Lecture 7: Fuel Economy of Vehicles

Fuel Economy of Vehicles

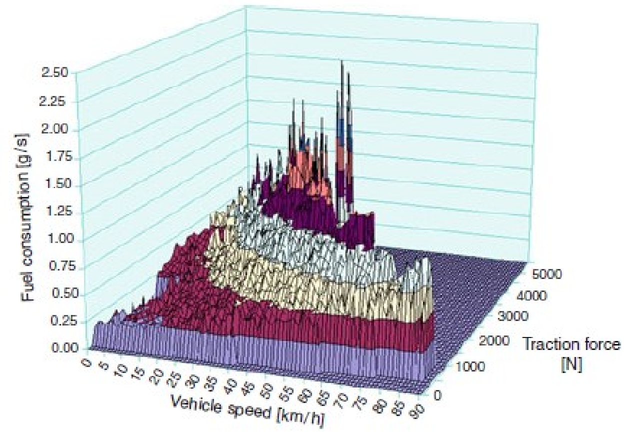
Prof. Sangyoung Park
Module ”Vehicle-2-X: Communication and Control“

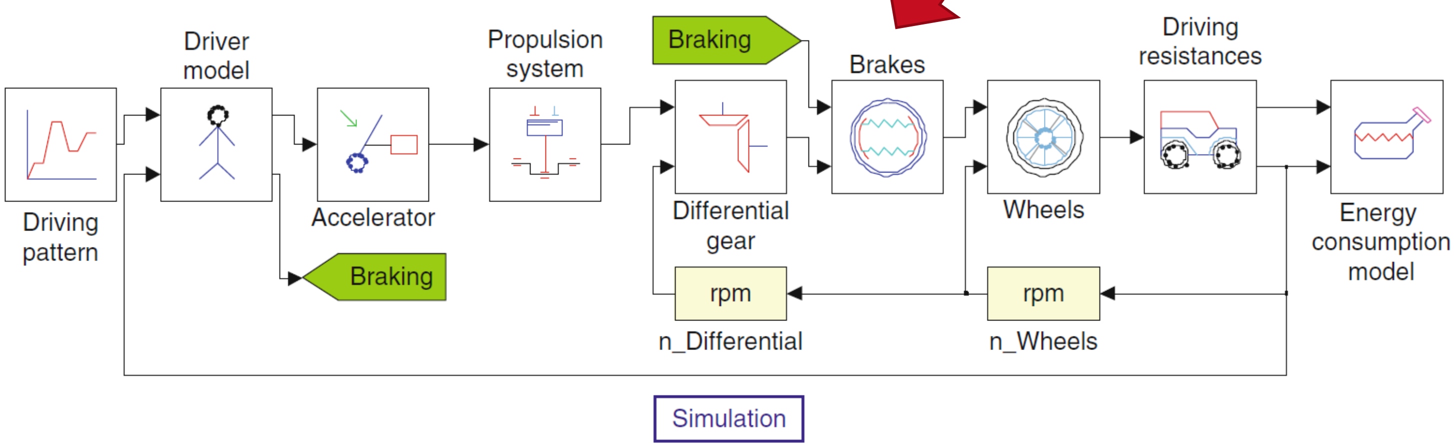
Rating the Efficiency of a Vehicle

- Rating the efficiency of a vehicle is a complex undertaking
- Vehicle's tank-to-wheel consumption is determined by a defined driving cycle (e.g., NEDC), which is carried out on a testbed at stringently monitored conditions
- Real world driving conditions can differ significantly
  - Traffic lights
  - Traffic jams
  - Uphill and downhill paths
  - Varying weather conditions

