MEEN 432 –Automotive Engineering

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Lecture 12: Energy Balance

- Cycle Energy Economy
- First Order Energy Balance Analysis

Fuel Economy

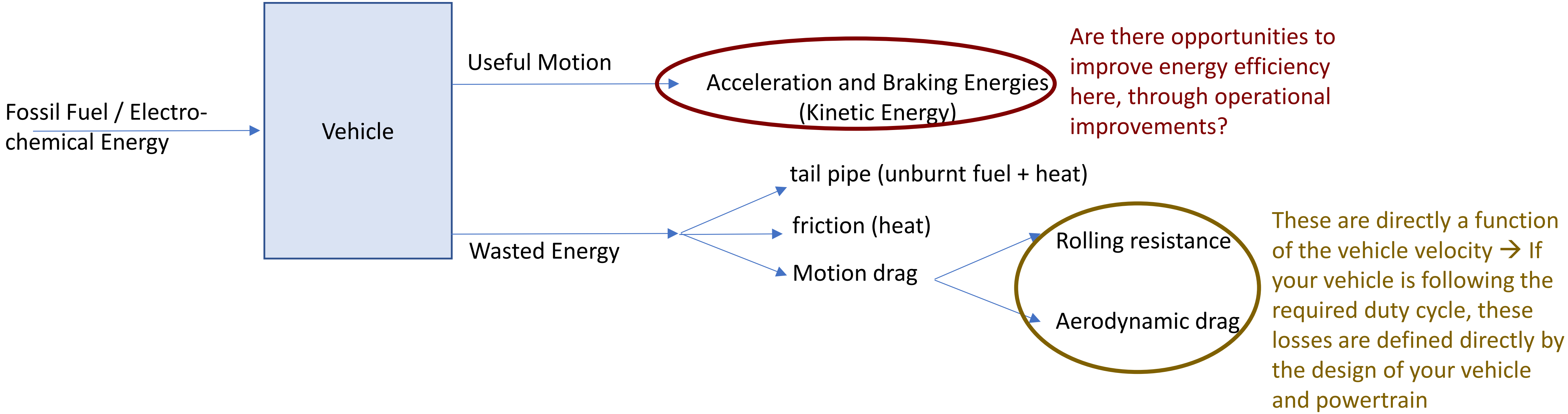
- Per drive cycle:
  - $mpg_{cycle} = l/f_g$ where the vehicle has traveled l miles and consumed f_g gallons of fuel over the cycle
- Composite fuel economy
  - $mpg = f(mpg_{hwy}, mpg_{urban})$
- Corporate Average Fuel Economy (CAFE)
  - Fuel economy weighted by the production volumes
  - CAFE standards are regulated across a company.

Considerations for EV/HEV for Fuel Economy

- Energy consumed (by battery): e_{bat}(kJ = kWs)
- Miles traveled during cycle: l miles
- Equivalent Electric Vehicle consumption for a given cycle:
  - $mpg_{e,cycle} = \frac{l\,(33.705)(3600)}{e_{bat}}$

Electric Vehicle - Single-Cycle City Test Procedure Summary - Following SAE J1634 May 1993 Recommended Practice, the battery is fully charged, the vehicle is parked overnight, and then the following day the vehicle is driven over successive city cycles until the battery becomes discharged (and the vehicle can no longer follow the city driving cycle). After running the successive city cycles, the battery is recharged from a normal AC source and the energy consumption of the vehicle is determined (in kW-hr/mile or kW-hr/100 miles) by dividing the kilowatt-hours of energy to recharge the battery by the miles traveled by the vehicle. The recharge energy includes any losses due to inefficiencies of the manufacturer's charger. To calculate the energy consumption in units of mpg_e (miles/gallon equivalent) we use a conversion factor of 33.705 kilowatt-hours of electricity per gallon of gasoline (which is basically a measure of the energy in gasoline (in BTUs) converted to electricity). The city driving range is determined from the number of miles driven over the city cycle until the vehicle can no longer follow the driving cycle.

Energy Flow Analysis



- We can write:

$$E_{cycle} = E_{losses} + E_{KE}$$

- where E_{cycle} is the energy required to drive the vehicle through the drive cycle – after powertrain losses, E_{losses} represents the aero and rolling resistance losses through the cycle, E_{KE} represents the energy required **from the energy source** to change the kinetic energies

Kinetic Energy Analysis

- Let’s define the Kinetic Energy as $T = \frac{1}{2}Mv^2$
- Then, the rate of change of T is: $\dot{T} = P = \ M\ v\ \dot{v} = Mva$
- For increasing T we apply a torque from the motor (use electro-chemical or fossil fuel energy)
- For decreasing T?
  - Nominally, a brake is used. This energy is dissipated at the wheel as thermal energy
    - In this case, $E_{KE} = E_{accn}$ i.e. only the energy required to accelerate the vehicle. The energy required to decelerate the vehicle comes from the brakes.
  - Could we (re)capture this KE, store it, and re-use it later?
    - This is the basic rationale for regenerative braking

First Order KE analysis

- We can keep track of the total change in KE as below:
  - $\Delta T \ = \int_0^t P_{KE}\, d\tau = \int_0^t m v \dot{v}\, d\tau = \int_{T^+} m v \dot{v}\, d\tau + \int_{T^-} m v \dot{v}\, d\tau$
    - where $T^+ = \ \{t \mid P_{KE}(t) \geq 0\}$ and $T^- = \ \{t \mid P_{KE}(t) < 0\}$
    - Essentially T^+ and T^- partition the duty cycle times in periods when there is acceleration and periods when there is braking
    - Correspondingly we can write: $\Delta T = \Delta T_{accn} + \Delta T_{brk}$
- Now, we also know that
  - $\Delta T \ := T(v_{final}) - T(v_{start}) = 0$ since $v_{start} = v_{final} = 0$ for typical duty cycles
- Therefore
  - $\Delta T_{accn} = -\Delta T_{brk}$
- Defining the energy that is ***absorbed*** by the brakes as E_{brk} we have
  - $E_{accn} = E_{brk}$

Regenerative Braking

- $E_{cycle} = E_{losses} + E_{accn} = E_{losses} + E_{brk}$
- Let us define the factor γ_1 that relates the braking (or acceleration) energy to the losses during a cycle: (this will depend on the type of cycle)
  - $E_{brk} = \gamma_1 E_{losses}$
- Then
  - $E_{cycle} = E_{losses}(1 + \gamma_1)$
- Now assume that we can actually "tap" the brake energy, and reuse it for supporting the driving losses and acceleration.
  - This is called "**regenerative braking**"
  - Clearly there is an underlying expectation that the energy can be stored temporarily somewhere so it can be used to drive the vehicle later!

