Electric Vehicle (EE60082)

Lecture 3: Vehicle Dynamics (part 2)

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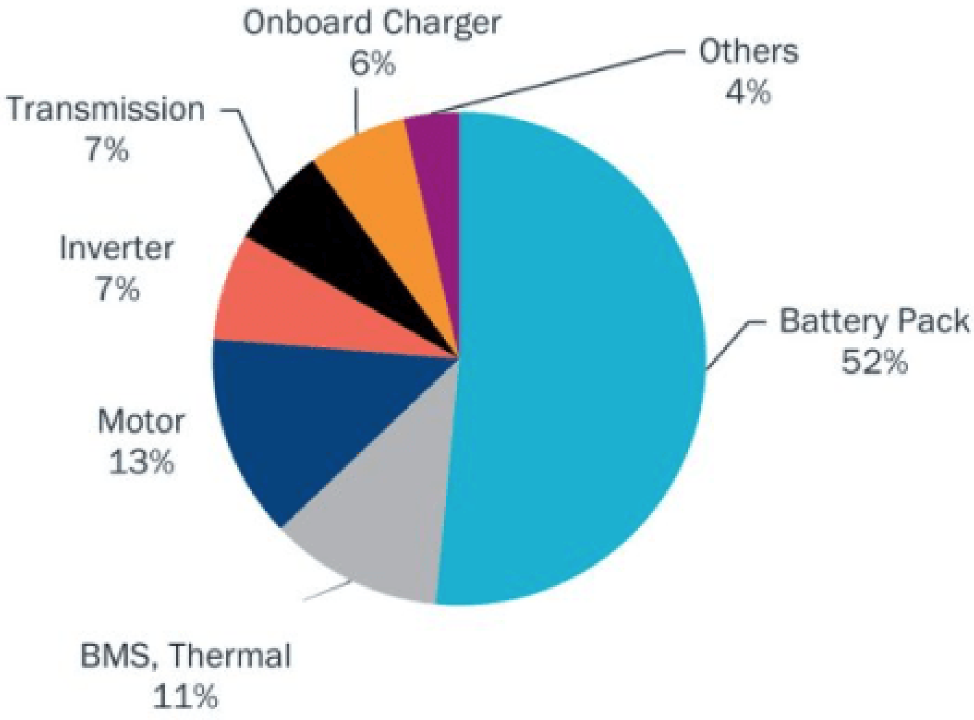
Cost breakdown for EV power train (recap)

EV power train cost:

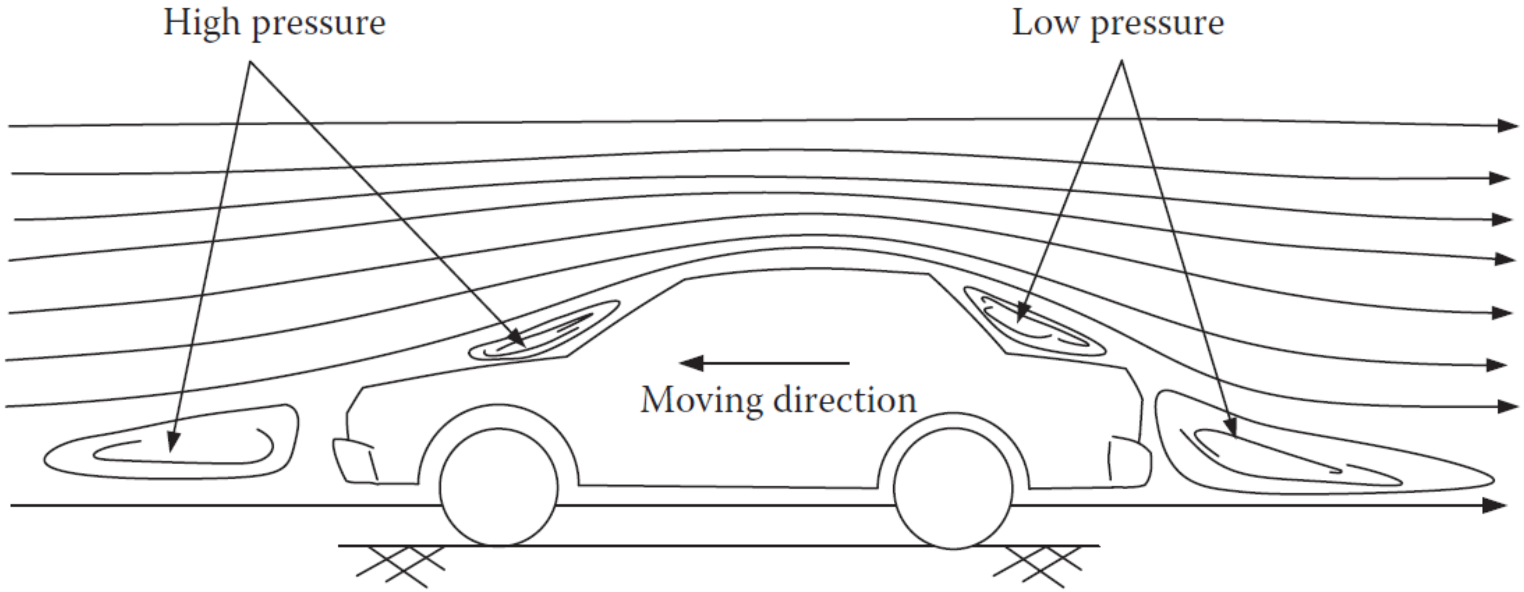
- about half the cost is due to the battery pack
- Power electronics cost is relatively low
  - Due to advanced power converter design
- Motor and thermal management have significant contribution



https://www.powertraininternationalweb.com/components/interact-analysis-which-ev-component-increased-price-the-most-in-2022/

Drag resistance (recap)

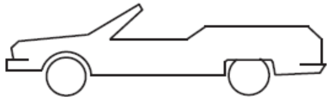
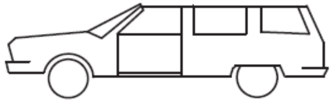
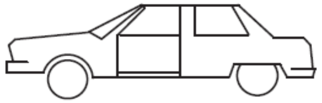
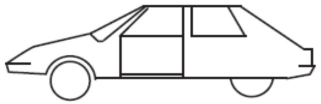
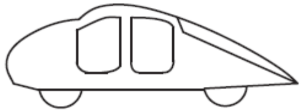
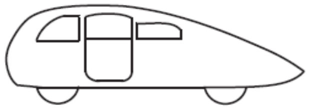
- Aerodynamic drag force
  - Skin Drag:
    - Car surface moves air with it
    - additional force is needed to overcome the friction between moving air and still air
    - depends on surface area
  - Shape Drag:
    - When car moves, there will be high pressure air region at front and low pressure air region on the back
    - This pressure difference creates backward force
    - Depends on car shape



- Aerodynamic drag force is given by, $$F_W = \frac{1}{2}\rho A_f C_D (V - V_w)^2$$
- ρ is air density, A_f is front area, C_D is drag co-efficient, V_w is wind velocity

Typical drag co-efficient (recap)

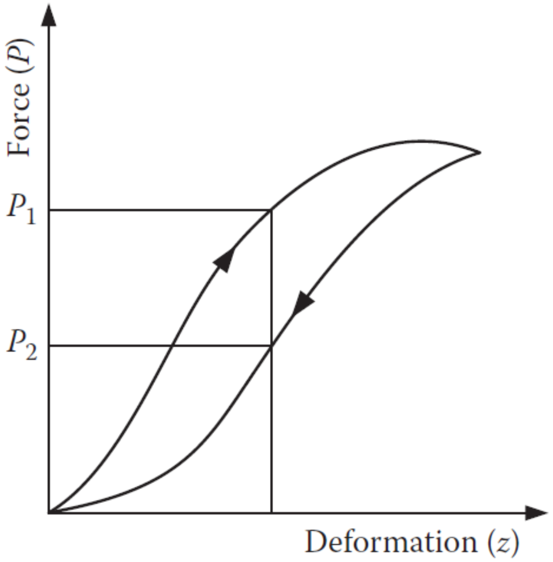
- Aerodynamic drag depends on,
  - vehicle body design, not directly on weight
  - wind velocity and direction

