Vehicle Propulsion Systems

Objectives

To introduce mathematical models and optimization methods that allow a systematic minimization of the energy consumption of vehicle systems.

Vehicle

A vehicle is a means of transport, such as bicycles, cars, motorcycles, trains, ships, and aircraft. Vehicles that do not travel on land are often called crafts, such as watercraft, sailcraft, aircraft, hovercraft and spacecraft. Most land vehicles have wheels.

Scope of the vehicle: **Passenger cars**

1. Autonomous
2. Refuelling time short
3. Transport 2-6 people
4. Acceleration 10-15 seconds to 100km/h, and 5%ramp at legal top speed

Powertrain

A group of components that generate power and deliver it to the road surface, water, or air, including the engine, transmission, driveshafts, differentials, and the final drive (drive wheels, caterpillar track, propeller, etc.).

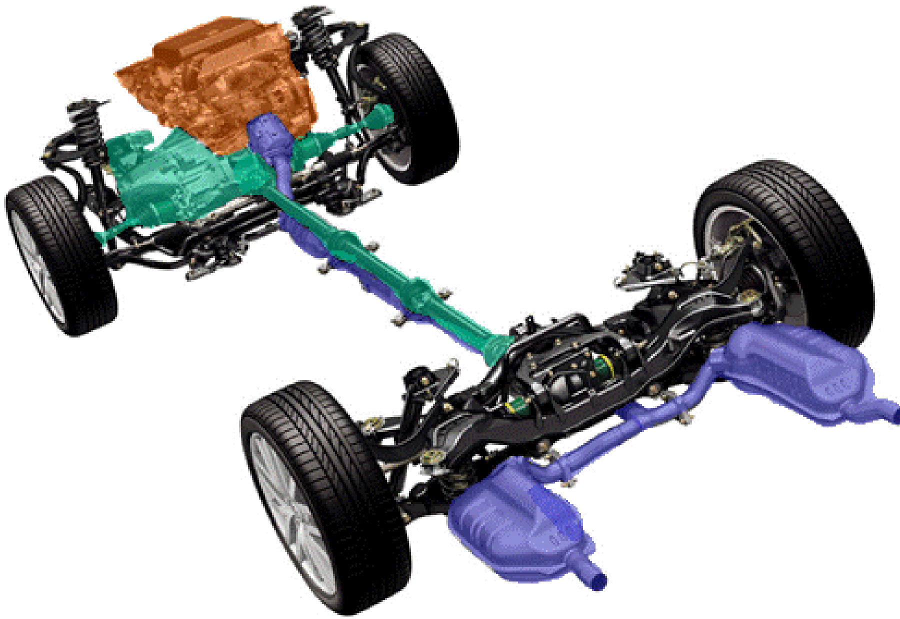
The vehicle Powertrain consists primarily of

•The Engine (Shown in orange), typically Diesel or Gasoline, but other combustion concept exist or are on the "horizon".

•The Transmission (Shown in green), either a manual, automatic, continuously /infinitely variable transmission, or a hybrid Powertrain with additional electrical components!

•After-treatment Systems such as catalysts or particulate traps (Shown in blue)

•Electronic Control Units (ECU) and Control Software



EPSRC

On-board energy carrier requirements

High energy density

Safe and no environmental hazards in production or operation.

Energy sources

Hydrocarbons: petroleum (Fossil/mineral or biofuel) , coal, and natural gas

Hydrogen – fuel cell

Batteries

Biofuel (agrofuel) can be broadly defined as solid, liquid, or gas fuel consisting of, or derived from biomass.

