METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

Emine Bostancı

Office: C-107

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2. Vehicle movement
3. Vehicle resistances
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7. Vehicle performance
   - Maximum speed
   - Gradeability
   - Acceleration time (0-100km/h, 60-100km/h)
8. Braking
9. Fuel Economy
   - Driving cycles

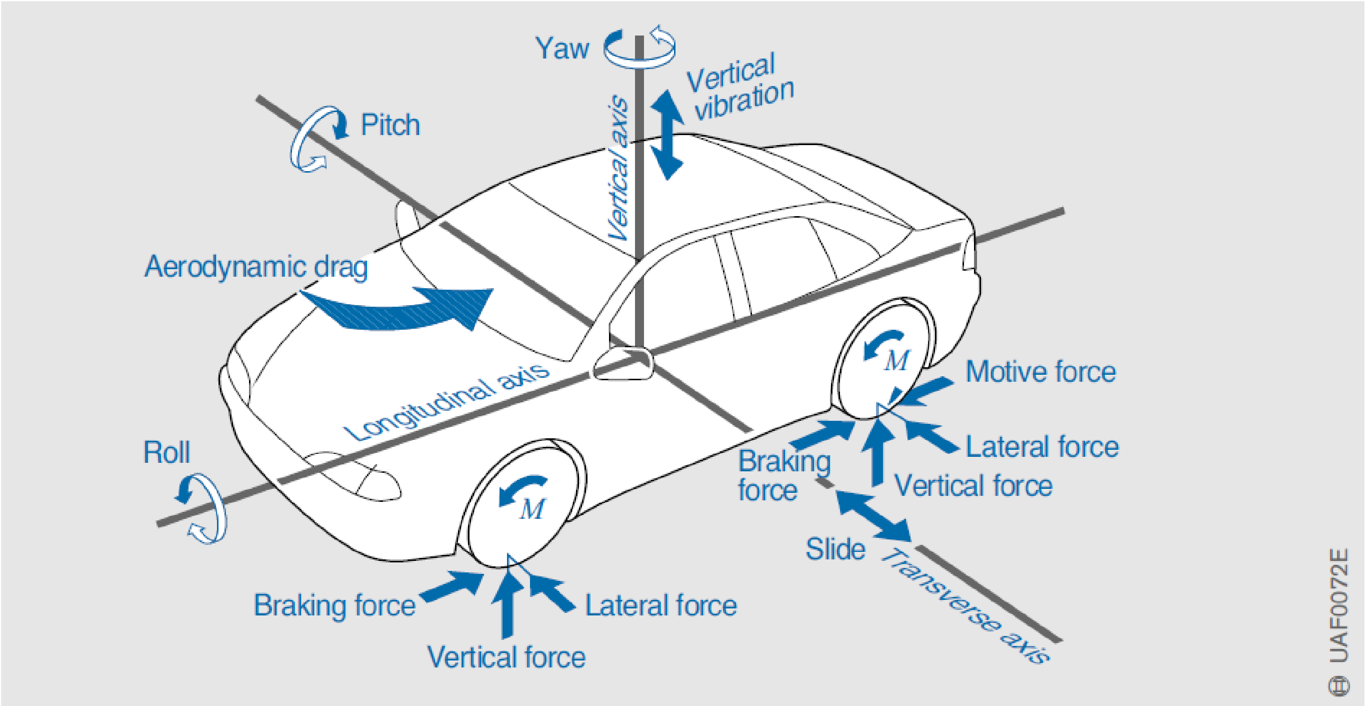
Vehicle Requirements

1. Performance

- Maximum speed on flat (level) road
- Gradeability: highest grade a vehicle can ascend maintaining a particular speed
- Acceleration time (0-100 km/h, 60-100 km/h)
- Drivability
- Lateral dynamics
- Vertical dynamics
- Range: Especially important for electric vehicles
- Charging duration: Especially important for electric vehicles

2. Emissions
3. Comfort
4. Security
5. Initial cost and fuel economy
6. Exterior and interior design
7. Visibility of the external environment

Forces Acting on a Vehicle

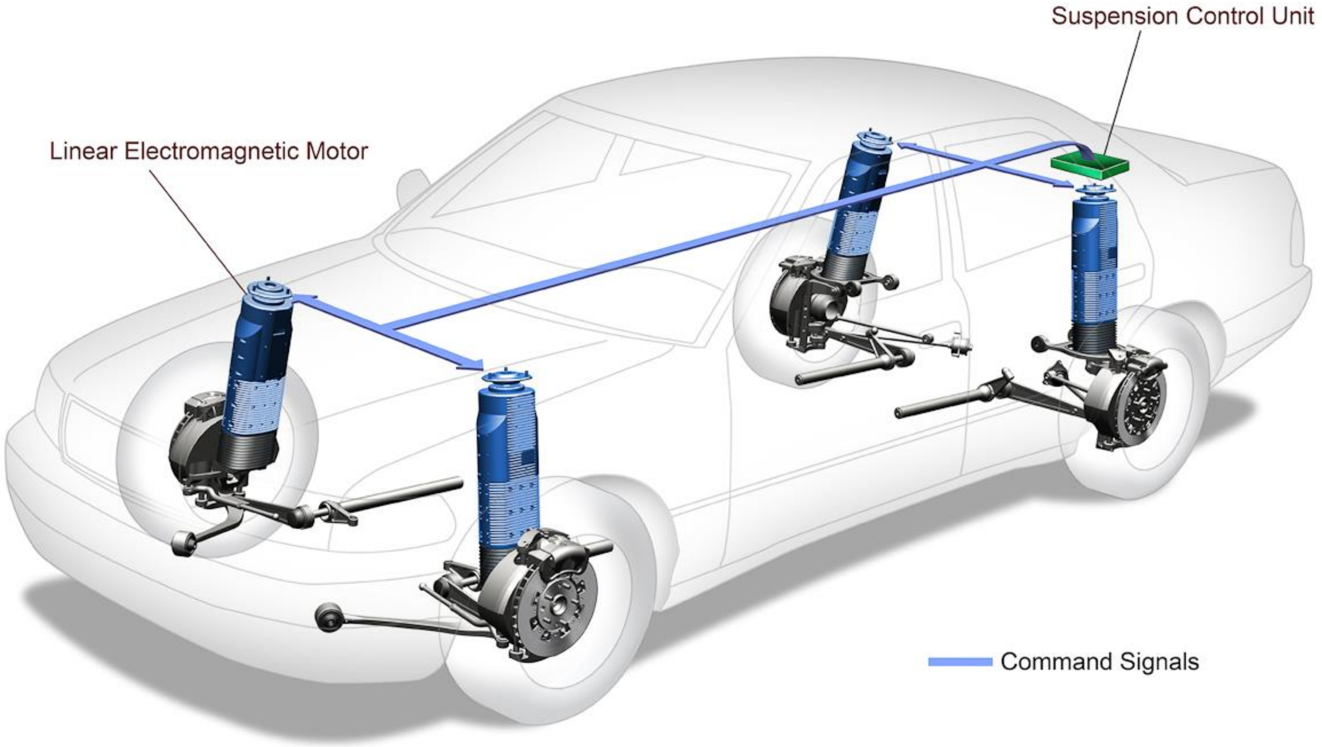


Source: K. Reif (Ed.), "Brakes, Brake Control and Driver Assistance Systems Function, Regulation and Components", 2014

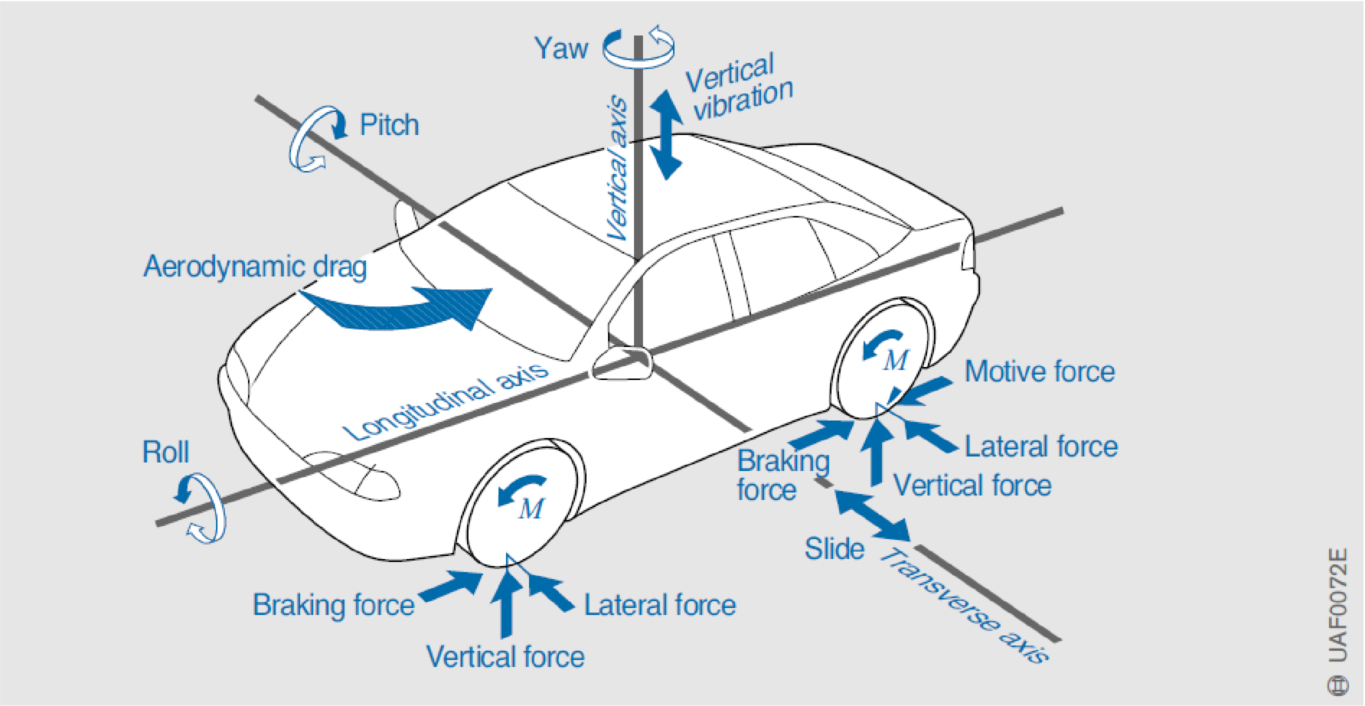
- Vertical forces
- Lateral forces
- Longitudinal forces
- Yaw (change of direction) forces

Vertical Axis

[BOSE Active Suspension comparison]



Forces Acting on a Vehicle



Source: K. Reif (Ed.), “Brakes, Brake Control and Driver Assistance Systems Function, Regulation and Components”, 2014

Only **longitudinal** forces are considered in the following analysis.

- Aerodynamic drag
- Rolling friction
- Grading resistance
- Tractive force
- Braking force

Vehicle is assumed to a rigid body.

Longitudinal Vehicle Movement

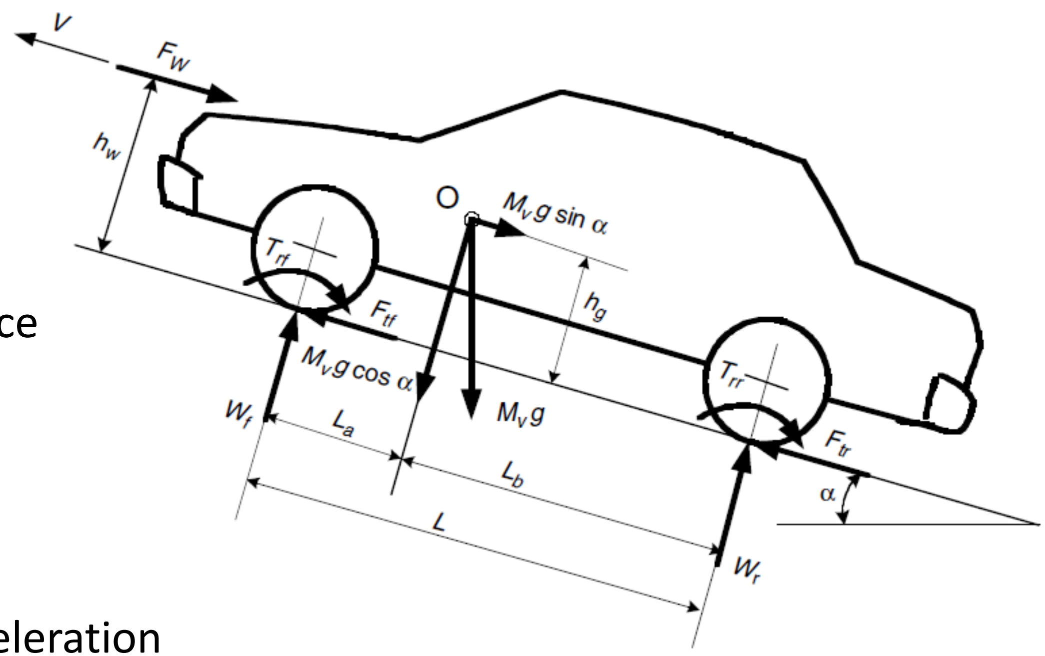
Total tractive force

Total resistance force

$$\Sigma F_t - \Sigma F_{rt} = \delta M \frac{dV}{dt}$$

Linear acceleration

Vehicle mass multiplied by mass factor δ that represents the effect of rotating masses



Net Tractive Force

$$F_{\text{tot}}(t) = \sum_i F_i\,(t) = M\,\frac{\mathrm{d}v(t)}{\mathrm{d}t}$$

$$F_{\text{tot}}(t) = F_t - F_r - F_{load}$$

F_t: Tractive force, it can be positive or negative.