First Order Regen Brake Analysis

- Let us assume that we can regenerate γ_2 fraction of the available braking energy, i.e.
  - $E_{regen} = \gamma_2 E_{brk} = \gamma_1 \gamma_2 E_{losses} = \frac{\gamma_1 \gamma_2}{1+\gamma_1} E_{cycle}$
- Therefore the effective energy needed to drive the cycle would be reduced as below:
  - $E_{cycleWithRegen} = E_{cycle} - E_{regen} = \left(1 - \frac{\gamma_1 \gamma_2}{1+\gamma_1}\right) E_{cycle} = \frac{1+\gamma_1-\gamma_1\gamma_2}{1+\gamma_1} E_{cycle}$
  - i.e. the energy consumption would be reduced by $\frac{1+\gamma_1-\gamma_1\gamma_2}{1+\gamma_1}$ or alternatively the “mpg” would be increased by $\frac{1+\gamma_1}{1+\gamma_1-\gamma_1\gamma_2}$
- First Order Analysis:
  - Assume we can regenerate up to 80% - i.e. $\gamma_2 = 0.8$
  - Assume two cases:
    - Case 1: $\gamma_1 = 0.11$ (cycle with relatively low acceleration and deceleration content)
    - Case 2: $\gamma_1 = 1$ (cycle with high acceleration and deceleration content)
  - The corresponding expected improvement in mpg would:
    - Case 1: increase of 8.6%
    - Case 2: **increase of 67%**

Motivation for regenerative braking

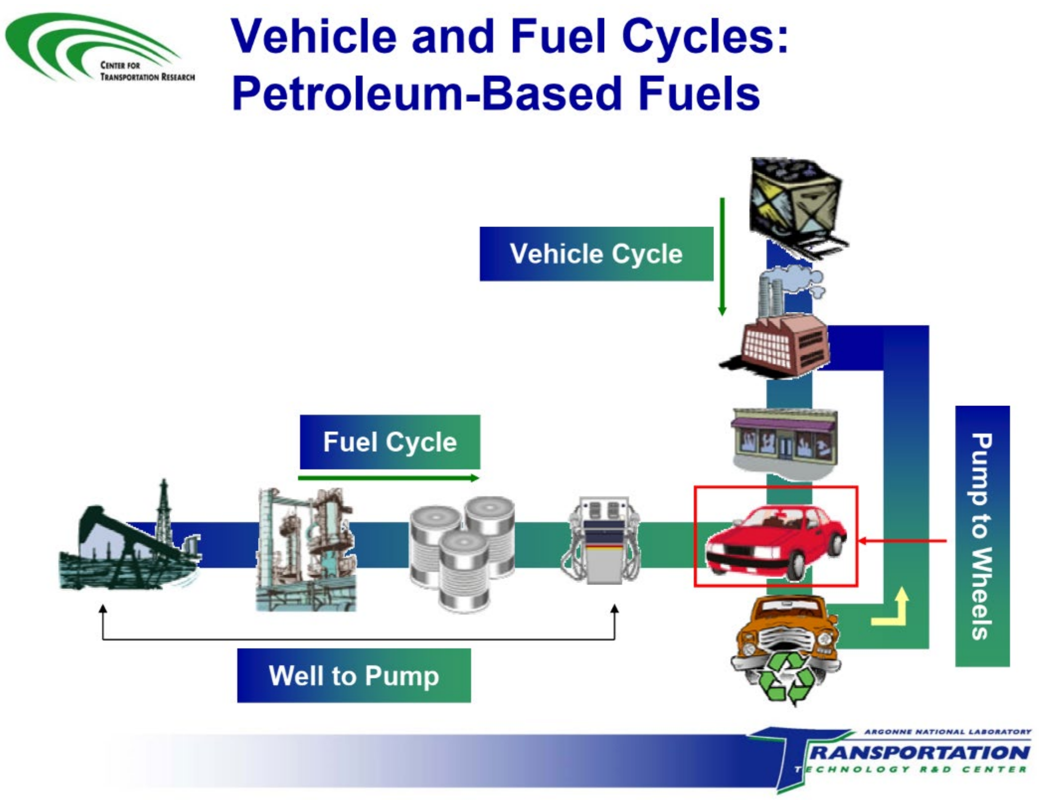
Electric Vehicle Regenerative Braking

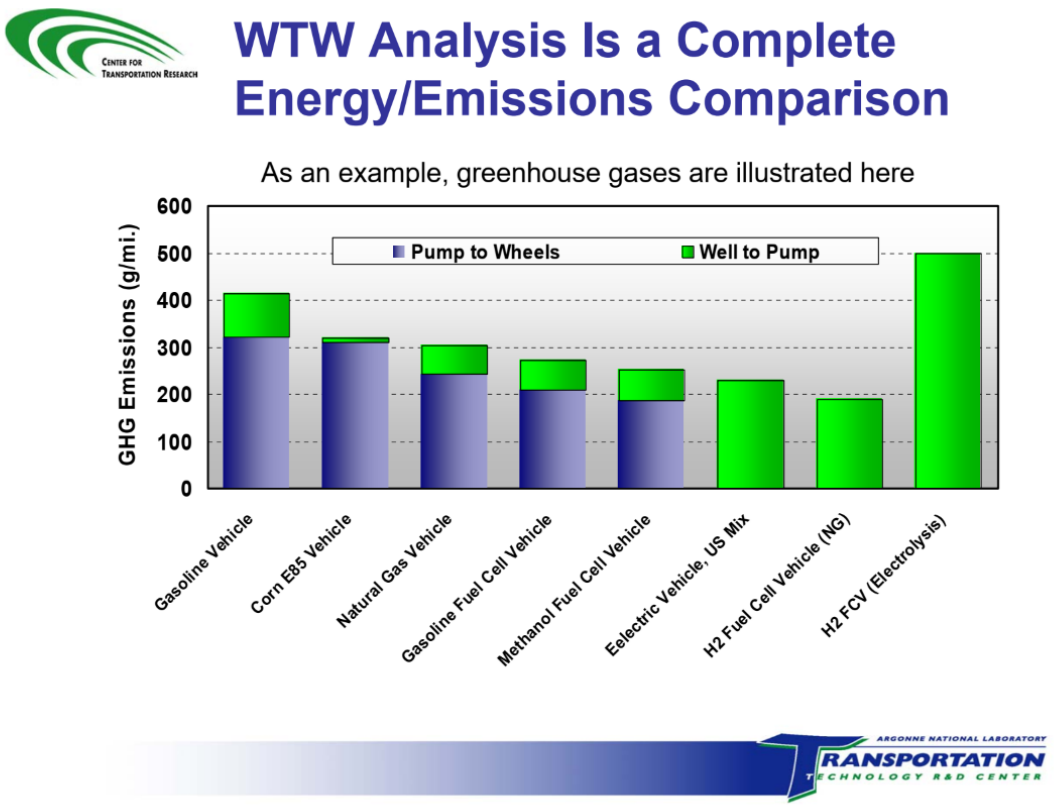
- The Electric Motor can provide positive and negative torque (and therefore power)!
  - When $\tau_m < 0$ when $\omega_m > 0$, then $i_{bus} = \tau_m \omega_m \eta_m / v_{bus}$ is negative, and so this translates to a negative i_{bat}
    - i.e. the battery is charged. (This is the natural way to store the recaptured braking energy)
- While it is tempting to use regeneration whenever possible, in reality many other factors temper that desire:
  - Charging a battery can lead to undesirable battery voltages – so it will be decided based on the SOC and the expected duty cycles in the near term.
  - Regenerative braking is “blended” with friction braking, especially at low speeds, to act as a safety backup.