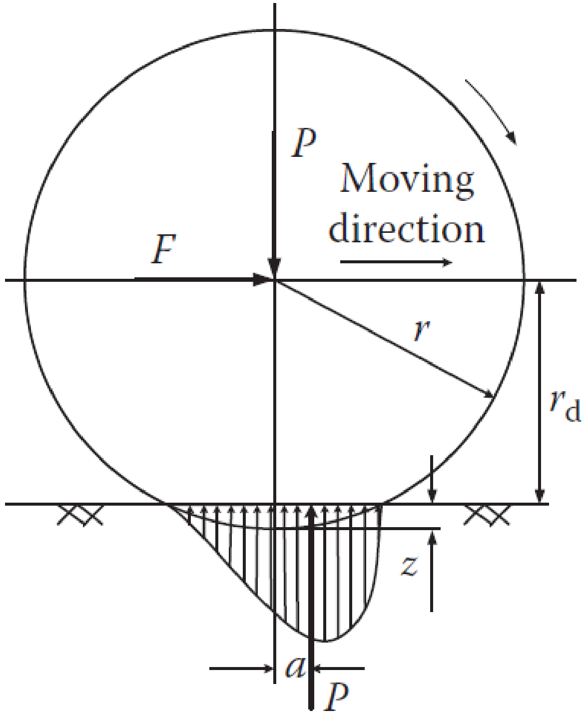
Vehicle type	Coefficient of aerodynamic resistance
 Open convertible	0.5…0.7
 Van body	0.5…0.7
 Ponton body	0.4…0.55
 Wedged-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3…0.4
 Headlamp and all wheels in body, covered underbody	0.2…0.25
 *K*-shaped (small breakaway section)	0.23
 Optimum streamlined design	0.15…0.20
Trucks, road trains	0.8…1.5
Buses	0.6…0.7
Streamlined buses	0.3…0.4
Motorcycles	0.6…0.7

- Drag is significantly higher at higher speed

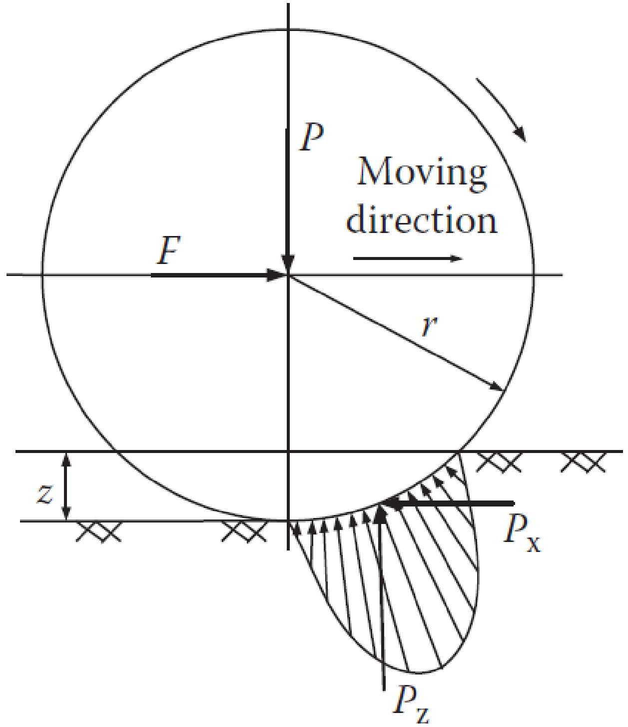
- Aerodynamics is extremely complex, drag resistance is based on empirical formulas