Biomass is grown from plants, including miscanthus, switchgrass, hemp, corn, poplar, willow and sugarcane

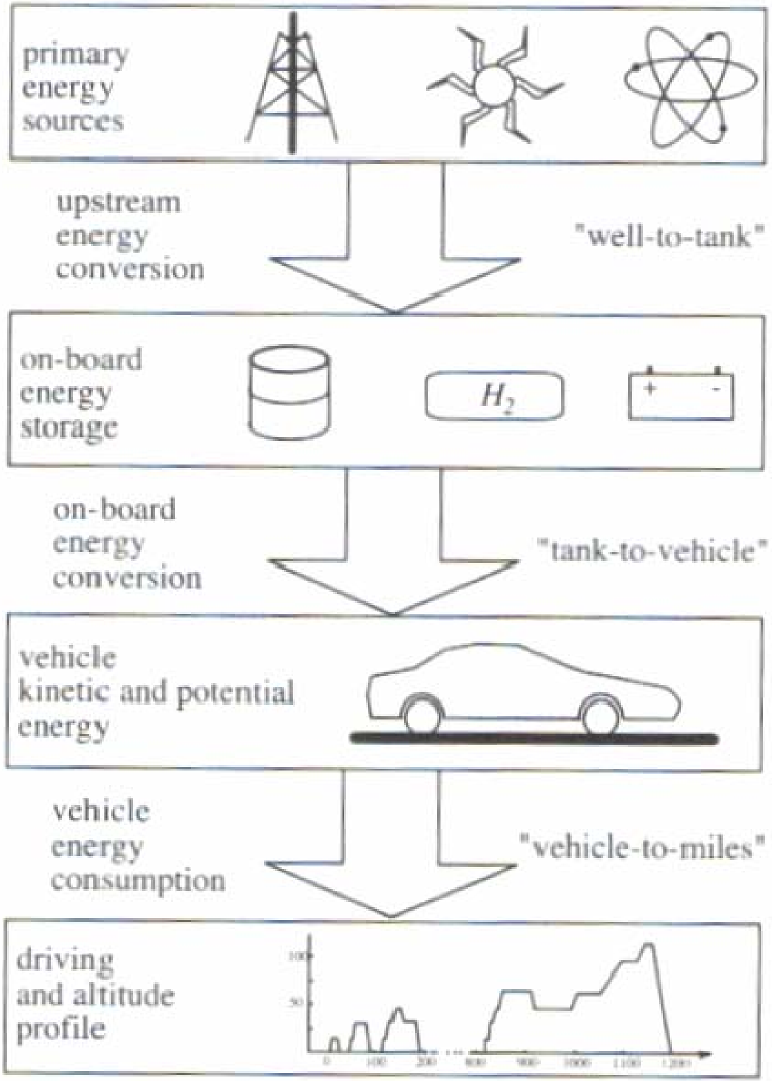
Vegetable Oil Fuel

To reduce the viscosity, biodiesel recipe:

1. 1 litre of vegetable oil.
2. 200 millilitres of methanol (95% pure).
3. 5 grams of sodium hydroxide.

Vegetable Oil Fuel Heaters

Vegetable Oil is much thicker than mineral diesel at typical ambient temperatures. Therefore, if a vehicle is to be powered by vegetable oil, the oil must be heated before it reaches the fuel filter and the engine's injectors,