Energy Balance - 1

- Powertrain Energy Balance analyzes the cascade of energy (and generation of GHG emissions) from the beginning to delivering power to the vehicles. This is a powerful way to analyze the contribution of the different components towards fuel economy (and emissions).
  - In turn, this provides a powerful way to prioritize component development, and set policies
- The scope of Energy Balance Analysis depends on your point of view:
- Policy Makers, Regulators: "Well to Wheel Analysis"
  - You consider energy (and GHG emissions) starting from the extraction of fuel, to the processing of the fuel, the manufacture of the vehicle, transportation, storage and retail of the fuel and the vehicle, and finally conversion the fuel to useful motion at your vehicle through your powertrain
- Automakers, Consumers: "Tank to Wheel Analysis"
  - You consider energy and emissions from what you fill into your tank to how it delivers your desired motion (through your powertrain)

Energy Balance – 2 – Well to Wheel Analysis





- Note the comparison above is for emissions (and not energy)
  - Electric Vehicles are NOT emissions free!!

Energy Balance - 3

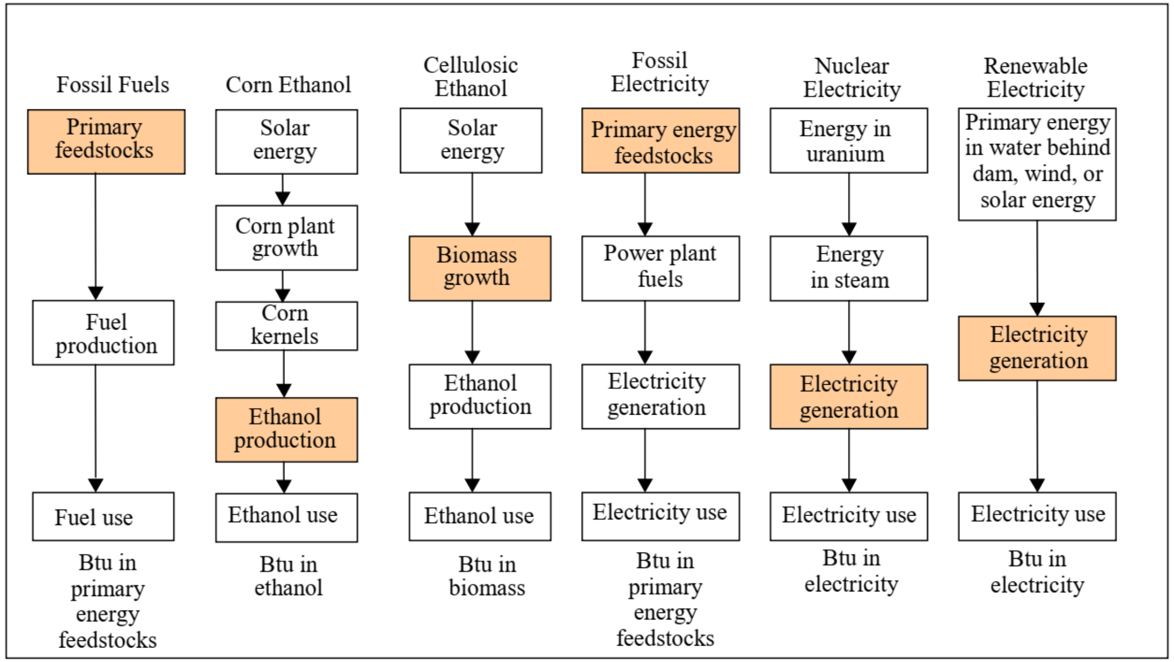


Figure 4-2 Energy Accounting System for Different Fuels in GREET

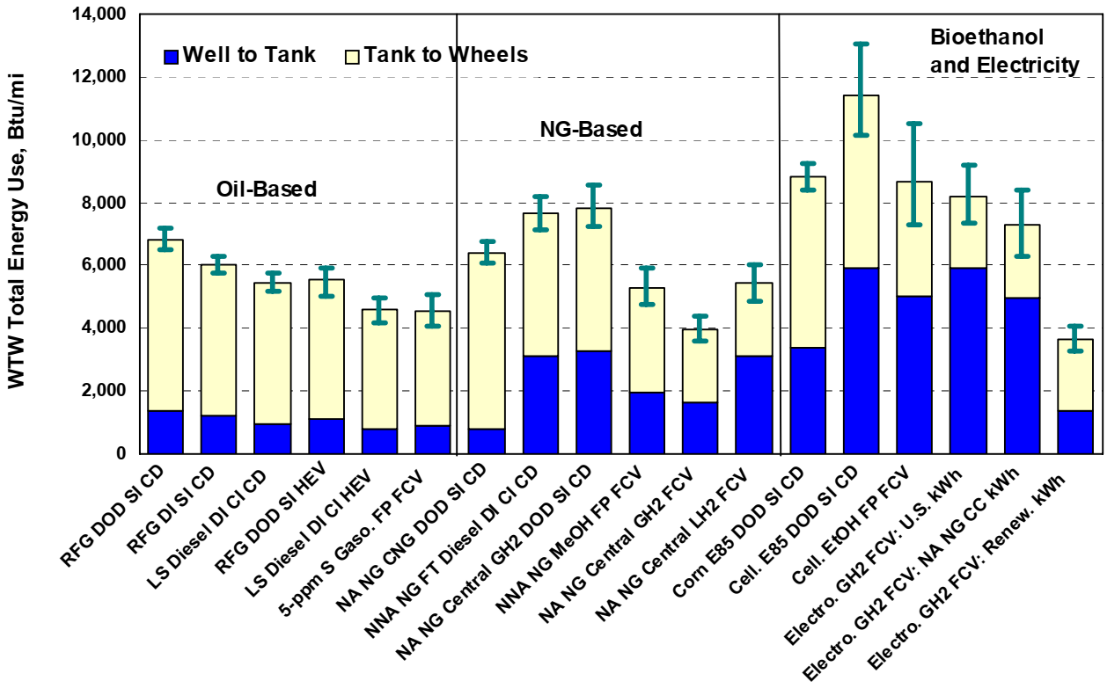
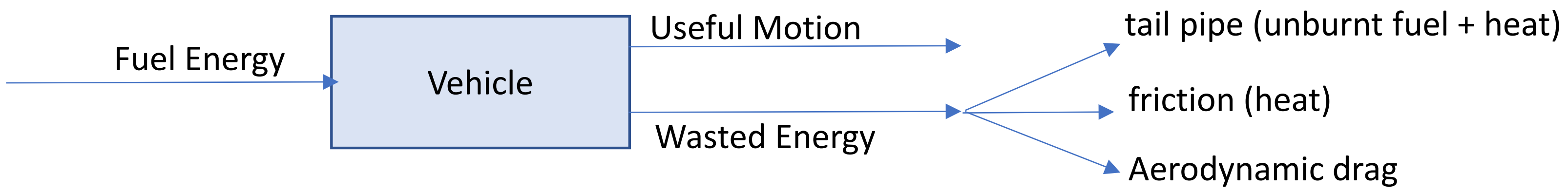


Figure 4-1 WTW Total Energy Use of 18 Vehicle/Fuel Systems (Btu/mi)

- GREET is a (relatively) popular emissions and energy modeling tool
- Such studies are done to look at various fuel and technology options

Energy Balance – 4 – Tank to Wheel Analysis



- Our interest is usually in looking at the (fossil) fuel energy used in delivering power to the vehicle.
  - An example analysis shown here

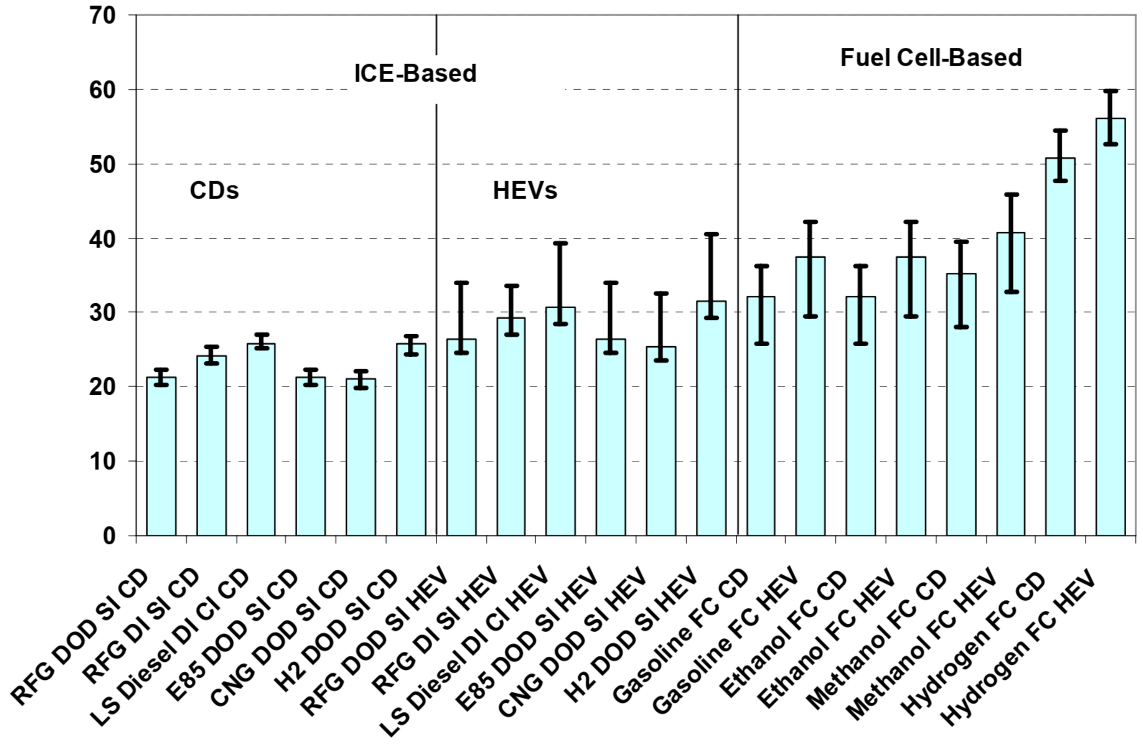


Figure 3-1 Fuel Economy Predictions with Superimposed Best-Case and Worst-Case Scenarios

Energy Balance - 5

- Comparisons need to be “fair” ➔ All the powertrain technologies need to deliver minimum requirements for a given vehicle platform
  - Subject to minimum performance requirements, individual parameters of each technology are optimized to produce the best fuel economy (and/or emissions) over duty cycles of interest

