AUBURN UNIVERSITY

Electric Vehicles

ELEC 5970/6970/6970-D01

Introduction to Electric Vehicles

References:

- Iqbal Husain, "Electric and Hybrid Vehicles, Design Fundamentals," Third Edition, March 2021, CRC Press, Taylor & Francis Group, ISBN: 978-0429-49092-7

Introduction
to
Electric Vehicles

April 25, 2022

Motor Vehicles Were the Top Commodity by Value Shipped from Seven States

The top commodity by value shipped out of Michigan, Indiana, Kentucky, Georgia, Missouri, Alabama, and Maryland in 2020 was motor vehicles. Electronics was the highest value commodity for nine states.

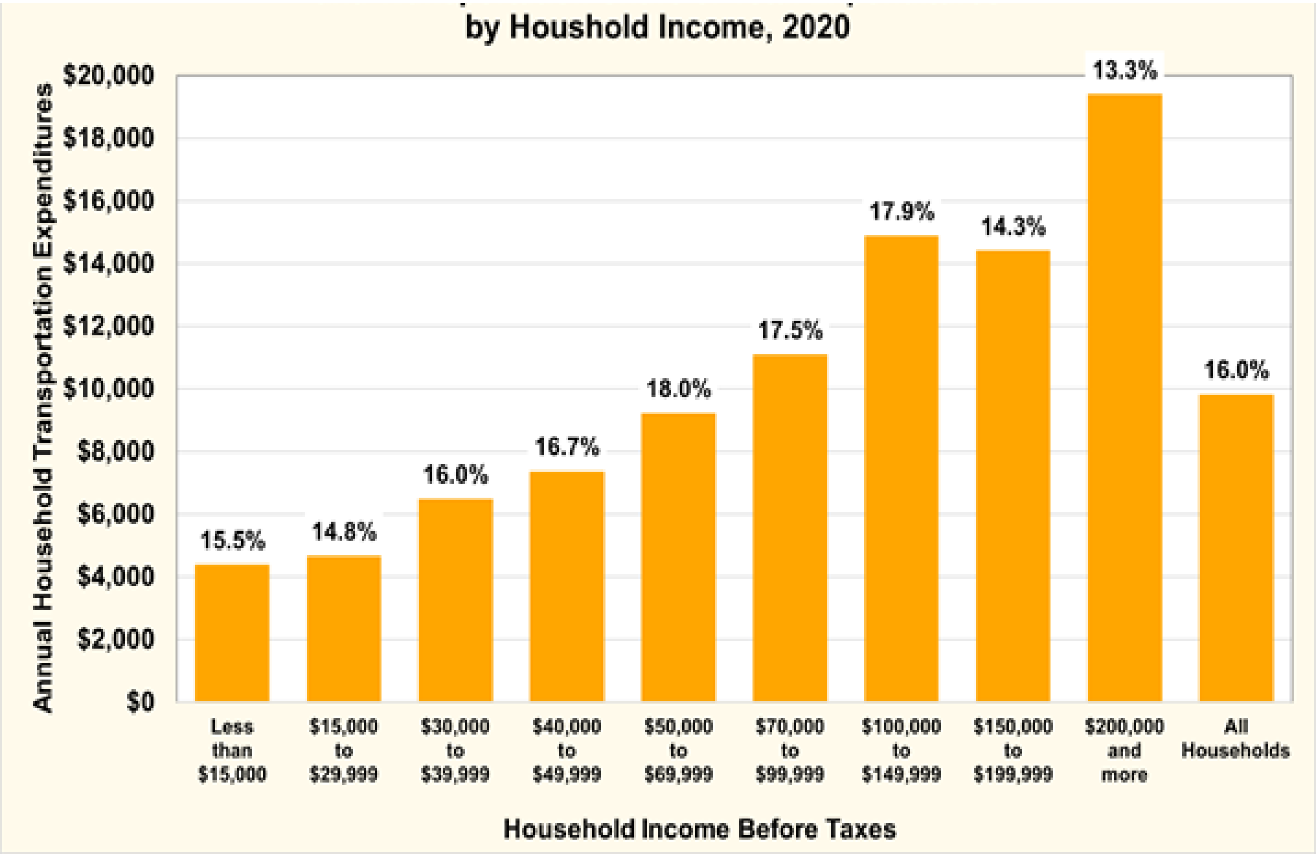
Top Commodity by Value Shipped Out of Each State, 2020

Vehicle Technologies Office

Transportation Analysis Fact of the Week #1248

July 25, 2022

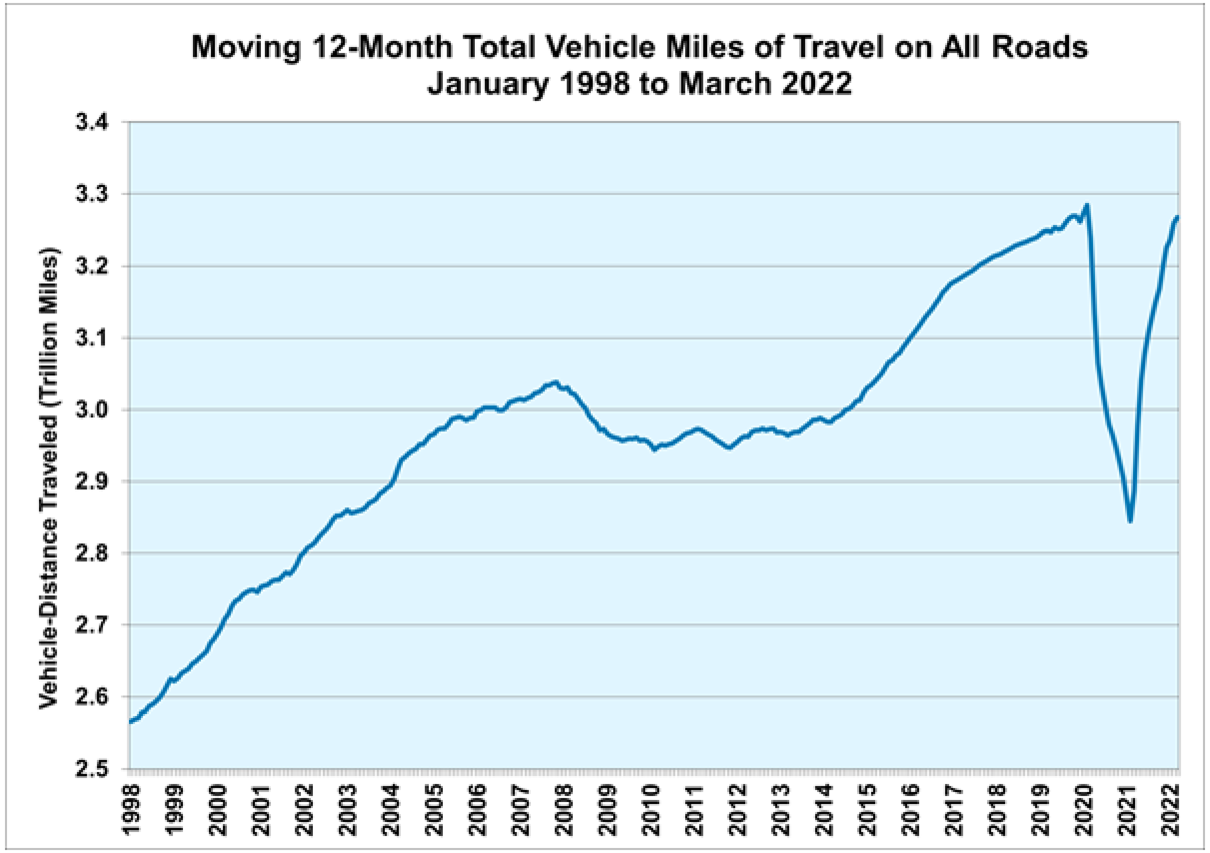
The Average U.S. Household Spent Nearly $10,000 on Transportation in 2020



Source: U.S. Department of Labor, Bureau of Labor Statistics, Consumer Expenditure Survey Tables, Table 1203 Income Before Taxes.

- The average American household spent $9,826 on transportation in 2020, which accounted for 16% of all annual household expenditures.
- Transportation expenditures include vehicle purchases, gasoline and motor oil, other vehicle expenses (maintenance, insurance, etc.), and public transportation costs.
- For households with incomes between $50,000 and $59,999, transportation accounted for 18% of total expenditures – the highest share of any income group.
- While those in the highest income group spent more on transportation overall, it made up only 13.3% of their household expenditures, the lowest share of any income group.

Total Miles of Travel on All Roads



Source: U.S. Department of Transportation, Federal Highway Administration, March 2022 Traffic Volume Trends, 2022.

- The moving 12-month total of vehicle miles traveled (VMT) in the United States illustrates nationwide trends of growth, flattening, or decline in VMT.
- VMT in the 12-month period ending in March 2022 matched the 12-month period ending in December 2019, before the start of the COVID-19 pandemic.
- Total U.S. VMT reached a peak of 3.28 trillion miles in the 12-month period ending in February 2020 but declined steeply the following year.
- Due to pandemic-related disruptions, the12-month period ending in February 2021 was the lowest point for total 12-month VMT since November 2002.

Alternative Vehicles

- Environmental and economical issues are the major driving force in developing electric and hybrid vehicles for urban transportation.

- Although, when efficiency is evaluated on the basis of conversion from crude oil to tractive effort at the wheels, the numbers for electric and hybrid vehicles are not significantly higher, it does make a difference.

