastructure-in-2018/
2) https://ww2.arb.ca.gov/sites/default/files/2020-09/ab8_report_2020.pdf
3) https://www.wardsauto.com/technology/costs-check-growth-fuel-cell-infrastructure
4) https://www.thedrive.com/tech/33408/why-we-still-cant-deliver-on-the-promise-of-hydrogen-cars
5) https://calmatters.org/environment/2020/01/why-california-hydrogen-cars-2020/?

The Crux of those Negative Reports?

From the WardsAuto.com article: [1]

"The current cost to construct a hydrogen fueling station is between $1 million and $2 million. . . this compares to an estimated $200,000 for an ultra-fast-charging electric-vehicle station equipped with a single 350-kW charger."

(But hydrogen stations) also have far greater capacity . . . a hydrogen station can refuel between 100 and 300 cars per day, (because) it takes only three to five minutes to refuel per car."

From the TheDrive.com article: [2]

"Despite more than half a century of development . . . hydrogen fuel-cell cars remain low in volume, expensive to produce, and restricted to sales in the few countries or regions that have built hydrogen fueling stations.

"(FCEV models have been) built in volumes of 1,000 a year or more . . . Meanwhile, 10 years after the first modern EVs went on sale, electric cars sell in the low millions a year globally - two orders of magnitude higher than their hydrogen counterparts."

From the CalMatters.org article: [3]

"The (hydrogen) technology remains expensive and hasn't gained wide traction, ceding the green-transportation crown to battery-powered electric vehicles, which are more widely available and support an ever-growing recharging network. "

1) https://www.wardsauto.com/technology/costs-check-growth-fuel-cell-infrastructure

2) https://www.thedrive.com/tech/33408/why-we-still-cant-deliver-on-the-promise-of-hydrogen-cars

3) https://calmatters.org/environment/2020/01/why-california-hydrogen-cars-2020/?

*Nevertheless, FCEV Well-to-Tank Analyses **have** been published:*

Further, some of those studies compare data for FCEVs with those for PEVs

A selection of those studies is given HERE in his note set's Resources webpage

I'll discuss a few of those studies now, but only briefly, partially in the interests of time,

but more out of my doubts about the accuracy FCEV modeling

The reasons for my doubts?

While optimum PEV technology & infrastructure are pretty well established & tested,

optimum Fuel Cell **technology** has not yet been determined,

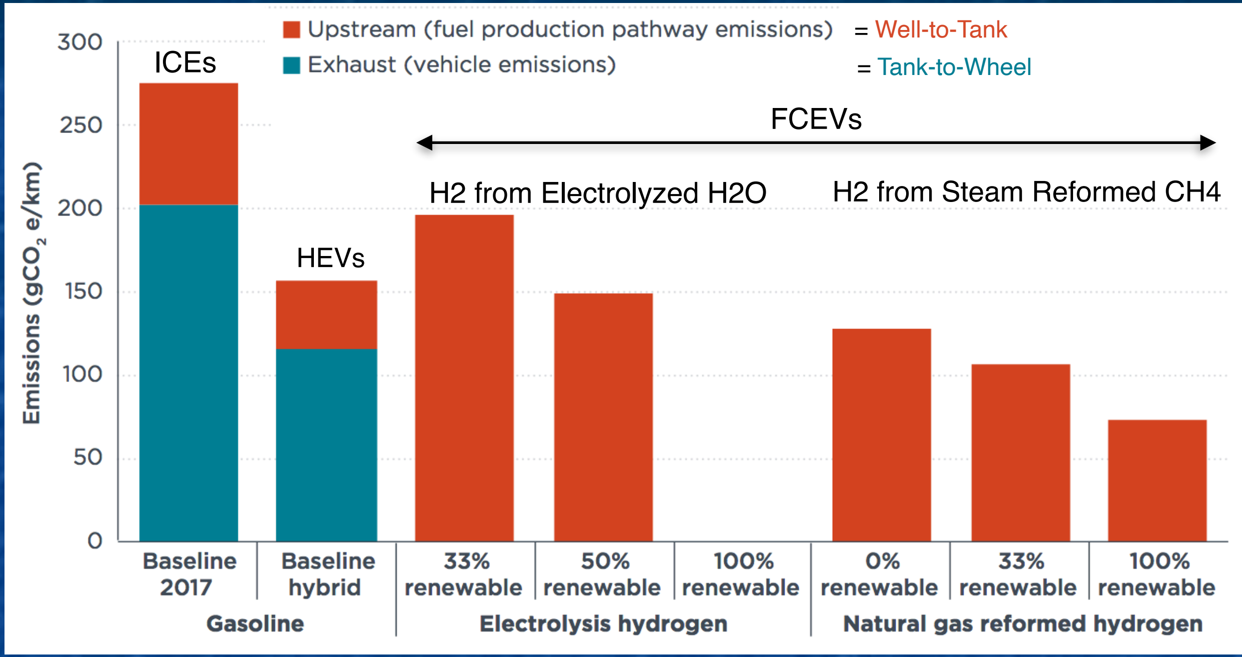
optimum FCEV **infrastructure** has not yet been determined,