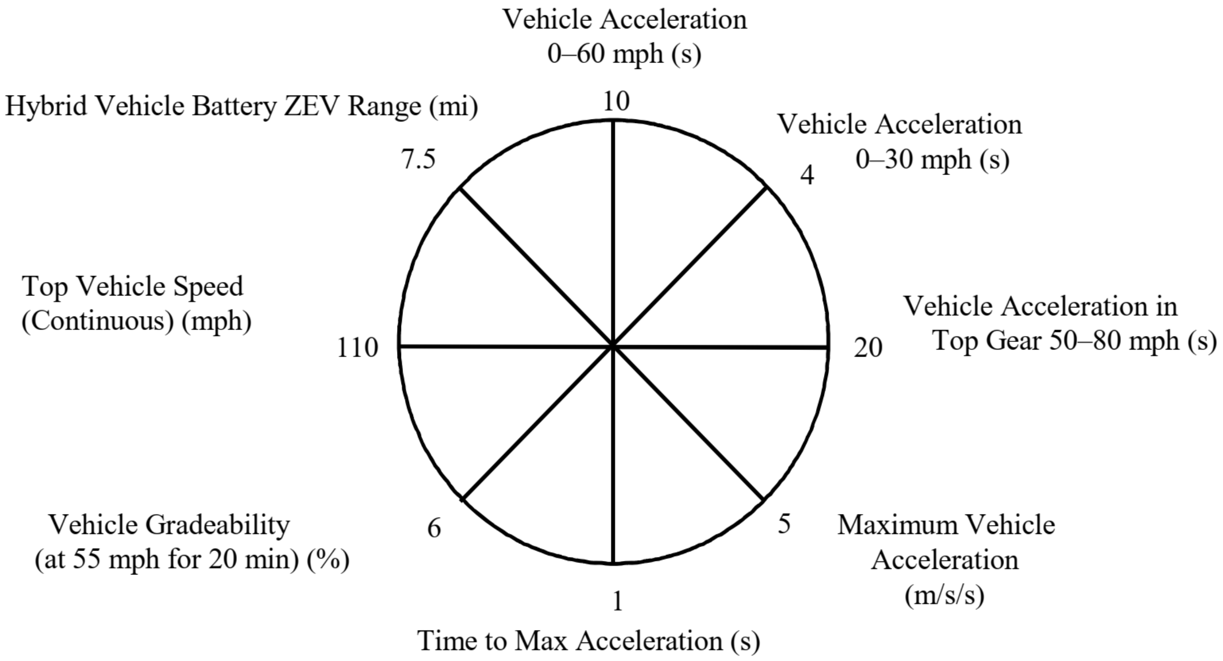


Figure 2-27 Minimum Vehicle Performance Requirements

Energy Balance – 6 – Simulation Approaches

- Given a duty cycle to be followed, two basic approaches for simulation:
  - Backward-propagating simulation
    - Vehicle motion “imposed”, and required torque and speeds propagated upstream towards the engine
    - Simple Euler-Integration technique used to calculate derivatives, to calculate accelerations and torques
    - Very Fast Simulations – enables large scale optimizations (large numbers of parameters, large number of design alternatives)
    - Less accurate capture of dynamic controls (a particular problem with complex hybrid-electric powertrains)
  - Forward-integrating simulations
    - Similar to your projects!
    - We don’t assume perfect drive cycle following, but the vehicle motion is a consequence of a driver (model) that is trying to follow the drive cycle
    - Various integration routines are considered
    - Simulations may become slower as system complexity increase
    - Higher accuracy in general

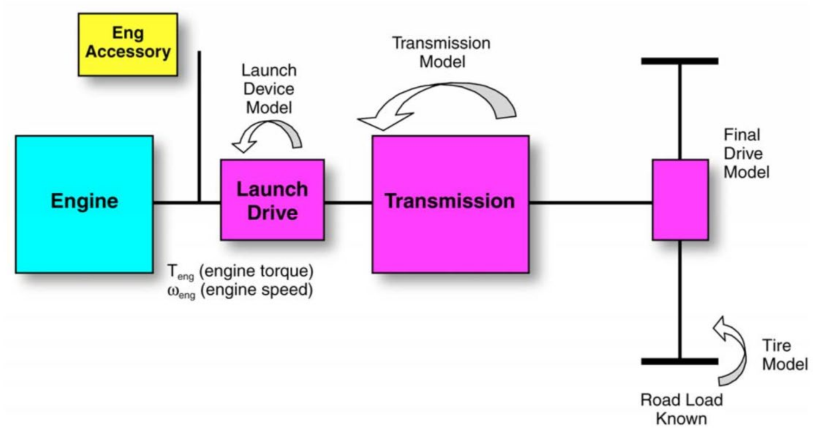
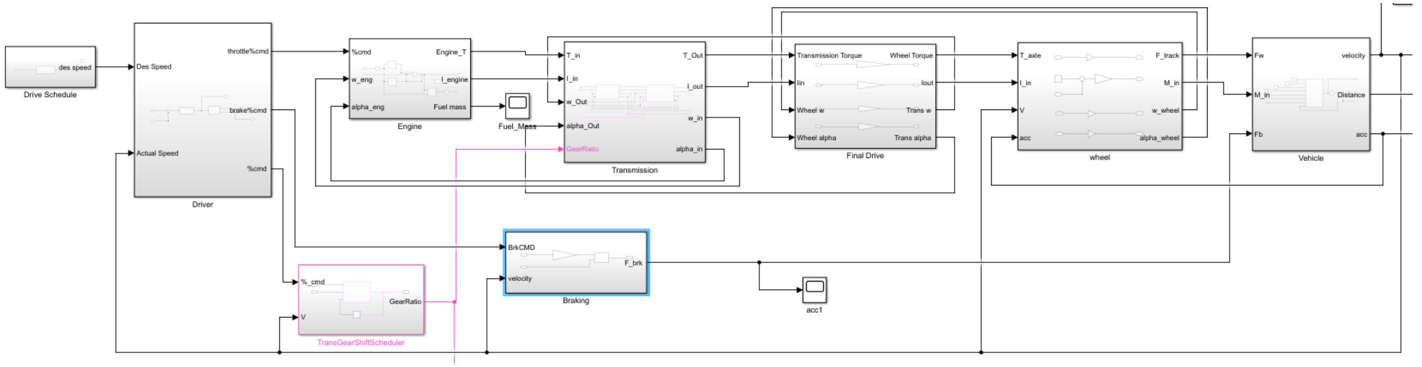