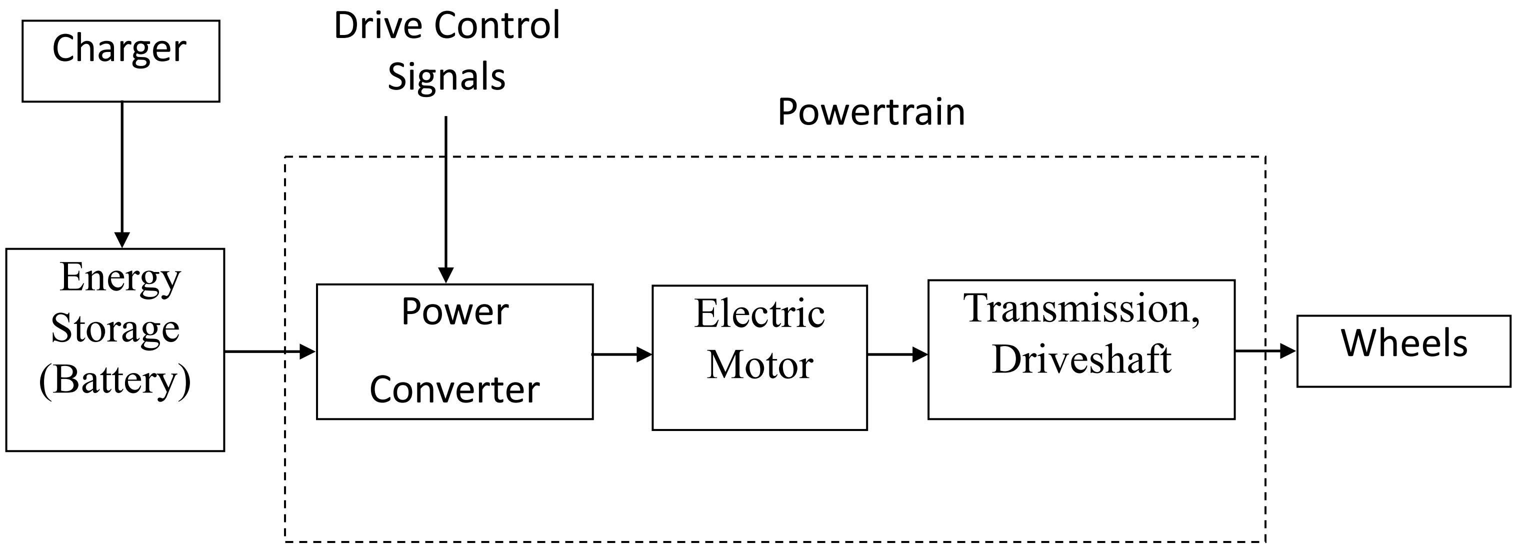
- Efficient power generation at localized plants together with very high motor and controller efficiency and advancements in battery or power source technology within the vehicle, the electric vehicles show immense promise in further overall efficiency improvement.

- Electric vehicle is the only alternative for a clean, efficient, and environmentally friendly urban transportation system.

Electric Vehicles

- <u>What is an Electric Vehicle?</u>

  <u>*Definition:*</u> An Electric Vehicle has two primary features:
  - The energy source is portable and electrochemical or electromechanical in nature.
  - Traction effort is supplied only by an electric motor.
- The drive train of the electric vehicle is the electromechanical system between the vehicle energy source and the road.



Hybrid Electric Vehicles

What is a Hybrid Electric Vehicle?

Definition: 'Hybrid electric vehicle' or simply 'hybrid vehicle' generally refers to vehicles that use an IC engine and one or more electric machines for propulsion.

A hybrid road vehicle is one in which the propulsion energy during specified operational missions is available from two or more kinds or types of energy stored, sources or converters, of which at least one source or converter must be on-board [IEC definition].

- Passenger hybrids have an IC engine with one or two electric machines.
- Triple hybrids with fuel cell engine, electric machine and IC engine are also possible.

Electric and Hybrid Vehicle Components

- Energy Conversion Devices
  - IC engine, electric machine, fuel cell
- Energy Storage Devices
  - Batteries, Ultracapacitors, flywheels
- Electronic Devices
  - Inverters, DC/DC converters, electronic controllers
- Power Transmission devices
  - Transmission, gears, clutches, power train

Electrical and Mechanical Power Transmission Paths

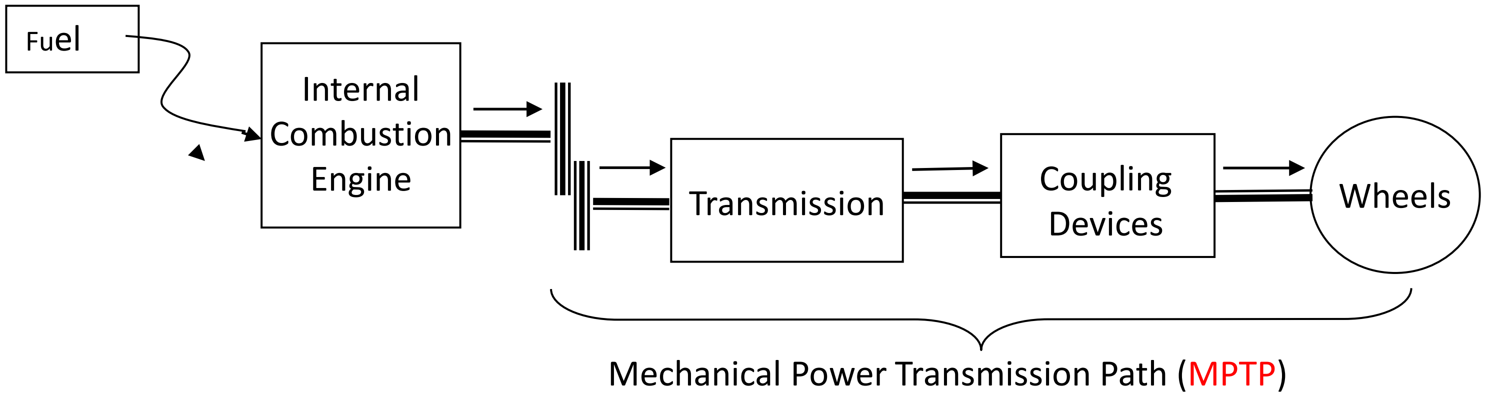


Figure 1.2 Power transmission path in a conventional ICE vehicle.

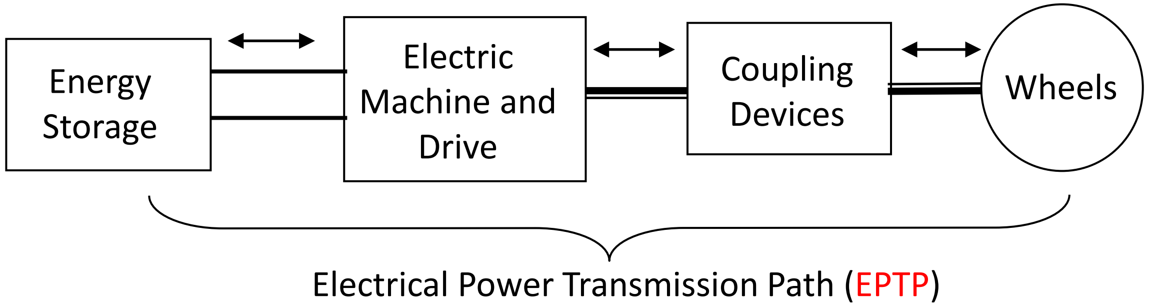
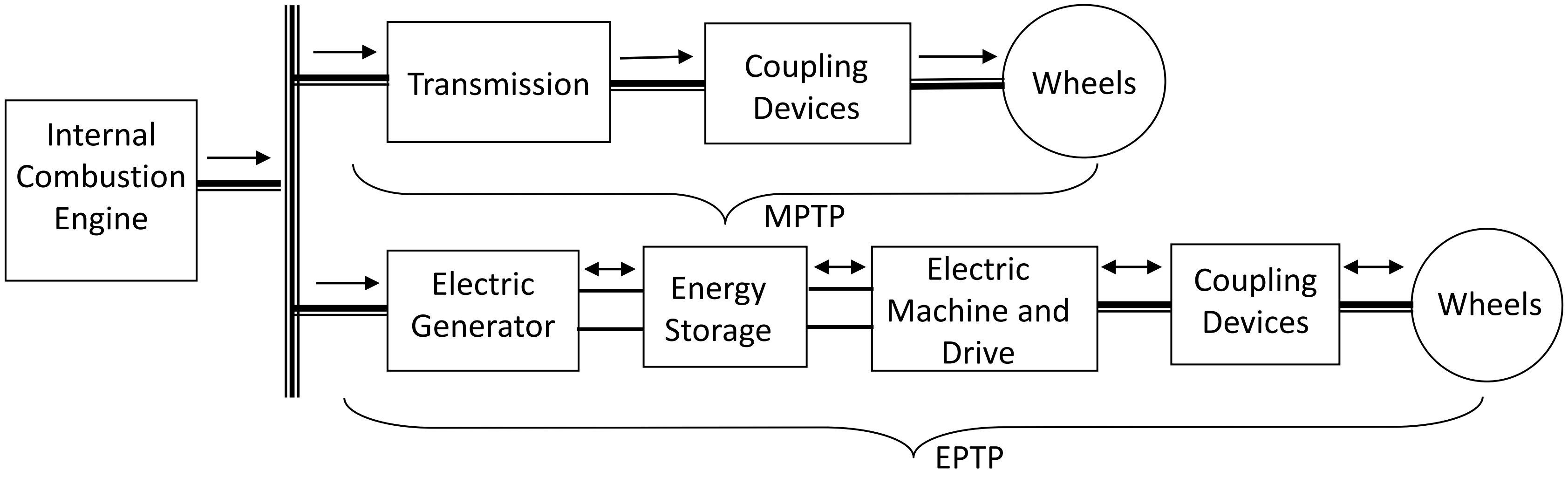