and neither has yet undergone much more than superficial testing

Nevertheless, onward:

Well-to-Wheel GHG emissions for ICE vs. HEV vs. FECV

From a 2017 study from the International Council on Clean Transportation in 2017: [1]



H2O Electrolysis H2, drawing power from:

33% Green Grid (= 2019 U.S):
FCEV GHGs fall between ICE & HEV

50% Green Grid: FCEV GHGs = HEV GHGs

100% Green Grid: FCEV GHGs => 0

NG Steam Reformed H2, drawing power from:

33% Green Grid (= 2019 U.S):
FCEV GHGs slightly lower than HEV

50% Green Grid: FCEV GHGs ~ 3/4 HEV GHGs

100% Green Grid: FCEV GHGs ~ 1/2 HEV GHGs

1) My recaptioned version of figure on page 9 of:
https://theicct.org/sites/default/files/publications/Hydrogen-infrastructure-status-update_ICCT-briefing_04102017_vF.pdf

From that figure:

For the **present day non-Green U.S. Grid**, considering GHG emissions alone:

FCEVs using electrolyzed H2 are **significantly worse** than Gasoline HEVs

FCEVs using Steam Reformed H2 are **only slightly better** than Gasoline HEVs

Why?(!)

Because GHGs from the non-Green-Grid electricity used for Electrolysis are worse than the CO2 emissions intrinsic to Steam Reforming's chemical reactions

Overall, the above would seem to make HEVs a **slightly better** near-term option