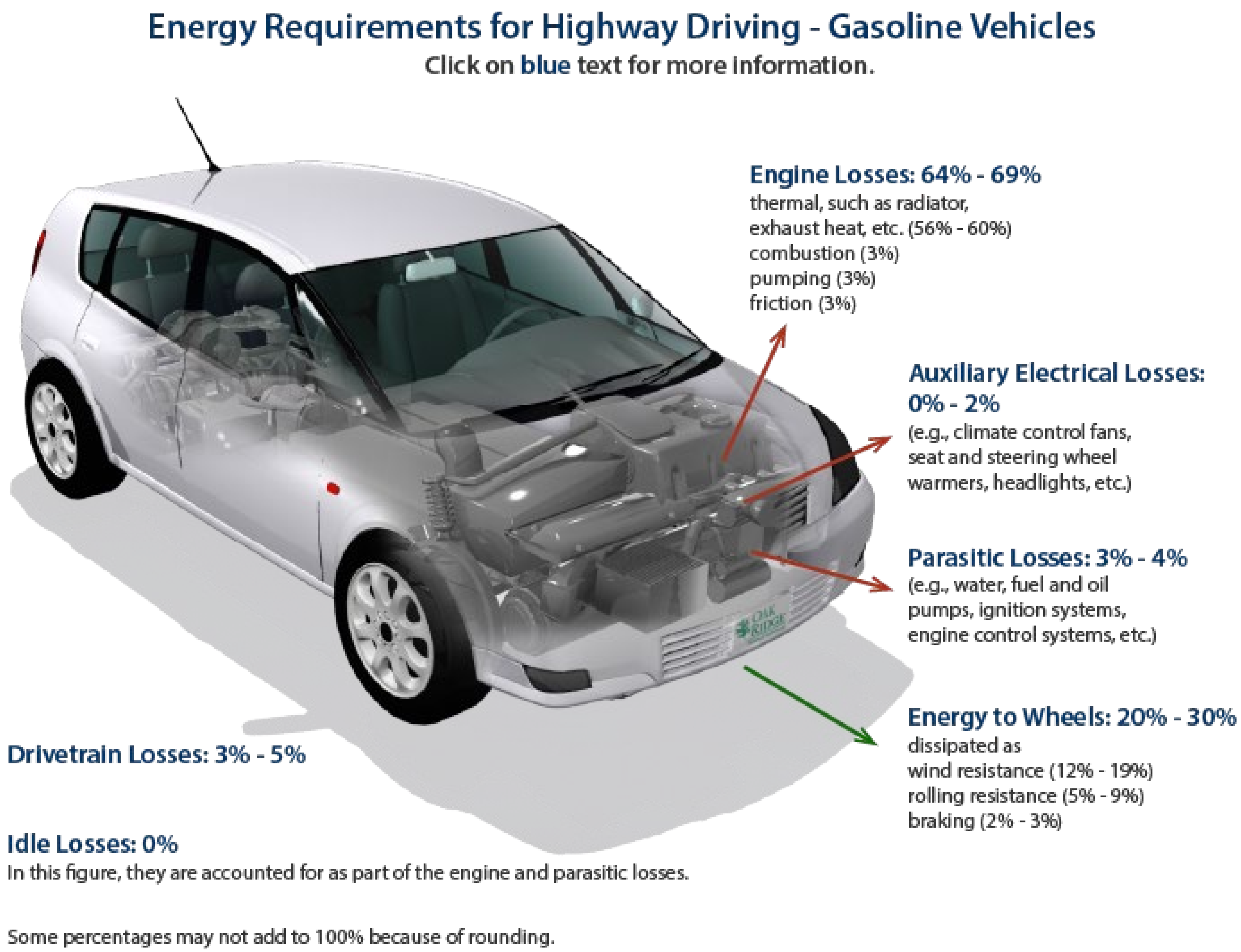
Figure 2-24 Reverse Analysis for Vehicle Duty-Cycle Simulation



- In either case, minimum vehicle requirements need to be considered as part of the optimizations

Energy Balance – 7 – epa

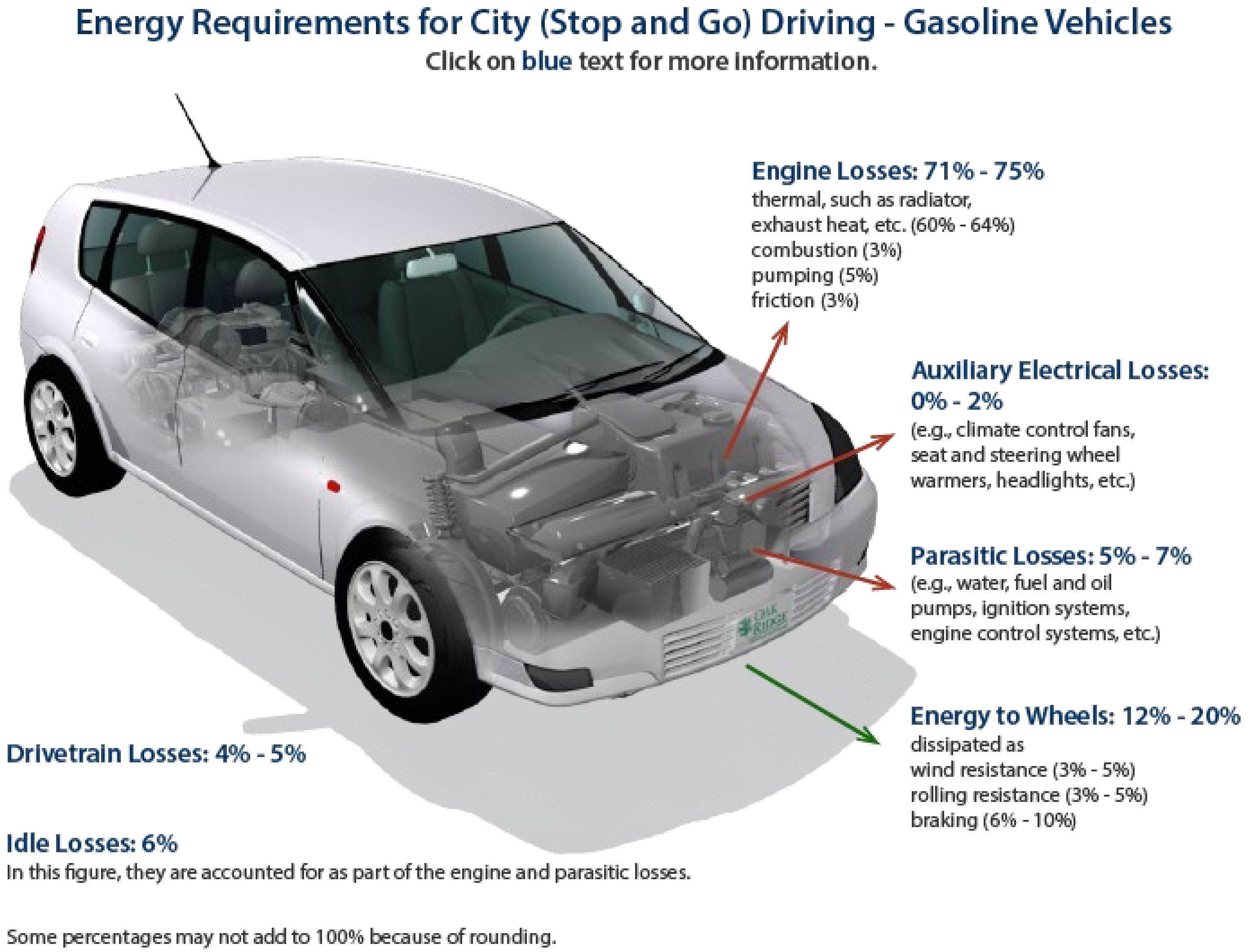
- Gasoline Vehicles, Highway driving
  - High wind-resistance (v^2 losses) between 12% - 19%
  - Minimal braking loses (2% - 3%)
    - Especially compared to wind and rolling resistnace