F_r: Friction force like aerodynamic windage and other mechanical friction. This component always directed against the direction of motion.

F_{load}: This is the sum of all load forces that produce the useable mechanical work and therefore represents function of the application. This can be the mass of the elevator car. In vehicle applications friction can also be considered as a part of the load force like rolling and aerodynamic friction in vehicles.

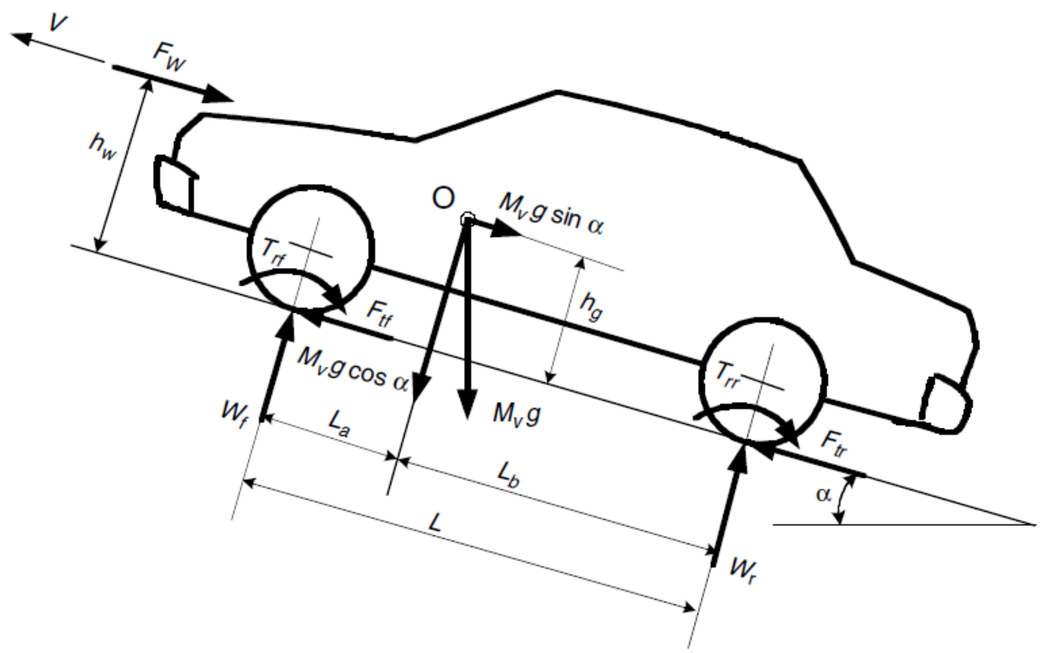
$\sum_i F_i\,(t) > 0\ \&\ v > 0$: Acceleration

$\sum_i F_i\,(t) < 0\ \&\ v > 0$: Deceleration

$\sum_i F_i\,(t) = 0$: Constant speed

Vehicle Resistances

1. Rolling resistance, F_r
2. Aerodynamic drag, F_w
3. Grading resistance, F_g



$$\Sigma F_t - \Sigma F_{rt} = \delta M \frac{dV}{dt}$$

$$\Sigma F_{rt} = F_r + F_w + F_g$$

Vehicle Resistance – Rolling Resistance

Produced by deformation processes which occur where the tire is in contact with the road. Depending on the tire and road characteristics tire and/or ground deforms and that causes asymmetric distribution of ground reaction forces.

Weight acting on tire-ground surface (normal load)

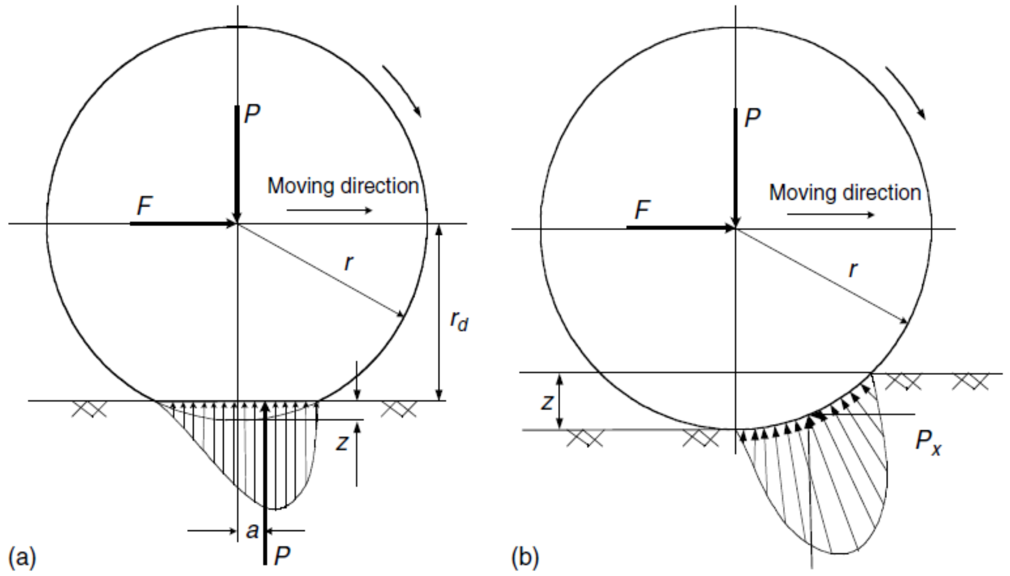
$$F_r = \frac{P\ a}{r_d} cos(\alpha)$$

Slope of road

Effective radius

$$F_r = f_r\ Mg\ cos(\alpha)$$

a/r_d: Coefficient of rolling resistance



Tire deflection and rolling resistance on a (a) hard and (b) soft road surface

Vehicle Resistance – Rolling Resistance

Produced by deformation processes which occur where the tire is in contact with the road.

$$F_r = f_r \, Mg \, cos(\alpha)$$

Rolling resistance coef. on concrete road (hard surface) can be estimated by the following equation for speeds up to 128 km/h:

$$f_r = f_0 + f_s \left(\frac{V}{100}\right)^{2.5}$$

$$f_r = 0.01\left(1 + \frac{V}{100}\right)$$

Vehicle Resistance – Aerodynamic Drag

- Turbulent air flow around vehicle body (85%) – Shape drag
- Friction of air over vehicle body (12%) – Skin drag
- Vehicle component resistance, from radiators, air vents and pipes under vehicle (3%)

$$F_w = \frac{1}{2}\rho A_f C_d (V + V_w)^2$$

Frontal area, m^2

Vehicle speed, m/sec

Wind speed, m/sec

Coefficient of aerodynamic drag

Density of air, typical value is $1.25 kg/m^3$

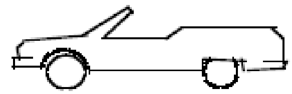
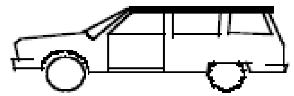
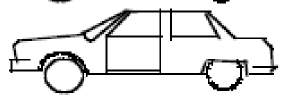
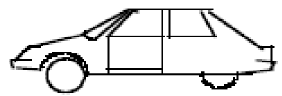
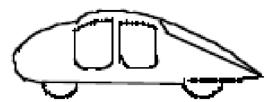
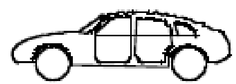
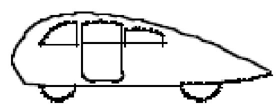
Aerodynamic tractive effort in N

Vehicle Resistance – Aerodynamic Drag

Frontal area m^2

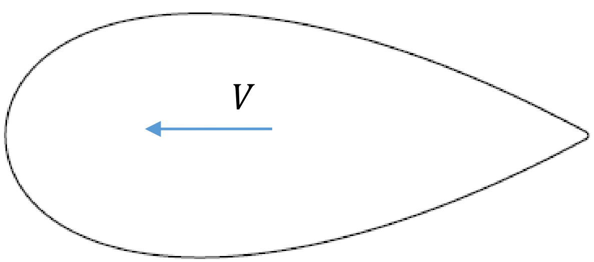
$$F_w = \frac{1}{2}\rho A_f C_d (V + V_w)^2$$

Coefficient of aerodynamic drag

Vehicle Type	Coefficient of Aerodymanic Resistance
 Open convertible	0.5–0.7
 Van body	0.5–0.7
 Ponton body	0.4–0.55
 Wedge-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 breakway 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

Indicative drag coefficients for different body shapes

Aerodynamic idea shape:



A teardrop of aspect ratio 2.4 with C_d=0.04

Vehicle Resistance – Aerodynamic Drag

VEHICLE	CHEVROLET VOLT	MERCEDES-BENZ CLA250	NISSAN LEAF SL (2012)	TESLA MODEL S P85 (2012)	TOYOTA PRIUS
BASE PRICE	$34,995	$30,825	$38,100	$93,390	$29,245
PRICE AS TESTED	$35,995	$35,855	$38,290	$100,520	$33,408
DIMENSIONS					
LENGTH	177.1 inches	182.3 inches	175.0 inches	196.0 inches	176.4 inches
WIDTH	70.4 inches	70.0 inches	69.7 inches	77.3 inches	68.7 inches
HEIGHT	56.6 inches	56.6 inches	61.0 inches	56.5 inches	58.7 inches
WHEELBASE	105.7 inches	106.3 inches	106.3 inches	116.5 inches	106.3 inches
WEIGHT	3766 pounds	3374 pounds	3353 pounds	4785 pounds	3180 pounds

C/D WIND TUNNEL TEST RESULTS	CHEVROLET VOLT	MERCEDES-BENZ CLA250	NISSAN LEAF SL (2012)	TESLA MODEL S P85 (2012)	TOYOTA PRIUS
DRAG COEFFICIENT	0.28	0.30	0.32	**0.24**	0.26
FRONTAL AREA	23.7 square feet	**23.2 square feet**	24.5 square feet	25.2 square feet	23.9 square feet
DRAG AREA (CD X FRONTAL AREA)	6.7 square feet	7.0 square feet	7.8 square feet	**6.2 square feet**	**6.2 square feet**
DRAG FORCE @ 70 MPH	84 pounds	88 pounds	97 pounds	**77 pounds**	78 pounds
AERO POWER @ 70 MPH	16 hp	16 hp	18 hp	**14 hp**	**14 hp**
AERO POWER @ 100 MPH	45 hp	48 hp	53 hp	**42 hp**	**42 hp**
FRONT-AXLE LIFT @ 70 MPH	-15 pounds	46 pounds	-12 pounds	23 pounds	-4 pounds
REAR-AXLE LIFT @ 70 MPH	26 pounds	44 pounds	11 pounds	17 pounds	17 pounds

REFERENCE AERO STARS

	DRAG COEFFICIENT	FRONTAL AREA, FT²	DRAG AREA, FT²
1996 GM EV1	0.21*	19.8	4.2
2001 HONDA INSIGHT	0.30	20.1	6.0
VOLKSWAGEN XL1	0.19†	16.1†	3.1

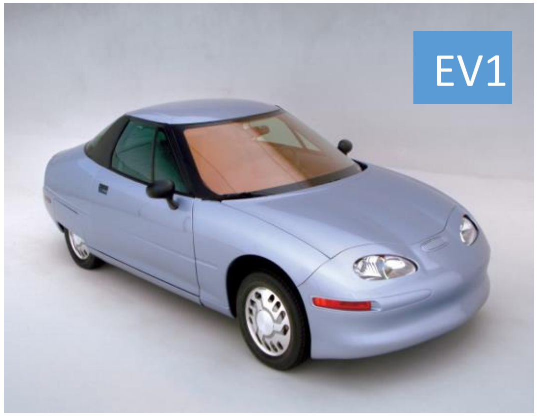
*GM figure †VW figure

Source: https://www.teslamotors.com/sites/default/files/blog_attachments/the-slipperiest-car-on-the-road.pdf