Modeling the Fuel Economy

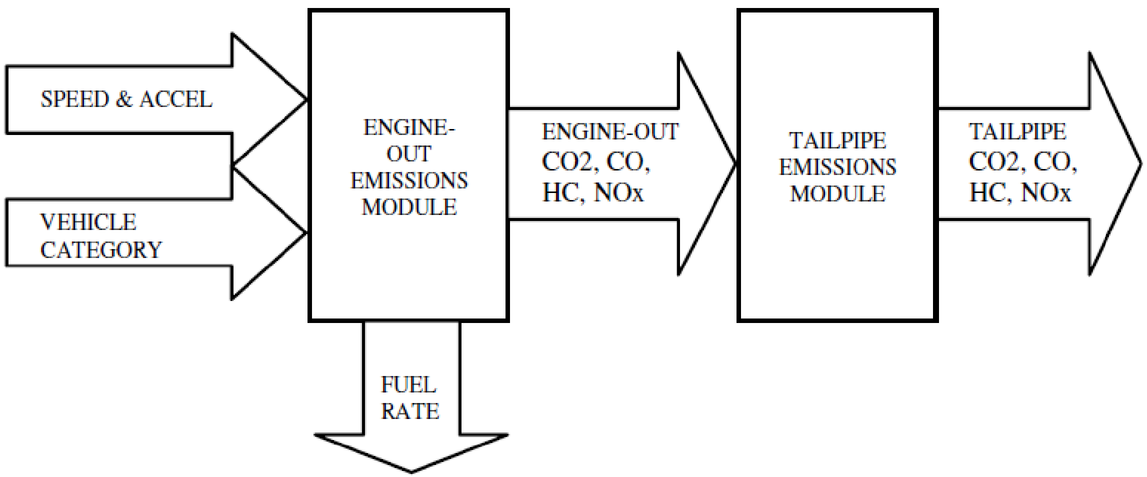
- How can we have accurate model of the fuel consumption?
- We could measure it





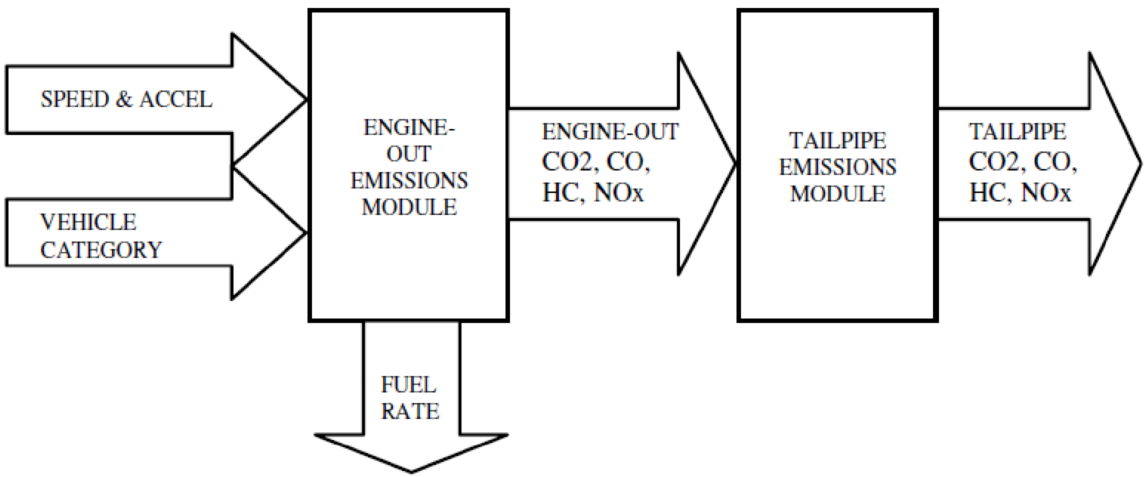
Fuel Consumption Model

- The model used in the Veins simulator
  - A. Cappiello, et al., “A statistical model of vehicle emissions and fuel consumption,”IEEE International Conference on Intelligent Transportation Systems, 2002
- EMIT (EMIssions from Traffic) model
  - A simple statistical model for instantaneous emissions (CO2, CO, HC, and NOx) and fuel consumption