But, unlike HEVs, FCEVs require substantial new infrastructure,

infrastructure likely having substantial construction monetary & emission costs,

seemingly instead making HEVs a **strongly better** near-term option

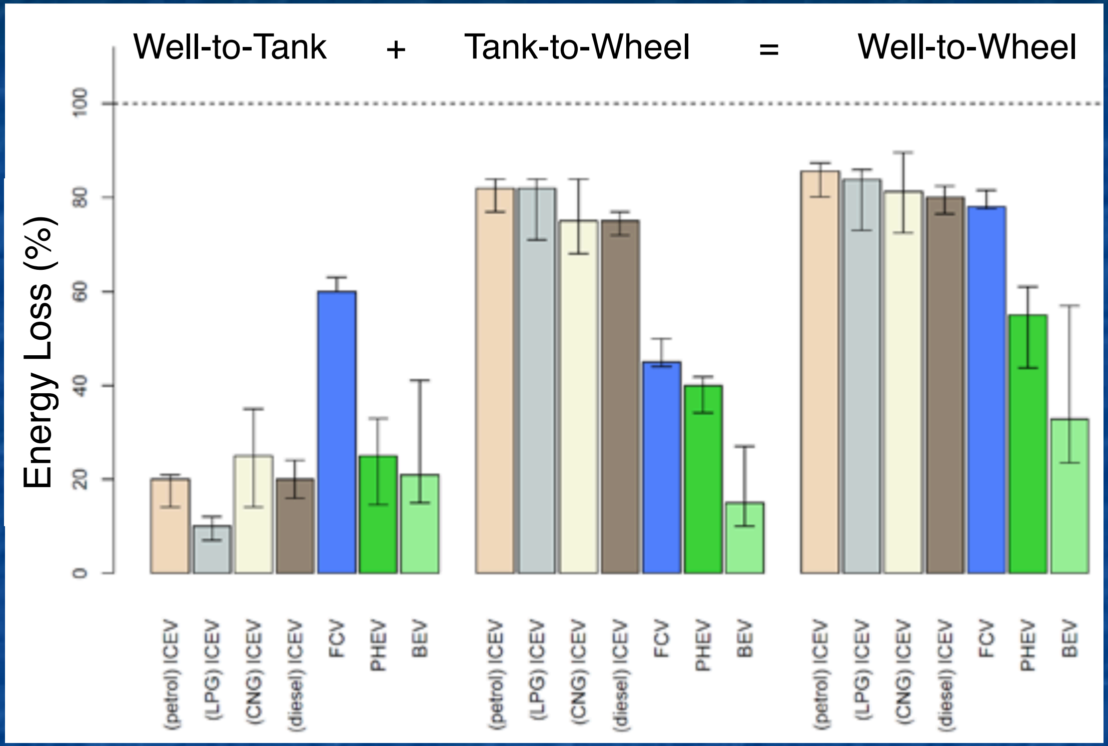
But what about the PEV option?

Further, rather than trying to cross compare FCEV WtW vs. PEV WtW studies,

do any studies DIRECTLY compare FCEVs & PEVs?

*A 2018 Australian study provides a **partial** FCEV to PEV comparison:*

"Partial" in that it compares W2W Energy use, but not W2W GHG emissions [1]



FCEVs ("FCVs") expend substantially more energy than PHEVs & PEVs ("BEVs")

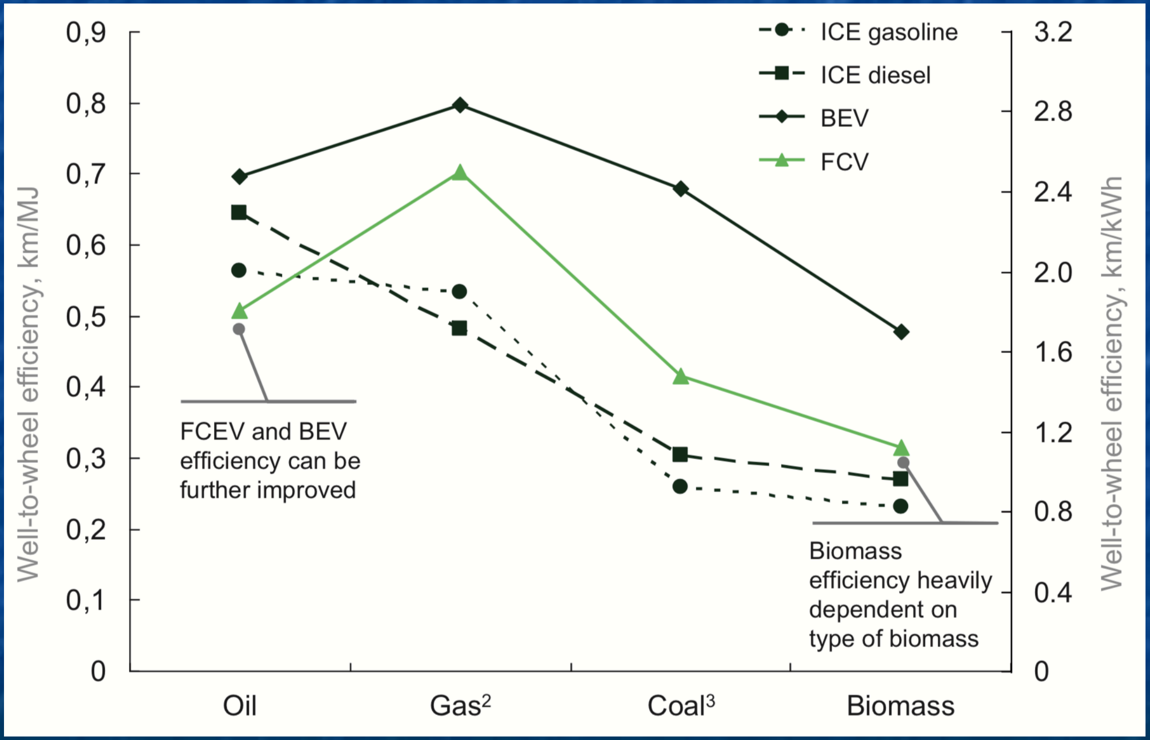
Which, although they do not calculate it, the authors state they expect will map into similarly higher GHG emissions for FCEVs compared to PHEVs & PEVs

