MEEN 432 –Automotive Engineering

Fall 2026

Instructor: Dr. Arnold Muyshondt

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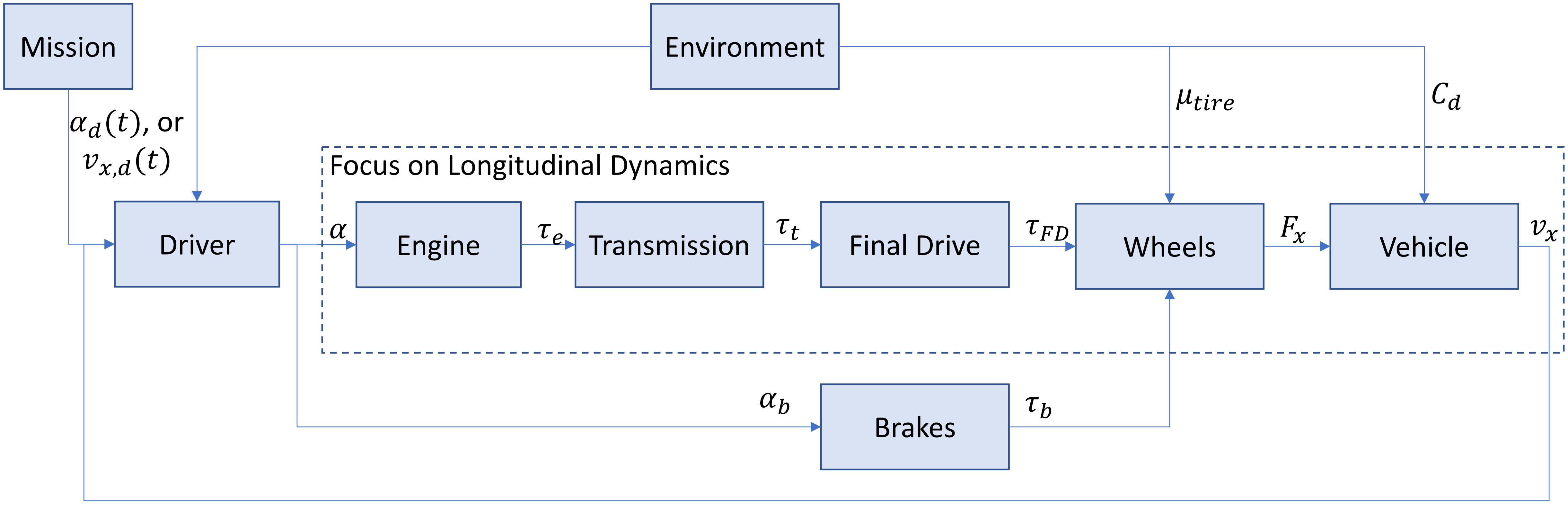
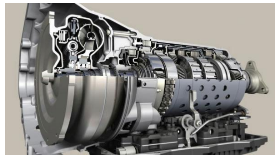
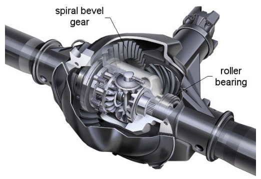
Lecture 15: Powertrain Architectures

- Powertrain Architectures
  - ICE, EV, HEV (Series, Parallel)
- Vehicle Specifications and Powertrain High Level Desgin