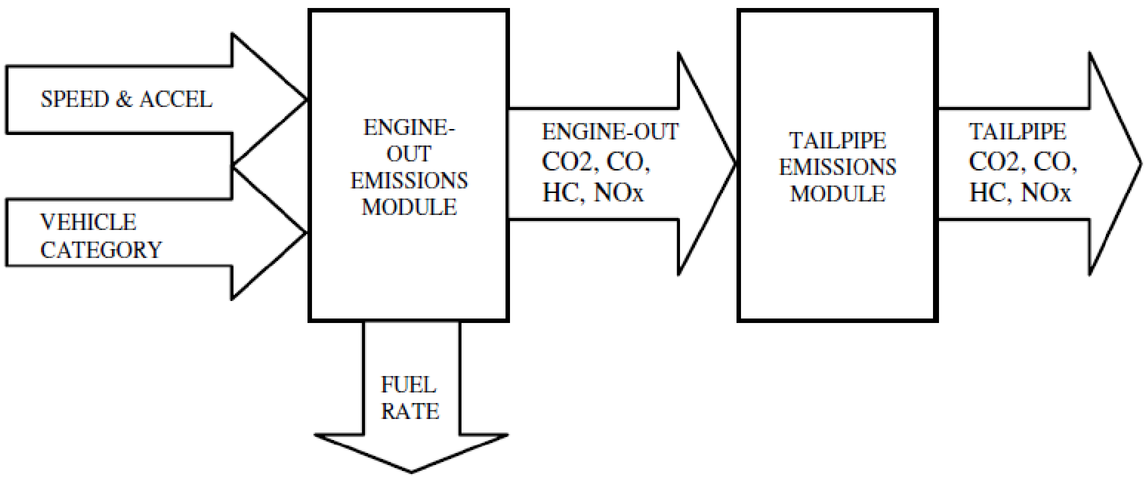
Fuel Consumption Model

- EMIT comprises two modules
  - Engine-out emissions module
  - Tailpipe emissions module
  - Allows for modeling of engine and catalyst technology improvements and vehicle degradation



Engine-out emission module

- Engine-out emission module
- Inputs
  - Second-by-second speed & acceleration
- Outputs
  - Second-by-second fuel consumption rate and engine-out emissions



Engine-out emission module

- Let i denote a generic emission species (i.e., CO2, CO, HC, NOx)
- EO_i denotes the emission index for species i
- EI_i is defined as the emissions index for species i
- Engine-out emissions are given by

$$EO_i = EI_i \cdot FR$$

- Where FR denotes the fuel consumption rate (g/s)

Engine-out emission module

- Fuel-rate is modeled as

$$FR = \begin{cases} \phi \cdot \left(K \cdot N \cdot V + \frac{P}{\eta} \right), if\ P > 0 \\ K_{idle} \cdot N_{idle} \cdot V, if\ P = 0 \end{cases}$$

- Where

ϕ: fuel/air equivalence ratio
K: engine friction factor (kJ/rev/liter)
V: engine displacement (liters)
η: engine indicated efficiency
K_{idle}: constant idle engine friction factor (kJ/rev/liter)
N_{idle}: constant idle engine speed (rev/s), and
P: engine power output (kW)

- When the engine power output is zero, fuel-rate is a small constant value
- Otherwise, fuel consumption is mainly dependent on the speed and power

Engine-out emission module

- ϕ: fuel/air equivalence ratio
- Ratio of stoichiometric air/fuel mass ratio (~14.5) to the actual air/fuel ratio
- Stoichiometric ratio corresponds to the mass of air needed to ideally oxidize a mass of fuel completely
- When $\phi > 1$: fuel-air mixture is called *rich* (more fuel)
  - Less efficient, produces more power, and burn cooler
- When $\phi < 1$: the mixture is *lean* (more air)
  - More efficient, cause higher temperatures

Engine Power Model

- $P = \frac{P_{tract}}{\epsilon} + P_{acc}$
- Where P_{tract} is the traction power requirement
- ϵ is the vehicle drivetrain efficiency
- P_{acc} is the auxiliary power requirement
- Traction power is

$$P_{tract} = A \cdot v + B \cdot v^2 + C \cdot v^3 + M \cdot a \cdot v + M \cdot g \cdot \sin \alpha \cdot v$$

- Where
- A: rolling resistance term (kW/m/s)
- B: speed-correction to rolling resistance term (kW/(m/s)^2)
- C: air drag resistance term (kW/(m/s)^3)

Enginer Power Model in Veins

- In TraCIMobiliy::calculateCO2emission()

```
double A = 1000 * 0.1326; // W/m/s
double B = 1000 * 2.7384e-03; // W/(m/s)^2
double C = 1000 * 1.0843e-03; // W/(m/s)^3
double M = 1325.0; // kg

// power in W
double P_tract = A*v + B*v*v + C*v*v*v + M*a*v; // for sloped roads: +M*g*sin_theta*v
```