Vehicle Resistance – Aerodynamic Drag

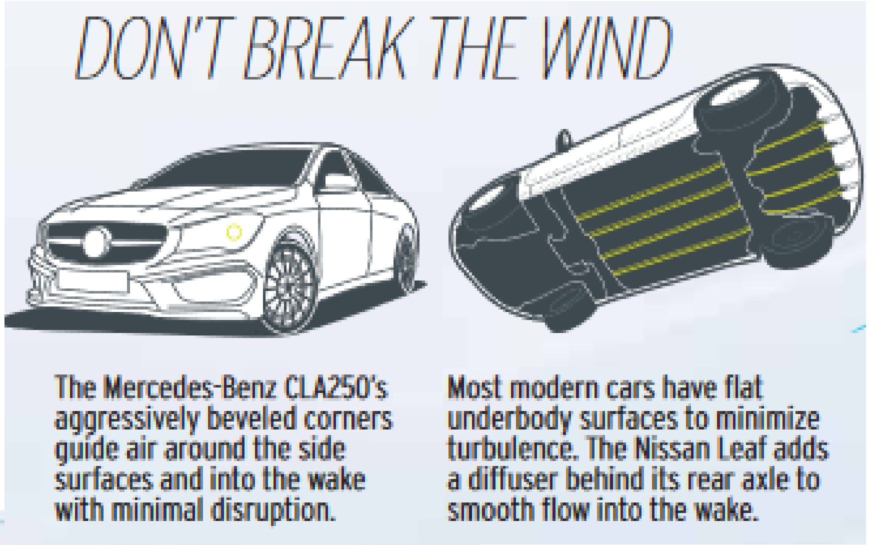
C_d	Car	Year
0.24	Tesla Model S	2012
0.24	Tesla Model X	2015
0.24	Toyota Prius	2016
0.212*	Tatra T77A	1935
0.21	Tesla Model 3	2017
0.195	General Motors EV1	1996
0.189	Volkswagen XL1	2013
0.07	Nuna, World Solar Challenge winner	2001–2007
0.0512	Ecorunner V (ShellEco-marathon) Prototype	2015

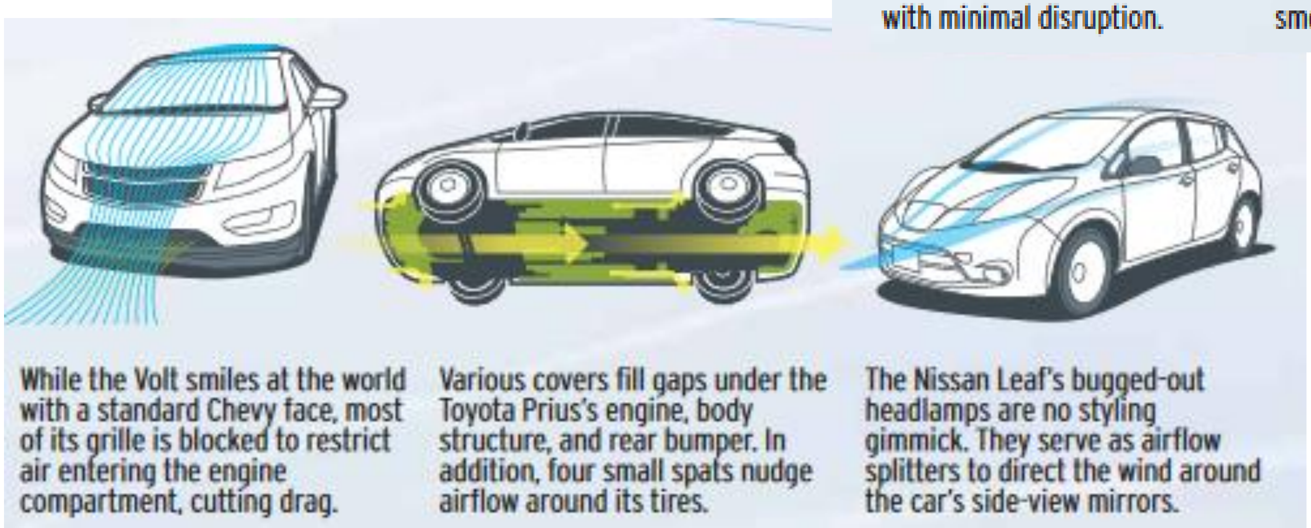
*according to some sources: 1:5 model test



Vehicle Resistance – Aerodynamic Drag

How is the aerodynamic drag reduced in electrified vehicles?





Source: https://www.teslamotors.com/sites/default/files/blog_attachments/the-slipperiest-car-on-the-road.pdf

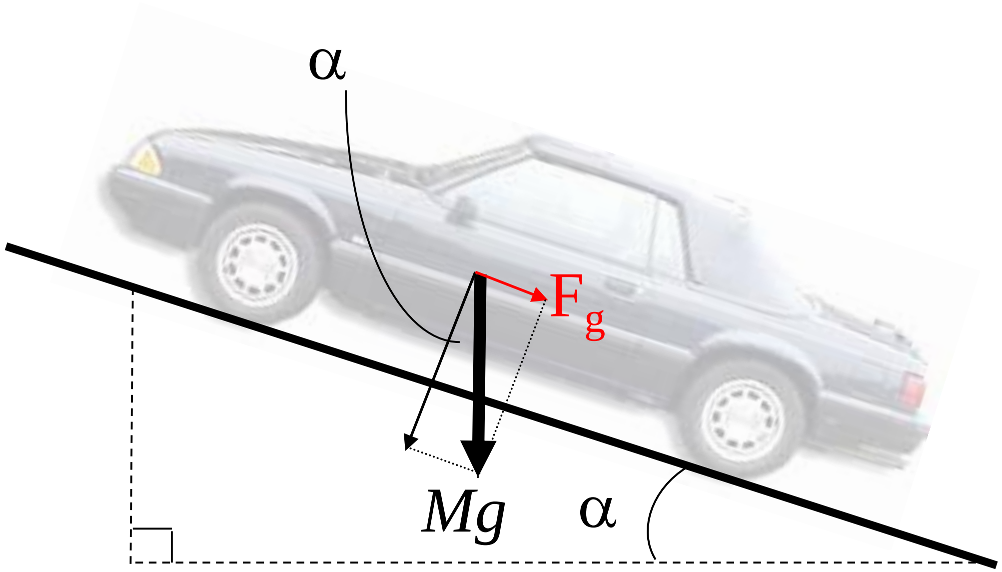
Vehicle Resistance – Grading Resistance

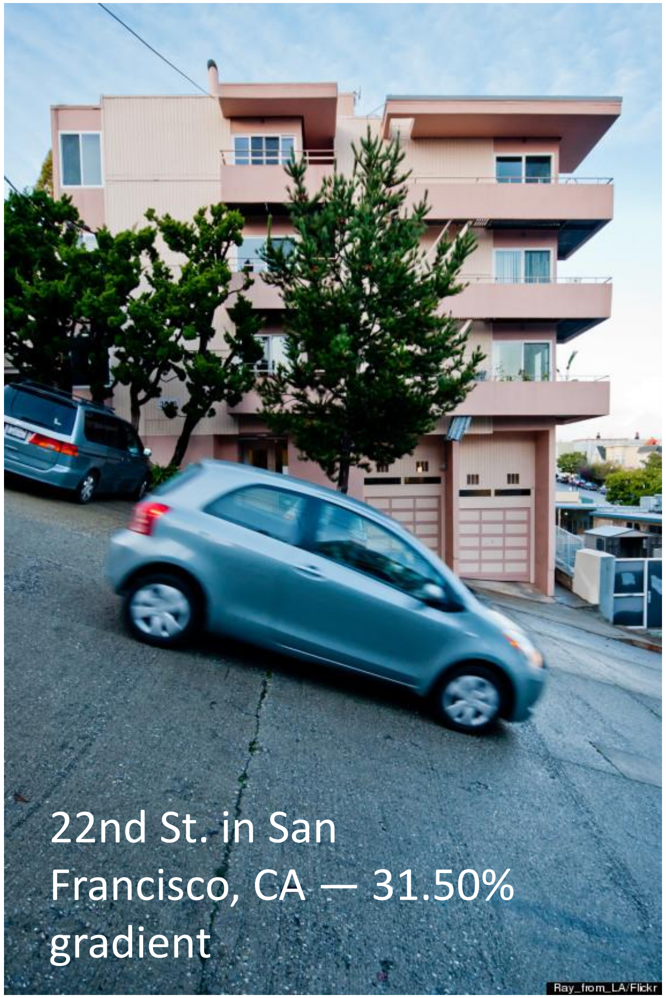
Gravitational force acting on the vehicle

Road angle

$$F_g = Mg\sin(\alpha)$$

Gravitational acceleration, m/s^2





Dynamic Equation

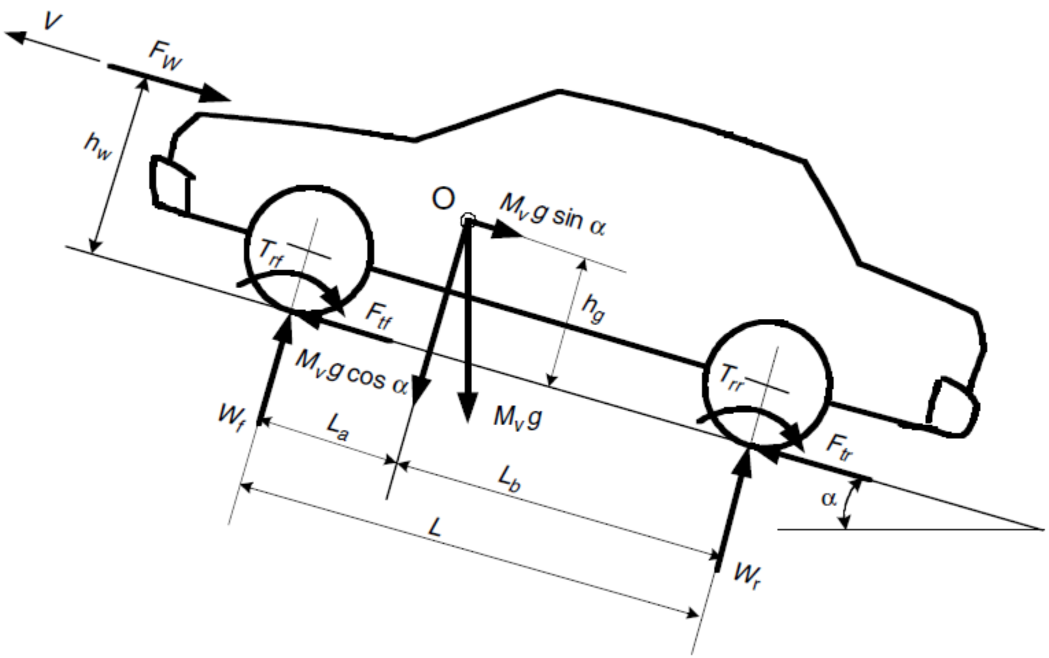
$$\delta M \frac{dV}{dt} = (F_{tf} + F_{tr}) - (F_{rf} + F_{rr} + F_{\omega} + F_g)$$

Rolling resistive force of rear tires

Rolling resistive force of front tires

Tractive force of rear tires

Tractive force of front tires



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Rolling resistive force of rear tires