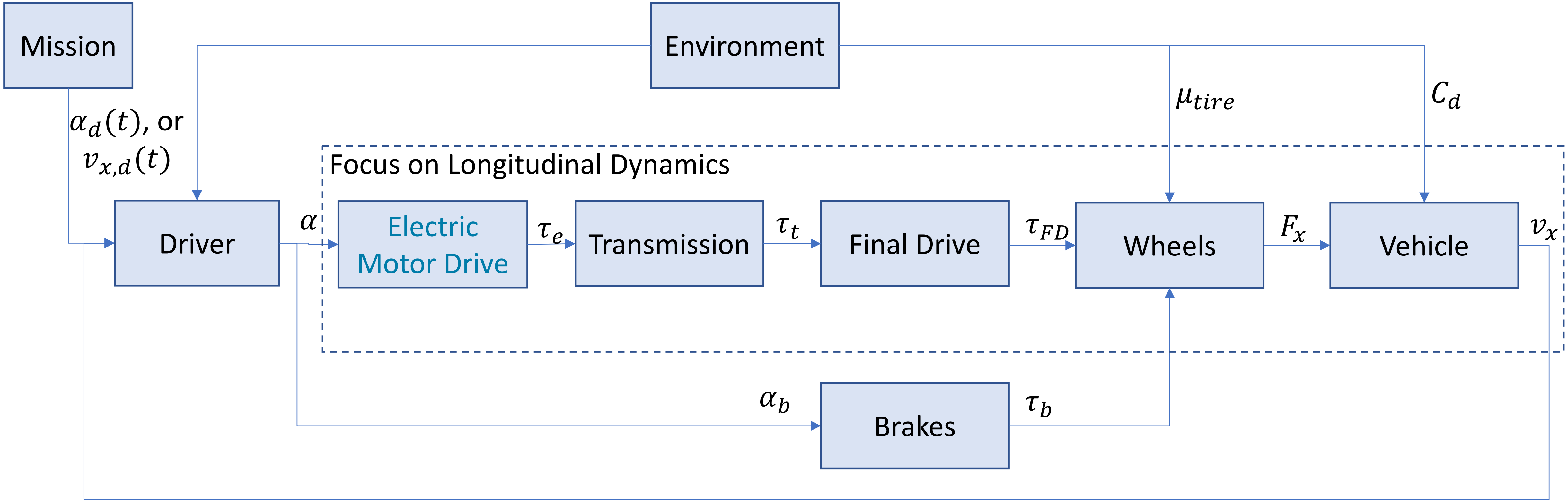
ICE Powertrain Architecture

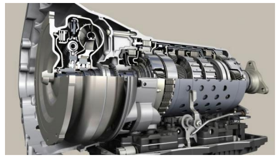


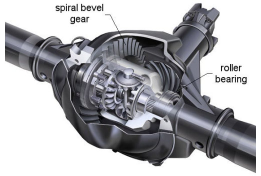




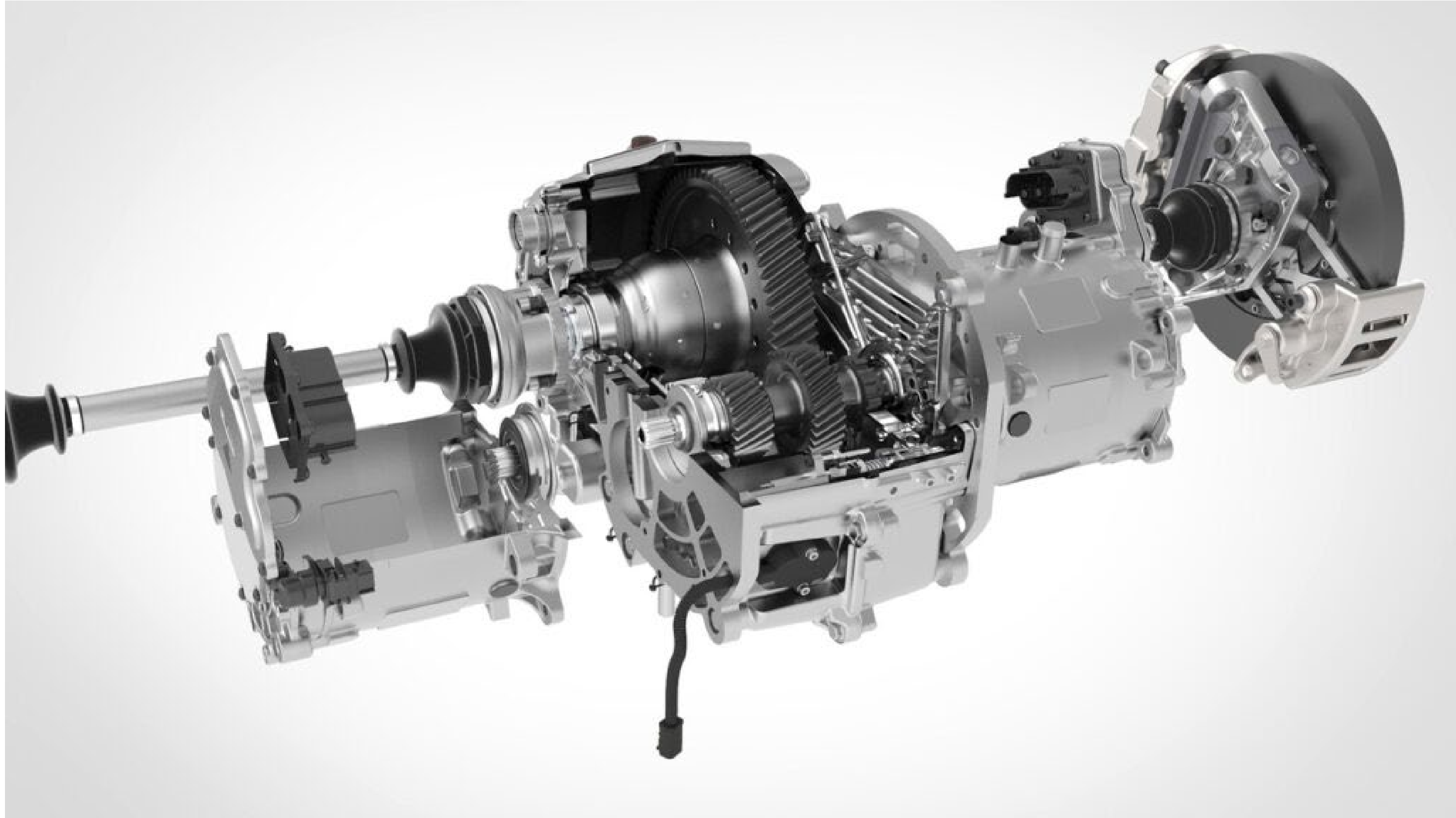
EV Powertrain Architecture



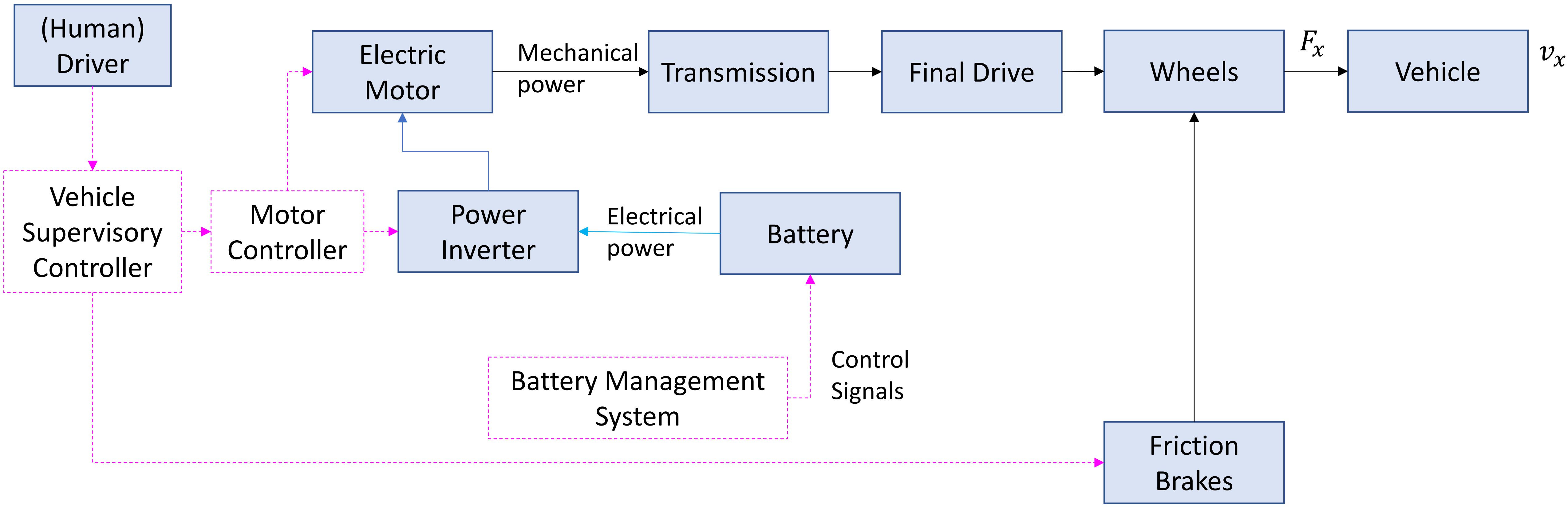




Other Electric vehicle Configurations – Multi-Speed Transmission



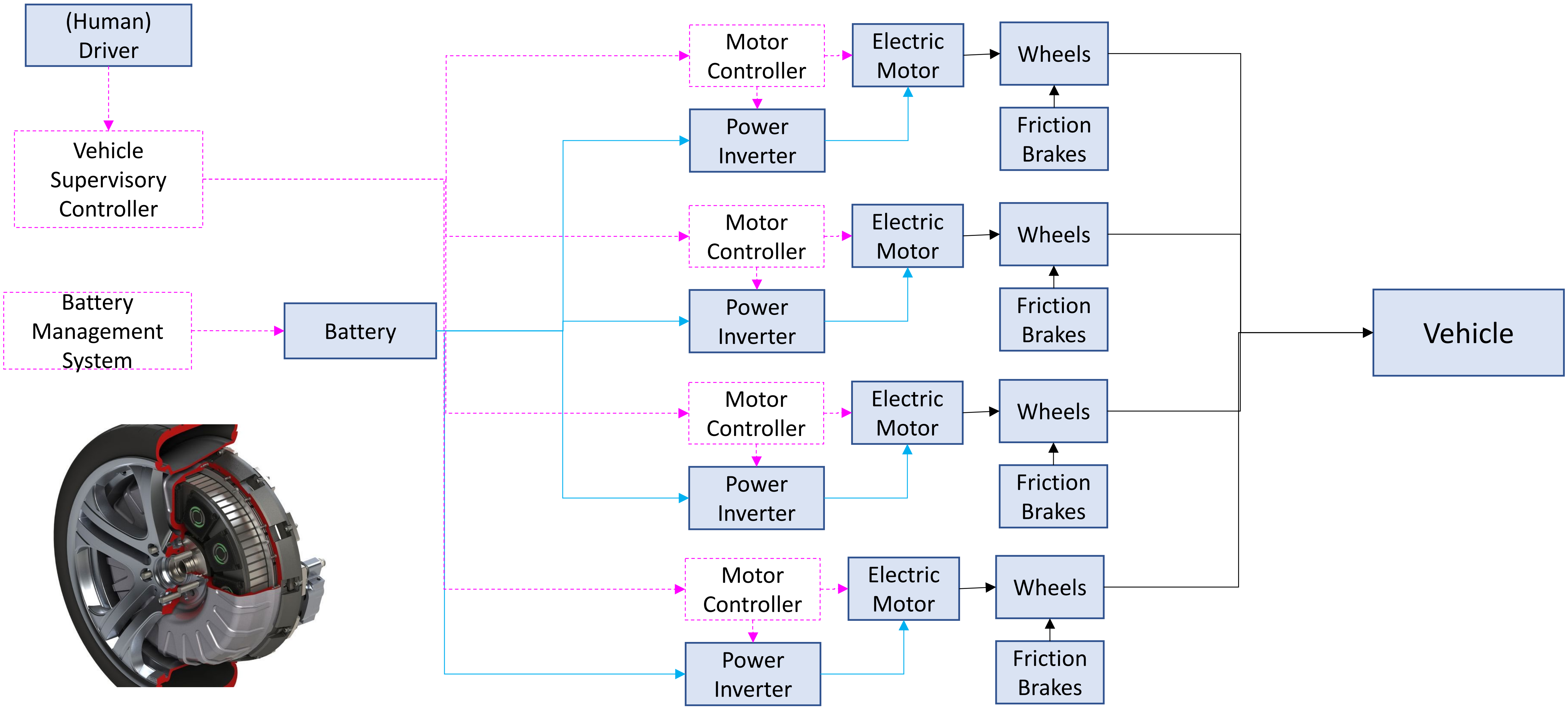
Electric Vehicle Architecture



Electric Vehicle Systems Control

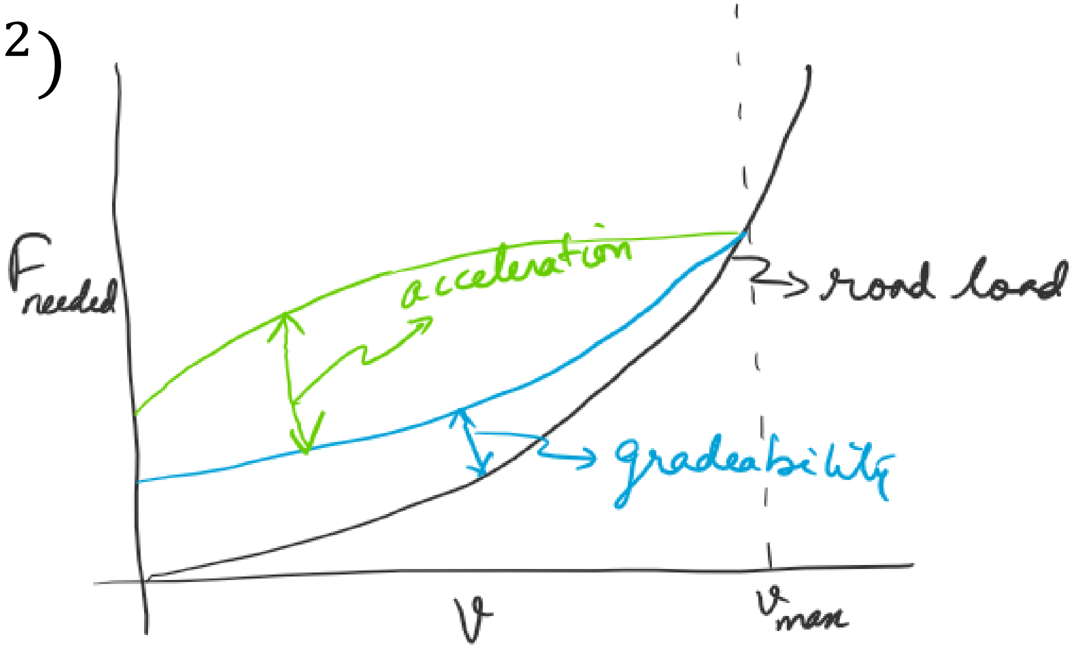
- Vehicle Supervisory Control (also known by many other names)
  - Critical for the performance of the vehicle. Some Key functions:
  - When to use regen vs. friction braking:
    - Maximize regen, ensure safety, ensure battery will not get overcharged
  - Interpret Driver
    - This will be driven by expected market segment for the vehicle
      - E.g. a sporty vehicle may interpret the same driver pedal value differently than for a sedan
    - Modulate the desired behavior based on battery, motor state
      - E.g. some EVs have a special performance mode that will draw a large amount of power (from Ultracaps, for e.g.) for a very short amount of time
  - Provide the driver with an accurate range available (estimation of SOC, state of energy, etc.)