Rolling resistance (recap)





On hard road surface



On soft road surface

- On hard road,
  - Car tire deforms
- On soft road,
  - road deforms
- Rolling resistance torque is created on wheels

$$T_r = Pa$$

$$F = \frac{T_r}{r_d} = \frac{Pa}{r_d} = Pf_r$$

Rolling resistance (recap)

Rolling resistance co-efficient,

$$f_r = f_0 + f_s V^2$$

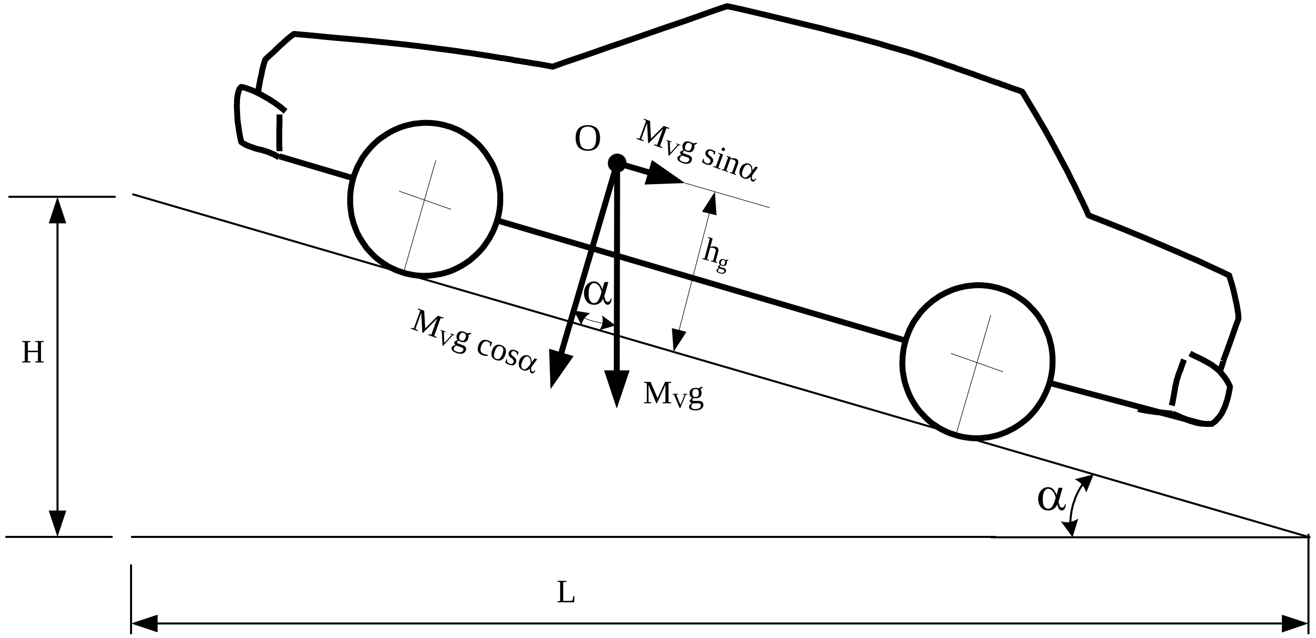
Rolling resistance co-efficient at low speed

Conditions	Rolling Resistance Coefficient
Car tires on concrete or asphalt road	0.013
Car tires on rolled gravel road	0.02
Tar macadam road	0.025
Unpaved road	0.05
Field	0.1–0.35
Truck tire on concrete or asphalt road	0.006–0.01
Wheel on iron rail	0.001–0.002

Grading resistance (recap)

The gravitational force, F_g depends on the slope of the roadway; it is positive when climbing a grade and is negative when descending a downgrade roadway. Where α is the grade angle with respect to the horizon, m is the total mass of the vehicle, g is the gravitational acceleration constant.