Rolling resistive force of front tires

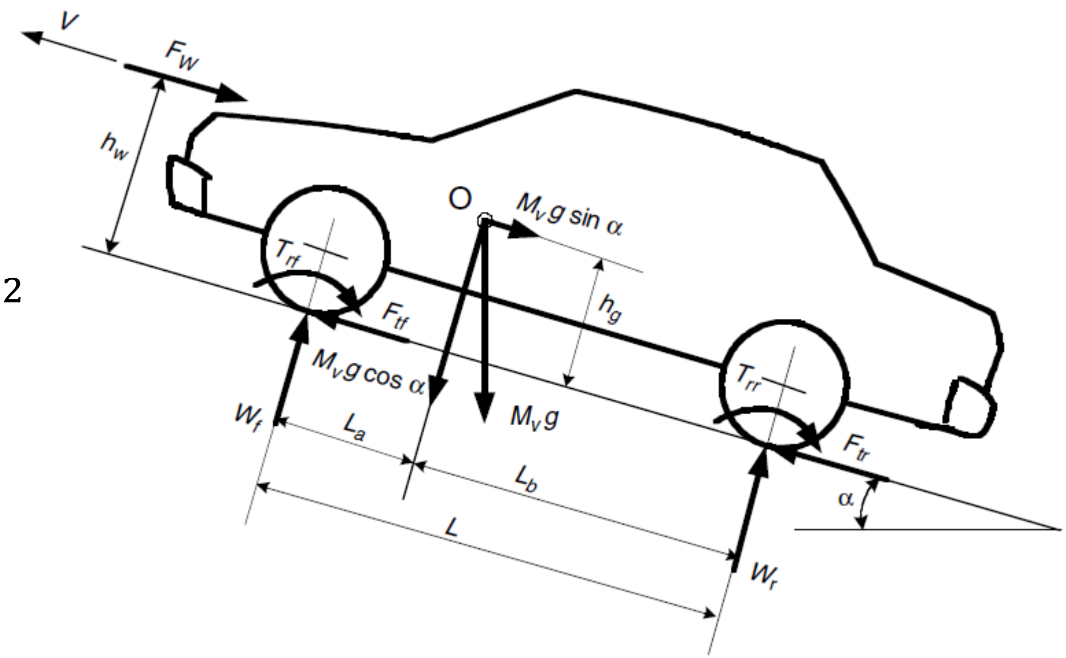
Tractive force of rear tires

Tractive force of front tires

$$F_r = f_r Mg\ cos(\alpha)$$

$$F_w = \frac{1}{2}\rho A_f C_d (V + V_w)^2$$

$$F_g = Mg\ \sin(\alpha)$$



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Rolling resistive force of rear tires

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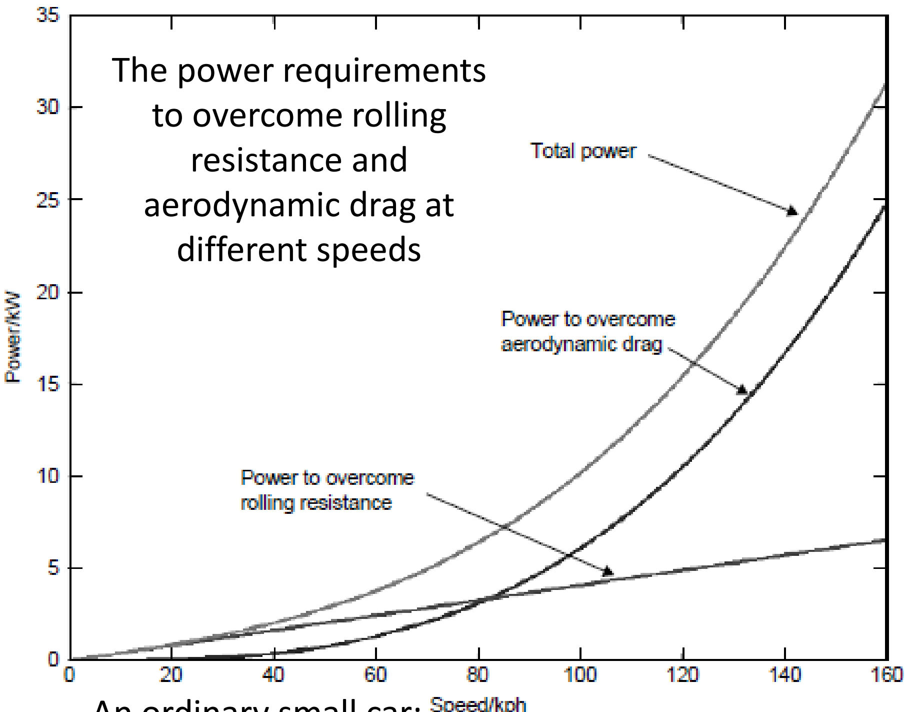


An ordinary small car:
C_d = 0.3, A_f=1.5 m^2, M= 1000 kg, and f_r = 0.015

Maximum Tractive Effort

The maximum tractive effort on the driven wheel is limited by the lowest of:

- The longitudinal force that the adhesive capability between the tire and ground can supply
- The maximum torque that the engine (ICE or electric machine) can supply

Maximum tractive effort depends on:

- Vertical load on the traction wheels
- Adhesive capability

$$F_{tf} = \mu W_f$$

$$F_{tr} = \mu W_r$$

Vertical load

Tractive effort coefficient

Load Transfer

Tractive effort depends on vertical load distribution among axels.

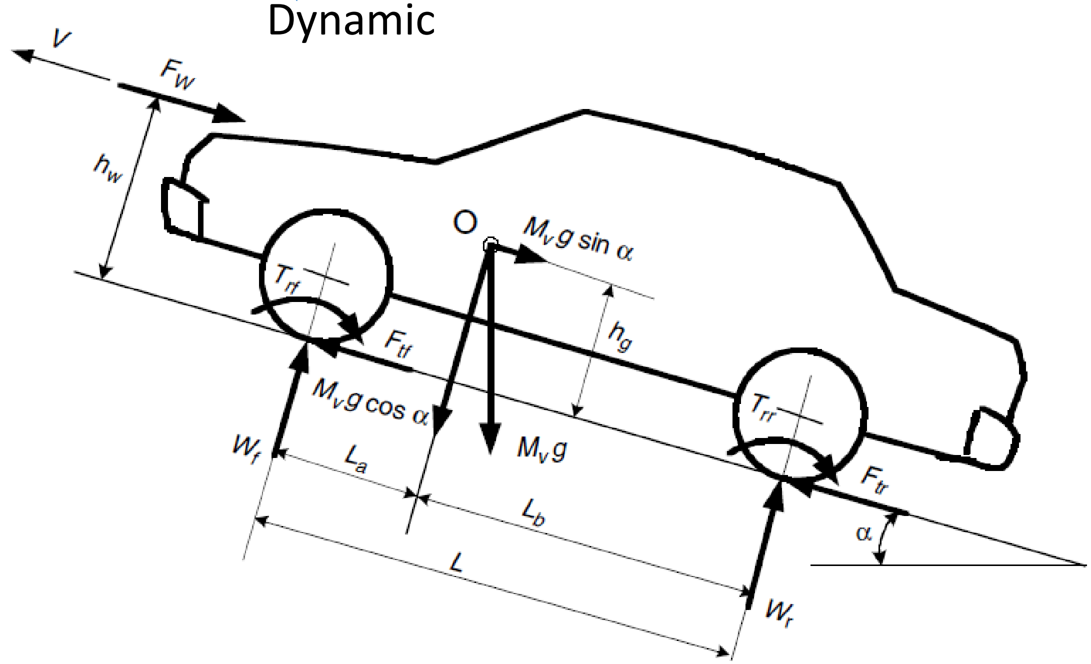
Normal loads on the front and rear axels are:

$$W_f = \frac{1}{L}\left\{L_b M_v g cos(\alpha) - h_g\left(F_g + M\frac{dv}{dt}\right) - h_w F_w\right\}$$

$$W_r = \frac{1}{L}\left\{\underbrace{L_a M_v g cos(\alpha)}_{\text{Static}} + \underbrace{h_g\left(F_g + M\frac{dv}{dt}\right) + h_w F_w}_{\text{Dynamic}}\right\}$$

$M_v = \delta M$ and h_w is the center of application of F_w

We can further simply the equations by assuming h_w= h_g



Maximum Tractive Effort

Tractive effort coefficient μ depends on:

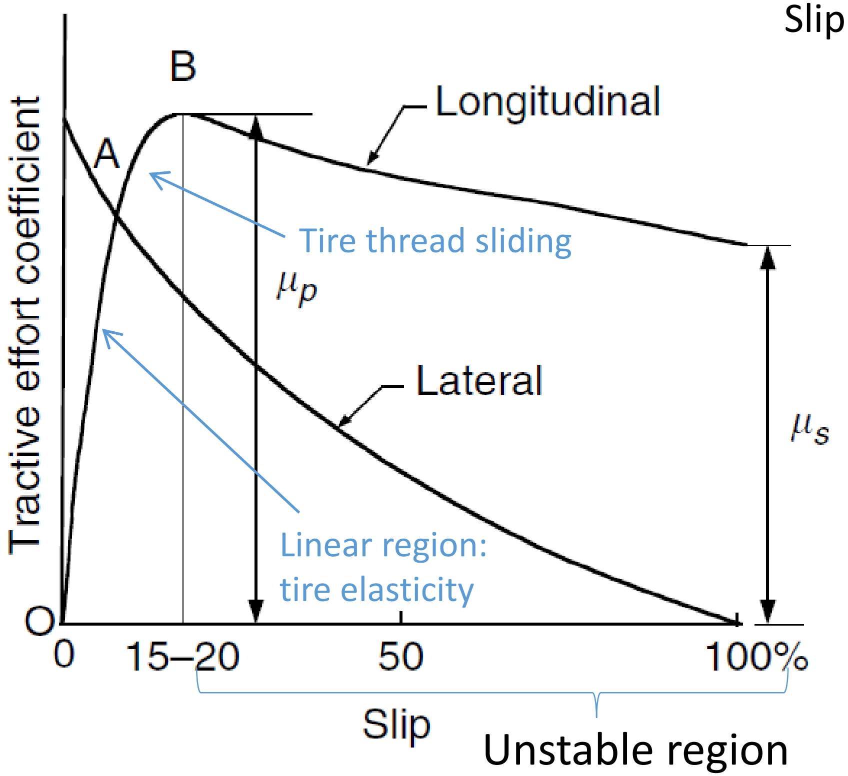
- Ground and tire characteristics

$$s = \left(1 - \frac{V}{r\omega}\right) x100\% = \left(1 - \frac{r_d}{r}\right) x100\%$$

Effective radius

Slip

Radius of free wheeling tire



Average Values of Tractive Effort Coefficient on Various Roads

Surface	Peak Values, μ_p	Sliding Values, μ_s
Asphalt and concrete (dry)	0.8–0.9	0.75
Concrete (wet)	0.8	0.7
Asphalt (wet)	0.5–0.7	0.45–0.6
Grave	0.6	0.55
Earth road (dry)	0.68	0.65
Earth road (wet)	0.55	0.4–0.5
Snow (hard packed)	0.2	0.15
Ice	0.1	0.07

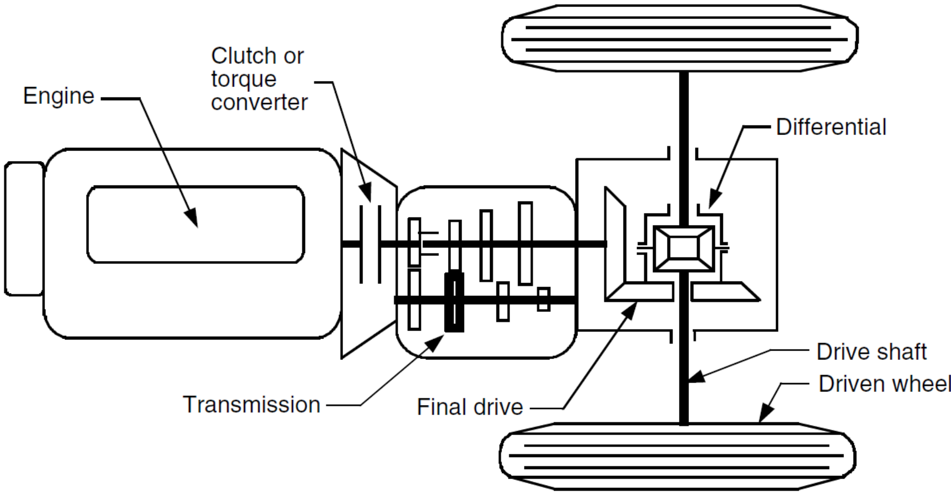
Maximum Tractive Effort

Vehicle road speed km/h	Tire condition	Dry road	Wet road (depth of water 0.2 mm)	Heavy rain (depth of water 1 mm)	Puddles (depth of water 2 mm)	Icy (black ice)
50	new	0.85	0.65	0.55	0.5	0.1 and below
	worn out	1	0.5	0.4	0.25	
90	new	0.8	0.6	0.3	0.05	
	worn out	0.95	0.2	0.1	0.0	
130	new	0.75	0.55	0.2	0	
	worn out	0.9	0.2	0.1	0	

Tractive effort coefficient, μ, for tires in various conditions of wear, on various road conditions and at various speeds

Source: K. Reif (Ed.), “Brakes, Brake Control and Driver Assistance Systems Function, Regulation and Components”, 2014