1) https://www.researchgate.net/publication/328782184_Where_are_we_heading_with_electric_vehicles

A European study reached similar conclusions:

From a study commissioned by a consortium of companies & NGOs involved in auto manufacture, fossil-fuels, electric power, wind power, H2 generation & fuel cells: [1]

"The well-to-wheel (energy) efficiency of FCEVs is comparable to ICEs, while BEV remains the most efficient"



Horizontal axis = Dominant "feedstock" used in directly or indirectly fueling the vehicle

1) Figure from page 28 in: https://www.fch.europa.eu/sites/default/files/documents/Power_trains_for_Europe.pdf

However, examined in more detail, that report also concluded that:

"BEVs are ideally suited to smaller cars and shorter trips"

"FCEVs are the lowest-carbon solution for medium/larger cars and longer trips"

Leading to that study's overall comparison of vehicle strengths & weaknesses:

	FCEV 	BEV 	PHEV 	ICE 
Perfor-mance	▪ Driving performance in similar range to ICE ▪ ~600 km average driving range ▪ Refueling only takes a couple of minutes ▪ Fewer services needed	▪ Limited energy storage capacity and driving range (150-250 km) ▪ Refueling time in the order of hours[2] ▪ Ideally suited to smaller cars and urban driving	▪ Driving range equal to ICE in ICE drive (>800km); 40-60 km in electric drive ▪ Similar top speed, gasoline refueling time & service intervals ▪ Battery recharging takes some hours	▪ Highest driving range ▪ Best top speed and refueling time ▪ Only service intervals shorter
Environ-ment	▪ High CO_2 reduction (~80%) compared to today with CCS & water electrolysis ▪ No local vehicle emissions ▪ Lowest carbon solution for medium/larger cars & longer trips	▪ High CO_2 reduction (~80%) if CCS or renewable energy is used ▪ Depends on electricity footprint ▪ No local vehicle emissions	▪ Considerable CO_2 reduction (~70%) ▪ Some local emissions in ICE drive ▪ Low CO_2 if 100% biofuels	▪ Highest CO_2 and local vehicle emissions ▪ Unlikely to meet EU CO_2 reduction goal for 2050 ▪ Low CO_2 if 100% biofuels
Econo-mics[1]	▪ Purchase price is ~€4,000 higher than ICE ▪ TCO comparable to ICE for larger, but not smaller cars ▪ Infrastructure cost comparable cost to BEVs	▪ Economic for smaller cars ▪ Purchase price higher than ICE ▪ TCO ~€3,000 higher than ICE TCO ▪ Fuel costs comparable to ICE due to high infrastructure cost	▪ Higher purchase price and TCO than ICE ▪ Better fuel economy than ICE for larger cars ▪ Low infrastructure cost	▪ Most economic vehicle ▪ Lowest purchase price ▪ Higher fuel or maintenance costs ▪ Existing infrastructure

In addition to such Well-to-Wheel FCEV to PEV comparisons:

Other studies & articles raise broader environmental concerns, for instance:

About the impacts of Li & Co mining as required for present day PEV batteries

or about the impacts of Pt mining as required for present day FCEV fuel cells

Many such articles are listed HERE on this note set's Resources webpage

The net result of all of the above controversies?