Other Electric Vehicle Configurations – Wheel Motors



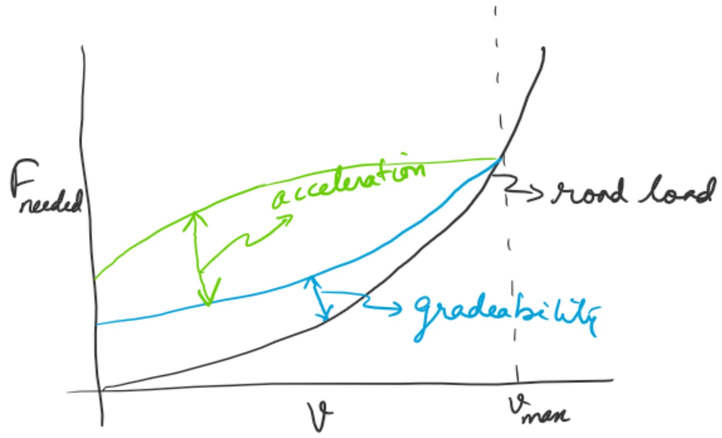
Vehicle Specifications

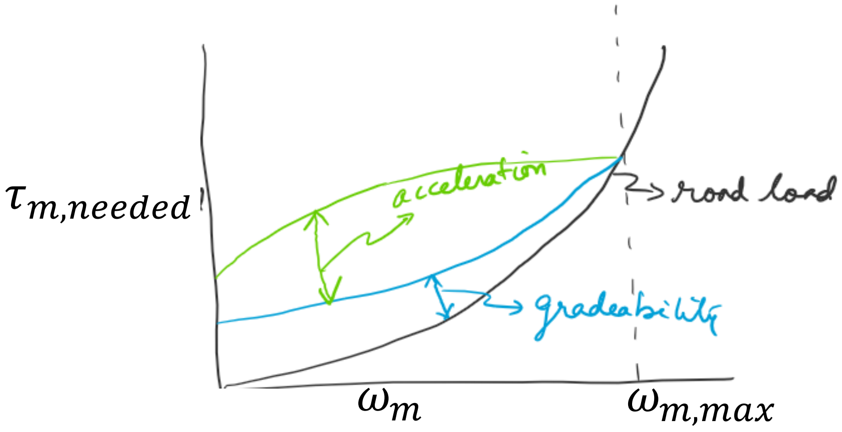
- $F_x = M\,\dot{v} + Mg\sin(\theta) + (c_0 + c_1 v + c_2 v^2)$
  - θ the grade of road
- Vehicle Specifications:
  - Max speed v_{max}
  - Gradeability $gr\% = \tan(\theta)$
  - Max acceleration at different speeds $a(v)$
- Powertrain Requirements specified as a graph of tractive force required for different velocities



Vehicle Specifications – 2

- Neglecting inertia effects ,we can write:
  - $v = r\,\omega_w = \frac{r}{G_{FD}}\omega_t = \frac{r}{G_{FD}G}\omega_m$
  - $F = \frac{1}{r}\tau_w = \frac{G_{FD}}{r}\tau_t = \frac{G_{FD}G}{r}\tau_m$
- Then we can redraw the vehicle requirements (tractive force vs speed) in terms of motor requirements (tau vs omega)





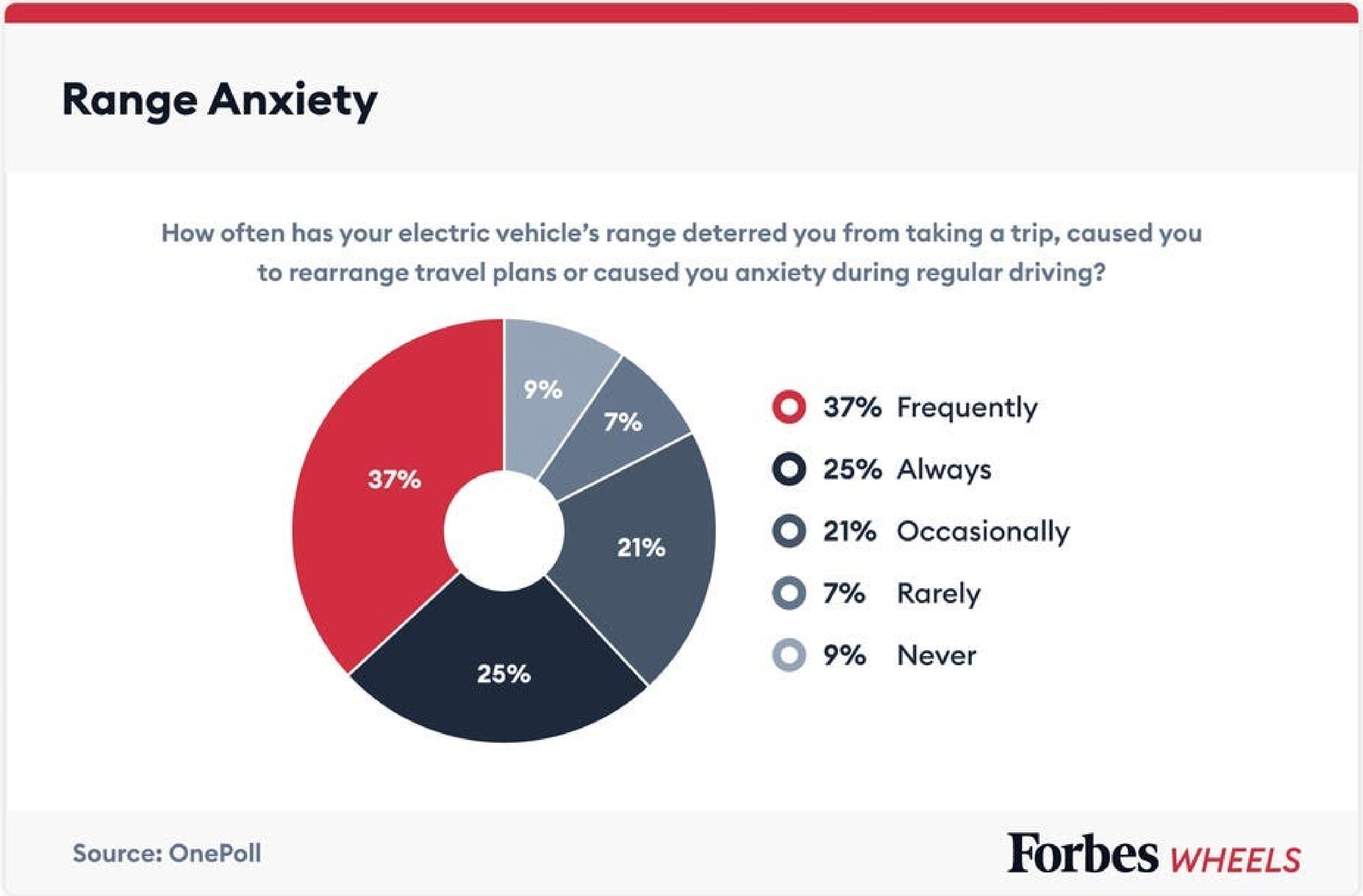
Vehicle Specifications – 3

- We can overlay the motor requirements (based on the vehicle level specifications) on the motor capabilities
- If you have multiple gears, you can “choose” the gear to meet the vehicle specifications at optimal efficiency!