$$F_g = mg\sin\alpha$$



Summary of resistances

- Drag resistance

$$F_W = \frac{1}{2}\rho A_f C_D (V - V_w)^2$$

- Rolling resistance

$$F_r = P f_r \qquad f_r = f_0 + f_s V^2$$

- Grading resistance

$$F_g = mg \sin\alpha$$

- ρ is air density,
- A_f is front area,
- C_D is drag co-efficient,
- V is vehicle velocity (in m/s)
- V_w is wind velocity (in m/s)
- P is vertical force on wheel
- f_0 and f_s are rolling resistance co-efficient
- α is slope angle of road

Gradeability

- The maximum grade that a vehicle is able to overcome is called maximum gradeability of the vehicle

- It is the ability of the vehicle to move forward on a steep slope and is an important criteria for vehicle performance

- Conditions for measuring maximum gradeability:
  - The vehicle speed $v \simeq 0$
  - F_W is negligible
  - The vehicle is not accelerating, i.e. $dv/dt = 0$
  - maximum tractive force delivered by engine at near zero speed

Maximum gradeability

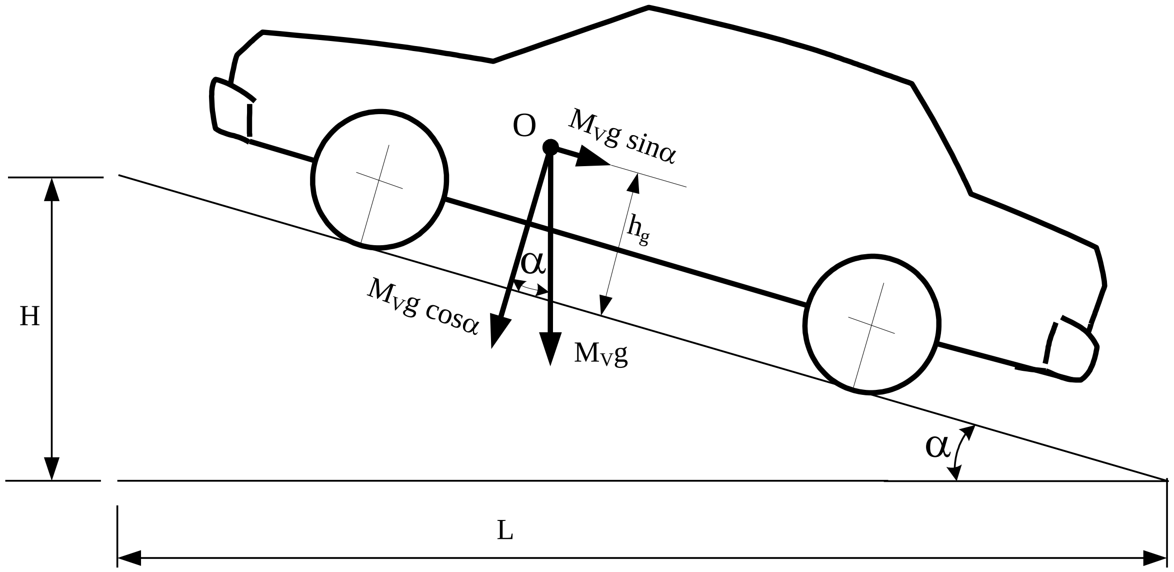
- Grade is defined as

$$\text{Grade}(\%) = \frac{H}{L} * 100 = \tan\alpha * 100$$

- To overcome a slope angle of α, minimum required tractive force

$$F_{TR} = F_g + F_r|_{v=0}$$

$$= mg\sin\alpha + mgf_0\cos\alpha$$



- Engine must be designed to provide enough force for the rated grade

Gradeability example

- typical four wheeler cars have gradeability above 25-30%
- Bus and trucks have higher gradeability, above 45%
- Grades for road and bridges are typically restricted around 6%
- Mountainous area often has higher grade roads, difficult to drive