The auto industry itself is fiercely divided on the question of FCEVs vs. PEVs

With VW and Tesla arguing strongly for a future auto industry based upon PEVs

While Toyota's is similarly adamant about an auto industry based upon FCEVs

Articles about this dispute are listed HERE on this note set's Resources webpage

But based upon my doubts about the immaturity of existing FCEV technology & data,

rather digging deeper into those disputes, I am going to move on to a final topic:

Autonomous Vehicles

And their possible environmental impact

My exploration of **Green(er) Cars and Trucks** has already run overly long

But given all of the attention now focused upon Autonomous Vehicles,

and given the environmental claims often associated with that discussion,

the possibility of their being a game changer must be addressed

The dream of robotic vehicles has deep historical roots [1]

But the recent rapid apearance of autonomous vehicles

can be attributed to two parallel technological developments

The first, going back to at least the 1980's, was based upon the realization that

new technology could reduce, if not completely eliminate,

those all too common **rear end collisions (a.k.a. "fender benders")**

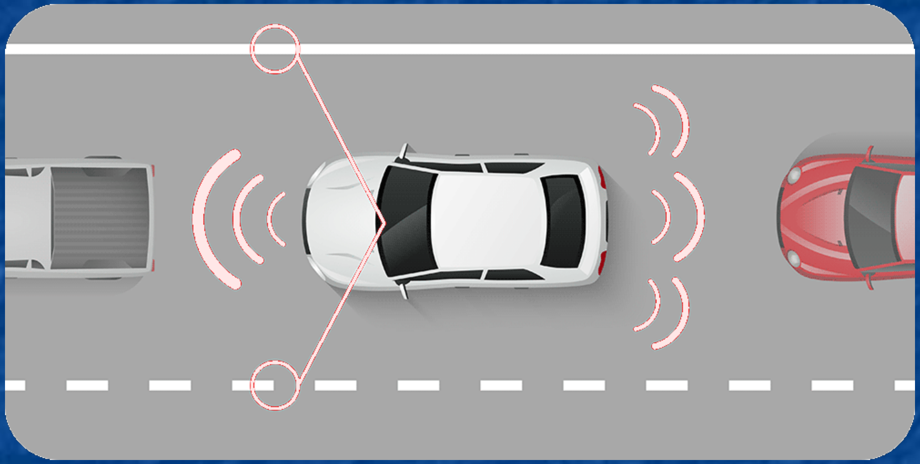
1) See, for instance: https://en.wikipedia.org/wiki/DARPA_Grand_Challenge

Figure: https://www.allstate.com/tr/car-insurance/first-fender-bender.aspx

That technology? Simple short-range front-bumper-mounted radar

As first tested by luxury car makers such as Mercedes,[1] radar + a little computation can easily warn a driver when brakes **absolutely must** be applied to avoid a collision

And from there it was a short jump to realizing that there was little downside risk to just bypassing the driver and applying those brakes automatically



Thus were born what we now call **Advanced Driver Assistance Systems (ADAS)** [2-4]

Figure: https://yourbrakes.com/automatic-braking-systems/

1) https://www.automoblog.net/2019/04/20/brief-history-high-tech-safety-features/