Power Train Tractive Effort



Torque on the wheels

Total efficiency of driveline

Torque output of plant

$$T_w = i_g i_0 \eta_t T_p$$

*Gear ratio of final drive

*Gear ratio of transmission

Tractive force

Speed wheels in rpm

$$F_t = \frac{T_w}{r_d}$$

$$n_w = \frac{n_p}{i_g i_0}$$

Longitudinal speed

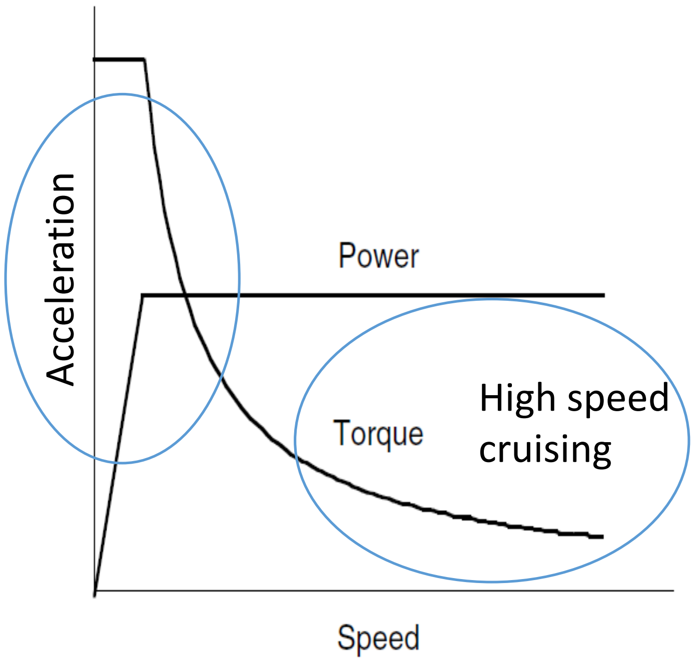
$$V = \frac{\pi\, n_w r_d}{30} \text{ (m/s)}$$

Clutch:	99%
Each pair of gears:	95–97%
Bearing and joint:	98–99%
Direct gear:	90%
Other gear:	85%

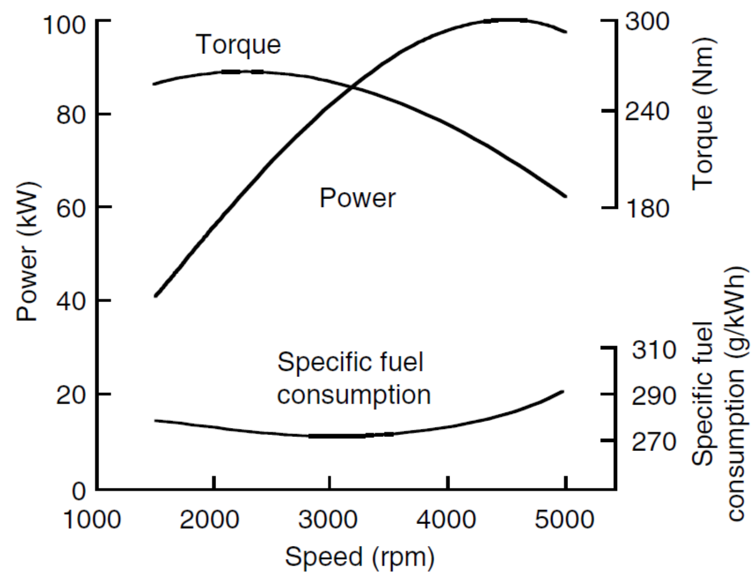
*Gear ratio is defined as the radio of n_p / n_w or T_w/T_p

Power Train Tractive Effort – Torque Output of Plant

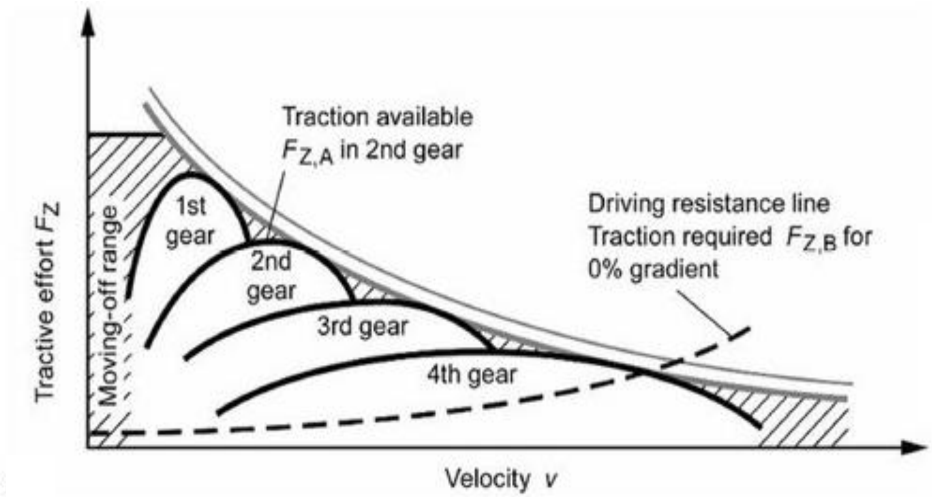
Ideal required performance characteristics:



Internal combustion engine (ICE) :



Why we need multi-speed gearboxes?



The proportion of shaded area, i.e. the proportion of impossible driving states, is significantly smaller when an output converter is used, and the power potential of the engine can be better applied.

https://www.quora.com/Why-do-electric-engines-have-a-wider-torque-range

2018 Golf R Technical Specifications

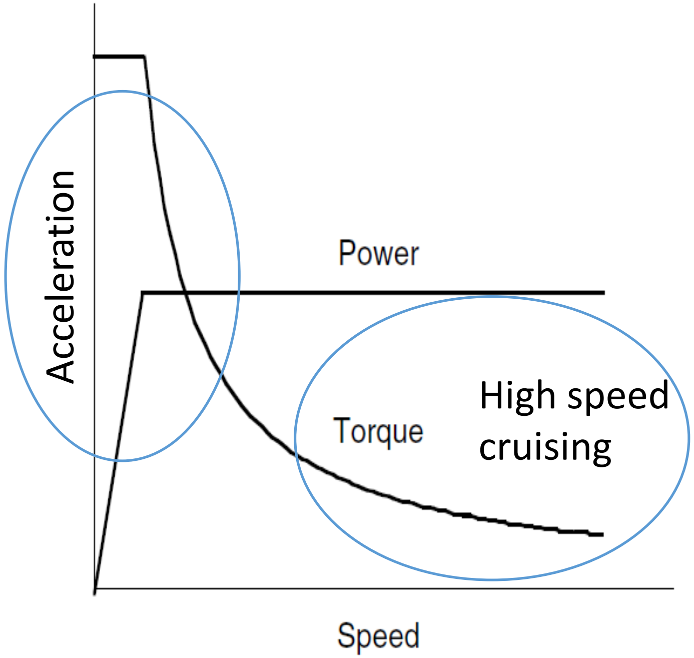
Golf R

4Motion permanent all-wheel-drive system	Manual	DSG
1st	3.36	3.19
2nd	2.09	2.75
3rd	1.48	1.9
4th	1.09	1.04
5th	1.1	0.79
6th	0.91	0.86
7th	-	0.66
Reverse	3.99	2.9
Final I	4.24	4.47
Final II	3.27	3.3

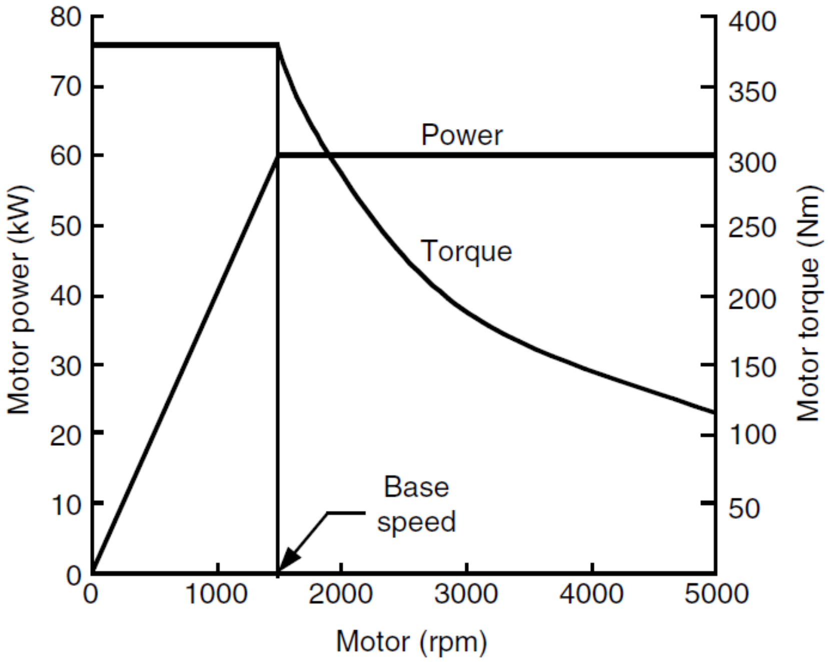
https://newspress-vwusamedia.s3.amazonaws.com/documents%2Foriginal%2F8665-2018VolkswagenGolfRTechnicalSpecifications.pdf

Power Train Tractive Effort – Torque Output of Plant

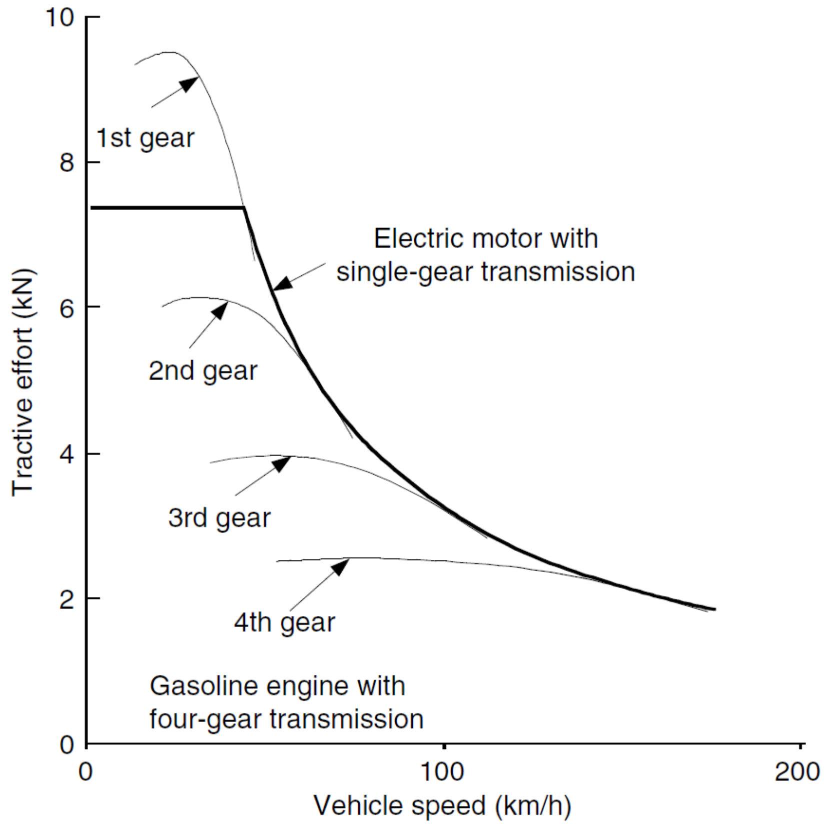
Ideal required performance characteristics:



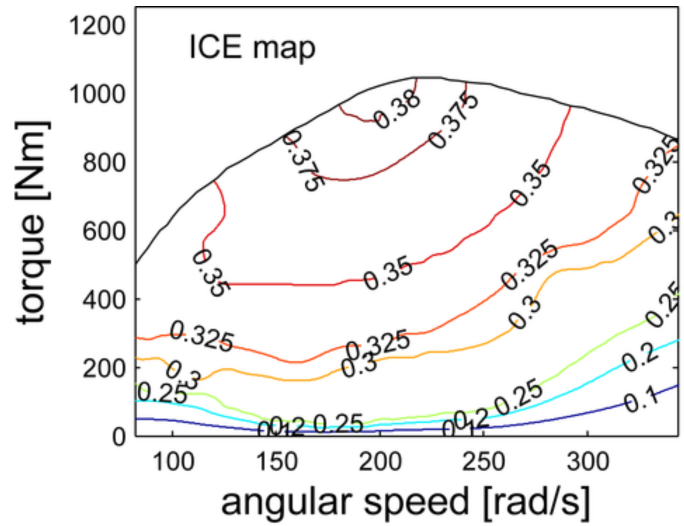
Electric machine:

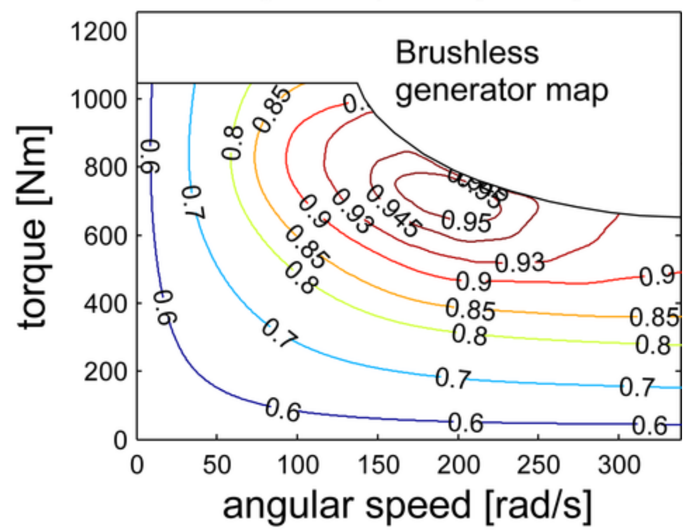


Power Train Tractive Effort: ICE vs. EM



With 4-speed gear box





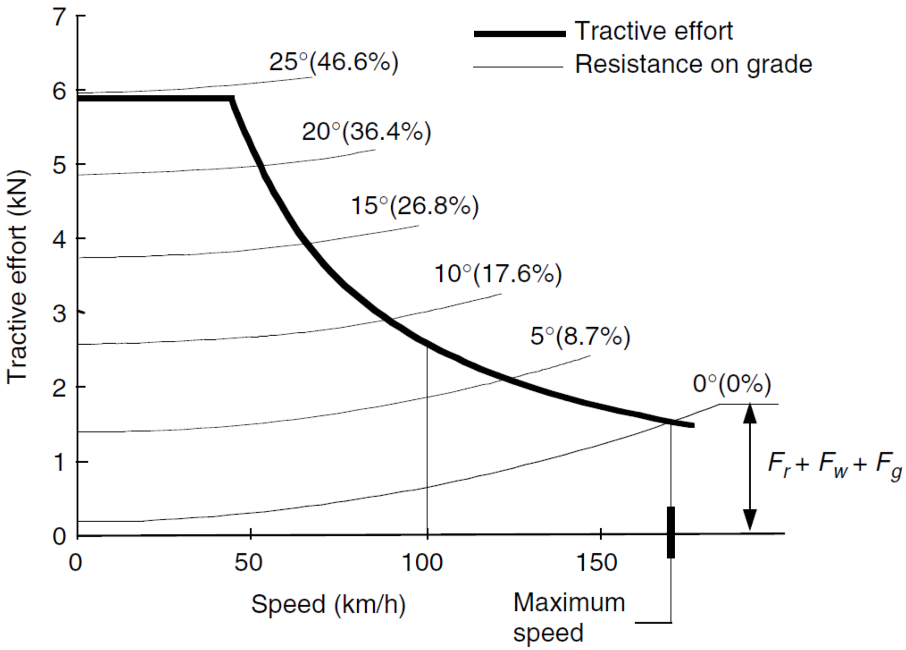
Source:
https://www.google.com/search?q=efficiency+of+ice&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjK2MirkPjMAhUFSSYKHRCcDYcQ_AUIBygB&biw=1920&bih=955#imgrc=dfIHwMEna1vZTM%3A

Vehicle Performance

1. Maximum speed
2. Gradeability
3. Acceleration time (0-100km/h, 60-100km/h)

Vehicle Performance - Maximum Speed of a Vehicle

The maximum speed of a vehicle is defined as the constant cruising speed that the vehicle can develop with full power plant load (full throttle of the engine or full power of the motor) on a flat road.



Tractive force

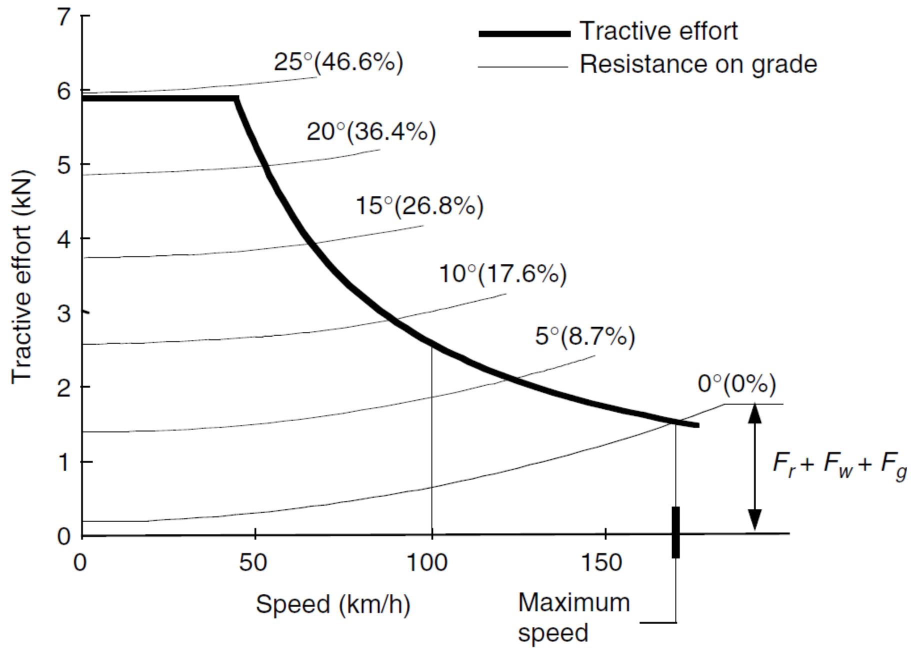
α=0 deg at maximum speed calculation

$$F_t = \frac{T_p i_g i_0 \eta_t}{r_d} = Mgf_r\cos(\alpha) + \frac{1}{2}\rho A_f C_d (V)^2 + Mg\sin(\alpha)$$

Vehicle Performance - Gradeability

Gradeability is usually defined as the grade (or grade angle) that the vehicle can overcome at a certain constant speed, for instance, the grade at a speed of 100 km/h (60 mph).

Gradability is measured either in degrees or percentage. A 45 degrees gradient is equivalent to 100 per cent.



Tractive force

α>0 deg at V= const.

$$F_t = \frac{T_p i_g i_0 \eta_t}{r_d} = Mgf_r\cos(\alpha) + \frac{1}{2}\rho A_f C_d (V)^2 + Mg\sin(\alpha)$$

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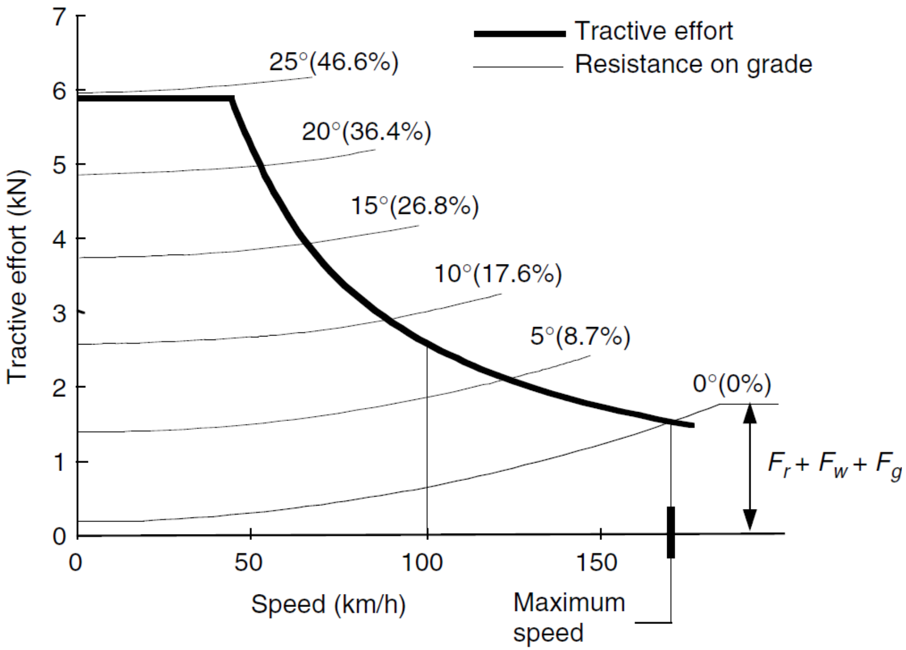


How much gradeability do we need?

45% is really steep!

Vehicle Performance - Acceleration Performance

The acceleration performance of a vehicle is usually described by its acceleration time and the distance covered from zero speed to a certain high speed (zero to 96 km/h or 60 mph, for example) on level ground.

$$a = \frac{dV}{dt} = \frac{F_t - F_r - F_w}{\delta M} = \frac{\frac{T_p i_g i_0 \eta_t}{r_d} - Mgf_r - \frac{1}{2}\rho A_f C_d (V)^2}{\delta M}$$

Vehicle mass multiplied by mass factor δ that represents the effect of rotating masses

For a conventional car:

Moment of inertia of wheels

$$\delta = 1 + \frac{J_\omega}{M_v r_d^2}$$

For a car with electric motor, we must also consider moment of inertia of electric motor (J_p).

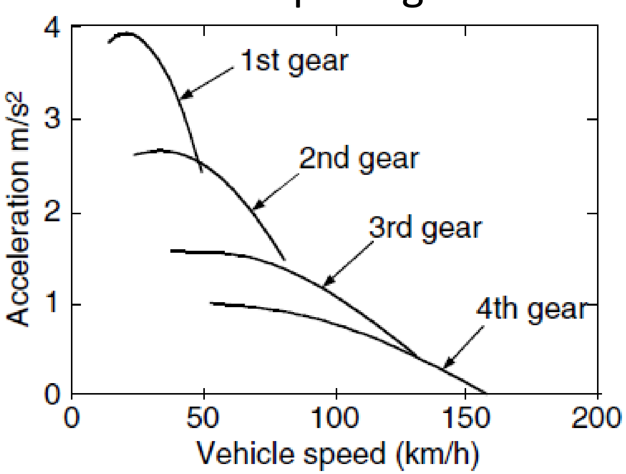
$$\delta = 1 + \frac{J_\omega}{M_v r_d^2} + \frac{\left(i_g i_0\right)^2 J_p}{M_v r_d^2}$$

Vehicle Performance - Acceleration Performance

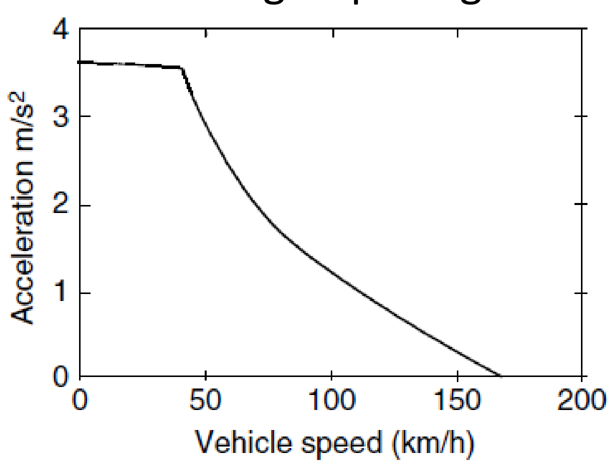
The acceleration performance of a vehicle is usually described by its acceleration time and the distance covered from zero speed to a certain high speed (zero to 96 km/h or 60 mph, for example) on level ground.

$$a = \frac{dv}{dt} = \frac{F_t - F_r - F_w}{\delta M} = \frac{\frac{T_p i_g i_0 \eta_t}{r_d} - Mgf_r - \frac{1}{2}\rho A_f C_d (V)^2}{\delta M}$$

ICE with 4-speed gear box



EM with single speed gear box



- T_p is a function of vehicle speed.