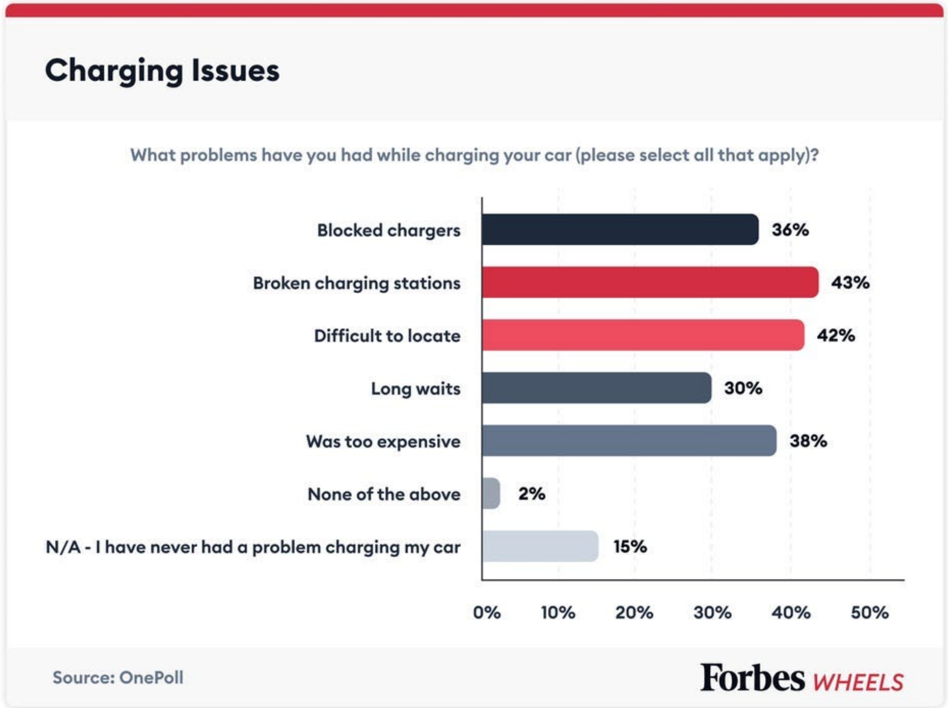
Powertrain Design Considerations

- Given a vehicle – identify power and torque needs from the specifications
- Given a set of motor choices, choose the one(s) that satisfy the max power need first
- Given the max speed and max torque curve of the motor:
  - Choose a gear ratio from available gear designs:
    - Confirm if the torque speed of requirement is satisfiable
      - Else iterate
    - If no single transmission can satisfy the requirement consider multiple gear ratios
      - You need to have a mechanism to "switch" gears
- Operational: (if you have multiple gears)
  - Choose operational gear to maximize some objective (e.g. maximize energy efficiency)

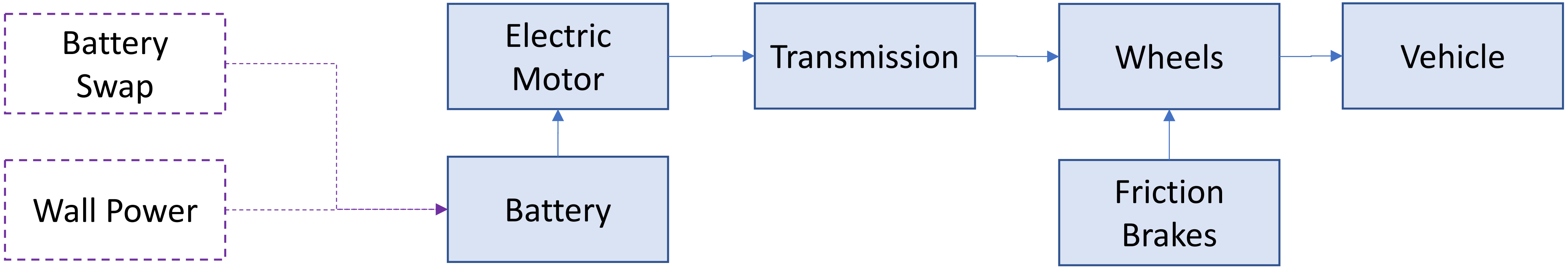
Key market challenge for Electric Vehicles



- How do you get the benefits of the EVs while addressing some key challenges (technical, infrastructure, policy, …)



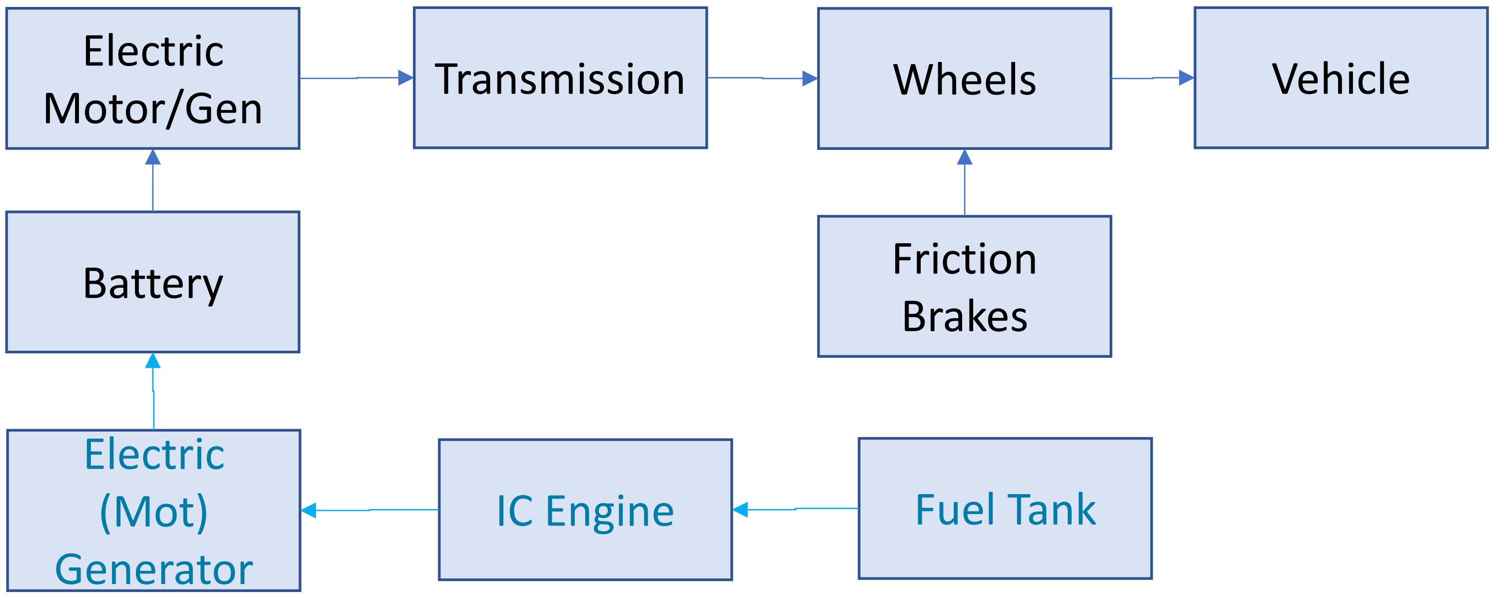
How to address "range anxiety"