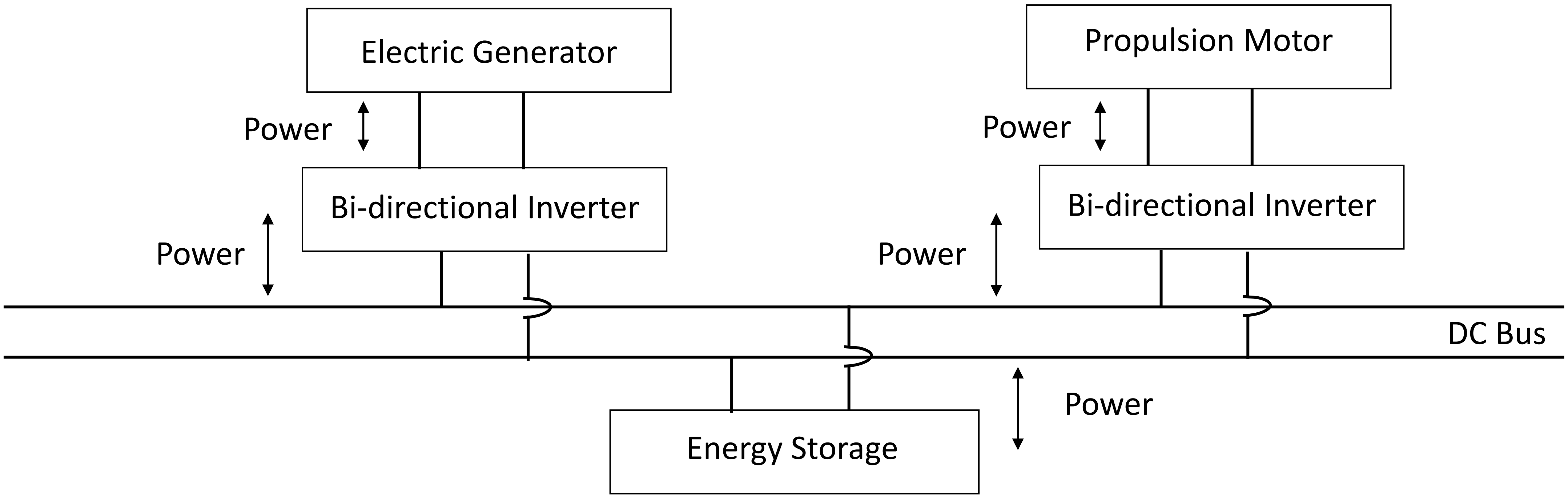
Figure 1.3 Power Transmission path in an electric vehicle.

Hybrid Vehicle Powertrain



- Powertrain shown for a charge sustaining hybrid which never needs to be plugged in.
- Hybrids that needs to be recharged from an electrical outlet to restore energy are known as charge depleting hybrids. Plug-in hybrids are charge depleting hybrids.
- Arrangements of the electric machines and IC engines for power transmission gives rise to a variety of hybrid architectures, such as series, parallel and series-parallel.

Electrical Components



- ❑ Electric Motor is primarily used for propulsion. However, the machine can also be used to capture regenerative energy
- ❑ Electric Generator is primarily used to recharge the storage system. However, the machine can also be used as a motor to meet peak acceleration demands.
- ❑ The electric machines need to have high power density, high starting torque, high efficiency and wide operating speed range.

Vehicle Mass and Performance

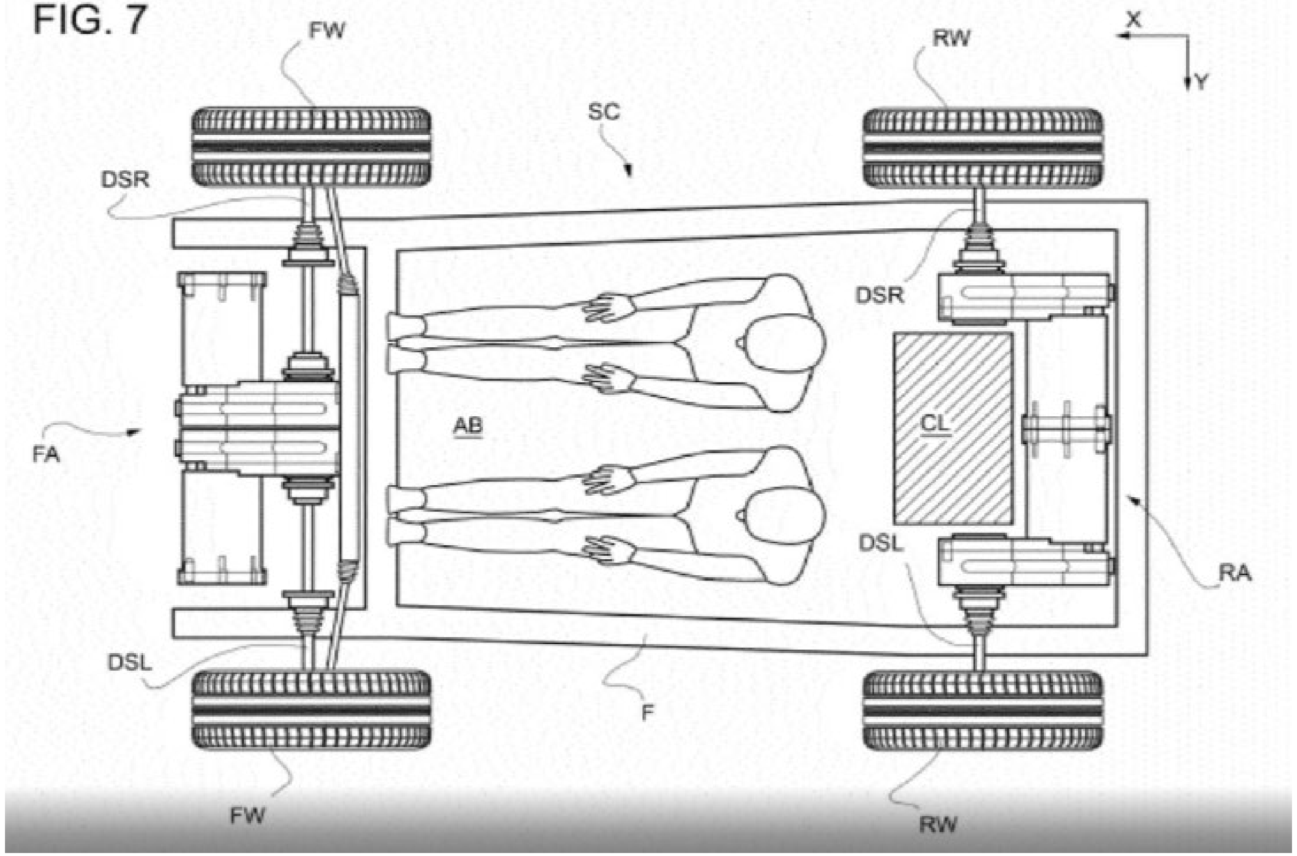
- Vehicle *curb mass* m_v is the total mass of the vehicle with all standard equipment, components, lubricants, full tank of gas but without any passenger or cargo.
- Vehicle *gross vehicle mass* m_{gv} is the curb mass plus the passengers and cargo.
- Vehicle *maximum gross vehicle mass* is the curb mass plus the maximum number of passengers and the maximum mass of the cargo that the vehicle is designed for.

Ferrari's new patent reveals a modular EV architecture

By Sagar

Posted on January 26, 2020

FIG. 7



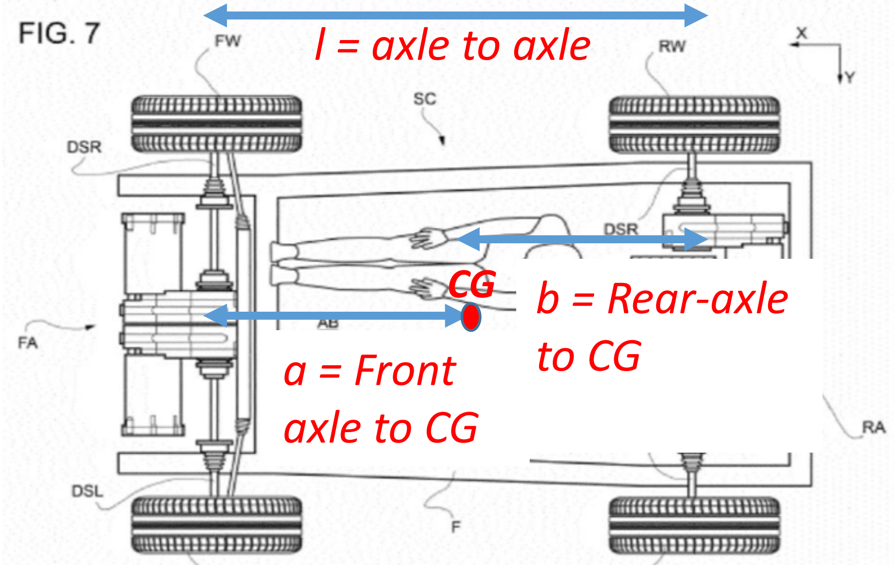
Vehicle Mass and Performance

- Front to rear mass distribution is critical for balance and good ride performance
- The front vehicle mass is $$m_{vf} = \frac{b}{l} m_v$$

  b = rear axle to vehicle center of gravity (CG)

  l = axle to axle length
- And the rear vehicle mass is $$m_{vr} = \frac{a}{l} m_v$$

  a = front axle to vehicle center of gravity (CG)



- A 60:40 or less ratio of front to rear vehicle mass distribution is required considering balance, ride performance and dynamic braking.

Vehicle Mass and Performance

- The sprung mass is the fraction of the vehicle curb mass that is supported by suspension including suspension members that are in motion.
- The unsprung mass is the remaining fraction of vehicle curb mass that is carried by the wheels and moving with it.
- A 10:1 ratio of sprung to unsprung mass is a desirable target, although a slightly lower ratio can be used for hybrid vehicles that may have more unsprung components.