Vehicle evaluation

- Maximum speed
- Maximum acceleration
- Maximum gradeability
- Fuel economy
- Range
- Emission
- Maintenance
- Comfort

Test conditions for speed and acceleration

- Road: test track with straight, flat, and smooth surface
- Weather:
  - Moderate ambient temperature
  - Minimal or no wind
  - No rain, snow, or ice
- Load: Typically includes only the driver
- Vehicle condition:
  - factory-standard condition
  - Tires are in good condition and fully inflated
  - Auxiliary loads such as air-conditioning turned off
- Optimal high quality fuel

Test conditions for gradeability

- Road: test track with straight, flat, and smooth surface
  - uniformly inclined road or test track
- Weather:
  - Moderate ambient temperature
  - Minimal or no wind
  - No rain, snow, or ice
- Load: With the maximum permissible load, including passengers and cargo.
- Vehicle condition:
  - factory-standard condition
  - Tires are in good condition and fully inflated
  - Auxiliary loads such as air-conditioning turned off
- Optimal high quality fuel

Vehicle dynamic equation

- Vehicle dynamic equation
  - $m\frac{dV}{dt} = F_{TR} - F_r - F_g$
  - Required tactive power:

$$F_{TR} = m\frac{dV}{dt} + F_r + F_g + F_w$$

$$F_r = mg\cos\alpha\,(f_0 + f_s V^2)$$

$$F_g = mg\sin\alpha$$

$$F_W = \frac{1}{2}\rho A_f C_D (V - V_w)^2$$

  - Power delivered by vehicle engine = $F_{TR}V$

Peak speed of a car

- The level road condition implies that grade *α=0*
- Vehicle is assumed to be at rest initially

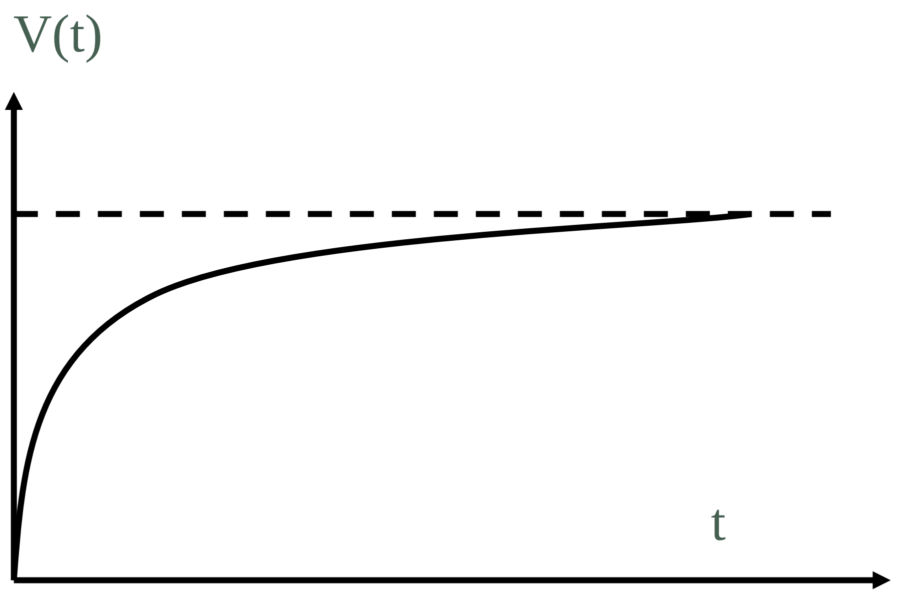
$$\frac{dV}{dt} = K_1 - K_2 V^2$$

where

$$K_1 = \frac{F_{TR}}{m} - g\,f_0\,, \qquad K_2 = \frac{\rho}{2m} C_D A_F + g\,f_s$$