- One solution to increase range is to increase size of the battery:
  - Higher Range Required ➔ Bigger Batteries
    - ➔ Heavier Vehicle
    - ➔ Bigger motors, higher losses
    - ➔ reduced range!
  - Iterate!!
- Another Solution: To add alternate on-board energy storage with higher energy density: the fuel tank!
  - ➔ Hybrid Electric Vehicles (HEVs)

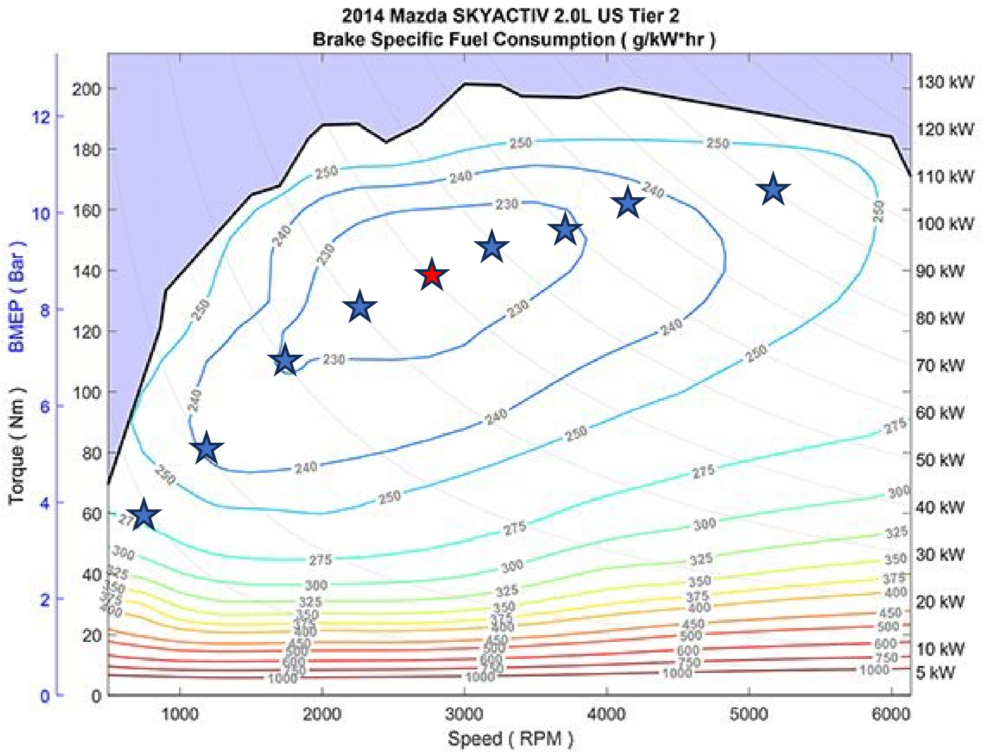
Hybrid Electric Vehicles (HEVs)

- HEVs combine the benefit of “regenerative braking” in EVs, with the high range of ICE-based vehicles
- One Architecture adds an on-board generator to charge the battery
  - Series Hybrid Electric vehicle



Series HEVs Control Modes - 1

- Key Observation about the Series-HEV configuration:
  - The engine power is “decoupled” from the vehicle power, i.e., the torque and speed of the engine can be different from the torque-speed needs at the wheel
  - Therefore, given an operational power, the engine is operated at maximum efficiency for that power level



★ Optimal operating point for power $p_{e,d}$: $\left(\frac{p_{e,d}}{\omega_e^*}, \omega_e^*\right)$

★ Optimal power $p_{e,d}^*$

Series HEVs Control Modes - 2

- Two primary operational modes:
  - Load Follower, Range Extender
- Load Follower → minimize battery storage
- Here the objective is for the engine to provide power "close" to the wheel needs:
  - $p_{e,d} \approx p_w$
- Power difference primarily due to dynamic transients of the load
  - Isolate power generation from power consumption
- Small Battery size requirement → ultra-capacitor a good candidate

Series HEVs Control Modes - 3

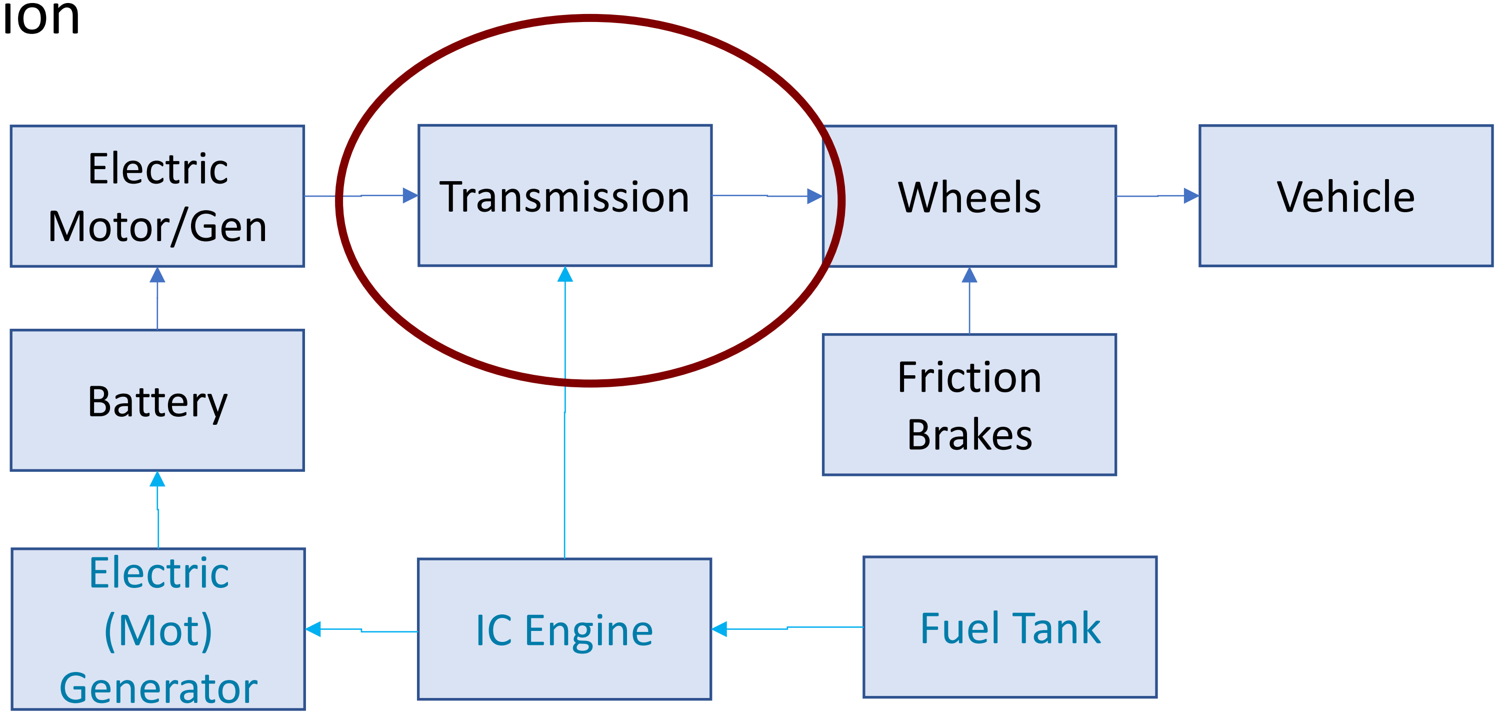
- Range Extender → Maximize Efficiency
  - $p^*_{e,d} = \max(\,argmax_{p_e}\,\eta)$ i.e., the most optimal power delivery point of the engine
  - The difference between $p_{e,d}$ and p_w is provided (or absorbed) by the battery
- Operational Strategy:
  - $SOC > \beta_{on} \Rightarrow p_{e,d} = 0\ (i.e. Engine\ OFF)$
  - $SOC < \beta_{off} \Rightarrow p_{e,d} = p^*_{e,d}$
- Larger battery required
- "Plug-in" Hybrids are essentially EVs that have an additional "ICE/generator" that will charge the battery
  - What operational mode do plug-in HEVs follow?