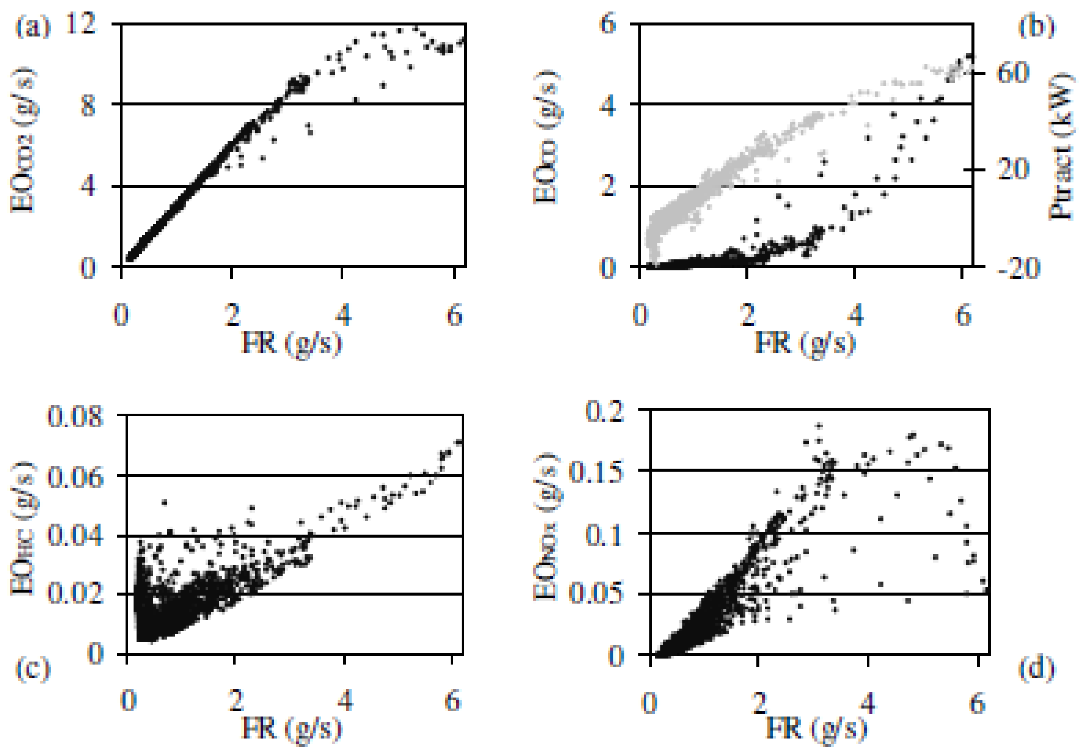
Emission Indices EI_i

- EI_i are modeled in various ways as a function of ϕ and FR
- Generally, more fuel is burned, more emissions are formed
- Hence, it can be approximated that

$$EO_i = \lambda + \mu \cdot FR$$

- CO2 is the principal product of complete fuel combustion, so it is linear to FR
- CO is sensitive to ϕ. Rich mixture leads to incomplete combustion due to lack of oxygen
- HC is also a product of incomplete combustion
- NOx is mainly dependent on the combustion temperature because the dissociation and subsequent recombination of atmospheric N2 and O2 that generate NO and NO2 is induced by high temperature. For very small values of FR very little NOx is emitted

Engine-Out Emission Rates vs Fuel Rate



Dotted gray in the second graph is traction power

Emission Model in Veins

- Assumptions
  - The effects on fuel rate of K, N, ϵ, and ϕ can be aggregated into the effects of v, v^2, v^3 and $v \cdot a$
- $FR = \begin{cases} \alpha_{FR} + \beta_{FR}v + \gamma_{FR}v^2 + \delta_{FR}v^3 + \zeta_{FR}av, if\ P_{tract} > 0 \\ \alpha'_{FR}, if\ P_{tract} = 0 \end{cases}$
- As we assumed EOi is a linear function of FR
- $EO_i = \begin{cases} \alpha_i + \beta_i + \gamma_i \mathrm{v}^2 + \delta_i v^3 + \zeta_i av, if\ P_{tract} > 0 \\ \alpha'_i, if\ P_{tract} = 0 \end{cases}$

```
// "Category 9 vehicle" (e.g. a '94 Dodge Spirit)
double alpha = 1.11;
double beta = 0.0134;
double delta = 1.98e-06;
double zeta = 0.241;
double alpha1 = 0.973;

if (P_tract <= 0) return alpha1;
return alpha + beta*v*3.6 + delta*v*v*v*(3.6*3.6*3.6) + zeta*a*v;
```