Vehicle Performance - Acceleration Performance

The acceleration performance of a vehicle is usually described by its acceleration time and the distance covered from zero speed to a certain high speed (zero to 96 km/h or 60 mph, for example) on level ground.

$$a = \frac{dv}{dt} = \frac{F_t - F_r - F_w}{\delta M} = \frac{\frac{T_p i_g i_0 \eta_t}{r_d} - Mgf_r - \frac{1}{2}\rho A_f C_d (V)^2}{\delta M}$$

Acceleration time:

$$t_a = \int_{v_1}^{v_2} \frac{\delta M}{\frac{T_p i_g i_0 \eta_t}{r_d} - Mgf_r - \frac{1}{2}\rho A_f C_d (V)^2} dv$$

Acceleration distance:

$$S_a = \int_{v_1}^{v_2} \frac{\delta M V}{\frac{T_p i_g i_0 \eta_t}{r_d} - Mgf_r - \frac{1}{2}\rho A_f C_d (V)^2} dv$$

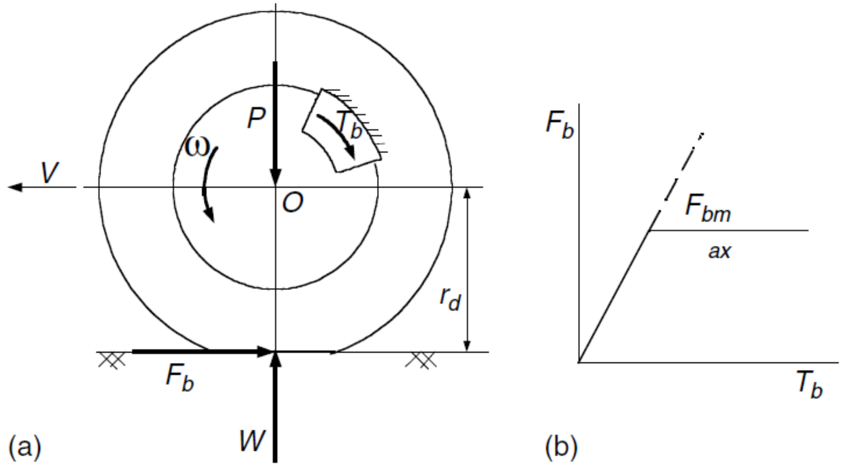
- T_p is a function of vehicle speed. → Numeric calculations!

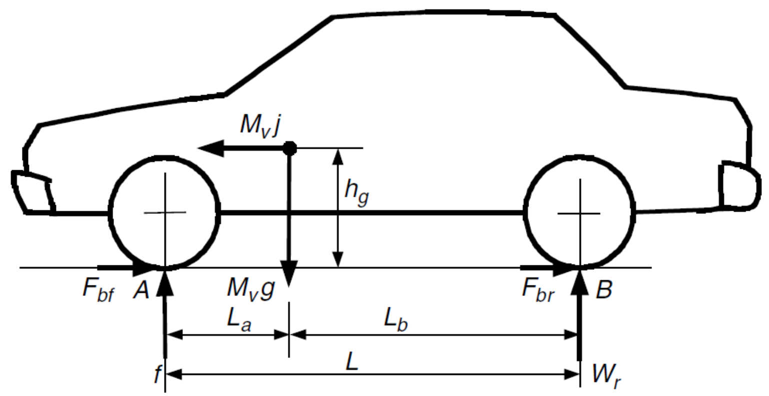
Vehicle Performance - Acceleration Performance

	CHEVROLET VOLT	MERCEDES-BENZ CLA250	NISSAN LEAF SL (2012)	TESLA MODEL S P85 (2012)	TOYOTA PRIUS
VEHICLE					
BASE PRICE	$34,995	$30,825	$38,100	$93,390	$29,245
PRICE AS TESTED	$35,995	$35,855	$38,290	$100,520	$33,408
DIMENSIONS					
LENGTH	177.1 inches	182.3 inches	175.0 inches	196.0 inches	176.4 inches
WIDTH	70.4 inches	70.0 inches	69.7 inches	77.3 inches	68.7 inches
HEIGHT	56.6 inches	56.6 inches	61.0 inches	56.5 inches	58.7 inches
WHEELBASE	105.7 inches	106.3 inches	106.3 inches	116.5 inches	106.3 inches
WEIGHT	3766 pounds	3374 pounds	3353 pounds	4785 pounds	3180 pounds
POWERTRAIN					
POWERTRAIN	DOHC 1.4-liter inline-4 + AC electric motor, CVT	turbocharged DOHC 2.0-liter inline-4, 7-speed dual-clutch automatic	AC electric motor, single-speed drive	AC electric motor, single-speed drive	DOHC 1.8-liter inline-4 + AC electric motor, CVT
POWER HP @ RPM	84 @ 4800 (engine)	208 @ 5500	107 @ 10,000	416 @ 8600	98 @ 5200 (engine)
TORQUE LB-FT @ RPM	271 @ 0 (motor)	258 @ 1250	187 @ 0	443 @ 0	153 @ 0 (motor)
DRIVEN WHEELS	front	front	front	rear	front
PERFORMANCE					
0-60 MPH	8.8 sec	6.3 sec	10.2 sec	4.6 sec	10.0 sec
1/4-MILE @ MPH	16.7 sec @ 85	14.9 sec @ 95	17.7 sec @ 78	13.3 sec @ 104	17.6 sec @ 79
TOP SPEED	101 mph (governor limited)	133 mph (governor limited)	94 mph (governor limited)	134 mph (redline limited)	115 mph (drag limited)
EPA CITY/HWY	35/40 mpg	26/38 mpg	126/101 MPGe	88/90 MPGe	51/48 mpg
	Performance results from C/D, November 2011.	*Performance results from C/D, December 2013.*	*Performance results from C/D, March 2014.*	*Performance results from C/D, January 2013.*	*Performance results from C/D, July 2009.*

Source: https://www.teslamotors.com/sites/default/files/blog_attachments/the-slipperiest-car-on-the-road.pdf

Braking





(a) Braking torque and braking force (b) Relationship between braking torque and braking force

Braking torque

$$F_b = \frac{T_b}{r_d}$$

Braking force

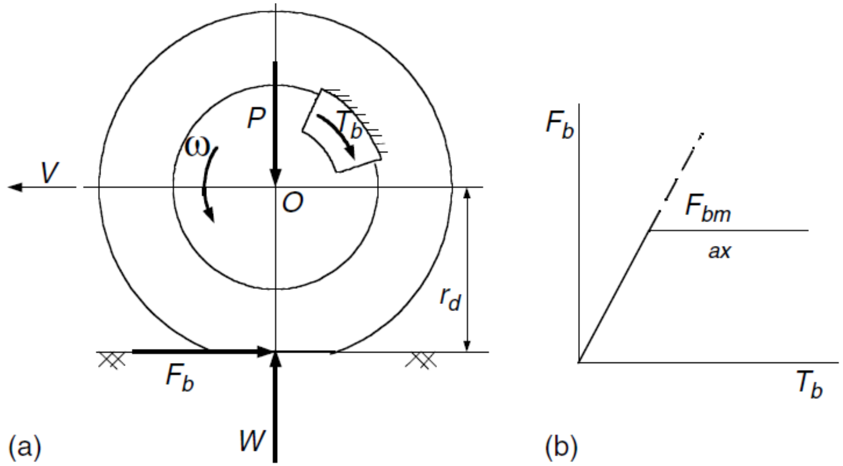
Adhesive coef. of tire-ground contact

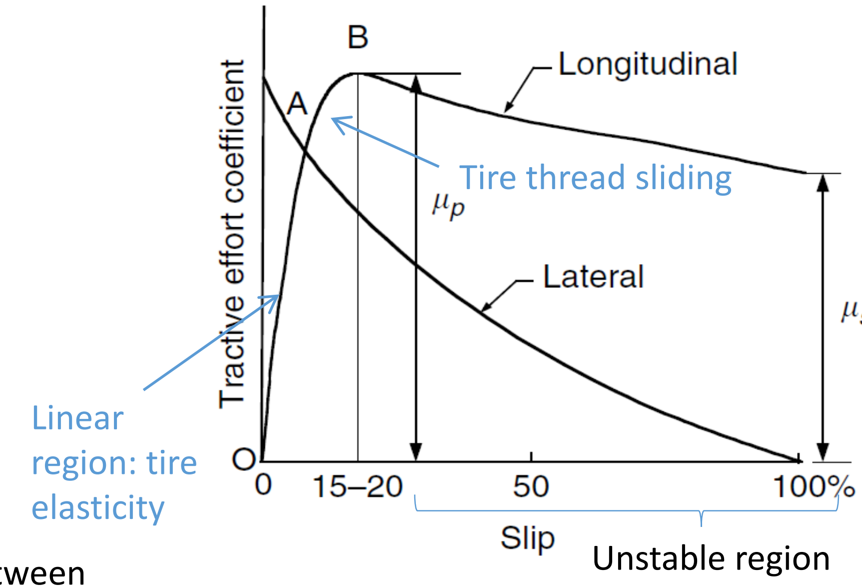
$$F_{bmax} = \mu W$$

Max. braking force

- How the axel loads are going to change during braking?
- Discuss the braking performance of front and rear wheels.

Braking





(a) Braking torque and braking force (b) Relationship between braking torque and braking force

Braking torque

$$F_b = \frac{T_b}{r_d}$$

Braking force

Adhesive coef. of tire-ground contact

$$F_{bmax} = \mu W$$

Max. braking force

The **antilock braking system (ABS)** prevents wheels from locking up.

- This system employs speed sensors to detect the wheel rotating speed.
- When a wheel lockup is detected, the braking pressure control system reduces the pressure and brings the wheel back to its rotation.

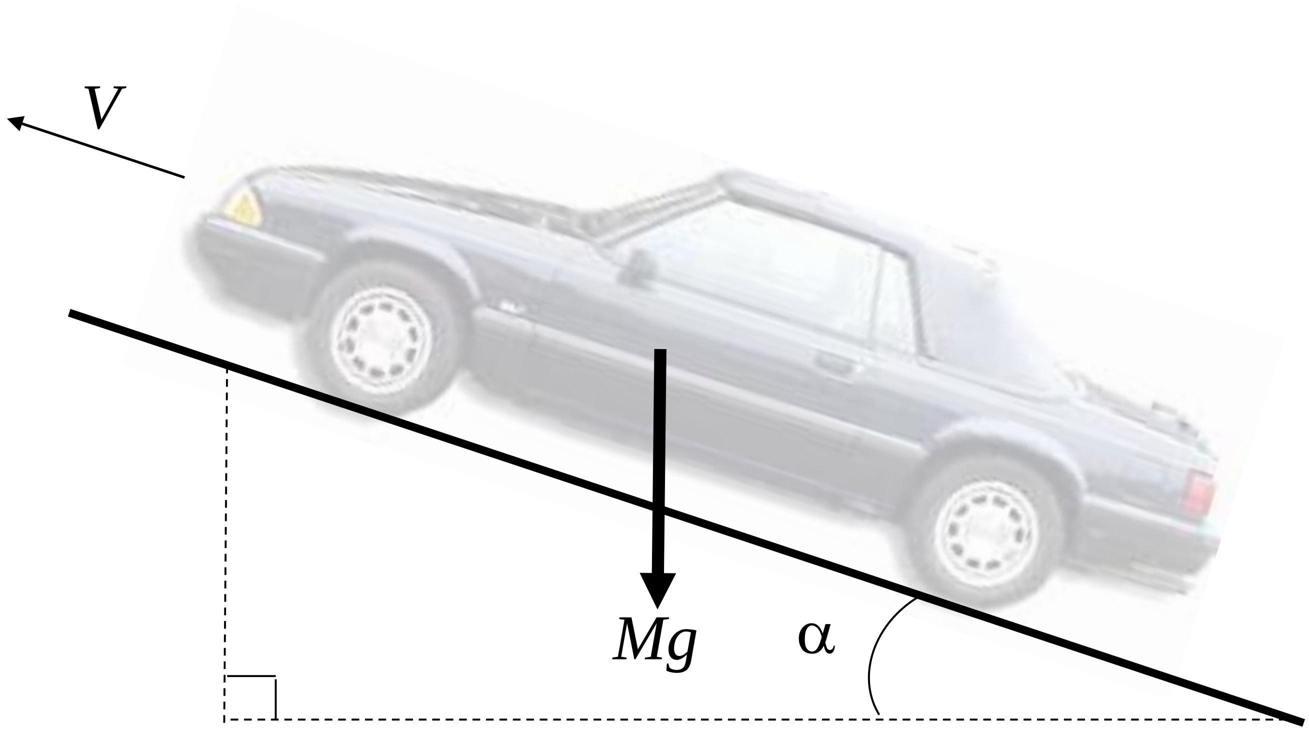
Summary of Longitudinal Forces on a Vehicle

Resistances

- Rolling resistance
- Aerodynamic resistance
- Grading resistance

Tractive force

Braking force



Content

1. Vehicle requirements
2. Vehicle movement
3. Vehicle resistances
4. Dynamic equation
5. Maximum tractive force
6. Powertrain tractive effort
7. Vehicle performance
    - Maximum speed
    - Gradeability
    - Acceleration time (0-100km/h, 60-100km/h)
8. Braking
9. Fuel Economy
    - Driving cycles

Fuel Economy

Fuel consumption in liter per 100 km travelling distance → liters/100 km

OR

Mileage per gallon fuel consumption → miles/gallon (mpg)