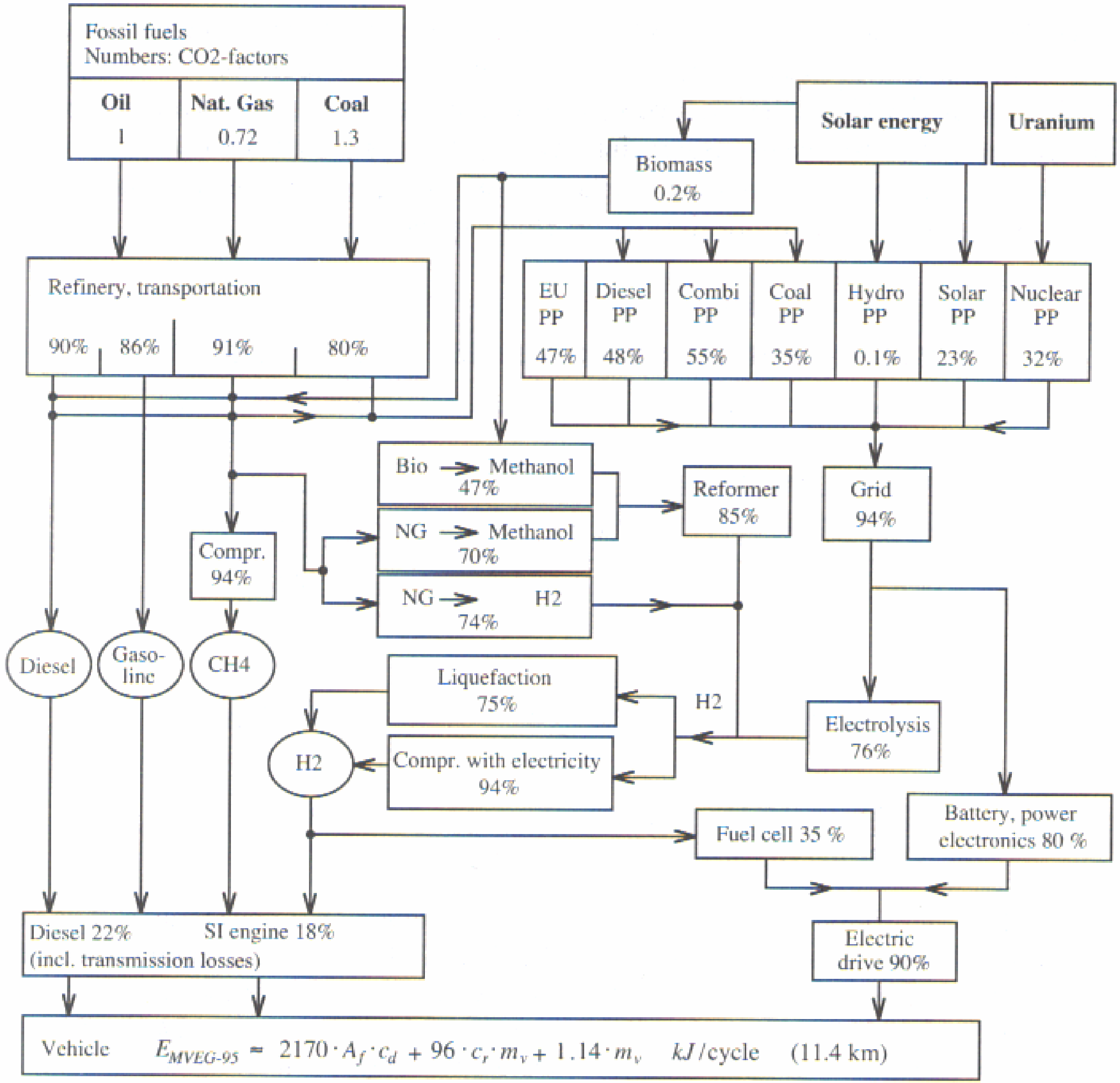


3 energy conversion steps:

- well to tank

- tank to vehicle

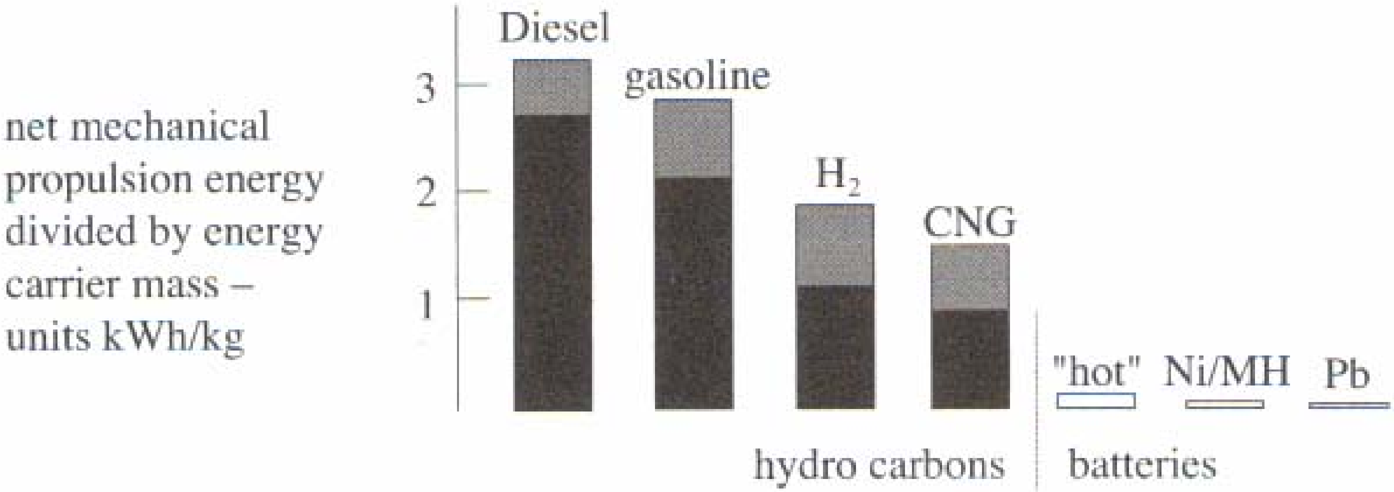
- vehicle to miles



Different paths to convert a primary energy source to mechanical energy needed to drive a car in the MVEG-95 test cycle.

PP-power plant

Energy Densities



Estimates of energy density of several on-board energy carriers. Black columns indicate actual values, gray columns indicate expected improvements.

- From tank to wheel energy
- CNG-compressed natural gas

Batteries as ‘fuel’

Electrochemical on-board energy carriers -Batteries have low density.
Used as auxiliary energy storage to improve IC efficiency (hybrid)

- Lead-acid 30Wh/kg
- Nickel-metal hydrides 60Wh/kg
- ‘hot’ batteries 150Wh/kg (such as sodium-nickle chloride ‘zebra’ battery)
- Improvements are slow
- Take long time to ‘refuel’

Pathway to better fuel economy

- Improve well to tank efficiency

  by optimizing upstream processes

- Improve tank to wheel efficiency

  by 1. improve the peak efficiency of components

  2. improve the part load efficiency

  3. recuperate kinetic and potential energy in the vehicle

  4. control propulsion system configuration

- Improve wheel to mile efficiency

  by reducing the vehicle mass and aerodynamic and rolling losses

Vehicle Energy

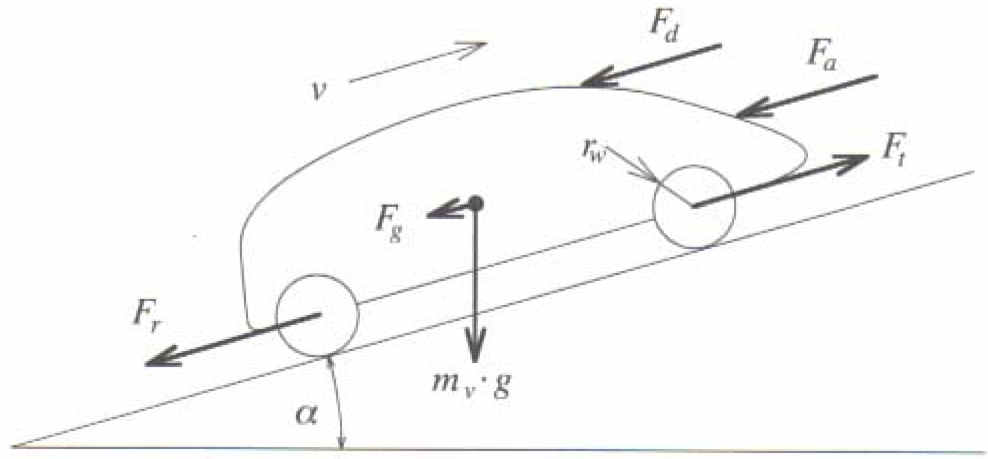
- Kinetic energy when have speed

- Potential energy when have altitudes

Vehicle Energy Losses (after engine)