Tailpipe Emissions Module

- Tailpipe emission rates TPi (g/s) are modeled as the fraction of the engine-out emission rates that leave the catalytic converter
- Catalytic converter: Exhaust emission control device that reduces toxix gases and pollutants in exhaust gas from an internal combustion engine into less-toxic pollutants by catalyzing a redox reaction
  - Carbon monoxide to carbon dioxide
  - HC to carbon dioxide and water
  - Nitrogen oxides to nitrogen

$$2\ CO + O_2 \rightarrow 2\ CO_2$$

$$C_xH_{2x+2} + [(3x+1)/2]\ O_2 \rightarrow x\ CO_2 + (x+1)\ H_2O$$

$$2\ CO + 2\ NO \rightarrow 2\ CO_2 + N_2$$

Tailpipe Emissions Module

- $TP_i = EO_i \cdot CPF_i$
- Catalyst efficiency is difficult to predict accurately
- Differs greatly from hot-stabilized to cold-start conditions
- Relies on empirical models using piecewise linear functions of engine-out emission rates

Auxiliary Systems Power Consumption

- Real world scenario example (10℃ ambient temperature)

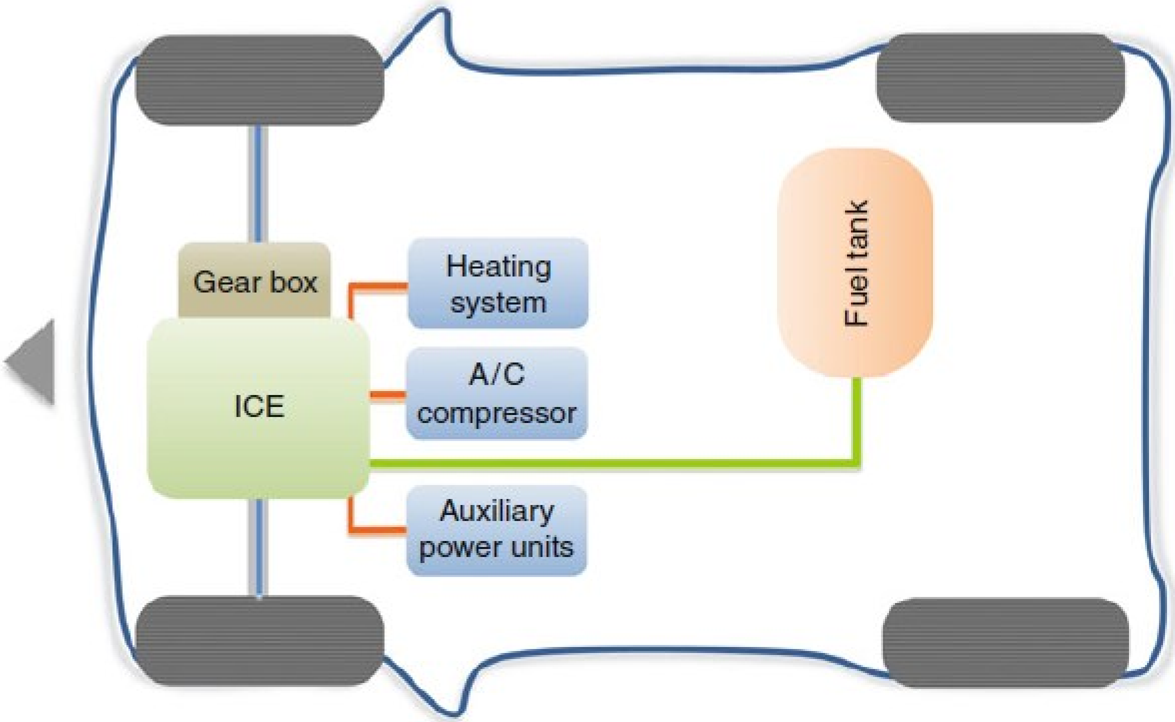
Auxilliary systems	ICE	Hybrid electric	Fuel cell electric	Battery electric
Heating system	0	0	0	2
Air conditioning	0.5	0.5	0.5	0.5
Other	0.5	0.5	0.5	0.5
Total	1	1	1	3