[Where the Energy Goes: Gasoline Vehicles (fueleconomy.gov)]

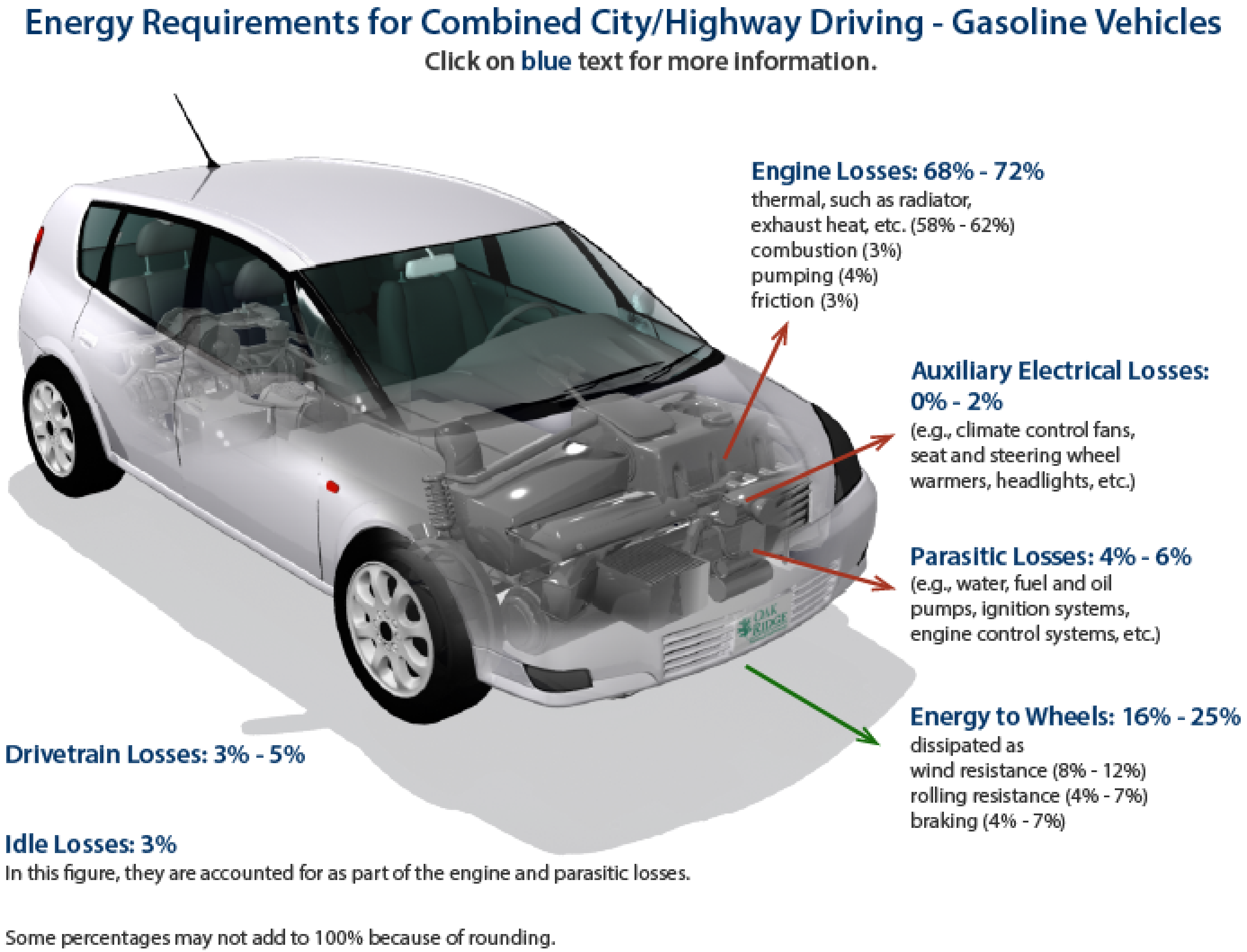
Energy Balance – 8 – epa

- Gasoline Vehicles, City driving
  - Low wind-resistance (v^2 losses) between 3% - 5%
  - Relatively high braking loses (6% - 10%)
    - Comparable to wind and rolling resistance!