- Aerodynamic drag
- Rolling friction
- Brake dissipation

Forces acting on vehicle on motion



Courtesy L.Guzzella et al

$$m_v \frac{dv(t)}{dt} = F_t(t) - \left(F_a(t) + F_r(t) + F_g(t) + F_d(t)\right)$$

where

$F_t(t): prime\_mover\_force$

$F_a(t): aerodynamic\_friction$

$F_r(t): rolling\_friction$

$F_g(t): gravity\_force\_component$

$F_d(t): other\_disturbance\_force$

Aerodynamic Friction

$$F_a(v) = \frac{1}{2}\rho_a A_f c_d v^2$$

Rolling Friction

$$F_r(v, p_t, \ldots) = c_r(v, p_t, \ldots) m_v g \cos(\alpha)$$

$$c_r : rolling\_friction\_coefficient$$

$$p_t : tyre\_pressure$$

$$\ldots : road\_surface\_condition, etc$$

Gravity force component

$$F_g(v) = m_v g \sin\alpha$$

Inertia resistance in rotary parts

$$Total\_inertia\_torque\_of\_wheels: \qquad T_{m,\omega}(t) = \Theta_w \frac{d\omega_w(t)}{dt}$$

$$Additional\_inertia\_force: \qquad F_{m,\omega}(t) = \frac{T_{m,\omega}(t)}{r_w}$$

$where\ \ r_w : wheel\_radius,$ using $v(t) = \omega_w(t) r_w$

$$F_{m,\omega}(t) = \frac{\Theta_w}{r_w{}^2} \frac{dv(t)}{dt}$$

$$Wheel\_inertia: \qquad m_{r,w} = \frac{\Theta_w}{r_w{}^2}$$

$$Total\_inertia\_torque\_of\_engine$$

$$Additional\_inertia\_force: \qquad F_{m,\omega}(t) = \frac{T_{m,\omega}(t)}{r_w}$$

$$T_{m,\omega}(t) = \Theta_e \frac{d\omega_e(t)}{dt} = \Theta_e \frac{d}{dt}\left(\gamma\omega_w(t)\right) = \Theta_e \frac{\gamma}{r_w}\frac{dv(t)}{dt}$$

$$where \qquad \gamma = gear\_ratio$$

$$Therefore, total\_inertia\_force\_of\_engine$$

$$F_{m,\omega}(t) = \Theta_e \frac{\gamma^2}{r_w^{\ 2}}\frac{dv(t)}{dt}$$

$$m_{r,e} = \frac{\gamma^2}{r_w^{\ 2}}\Theta_e$$

$$Equivalent\_mass\_of\_rotating\_parts:$$

$$m_r = m_{r,w} + m_{r,e} = \frac{\Theta_w}{r_w^{\ 2}} + \frac{\gamma^2}{r_w^{\ 2}}\Theta_e$$

$$\left(m_v + m_r\right)\frac{dv(t)}{dt} = F_t(t) - \left(F_a(t) + F_r(t) + F_g(t) + F_d(t)\right)$$

where

$$m_r = \frac{\Theta_w}{r_w^{\;2}} + \frac{\gamma^2}{r_w^{\;2}}\Theta_e$$

$F_t(t): prime\_mover\_force$

$F_a(t): aerodynamic\_friction$

$F_r(t): rolling\_friction$

$F_g(t): gravity\_force\_component$

$F_d(t): other\_disturbance\_force$

Regard $F_m = m_r \dfrac{dv(t)}{dt}$ as resistance

$$m_v \frac{dv(t)}{dt} = F_t(t) - \left(F_m + F_a(t) + F_r(t) + F_g(t) + F_d(t)\right)$$