Comparison ICEV, HEV, FEV, BEV

Energy Storage Systems

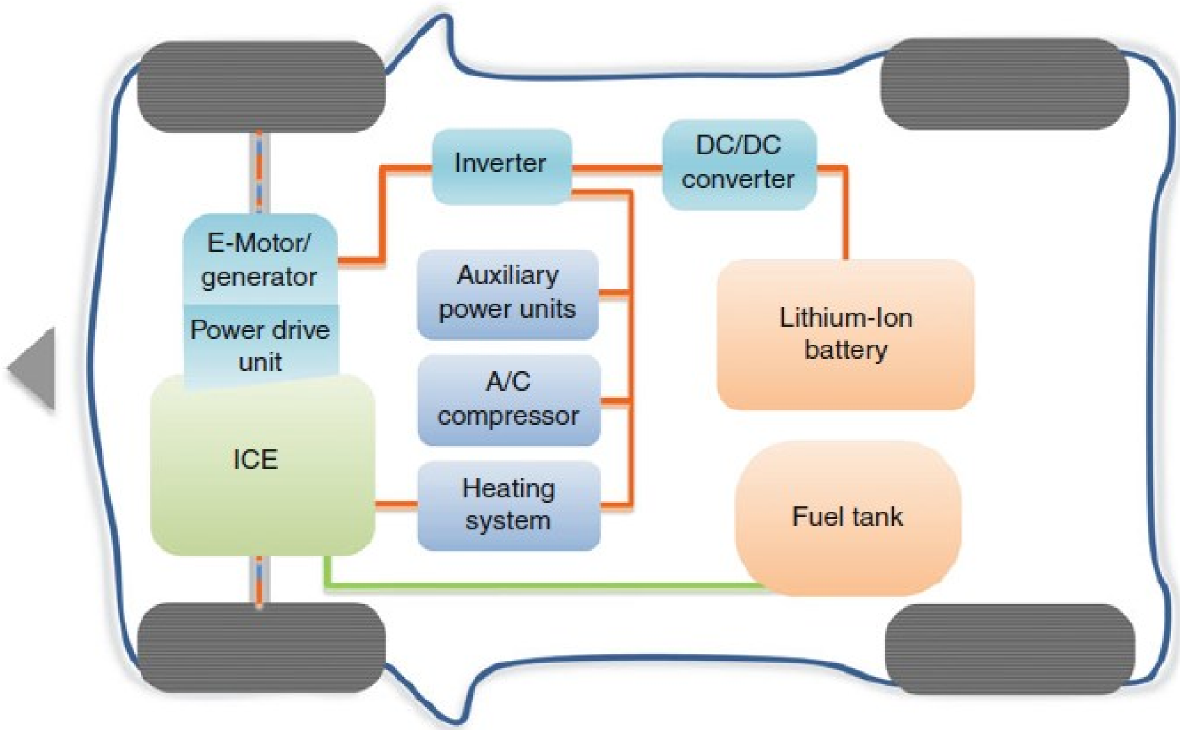
- Nickel-Metal-Hydride Battery (NiMH): Widely used in hybrid electric vehicles due to high energy density
- Lithium-ion battery (Li-ion): Highest energy density among rechargeable electrochemical cells
- Fuel cell: Supplies electric energy by converting chemically bound energy. Energy density (hydrogen) of orders of magnitude higher. Typically constrained by power capacity