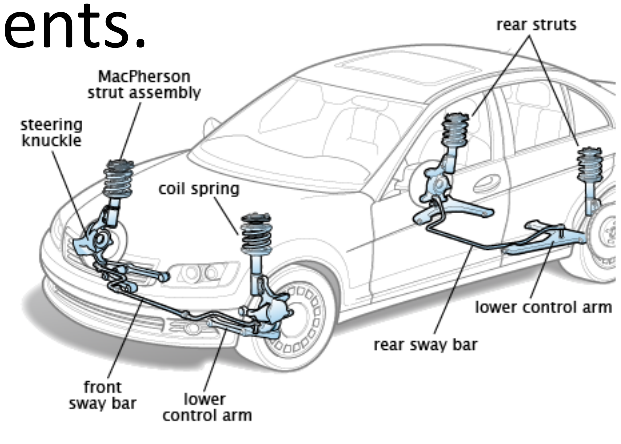


Image courtesy of ClearMechanic.com

Vehicle Mass and Performance

- The equivalent mass to be used in the design calculations is given by

k_m is mass factor related to the translational equivalent of all rotating inertia

$$m_{eq} = k_m m_v + N_p m_p$$

N_p = the number of persons in vehicle
m_p = the average mass of a person

- The mass factor is given by

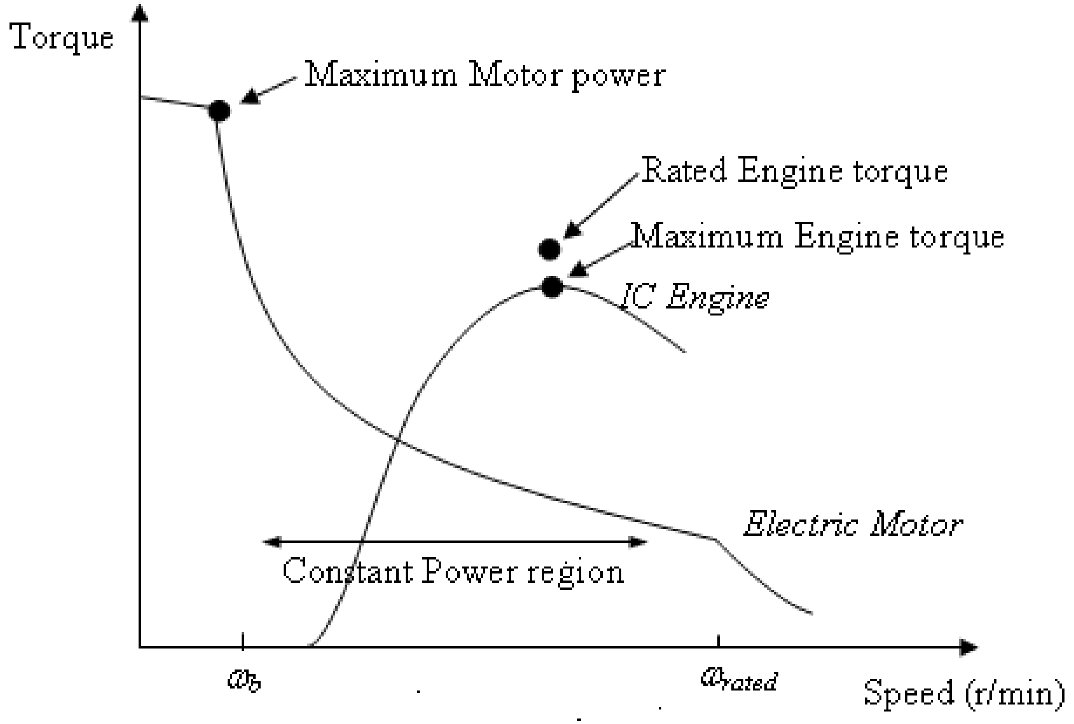
$$k_m = 1 + \frac{4J_w}{m_v r_{wh}^2} + \frac{J_{eng}\xi_{eng}^2 \xi_{FD}^2}{m_v r_{wh}^2} + \frac{J_{em}\xi_{em}^2 \xi_{FD}^2}{m_{cv} r_{wh}^2}$$

$\varsigma_{eng,em,FD}$ = gear ratio of engine, electric machine, and final drive

- k_m is a dimensionless mass factor that accounts for the inertia of all the rotating components such as wheels, driveline components, engine with ancillaries and hybrid electric machines.

Electric Motor and IC Engine Ratings

Comparison between ICE and electric machines



$$Power\ (Watts) = Torque\ (N-m) \times Speed\ (rads/s).$$

Electric Motor and IC Engine Ratings

- Rated HP of electric motor is derated.
- For short periods, motors can deliver 2 to 3 times rated HP.
- Torque can be maximum under stall conditions.
- ICE maximum HP is derived under idealized lab conditions.
- Transmission is essential for ICE to match vehicle speed.
- Electric motor can be directly coupled with a single gear.

Advantage of Electric Propulsion

- The wide speed range operation of electric motors enabled by power electronics control makes it possible to use a single gear-ratio transmission, eliminating multiple-gears

  $\Rightarrow$ Great advantage in EV propulsion system

- The gear ratio depends on the maximum motor speed. Higher motor speed is desired for higher power density of motor

  $\Rightarrow$ A compromise is necessary between the maximum motor speed and the gear-ratio to optimize the cost.

EV/HEV Motor Requirements

- Flexible drive control
- Fault tolerance and ruggedness
- High efficiency
- High speed
- Low acoustic noise and EMI
- Wide constant power region
- High torque to inertia and power to weight ratios
  - Large T_e/J results in good acceleration
- High peak torque capability (300-400% rated power)

EV History

- Pre 1830 - Steam powered transportation.
- 1831 - Faraday's law and the invention of DC motor.
- 1834 - Non-rechargeable battery powered electric car.
- 1851 - Non-rechargeable 19-mi/h electric car.
- 1859 - Development of lead storage battery.
- 1874 - Battery powered carriage.
- Early 1870's - Electricity produced by dynamo-generators.
- 1881 First electric vehicle (Gustave Trouve), Int'l Exhibit of Electricity, Paris, FR.
- 1894 Count Felix Carli (Italy) assembled first hybrid electric car
- 1897 First petrol-electric car by Justus B. Entz, Electric Storage Battery Co. of Philadelphia, U.S.
- 1899 Paris Salon. Pieper vehicle, a gas-electric parallel hybrid
- 1900 - 4,200 automobiles sold:
  - 40% steam-powered
  - 38% electric powered
  - 22% gasoline powered

Early Electric Vehicle Specifications

- 1897 - French Krieger Co. EV: Weight - 2230 Lbs., Top Speed - 15mph, Range - 50mi/charge.
- 1900 - French B.G.S. Co. EV: Top Speed - 40mph, Range - 100 mi/charge.
- 1915 - Woods EV: Top Speed - 40 mph, Range - 100 mi/charge.
- 1915 - Lansden EV: Weight - 2460 Lbs., 93 mi/charge, 1 ton payload capacity.
- 1912 - 34,000 EVs registered; *EVs outnumber gas powered vehicles 2-to-1.*
- 1920's - EVs disappear and ICEVs become predominant.

Disappearance and Resurgence of EVs

Factors that Led to the Disappearance of EV

- Invention of starter motor in 1911 made gas vehicles easier to start.
- Improvements in mass production of Henry T (gas-powered car) vehicles which sold for $260 in 1925 compared to $850 in 1909. EVs were more expensive.
- Rural areas had very limited access to electricity to charge batteries, whereas, gasoline could be sold in those areas.

Resurgence of EVs in 1960's

- Resurgence of EV research and development in 1960's due to increased awareness of air quality.
- Congress introduces bills recommending the use of Evs as a means of reducing air pollution.

1960's and 1970's

- 1960's : Major ICEV manufacturers become involved in EV R&D (e.g., GM, Ford).
- Case Study: Electrovair I (1964) and Electrovair II (1966) at GM
  - Motor - 3-phase induction motor, 115 HP , 13000 rpm.
  - Battery - Silver-Zinc (Ag-Zn), 512V, 680 Lbs.
  - Motor Drive - DC-to-AC inverter using SCR
  - Top Speed 80mph; Range: 40 to80 miles; Vehicle weight 3400Lbs
- 1970's: Gasoline prices increase dramatically as energy crisis increases. This led to immense interest in EV.
- In 1975, 352 electric vans were delivered to US postal service for testing.
- Case Study: Modified Chevy Chevette EV
  - Motor - Separately excited DC, 34HP, 2400 rpm.
  - Initial Battery Pack - Ni-Zn, 120V, 735 Lbs.
  - Auxiliary Battery - Ni-Zn, 14V.
  - Motor Drive - Armature DC Chopper using SCRs, Field DC Chopper using BJTs.
  - Top Speed 60mph; Range: 60 to 80 miles.

End of Lecture 3

Additional Factors

- August 26, 1968 - "The Great Electric Car Race" cross- country competition (3300 miles) between an EV from Caltech and an EV from MIT generated public interest in Evs and provided an extensive road test of EV technology.
- The 1960's technology was not mature enough to produce a commercially viable EV.
- In 1976, Congress enacts Public Law 94-413, the *Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976*. This act authorizes a federal program to promote electric and hybrid vehicle technologies and to demonstrate the commercial feasibility of electric vehicles.
- Department of Energy (DOE) standardizes EV performance.

1980's and 1990's

Technological Developments Effecting EV Design

Improvements of high power, high frequency semiconductor switches, along with μ-processor revolution, led to improved power converter design.

Organizational Support

Legislation passed by the California Air Resources Board: By 1998, 2% of all vehicles (about 40,000) will be zero emission vehicle (ZEV). By 2003, 10% (about 500,000) will be EV. More than one dozen eastern states have also adopted this law to comply with federal regulations on emission standards.

Trends in EV/HEV developments

- Department of Energy and auto manufacturer's introduce collegiate level student competitions
- High level of activity at GM, Ford and Chrysler.
- High levels of activity overseas.
- High levels of hybrid vehicle activity.
- A boom in individual ICEV to EV conversions.