Performance and Drivability

- Top speed
- Maximum gradient at which vehicle reaches legal top speed
- Acceleration time to 100km/h (60miles/h)

Top speed power (aerodynamic resistance dominant)

$$P_{\max} \approx F_a v_{\max} = \frac{1}{2}\rho_a A_f c_d v_{\max}^3$$

Performance and Drivability

Uphill driving power

$$P_{\max} \approx v_{\min} m_v g \sin\alpha_{\max}$$

Performance and Drivability

Energy required to accelerate the vehicle from 0 to v_0 (estimate)

$$E_0 = \frac{1}{2} m_v v_0^2$$

Let mean power

$$\overline{P} = \frac{E_0}{t_0}$$

Take

$$\overline{P} = \frac{P_{\max}}{2}$$

Time required to accelerate the vehicle from 0 to v_0

$$t_0 = \frac{E_0}{\overline{P}} = \frac{m_v v_0^2}{P_{\max}}$$

e.g. $t_0 = 10\text{seconds}$,

$$P_{\max} = \frac{m_v v_0^2}{t_0} = \frac{1000kg \times (100{,}000m/3600s)^2}{10s} = 77.16KW = 103.6HP$$

Vehicle Operating Modes

When coasting on horizontal road and without disturbances

$$m_v \frac{dv(t)}{dt} = -\frac{1}{2}\rho_a A_f c_d v^2(t) - m_v g c_r$$

or

$$\frac{dv(t)}{dt} = -\frac{1}{2m_v}\rho_a A_f c_d v^2(t) - g c_r$$

or

$$\frac{dv(t)}{dt} = -\beta_1{}^2 v^2(t) - \beta_2{}^2$$

where

$$\beta_1 = \sqrt{\frac{1}{2m_v}\rho_a A_f c_d}\,, \qquad \beta_2 = \sqrt{g c_r}$$

Vehicle Operating Modes

When coasting on horizontal road and without disturbances

$$\frac{1/\beta_1^{\,2}}{v^2(t)+\left(\frac{\beta_2}{\beta_1}\right)^2}\,dv(t)=-dt$$

$$\text{Integration}:\frac{1}{\beta_1^{\,2}}\int_{v_0}^{v}\frac{1}{v^2(t)+\left(\frac{\beta_2}{\beta_1}\right)^2}\,dv(t)=-\int_0^t dt,\qquad \frac{1}{\beta_1^{\,2}}\left[\frac{\beta_1}{\beta_2}\arctan\frac{\beta_1}{\beta_2}v(t)\right]_{v_0}^{v}=-t\Big|_0^t$$

$$\arctan\frac{\beta_1}{\beta_2}v(t)-\arctan\frac{\beta_1}{\beta_2}v(0)=-\beta_1\beta_2 t$$

$$v(t)=\frac{\beta_2}{\beta_1}\tan\left(\arctan\frac{\beta_1}{\beta_2}v(0)-\beta_1\beta_2 t\right)$$

This is a slop with negative gradient – coasting gradient

Vehicle Operating Modes

When coasting on horizontal road and without disturbances

$$m_v \frac{dv(t)}{dt} = -\frac{1}{2}\rho_a A_f c_d v^2(t) - m_v g c_r$$

$$v(t) = \frac{\beta_2}{\beta_1}\tan\left(\arctan\frac{\beta_1}{\beta_2}v(0) - \beta_1\beta_2 t\right)$$

3 operating modes can be identified from the vehicle speed curve

Traction mode: gradient > coasting gradient
Braking mode: gradient < coasting gradient
Coasting mode: gradient = coasting gradient

Example : For a full size vehicle

$$m_v = 1500\,kg,\ A_f c_d = 3.5 \times 0.2 = 0.7 m^2,\ c_r = 0.013,\ v_0 = 100\,km/h = 27.78\,m/s$$