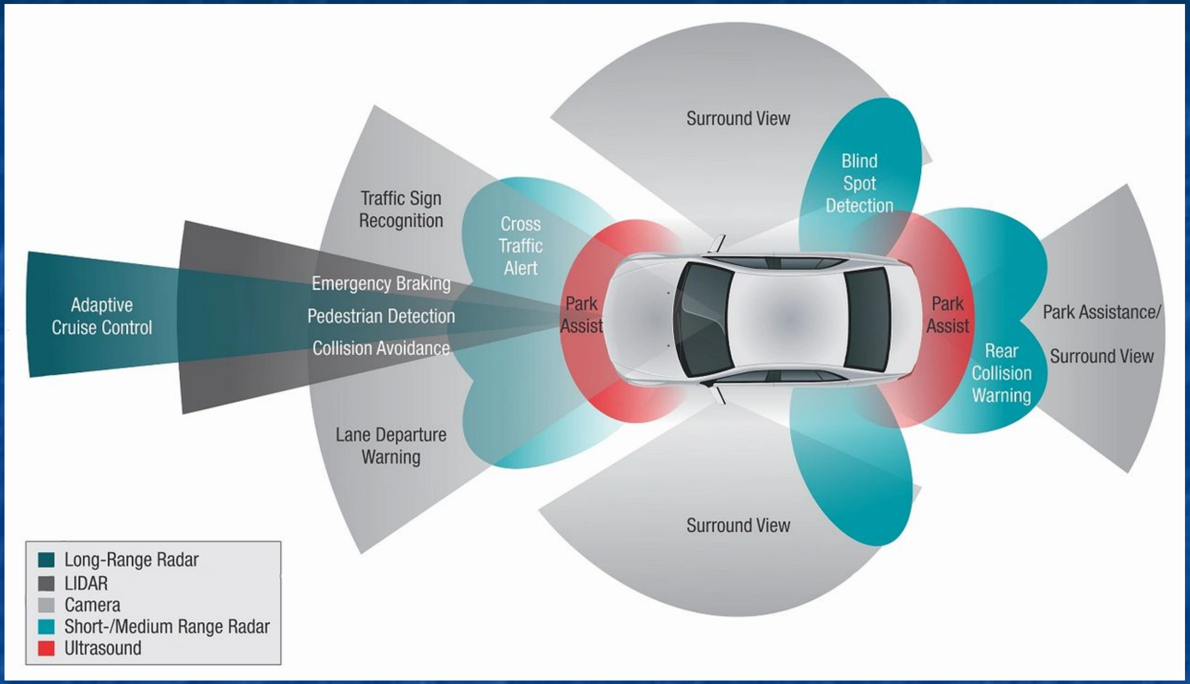
2) https://www.its.dot.gov/history/offline/download.pdf

3) https://en.wikipedia.org/wiki/Advanced_driver-assistance_systems

4) https://bmwglass.com/details/f/adas-sensor-calibration-425578c823be

The range of ADAS sensor options has since hugely multiplied:

To include microwave, laser, sound and camera-based possibilities



Which allow for sensing and driver warnings about:

front & rear-end collisions, stationary object avoidance (e.g., pedestrians),

lane holding deviations / departures, vehicles in driver's blind spots

or even camera-image-recognition reading of roadway warning signs

Figure) https://bmwglass.com/details/f/adas-sensor-calibration-425578c823be

But expanded sensing hasn't always lead to expanded automation

Because, while automated fender-bender braking had little downside risk,

actions such as fixed object avoidance, lane handling, and lane changing

open all sorts of possibilities for making a bad situation much much worse

Auto manufacturers thus hesitated to automate drivers completely "out of the loop"

But in the early 2000's, military forces faced increasing losses due to IEDs [1]

many if not most of which were not occurring on or even near desert battlefields,

but were instead associated with delivering supplies **to** those battlefields

In 2004 the U.S. **Defense Advanced Research Projects Agency (DARPA)** thus decided

to sponsor a **Grand Challenge** with millions of dollars in prize money for teams,

coming from anywhere in the world, from any sort of organization,

whose Autonomous Vehicle could successfully navigate a crude desert trail

1) Improvised Explosive Devices

*The first race was held in 2004 on a **120 km** California desert trail:* [1]

No Autonomous Vehicle came even close to completing the course,

with Carnegie-Mellon University's vehicle going the farthest, a paltry **11.78** km

But in a second 2005 race, all 23 vehicles surpassed that previous **11.78** km mark,

and five vehicles made it to the very end of that year's **212 km** desert course

Stanford University's team (led by a professor recruited from Carnegie-Mellon)

beat second place Carnegie-Mellon (adding both sand **and** salt to the wound) [2]