EV Case Studies

1. GM Impact 3 (1993 completed)
   - Motor - one, 3-phase induction motor, 137 hp, 12000rpm.
   - Battery-pack - Lead-acid (26), 12V batteries connected in series (312V), 869Lbs.
   - Motor Drive - dc-to-ac inverter using IGBTs.
   - Top Speed - 75 mph
   - Range - 90 miles in highway.
   - Acceleration - 0 to 60 miles in 8.5 secs.
   - Vehicle Weight - 2900 Lbs.

2. Saturn EV1 (Introduced in 1995)
   - Commercially EV made by GM.
   - Leased in California and Arizona for a total cost of about $30,000.
   - System and Characteristics:
     - Motor - one, 3-phase induction motor
     - Battery-pack - Lead-acid batteries
     - Motor Drive - dc-to-ac inverter IGBTs.
     - Top Speed - 75 mph
     - Range: 90 miles highway, 70 miles city.
     - Acceleration - 0 to 60 miles in 8.5 secs.
   - Testbed for mass production of EVs.

Recent EVs and HEVs

HEVs

- Toyota Prius, Camry, Lexus
- Honda Insight, Civic
- Ford Escape, Fusion
- GM Saturn, Malibu, Tahoe (Two-mode)

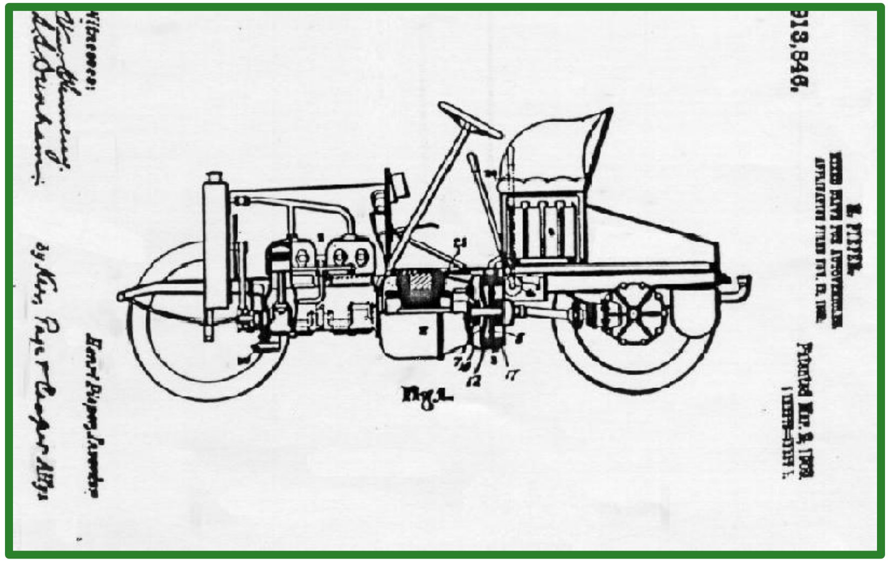
EVs

- Telsa Roadster
- Nissan Leaf

Interest in Hybrid Electric Vehicles

- Honda Insight and Toyota Prius HEVs are commercially available since 1998

- HEV patents date to 1905 in US and UK.



Source: Gerry Skellenger, GM HEV Retired, Gedask LLC

Customer Acceptance of Hybrid Vehicles

- The automotive manufacturers were highly surprised by the consumer acceptance of the HEV's.
- HEVs are in short supply and the lead automotive manufacturers are controlling the output.
- The Hybrid Electric Vehicles represented ~1% of total sales in 2005, but estimations project sales to increase significantly by 2015.
- The demand for all types of HEV's is all around the globe: the Europe, the Americas, and the Asia Pacific.
- HEV's today are in the growth phase of customer acceptance.
- Battery EVs have also started entering the market. As battery technology is improved, the Battery EVs will capture certain market share of the HEVs.

Consumers Willing to Pay for Hybrids

- Customers willing to extra for:
  - Fuel Economy
  - Increased Efficiency
  - Reduced Emissions
  - High Performance

How Hybrids Increase Efficiency and Reduce Emissions

- The engine is smaller since the electric motor does much of the work. (Engine downsizing)
- The engine can shut off when the car stops. (Start-stop)
- We can choose to operate the engine only at its highest efficiency. (Operating point Optimization)
- Use only electric machine for low driver demand. (Electric mode)
- The electrical system can be used to prepare emission controls for cold starts. (Emissions control)
- Braking energy can be recovered and stored in the batteries. (Regenerative Braking)

Hybrids for Performance

Hybrids deliver performance with improved fuel economy

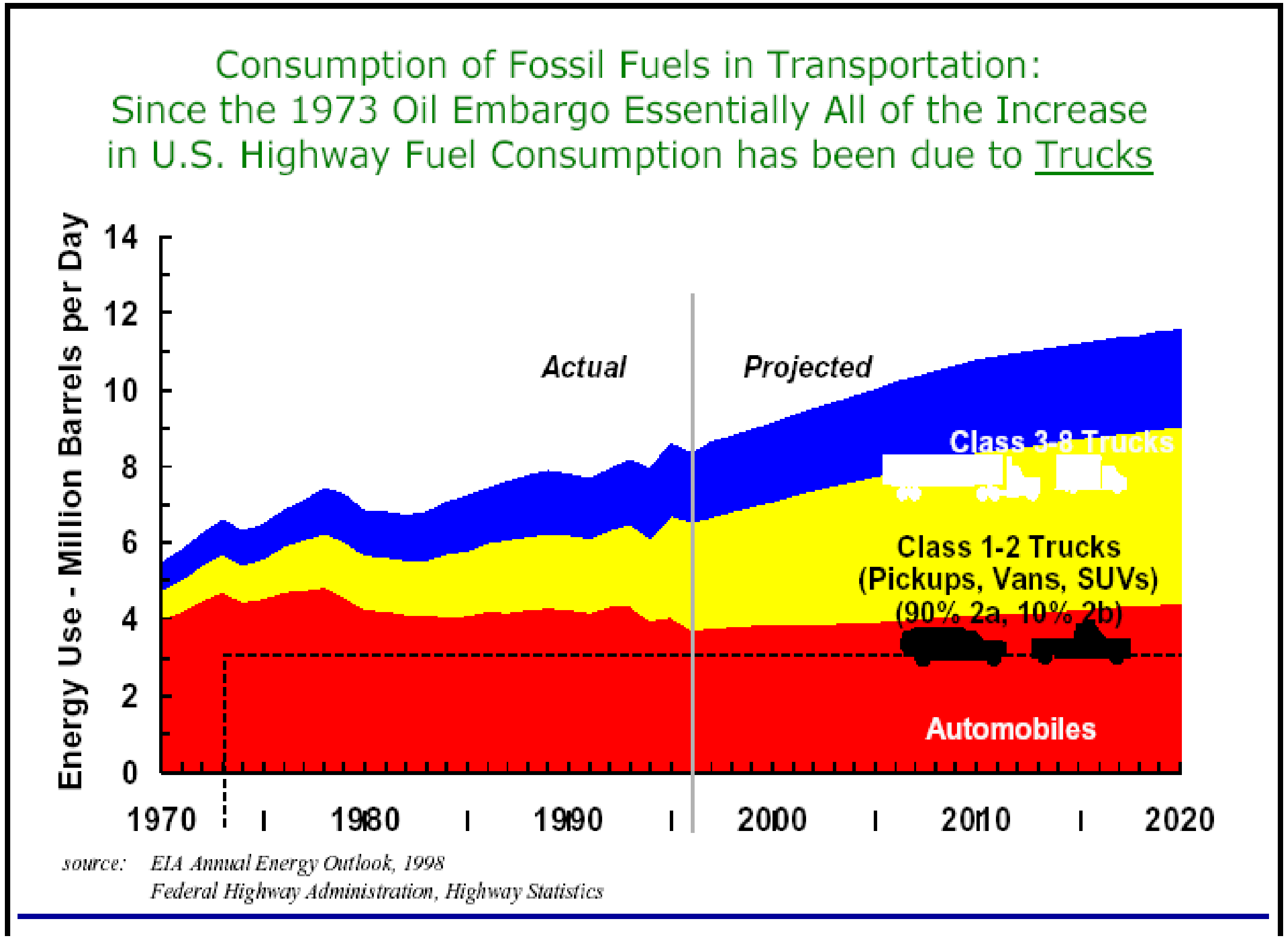
- Toyota Camry V6
  - 3.5L DOHC 16-Valve Engine
  - 268HP @6200rpm
  - 248 ft.Lbs. torque @ 4700rpm
  - Curb weight 3516 Lbs
  - EPA MPG 22/31
  - Luggage Space 14.5 Cu.ft.

- Toyota Camry Hybrid
  - Net Power 187hp
  - 2.4L DOHC 16-Valve Engine
  - Electric Machine 105kW
  - Curb weight 3680 Lbs
  - EPA MPG 40/33
  - Luggage Space 10.6 Cu.ft.