The velocity profile:

$$V(t) = \sqrt{\frac{K_1}{K_2}}\ \tanh\left(\sqrt{K_1 K_2}\ t\right)$$



Peak speed of a car

The velocity profile:

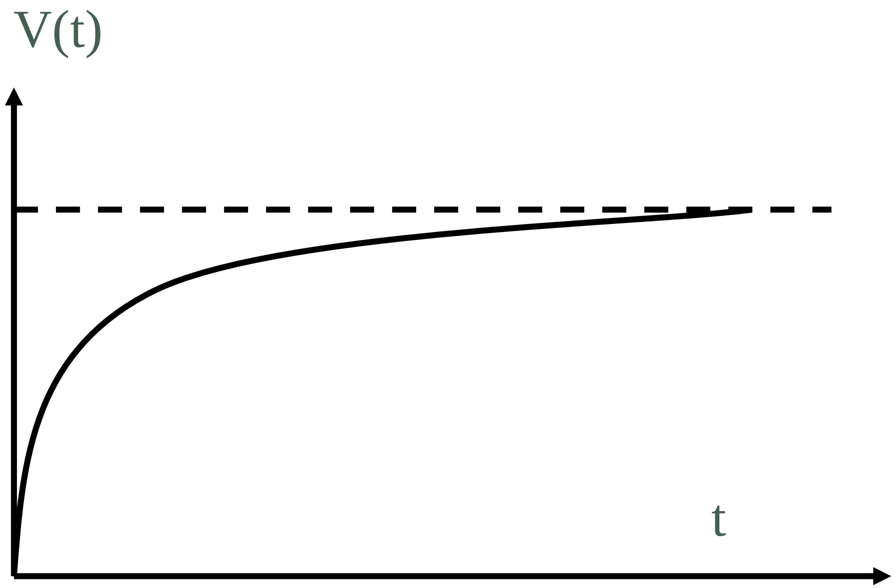
$$V(t) = \sqrt{\frac{K_1}{K_2}}\ \tanh(\sqrt{K_1 K_2}\ t)$$

Terminal Velocity:

$$V_T = \lim_{t\to\infty} v(t) = \sqrt{\frac{K_1}{K_2}}$$

The time to reach a desired velocity V_f

$$t_f = \sqrt{\frac{1}{K_1 K_2}}\ \tanh^{-1}(\sqrt{\frac{K_2}{K_1}}\ V_f)$$



Power and energy requirement

Tractive power: *The instantaneous tractive power delivered by the propulsion unit is* $P_T(t) = F_T\, v(t)$.

$$P_T(t) = F_{TR} V_T \tanh(\sqrt{K_1 K_2}\ \ t)$$

The mean tractive power over the acceleration interval Δt *is*

$$\overline{P}_T = \frac{1}{t_f} \int P_T(t)dt = \frac{F_{TR} V_T}{t_f} \frac{1}{\sqrt{K_1 K_2}} \ln[\cosh(\sqrt{K_1 K_2}\ \ t_f)]$$

Energy required during an interval

$$\Delta e_T = \int_0^{t_f} P_T(t)dt = t_f \overline{P}_T = F_{TR} V_T \frac{1}{\sqrt{K_1 K_2}} \ln[\cosh(\sqrt{K_1 K_2}\ \ t_f)]$$

Example

A vehicle has following parameter values:

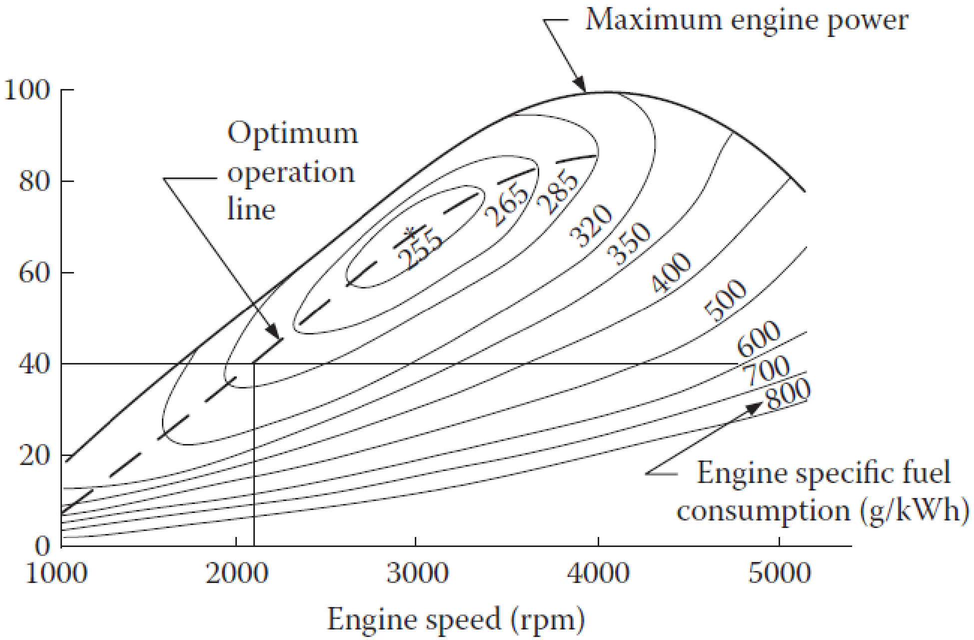
$$m=692kg,\ C_D = 0.2,\ A_F = 2m^2,\ f_0 = 0.009,$$

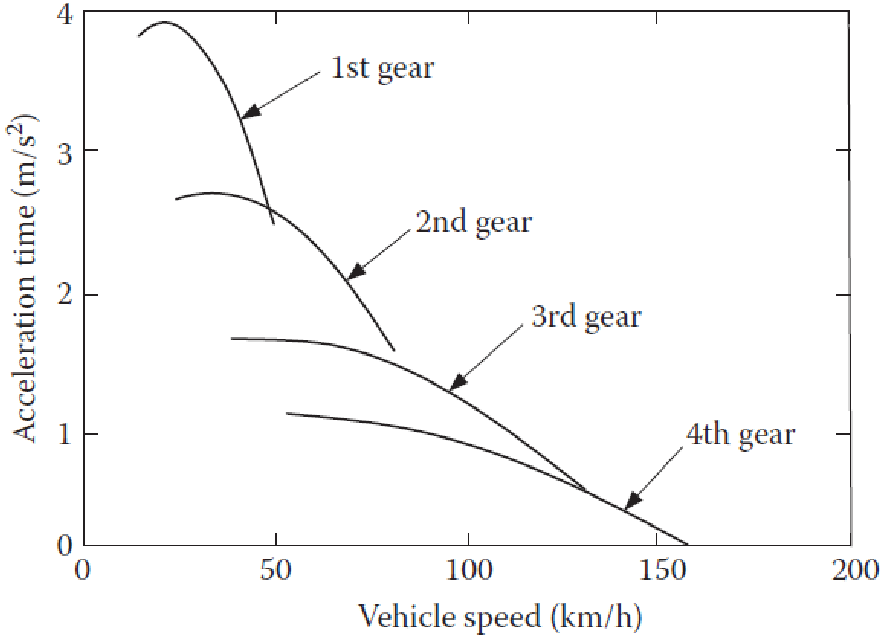
$$f_s = 1.75\ s^2/m^2,\ \rho = 1.18\ kg/m^3,\ g = 9.81\ m/s^2$$

The vehicle is accelerated with constant tractive force of 500N produced by the powertrain.

- (a) find terminal velocity
- (b) calculate the time required to accelerate to 100kmh
- (c) calculate the instantaneous tractive power.

Gear transmission efficiency





- Good condition gear assembly efficiency is above 90%
- With time, efficiency drops due to wear and tear

Thank you!