Series HEVs – Efficiency First Order Analysis

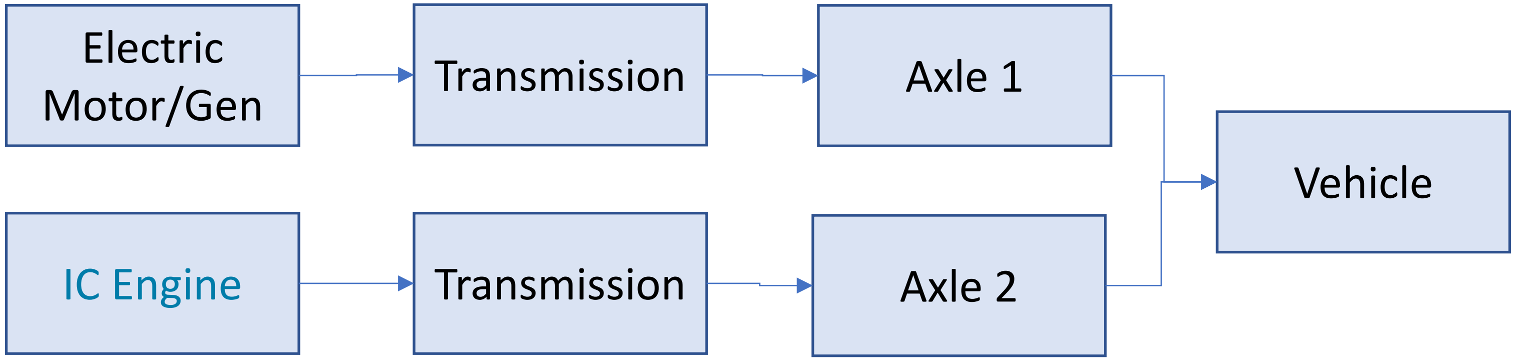
- Wall Power: $p_{bat} = p_{wall}\eta_{bat} = p_{fossil}\eta_{utilities}\eta_{bat}$
- Series Hybrid: Range Extender Strategy
  - $p_{bat} = p_{fuel}\eta_{eng}^{*}\eta_{EDT}\eta_{bat}$
    - Note that η_{eng}^{*} is the peak efficiency of the engine
  - $p_{wheels} = p_{bat}\eta_{bat}\eta_{EDT} = p_{fuel}\eta_{eng}^{*}\eta_{bat}^{2}\eta_{EDT}^{2}$
- Series Hybrid: Load Follower Strategy
  - $p_{wheels} = p_{fuel}\eta_{eng}\eta_{EDT}^{2}$
    - Note that η_{eng} is the operational efficiency of the engine
  - Compare with regular vehicles: $p_{wheels} = p_{fuel}\eta_{eng}\eta_{T}$
    - $\eta_T \geq 90\%, \eta_{EDT} \approx 80\%$
- Can we combine the advantages of Series Hybrid with direct power transmission?
  - Parallel Hybrid Electric transmission

Parallel HEVs

- An alternative HEV architecture to Series-HEVs is the Parallel HEVs
- The ICE is directly connected to the wheels, “along” with the electric motor
  - P-HEVs are inherently more complex – both in construction as well as in operation

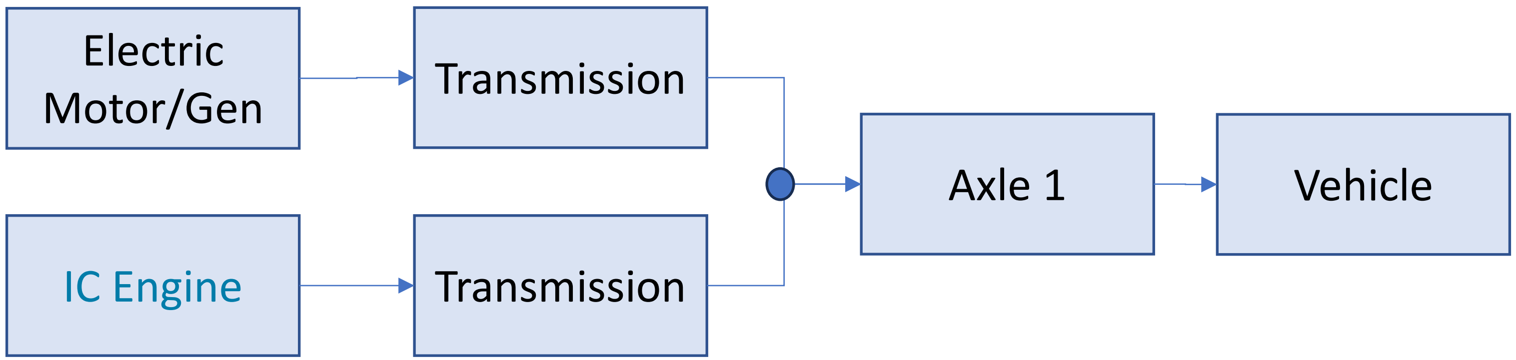


Parallel HEV – 1



- The simplest HEV configuration is what is called the “mild parallel hybrid”
- An electric motor is added to the second axle of the vehicle
  - Provides automatic “all-wheel-drive” capabilities
  - Enables regen
  - Battery sized only to absorb regen
- Controllability of the vehicle and “drive feel” important considerations
  - Cost-benefit a concern