Stanford's Winning 2005 AV

Photo from page 28 in: https://www.its.dot.gov/history/offline/download.pdf

This surprisingly rapid progress caught the attention of the world's auto industry which,

following Stanford's lead, hired away large portions of both responsible faculties

Hence, seemingly overnight, the Autonomous Vehicle industry was born

1) https://en.wikipedia.org/wiki/DARPA_Grand_Challenge 2) DISCLOSURE: Holding Stanford degrees, I followed this competition closely

*How might Autonomous Vehicles be **MORE** environmentally friendly?*

Most such claims are associated with **highway driving** where automation facilitates:

Vehicle Merging [1]

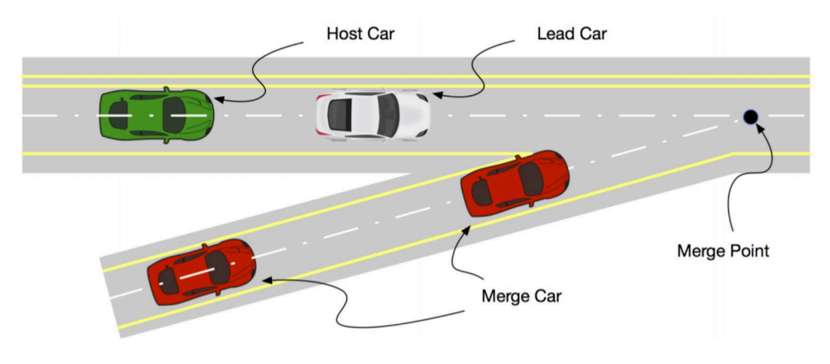


Figure 5. Lane merge scenario [125].

Platooning [2]

Both allow for vastly denser yet steadily moving traffic, doing that without the need to enlarge those highways, avoiding the large associated environmental impacts

Platooning (at right in an actual 1997 California test) **also** reduces energy consumption because following vehicles "draft" in air **already** set in motion by the lead vehicle

1) https://www.mdpi.com/2218-6581/7/4/67 *2) 1) https://www.fhwa.dot.gov/publications/publicroads/07july/07.cfm*

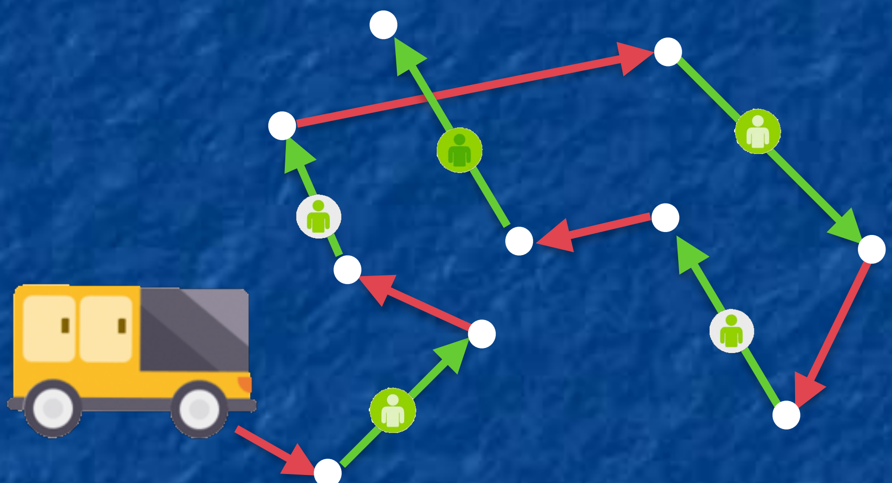
*How might Autonomous Vehicles be **LESS** environmentally friendly?*

Most of these concerns are instead associated with **city driving**

One concern is that people now hesitating to drive in dense urban environments,

such as the elderly, might take advantage of self-driving Autonomous Vehicles,

increasing total vehicle distance traveled & associated environmental impact



Another concern is that on-demand sharing of Autonomous Vehicles means that,

in addition to vehicle distances driven **with** passengers (green arrows),

vehicles will also drive long distances **without** passengers (red arrows),

FURTHER increasing vehicle distance traveled & environmental impact

Which AV effects win out? The environment friendly or unfriendly ones?