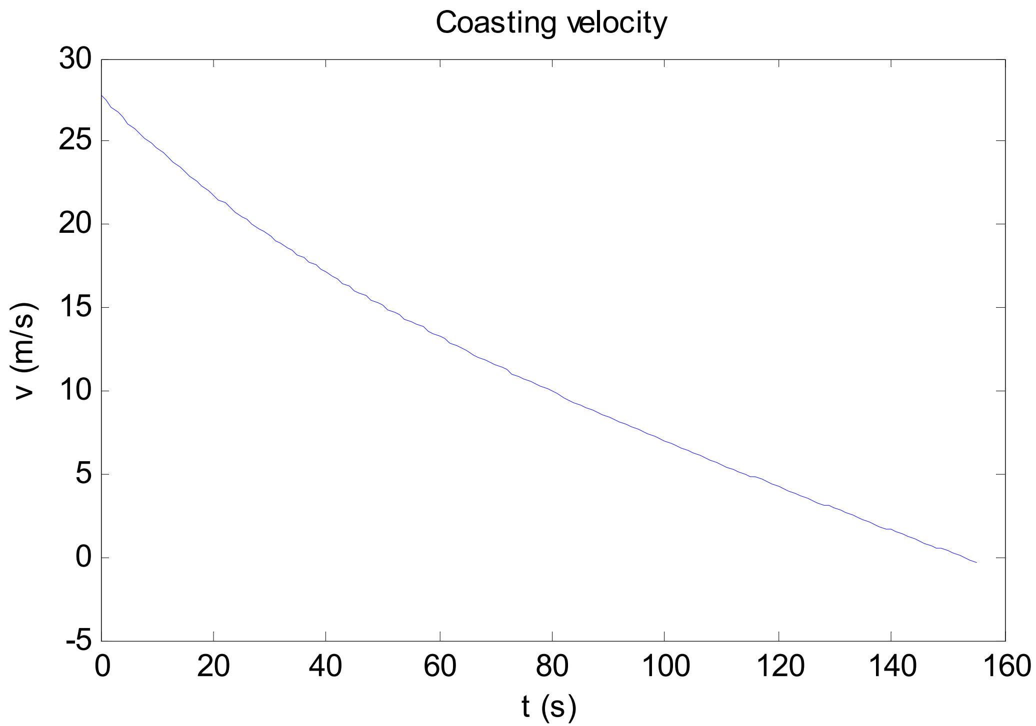
$$\beta_1 = \sqrt{\frac{1}{2m_v}\rho_a A_f c_d} = \sqrt{\frac{1}{2\times 1500} 1.2 \times 3.5 \times 0.2} = 0.0167$$