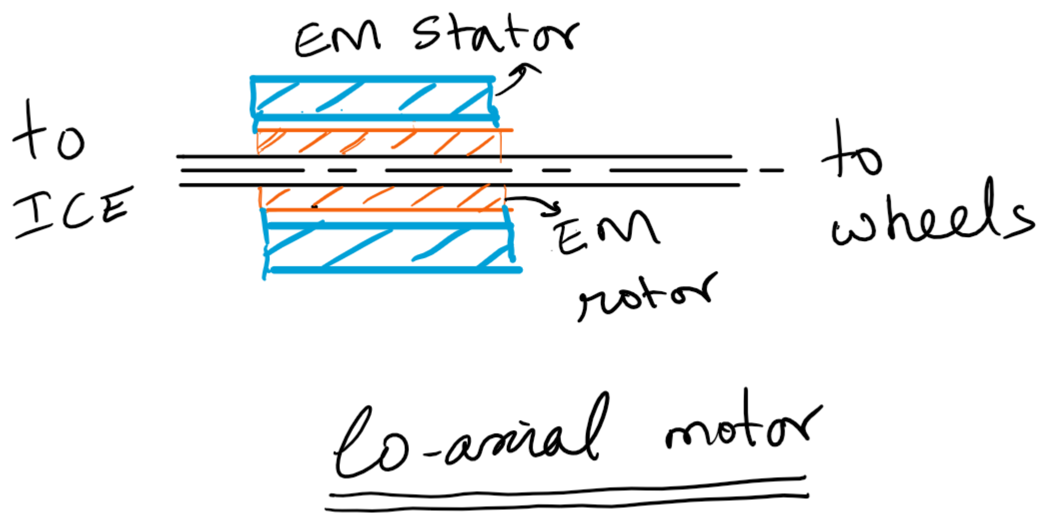
Parallel HEV – 2

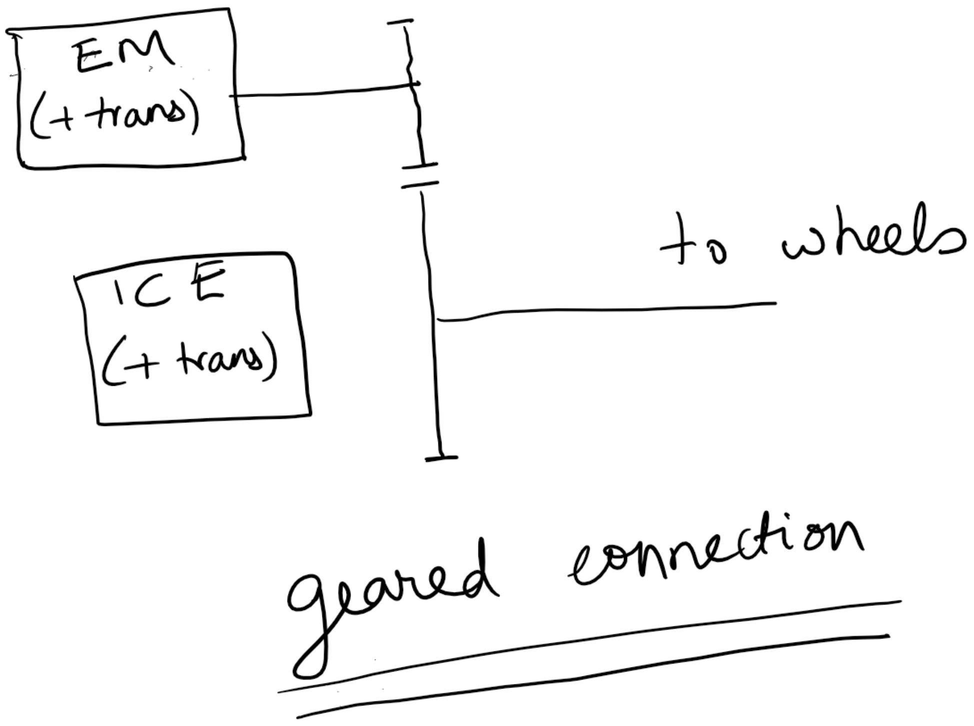


- Many typical Parallel HEVs have the electric motor and ICE directly connected through a transmission to the same axle of the vehicle
- $\omega_e = G_{ICE}\omega_w$ and $\omega_m = G_m\omega_w$
  - Therefore $\omega_e = \frac{G_{ICE}}{G_m}\omega_m$
    - for a given gear, the speeds of the motor and the ICE cannot be controlled independently
- If the transmissions are multi-gear, then there is some operational flexibility in choosing the gear
  - Typical Parallel HEVs have a single speed transmission for the motor and multi-speed for the ICEs
- The torques (and hence the powers) from the ICE and EM can be chosen independently, and define the operational strategy of the vehicle

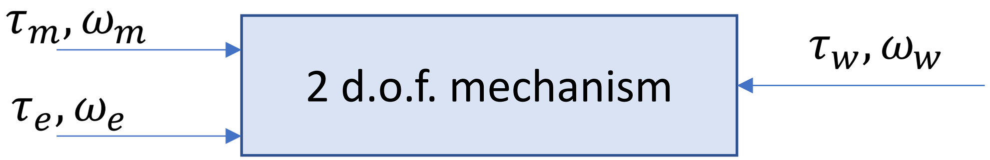
Parallel HEV – 3

- 1 d.o.f. Mechanizations of the EM/ICE connection
  - $\omega_e = G_1 \omega_w ; \omega_m = G_2 \omega_w$ Given a wheel speed, the engine and motor speeds are fixed





Parallel HEV - 4



- For higher flexibility (and optimization) of the powertrain operations, we consider 2 d.o.f. mechanizations
  - $\omega_e + G_2\omega_m = G_1\omega_w$ i.e. given a wheel speed, we have additional flexibility to choose the engine xor moto speed
    - Choose $\omega_m = (G_1 - G) \,/\, G_2 \; \omega_w$, then
    - Then $\omega_e = G\;\omega_w$ i.e. the effective speed ratio is G
  - These mechanizations are variants of the "planetary gear"
- Power balance: (neglect losses for now)
  - $\tau_m\omega_m + \tau_e\omega_e + \tau_w\omega_w = 0; \tau_m \frac{(G_1 - G)}{G_2} + \tau_e G = -\tau_w$
    - The torque equation is more complicated than before; correspondingly the control of these devices is more involved

Parallel HEV -5

- The 2 d.o.f. mechanizations use the planetary gear train to "split/combine" mechanical power from two shafts operating at different torque and speeds
  - A great example of such a system is Toyota's Prius drive train:

    Know Your Toyota Mechanical: Power Split Device