A number of studies, and reviews of studies, have tried to answer those questions

A collection of such sources is listed HERE on this note set's Resources webpage

My original plan was to describe selected studies from that collection in some detail

But reading through that collection, I saw the same pattern over and over again,

which can be amply demonstrated by summarizing just two of those sources:

- A review commissioned by the California Air Resources Board

but performed by the University of California at Berkeley [1]

- And a review by the International Council on Clean Transportation [2]

1) https://ww2.arb.ca.gov/sites/default/files/2020-06/automated_vehicles_climate_july2014_final1.pdf

2) https://theicct.org/sites/default/files/publications/New-mobility-landscape_ICCT-white-paper_27072017_vF.pdf

From California's Air Resources Board / UC Berkeley:

In this 2017 review, data from five source studies was summarized thusly:

Study	Metric	Effect Magnitude	Time Frame	Notes
Anderson et al. (RAND), 2014	Fuel Economy	+100% - +1000%	2050+	Based on aggressive vehicle weight reductions
Brown et al., 2014	Fuel Demand	-91% - +173%	90% AV penetration	Range based on scenarios with different effects
Fagnant & Kockelman (Eno Center), 2013	VMT	+9%	90% AV penetration	Estimates also given for lower market share; fuel efficiency gains assumed
	Fleet size	-42.6%		
Fagnant & Kockelman, 2014	Energy use	-12%	Fleet is all shared AVs	Per shared AV, vs. avg. light-duty vehicle
	GHG	-5.1%		
Spieser et al., 2014	Fleet Size	-66%	Fleet is all shared AVs	No energy-only outputs modeled

Concerning the huge uncertainties seen in **Effect Magnitude**, the report concluded:

"First, there are **too few reliable studies covering too wide a range of outcomes** to allow drawing comfortable conclusions.

Second, **comparisons are challenging as the range of modeled output measures vary**.

Third, researchers are **relying on assumptions and estimates mapped onto AVs from other automobile and travel studies**.

The findings are probably best thought of as bounding or order-of-magnitude estimates at this early stage."

1) https://ww2.arb.ca.gov/sites/default/files/2020-06/automated_vehicles_climate_july2014_final1.pdf

From the International Council on Clean Transportation [1]

Which summarized one particularly comprehensive source via this table:

Study	New mobility category	Metric	Effect
Brown et al. (2014)	Fully autonomous, semi-autonomous	Platooning	–10% energy use
		Efficient driving	–15% energy use
		Efficient routing	–5% energy use
		Travel by underserved	+40% energy use
		Efficient driving (additional)	–30% energy use
		Faster travel	+30% energy use
		More travel	+50% energy use
		Light-weighting and size optimization	–50% energy use
		Less time searching for parking	–4% energy use
		Higher occupancy	–12% energy use
		Electrification	–75% energy use
		Net outcome	–95% to +173% energy use

95% energy reduction to 173% energy increase!

From other sources, concerning ride-shared EVs there were predictions of either:

5.6% reduction in GHG emissions / 12% energy reduction / 11% more travel

4-8% reduction in GHG emissions

31-54% reduction in GHG emissions

87-94% reduction in GHG emissions

1) https://theicct.org/sites/default/files/publications/New-mobility-landscape_ICCT-white-paper_27072017_vF.pdf

A third review actually spanned 22 different source studies

But the resulting huge range of GHG predictions was essentially identical

Those cumulative predictions provide answers to my earlier my questions:

Might Autonomous Vehicles be an Environmental Game Changer? YES

Could this be a change for the better? YES

Could this be a change for the worse? YES

It's all going to come to our wisdom in making choices

Which ends up being a theme spanning this entire note set:

There are a huge number of ways that **YOU AND I** can clean up Cars & Trucks

It's all going to come down to **OUR** wisdom in making choices

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.