Internal Combustion Engine Vehicle



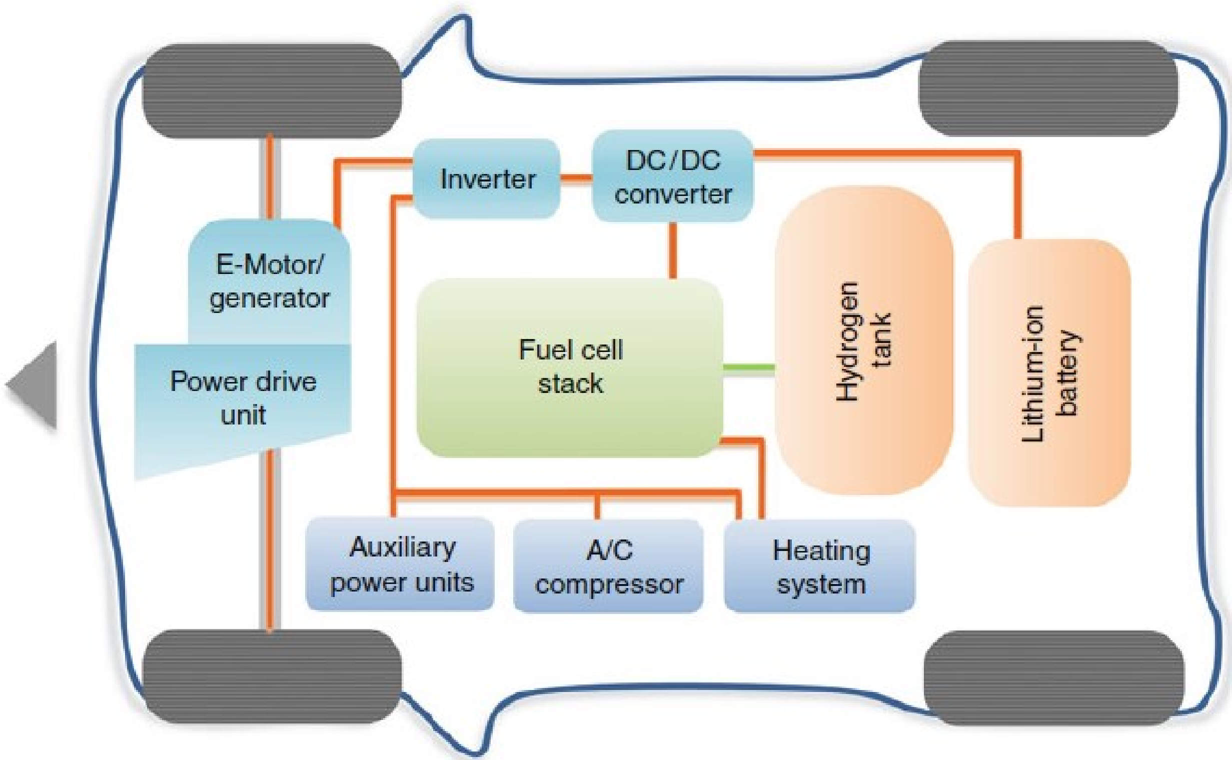
Hybrid Electric Vehicle

- Power split hybrid
  - ICE runs only when necessary and operates are high efficiency range
  - Motor and engine can supply power separately as well as together
  - Efficiency becomes a bit lower at highway speeds as high power is required and components are forced to operate at lower efficiency range



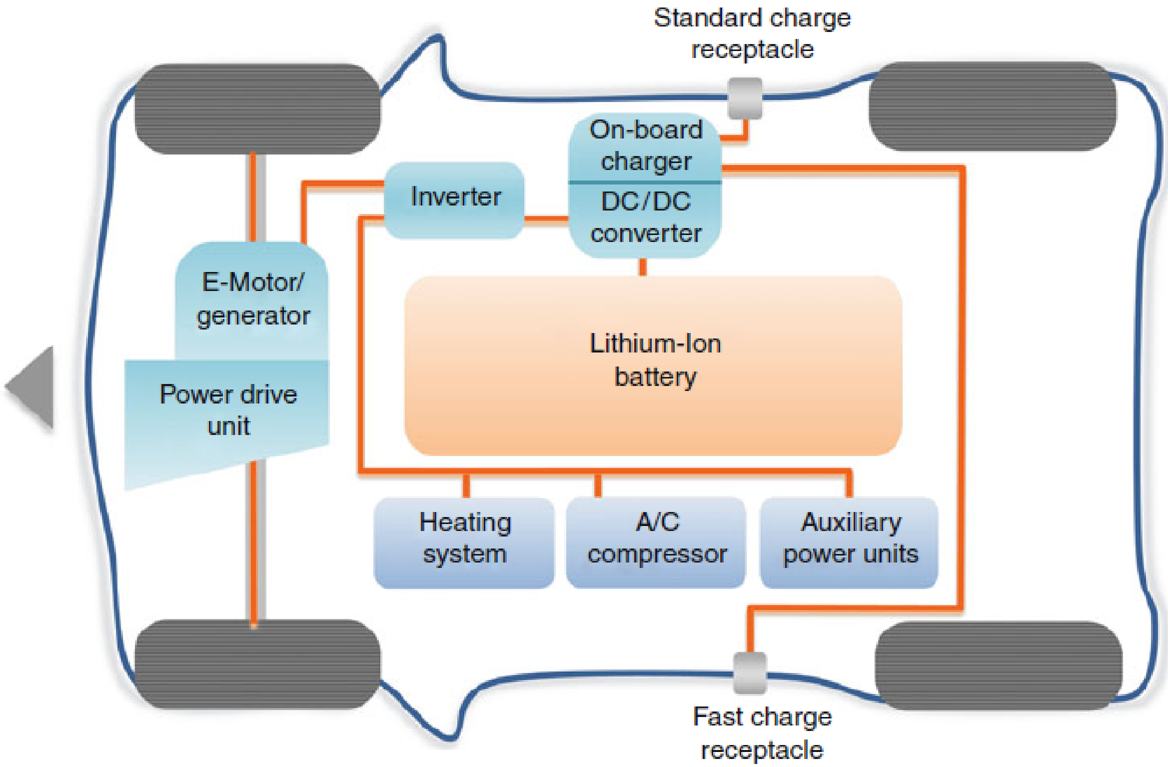
Fuel Cell Vehicle

- Products of controlled reaction between hydrogen and oxygen are heat and water
- The reaction temperatures of commonly used proton exchange membrane fuel cells are around 80℃
- Fuel cells are limited in power, so often used together with buffer batteries