Energy Situation

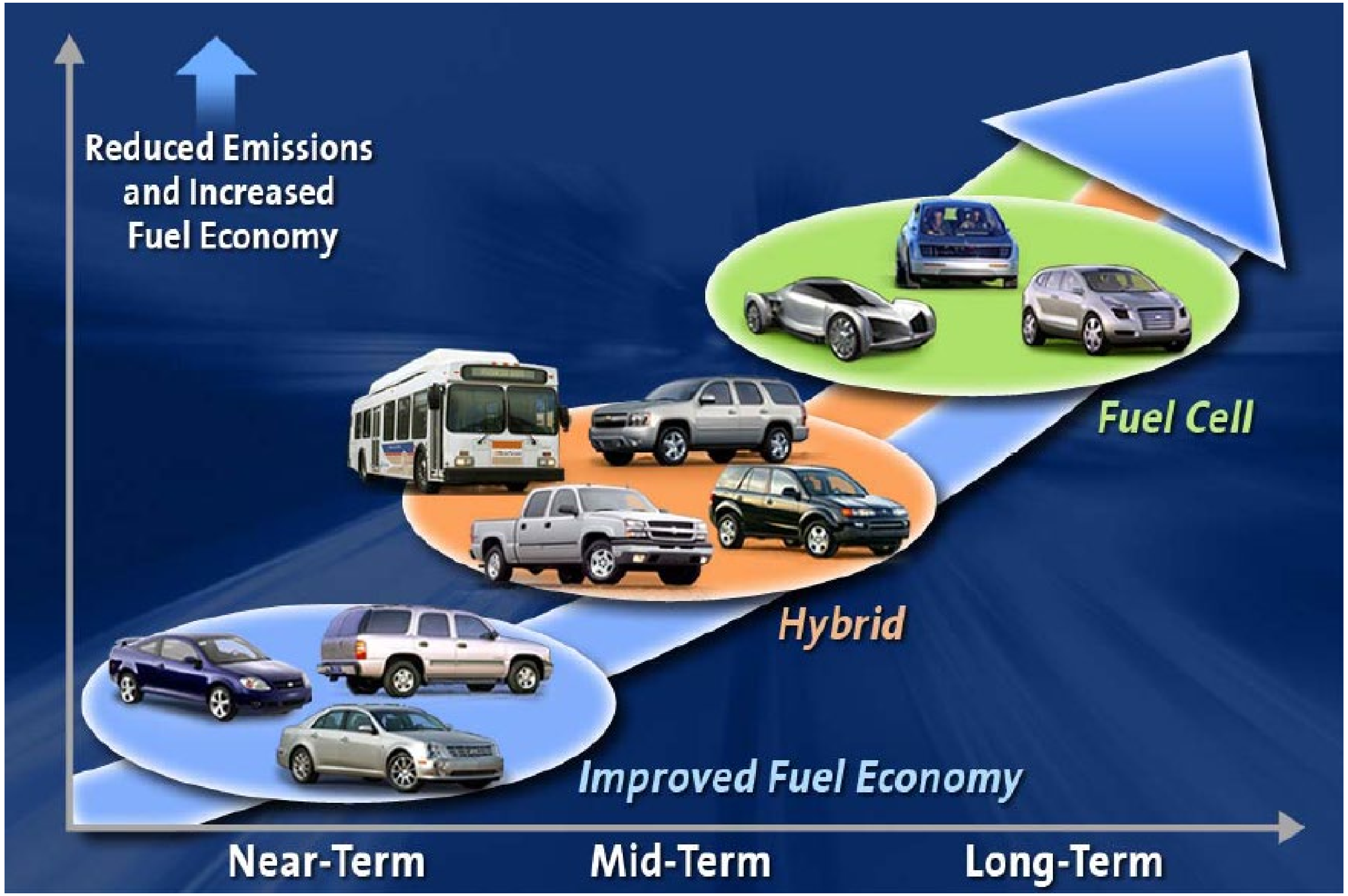
- More than 42 % of petroleum used for transportation in U.S. is imported;
- Total energy consumption is 22 Million barrels per day, more than half of which is imported
- EV uses 2 barrels of oil in its lifetime (based on 4 mi/ kWH).
- ICEV uses 94 barrels of oil in its lifetime (based on 28 mi/gal).
- The world energy situation is going to get far worse during our lifetimes.
- Alternative fueled vehicles represent an immediate alternative.
- HEVs and EVs would shift the energy requirement to alternative sources

Fossil Fuel Consumption for Transportation in U.S.



Source: Zoran Filipi, SAE Hybrid Symposium 2006

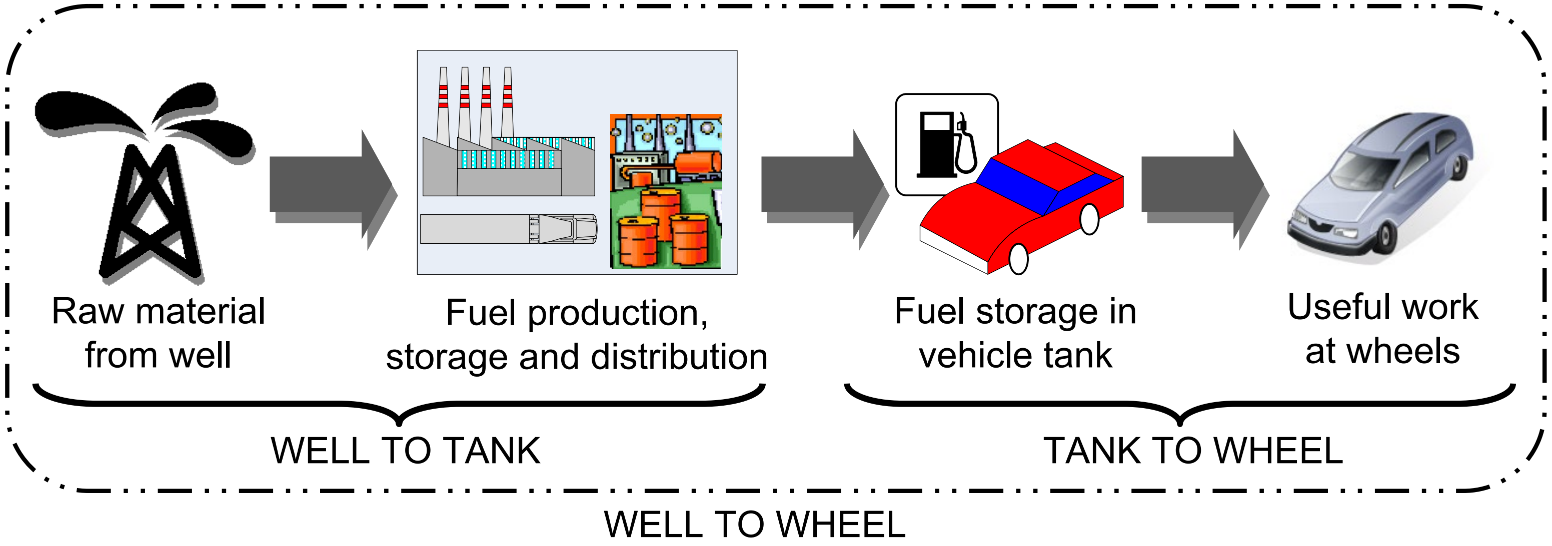
Vehicle Technology Projection



Source: Micky Bly, GM

Well-to-Wheel Analysis

- Measure of the overall efficiency analysis of a vehicle starting from the extraction of raw fuel to the wheels including the efficiencies of energy conversion, transport and delivery at each stage.
- Can be analyzed using the GREET model developed by Argonne National Labs.
- GREET model has more than 100 fuel production pathways and more than 70 vehicle systems.



WTW Analysis using GREET

	SI ICEV (Baseline CG and RFG)	Plug-in SI HEV (Gasoline and Electricity)	Battery EV (Electricity)
Total Energy (Wh)	257,551 Oil	526,261 Oil-Coal	1,632,131 Coal
WTT Efficiency	79.5%	66.5%	38.0%
TTW Efficiency	21.9%	23%	48.51%
WTW Efficiency	17.41%	15.29%	18.43%
CO_2 (grams/ Million BTU)	17,495	57,024 Oil-	219,704
CH_4 (grams/ Million BTU)	109.120 Oil	145.658 Coal	296.031 Coal
N_2O (grams/ Million BTU)	1.152	1.535	3.111
VOC(volatile organic compound): Total (grams/ Million BTU)	27.077	25.630	19.679
CO: Total (grams/ Million BTU)	15.074	23.553 Oil-	58.448 Coal
NOx: Total (grams/ Million BTU)	50.052 Oil	87.100 Coal	239.571