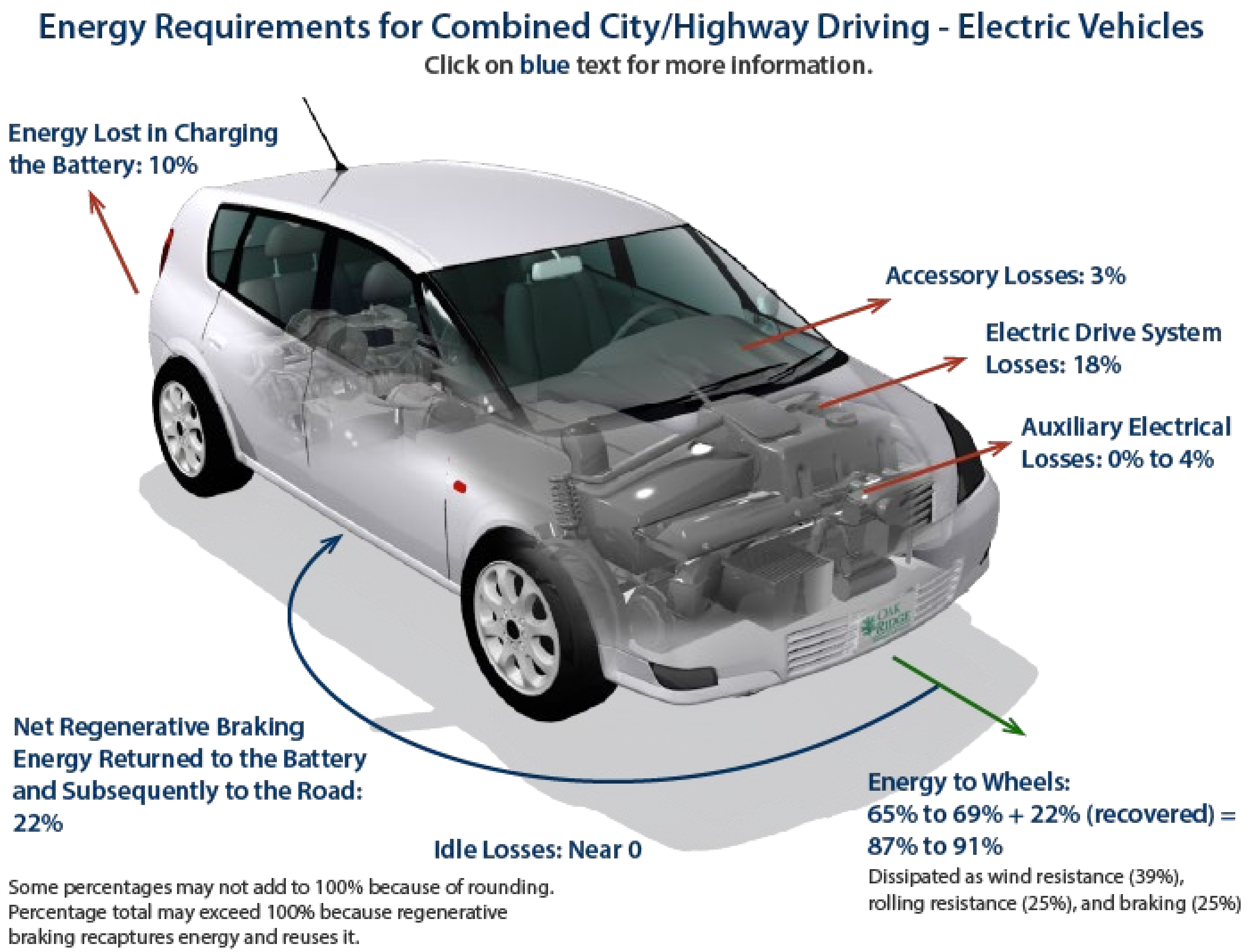
Energy Balance – 9 – epa

- Gasoline Vehicles, Combined Cycle
  - Notice that we lose up to 68 to 72% of energy right at the engine!
    - The exhaust alone takes away 60%!



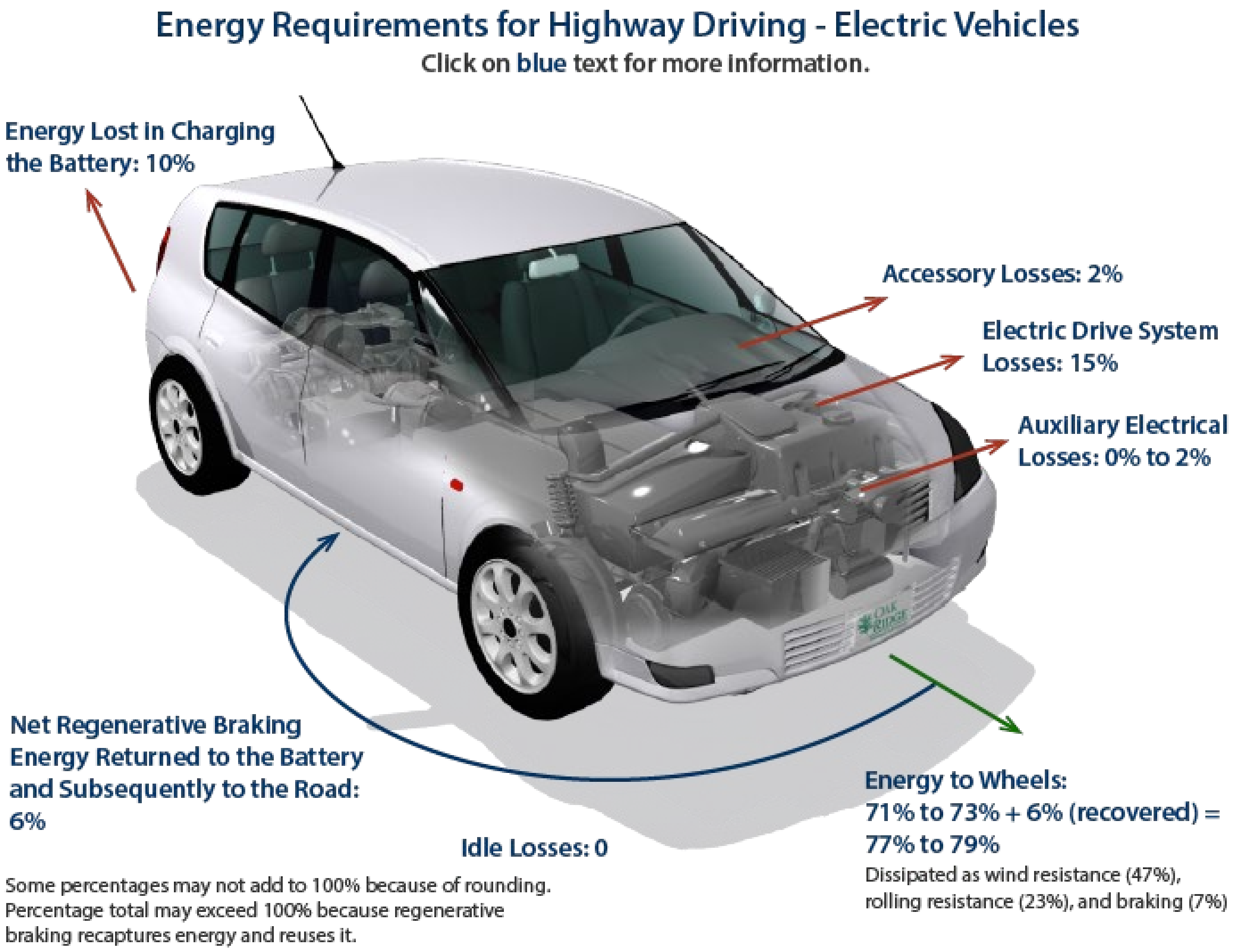
Energy Balance – 10 – epa

- Electric Vehicles
  - Combined cycle
  - We lose only 10% (charging) + 18% (electric drive system) = 28% at the "engine"



Energy Balance – 11 – epa

- Electric Vehicles – Highway cycle
  - Drive train losses even smaller at 15% (gear ratios optimized for highway driving conditions)
  - Relatively small, but still significant, regenerative braking



Energy Balance – 12 – epa

- Electric Vehicles – City Cycle
  - Lower eta because motor speeds operating outside optimal ranges (especially near 0 speeds)
  - Significant regenerative braking – up to 34%