Battery Electric Vehicle

- Energy used to propel the vehicle is from an external source (chargers)
- Battery-DC-DC converter-inverter-motor



Internal Combustion Engine Vehicle

- Vehicle specification example

	ICE vehicle	HEV	Fuel cell	BEV
Curb weight	1,400 kg	1,500 kg	1,500 kg	1,700 kg
Air drag coefficient	0.31	0.31	0.32	0.32
Cross sectional area	2.22 m^2	2.22	2.38	2.38
Rolling resistance	0.012	0.012	0.012	0.12
Tank capacity	50 L	45 L	4 kg H2 @ 700 bar	24 kWh
Max power	105 kW	100 kW	75 kW	75 kW
Note	6-speed manual	With 50 kg NiMH	With 50 kg Li-ion	Battery (300 kg)

Tank-to-Wheel Energy Consumption

- “Tank-to-Wheel”
  - Energy transfer chain from the on-board energy storage system (fuel tank/battery/hydrogen tank) to wheels during vehicle operation
  - ICE vehicle performs appears to be lower because of the lower engine efficiency (max 50%)
  - The results are even worse for urban driving scenarios
    - Engines are forced to operate in the low efficiency area

Fuel Economy: ICE vs Electric

Driving conditions			Energy consumption [MJ/100 km]			
Test cycle	Average speed [km/h]	Ambient scenario	ICE (Diesel)	Hybrid electric (Gasoline)	Fuel cell electric	Battery electric
NEDC New European driving cycle	33	Type approval	164	136	98	71
		Real-world	188	161	108	108
UDC Urban driving cycle	19	Type approval	192	137	101	64
		Real-world	230	169	116	129
EUDC Extra urban driving cycle	65	Type approval	147	134	97	75
		Real-world	162	156	105	96
Freeway 100	97	Type approval	146	149	102	84
		Real-world	159	159	110	100
Freeway 130	125	Type approval	193	207	151	117
		Real-world	207	218	161	131

Primary Energy Consumption

- Do electric vehicles ensure lower carbon emission?
- Depends, we have to look at primary energy consumption
- We have to look at where the energy for electric vehicles are coming from
- Calculations based on a typical electric energy mix for a region with 40% non-carbon primary sources

Energy source	Process stages	Efficiency [%]
Fossil fuels	Production and distribution	90
Electricity	Storage of electricity in accumulator batteries (regular charge)	75
	Average power generation efficiency	50
Hydrogen (from methane reformation)	Production of H_2 from methane reformation	75
	Compression of H_2 for pressure fueling at 700 bar	85
Hydrogen (from electrolysis)	Average power generation efficiency	50
	Production of H_2 from electrolysis	75
	Compression of H_2 for pressure fueling at 700 bar	85

Primary Energy Consumption

- Electrification should be done together with the “energy transition”
- Cleaner grid is required (but keep in mind that data is at least 10 years old)

Propulsion concept	Consumption	Tank-to-wheel energy consumption [MJ/100 km]	Primary energy consumption [MJ/100 km]		Maximum range [km]
ICE diesel					
	Liter $_{Diesel}$/100 km				
NEDC Type approval	4.6	164	182		1,070
NEDC Real-world	5.3	188	208		940
Hybrid electric					
	Liter $_{Gas}$/100 km				
NEDC Type approval	4.2	136	151		1,080
NEDC Real-world	4.9	161	179		910
Fuel cell electric					
	kg H_2/100 km		Methane reformation	Electrolysis	
NEDC Type approval	0.8	98	153	306	490
NEDC Real-world	0.9	108	169	338	445
Battery electric					
	kWh/100 km				
NEDC Type approval	20	71	189		122
NEDC Real-world	30	108	289		80

References

- A. Cappiello, et al., “A statistical model of vehicle emissions and fuel consumption,” IEEE International Conference on Intelligent Transportation Systems, 2002
- Handbook of Intelligent Vehicles