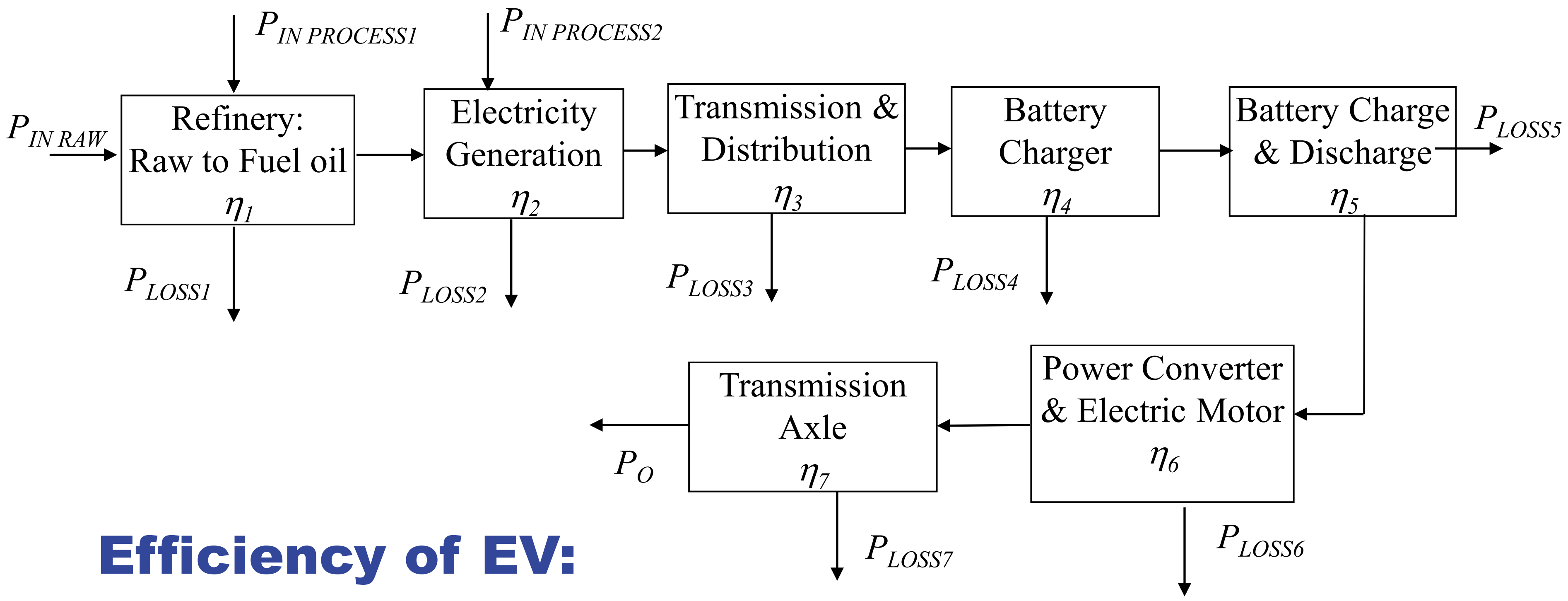
COMPARISON OF EV and ICEV

Basis for comparison

- Efficiency
- Pollution
- Operating Cost
- World Energy Situation

Efficiency Comparison

Complete EV Process

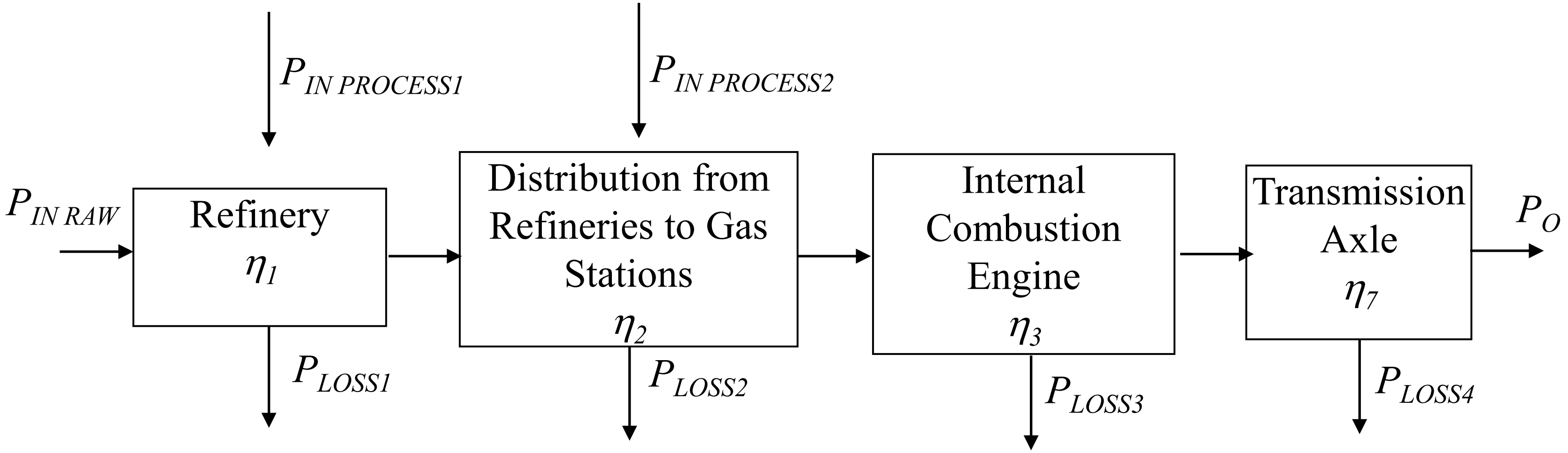


Efficiency of EV:

$$\eta_{EV} = \frac{P_0}{P_{IN}} = \frac{P_0}{P_0 + \sum_{i=1}^{7} P_{LOSS\,i}} = \frac{P_0}{P_6}\frac{P_6}{P_5}\frac{P_5}{P_4}\frac{P_4}{P_3}\frac{P_3}{P_2}\frac{P_2}{P_1}\frac{P_1}{P_{IN}} = \eta_1\eta_2\eta_3\eta_4\eta_5\eta_6\eta_7$$

Efficiency Comparison

Complete ICEV Process



Efficiency of ICEV:

$$\eta_{ICEV} = \eta_1\eta_2\eta_3\eta_4$$

Well-to Wheel Efficiency Comparison

ICEV	Efficiency (%)		Battery EV	Efficiency (%)		FCEV	Efficiency (%)	
	Max.	Min.		Max.	Min.		Max.	Min.
Crude oil			Crude oil			Crude oil		
Refinery(petroleum)	90	85	Refinery (fuel oil)	97	95	Refinery (petroleum)	90	85
Distribution to fuel tank	99	95	Electricity generation (Coal Power Plant)	40	33	Distribution to fuel tank	99	95
Engine	22	20	Transmission to wall outlet	92	90	Fuel Processor	76	70
Transmission/axle	98	95	Battery charger	90	85	PEM Fuel Cell	60	35
			Battery (lead/acid)	75	75			
			Motor/Controller	85	80	Motor/Controller	85	80
			Transmission/ axle	98	95	Transmission/ axle	98	95
Wheels			Wheels			Wheels		
Overall efficiency (crude oil to wheels)	19	15	Overall efficiency (crude oil to wheels)	20	14	Overall efficiency (crude oil to wheels)	34	15

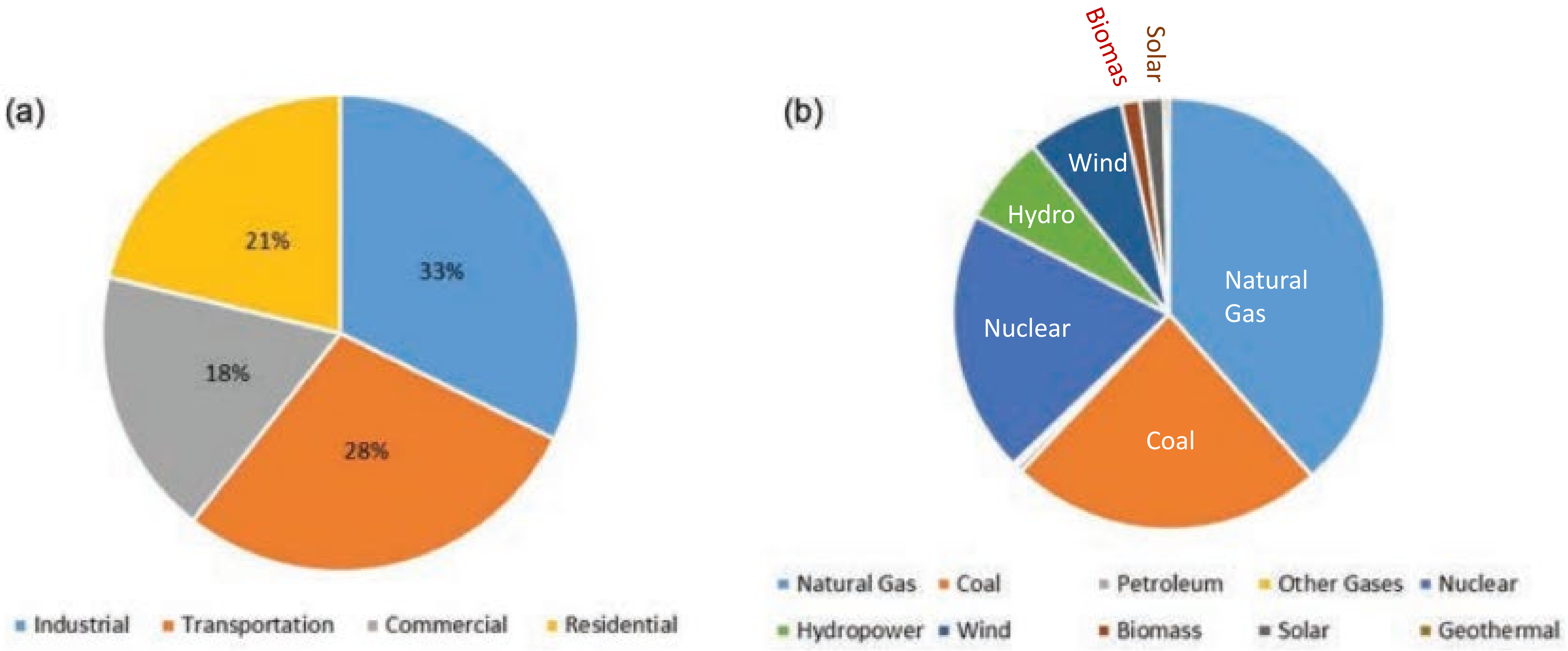


FIGURE 1.10 2019 US energy usage and generation: (a) energy consumption by end-use sector and (b) electricity generation by source.

Pollution Comparison

With 100% electrification (i.e. every ICEV replaced by EV)

- CO_2 in air , linked to global warming , would be cut in half.
- Nitrogen oxides (greenhouse gas – global warming) would be cut slightly depending on government regulated utility emission standards.
- Sulfur dioxide, linked to acid rain, would increase slightly.
- Waste oil dumping would decrease, since EVs don't require crankcase oil.
- EVs reduce noise pollution since they are quieter than ICEVs.
- Thermal pollution by large power plants would increase with increased EV usage.

Conclusion: EVs will considerably reduce the major causes of smog, substantially eliminate ozone depletion, and reduce greenhouse gases. With stricter SO_2 power plant emission standards, EVs would have little impact on SO_2 levels. Pollution cuts are the driving force behind EV usage.

CAPITAL AND OPERATING COST COMPARISON

- Initial EV capital costs are higher than ICEV capital cost. However, EV capital costs are expected to decrease as volume increases. Capital costs of EVs could exceed capital costs of ICEVs due to the cost of the battery.

- Total life cycle cost of an EV is projected to be less than that of a comparable ICEV.

- EVs are more reliable and will require less maintenance.