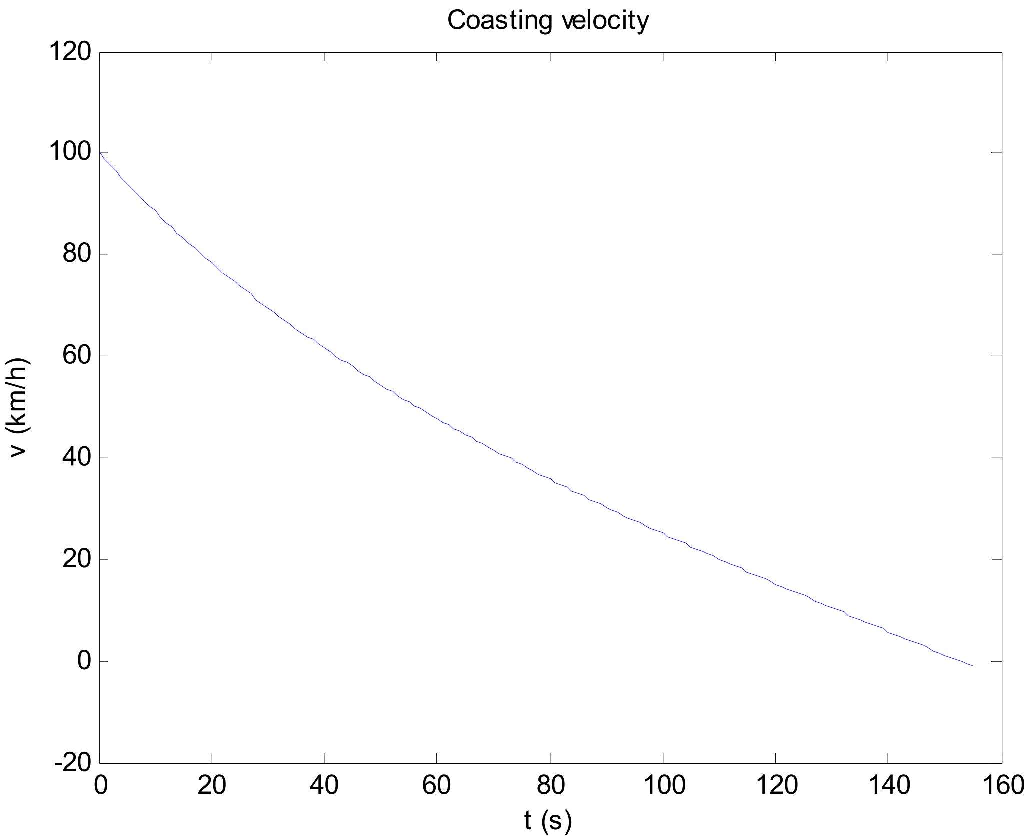
$$\beta_2 = \sqrt{g c_r} = \sqrt{9.8 \times 0.013} = 0.3569$$

$$v(t) = 21.37 \tan\left(\arctan\left(0.0468 \times 100000 / 3600\right) - 0.0060t\right)$$

or

$$v(t) = 21.37 \tan\left(0.9151 - 0.0060t\right) \qquad m/s$$




Coasting velocity
120
100
80
60
40
20
0
-20
v (km/h)
0
20
40
60
80
100
120
140
160
t (s)

Vehicle Operating Modes

- Traction

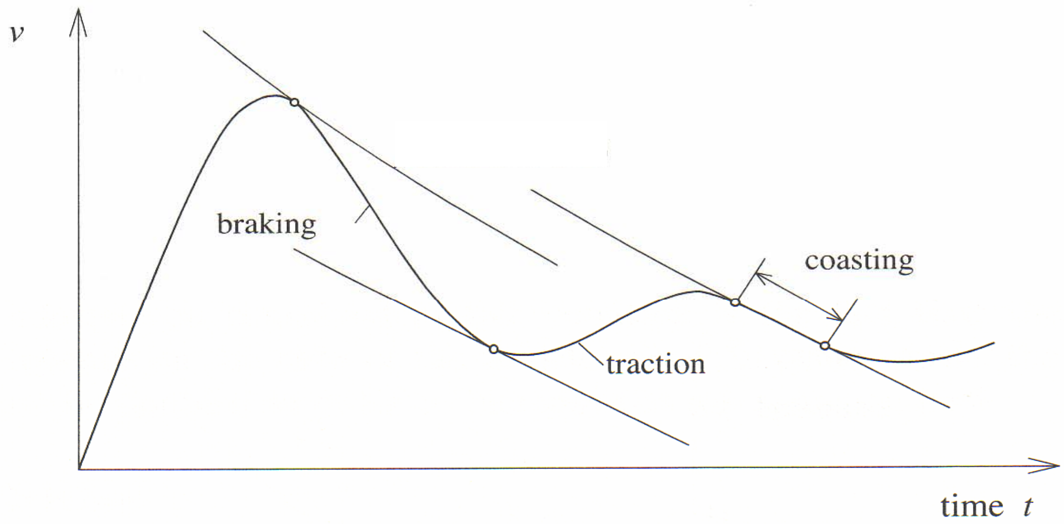
  $F_t > 0$

- Braking

  $F_t < 0$

- Coasting

  $F_t = 0$



Modes of vehicle motion.

L.Guzzella et al