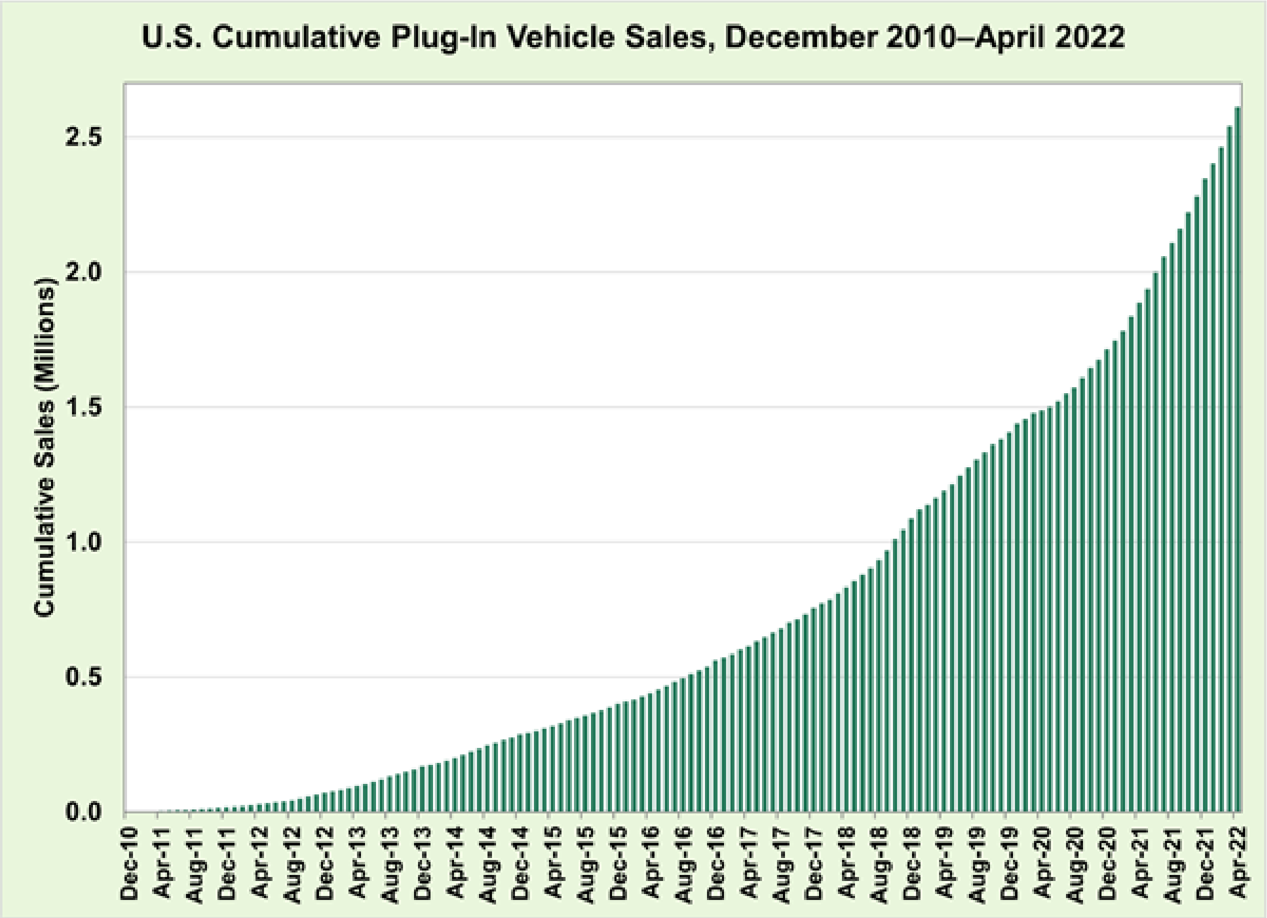
U.S. DEPENDENCE ON FOREIGN OIL:

- 42 % of petroleum used for transportation in U.S. is imported.
- EV uses 2 barrels of oil in its lifetime (based on 4 mi/ kWH).
- ICEV uses 94 barrels of oil in its lifetime(based on 28 mi/gal).

Impediments to EV/HEV/FCEV Changeover

- EV/HEV/FCEV capital costs – Component cost and initial low volume production make EV/HEV/FCEV's expensive.
- EV range – Limitations in the zero emission range for EVs due to the battery technology
- Complexity : two power plants and its accessories increases complexity in all types of hybrid vehicles
- Energy Storage system life cycle and durability
- Infrastructure –
  - Battery charging facilities. Residential and public charging facilities/stations. Off peak charging at night.
  - Hydrogen refueling facilities
  - Standardization of EV plugs , cords , outlets , safety issue.
  - Sales and distribution.
  - Service & technical support.
  - Parts supply.

Cumulative Plug-in Vehicle Sales in the US Reached 2.6 million in April 2022

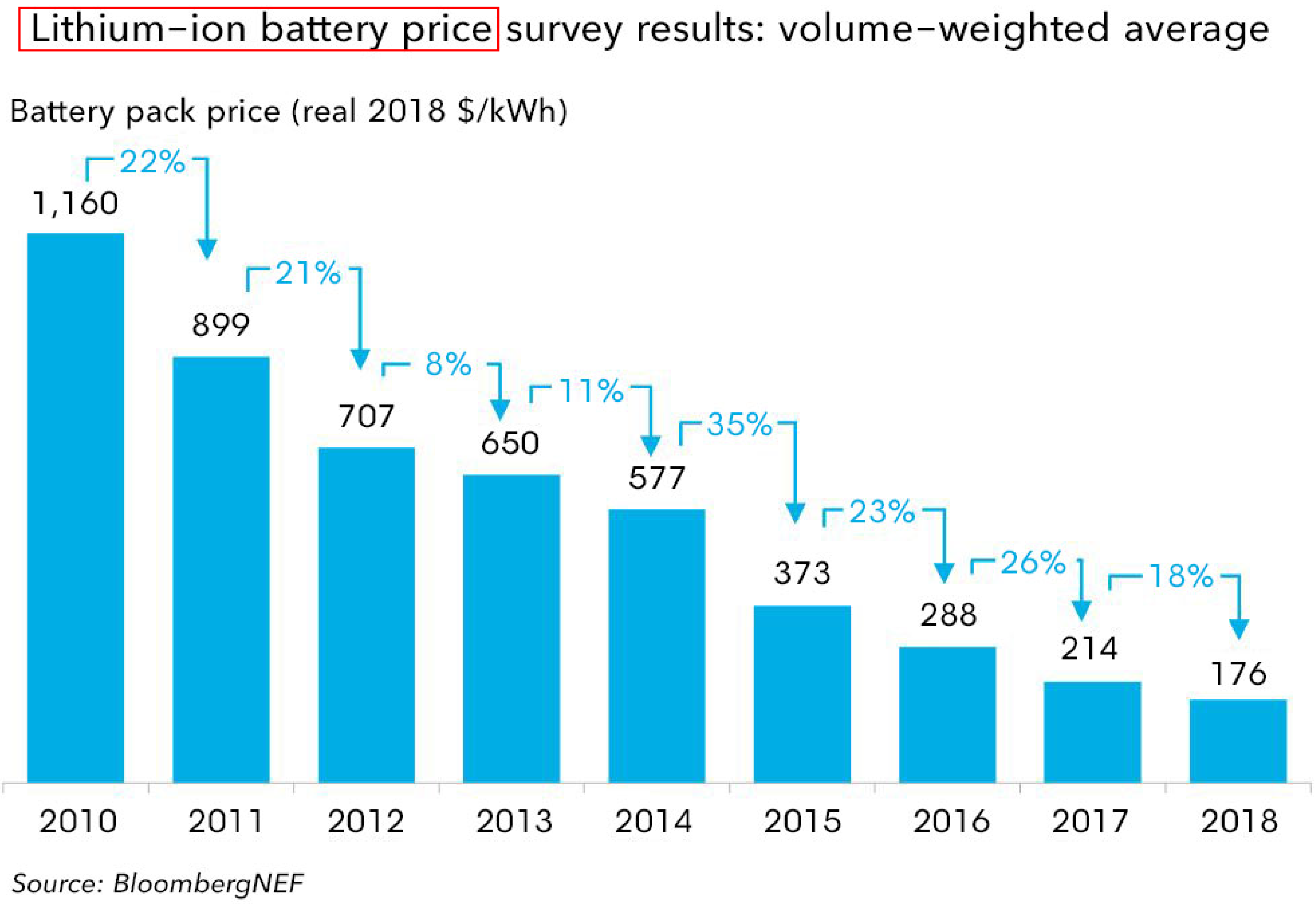


Note: Plug-in vehicles refers to both plug-in hybrid electric vehicles and all-electric vehicles.

Source: Argonne National Laboratory, Light Duty Electric Drive Vehicles Monthly Sales Update.

- Mass market plug-in vehicle sales began in the United States at the end of 2010 with just a few models available to consumers.
- As new plug-in models have been introduced and production volumes have increased, sales have accelerated accordingly.
- It took nearly eight years to reach one million cumulative sales but just two and a half more years to reach two million cumulative sales. Just 10 months after reaching two million in June 2021, cumulative sales climbed to 2.6 million as of April 2022.

3.5.2.3 Battery (BEV)



EV IMPACT ON JOB MARKET

- EVs will create jobs for electrical engineers in:
  - Design and development of the electrical systems of an EV (e.g. power converters, motors)
  - Power generation: increased utility demand due to EV usage.
  - EV infrastructure: design and development of charging stations.

Electric vehicle occupations

- Workers from a variety of educational and employment backgrounds are employed in the electric vehicle industry:
  - The scientists/engineers who conduct research in electric drive technology
  - The manufacturing workers who build the vehicles
  - The automotive maintenance technicians who repair the vehicles.
- Most of these occupations require specialized training or work experience in electric vehicle manufacturing and maintenance.