Factors effecting fuel economy:

1. Internal combustion engine and/or electric motor efficiency characteristics
2. **Gear number and ratios**
3. Transmission efficiency
4. **Vehicle resistance (shape, weight and tire characteristics)**
5. Vehicle speed
6. **Operating conditions (terrain, wind, outside temperature, loads and exterior loading such as bikes)**

Fuel Economy – Operating Points of internal Combustion Engine (ICE)

Engine power output P_e in kW:

$$P_e = \underbrace{\frac{v}{1000\, n_t}}_{\text{Resultant efficiency}} \Big(\underbrace{f_r\, Mg\, cos(\alpha) + \frac{1}{2}\rho A_f C_d (V + V_w)^2 + Mg\,\sin(\alpha)}_{\text{Resistances}} + \underbrace{\delta M \frac{dV}{dt}}_{\text{Acceleration}}\Big)$$

Engine rotational speed n_e in rpm:

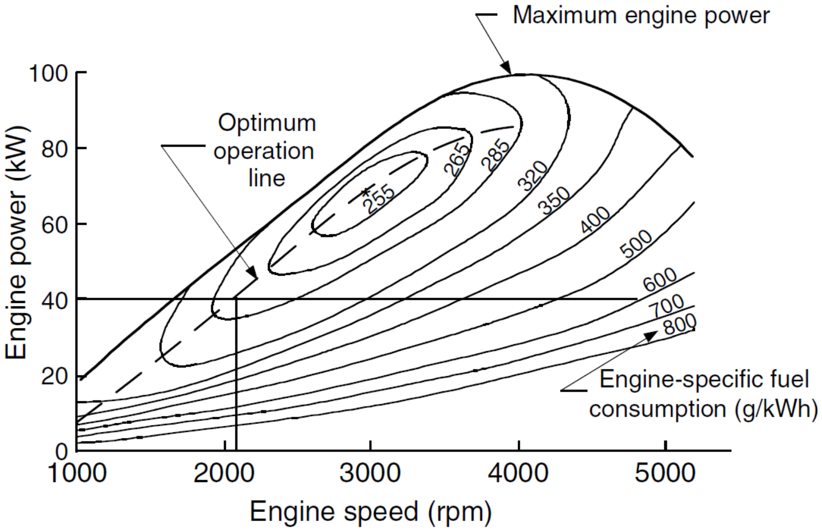
$$n_e = \frac{v}{r_d} \underbrace{i_g i_0}_{\text{Transmission ratio}} \frac{60}{2\pi}$$

Time rate of fuel consumption:

$$Q_{fr} = \frac{P_e g_e}{1000\gamma_f} \frac{1}{3600} \ (l/sec)$$

Specific fuel cons. in g/kWh

Mass density in *kg/l*



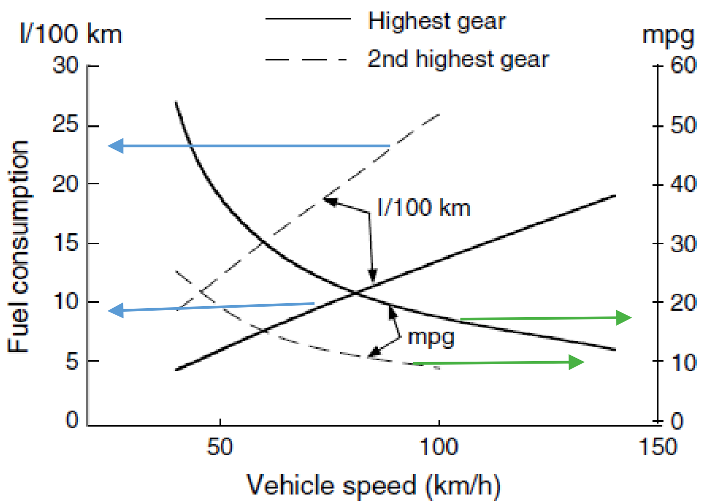
Total fuel consumption within *S* at v :

$$Q_s = \frac{P_e g_e}{1000\, \gamma_f} \frac{1}{3600} \frac{S}{v} \ (l)$$

Fuel Economy – Gear Number and Ratios

Improved fuel economy:

- Higher gear ratios or continuous variable transmission (CVT)



Fuel economy characteristics of a typical vehicle at constant speed

- ➢ The parameters of the transmission, especially gear number and gear ratios, have a considerable influence on the fuel economy.
- ➢ These parameters should be selected such that the engine will operate close to its fuel optimum region.

Fuel Economy – Vehicle Resistances

Basic techniques to reduce vehicle resistances:

1. Light weight design: Reduces rolling, grading and acceleration resistance

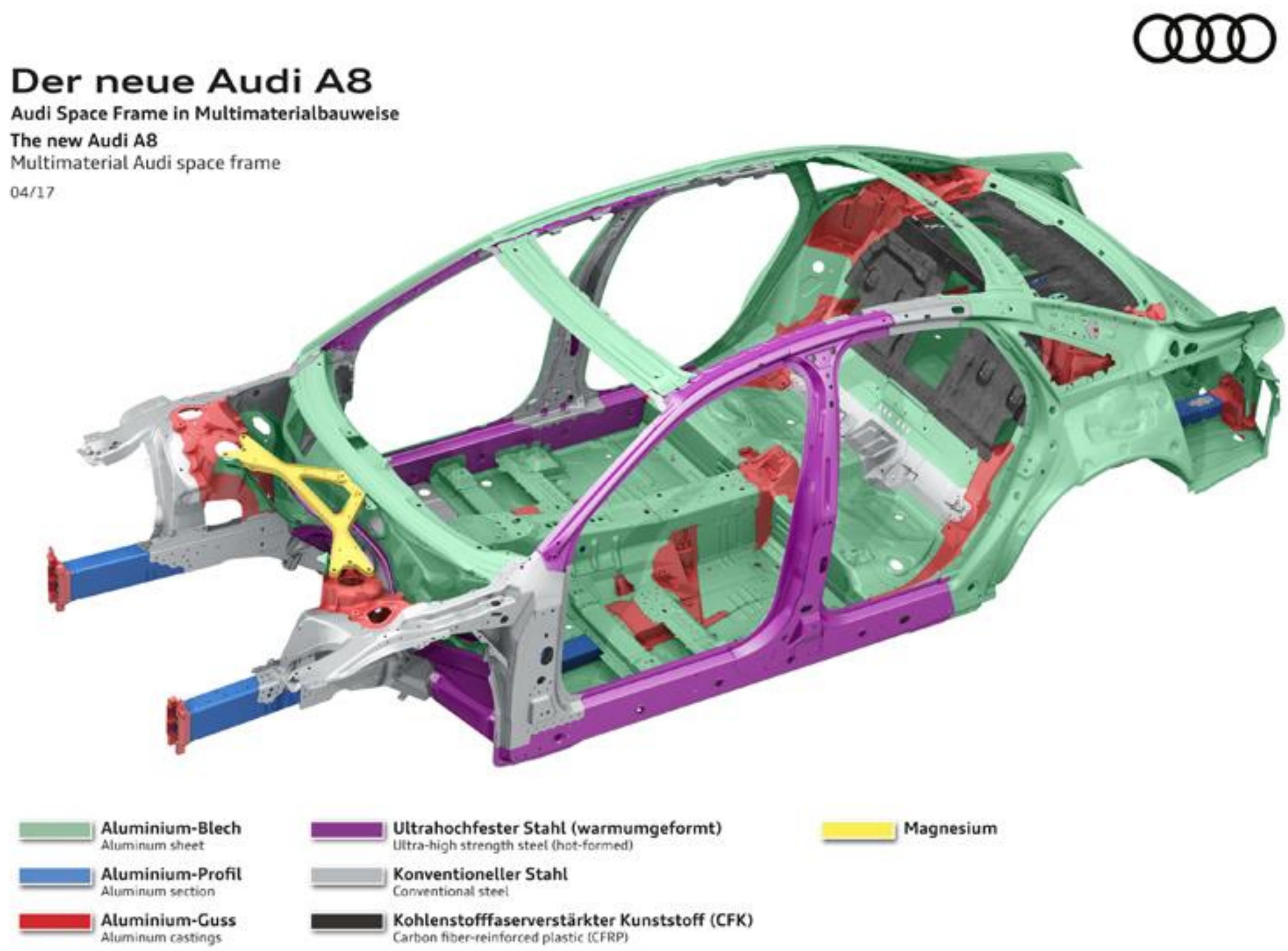
Material	Density ρ (kg/m^3)	Fracture stress σ (MPa)	Young's Modulus E (GPa)	Strength to mass σ/ρ	Rigidity to mass E/ρ
Mild steel	7850	465	207	0.059	0.026
Stainless steel, FSM 1	7855	980	185	0.125	0.024
Aluminium alloy (DTD 5050B)	2810	500	71	0.178	0.025
Magnesium alloy (AX 31) (DTD 742)	1.780	185	45	0.104	0.025
Carbon fibre reinforced plastic, 58% unidirectional fibres by volume in epoxy resin	1500	1050	189	0.70	0.126
Glass reinforced plastic (GRP), 80% uniaxial glass by weight in polyester resin	2000	1240	48.2	0.62	0.024

Comparison of material properties

Source: Larminie, J. and Lowry J., "Electric Vehicle Technology Explained", 2nd edition, John Wiley & Sons, 2012

Fuel Economy – Vehicle Resistances

Multi-material frame to reduce weight



Fuel Economy – Vehicle Resistances

Carbon fiber reinforced polymer monocoque

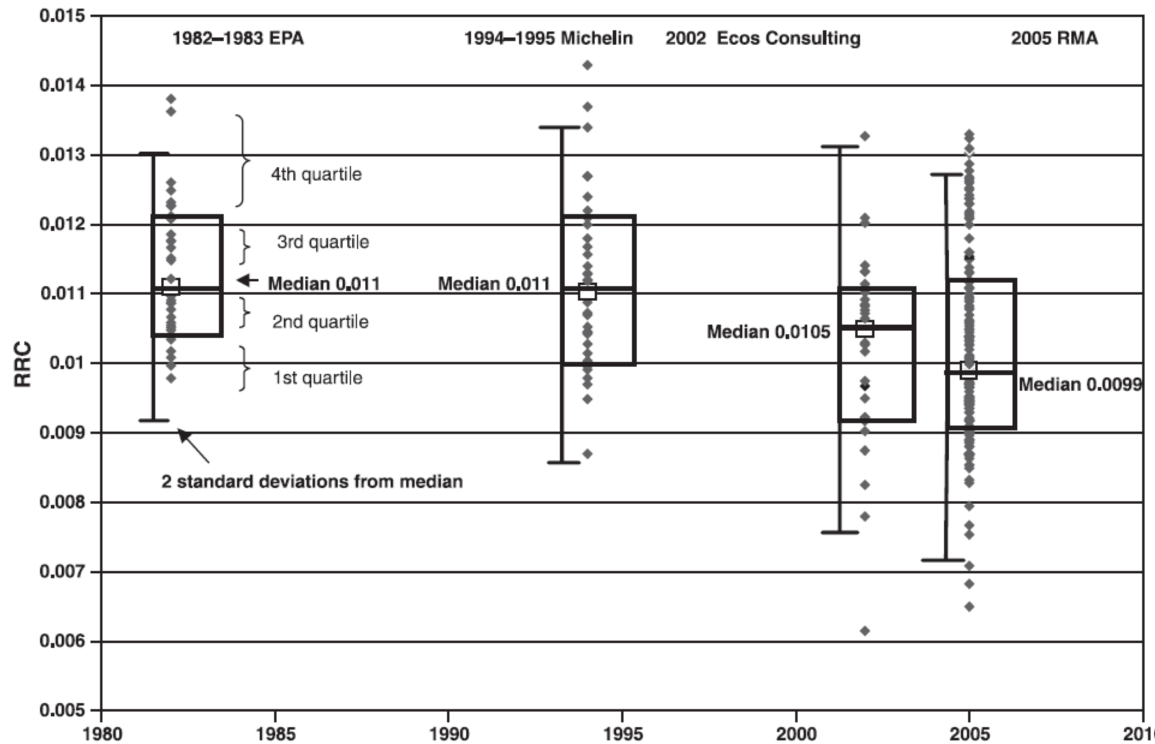
Aluminum crash tubes

https://www.greencarcongress.com/2013/06/xl1-20130624.html

Fuel Economy – Vehicle Resistances

Basic techniques to reduce vehicle resistances:

1. Light weight design: Reduces rolling, grading and acceleration resistance
2. High efficiency tires: Lower rolling resistance



Rolling resistance values for passenger tire samples, 1982 to 2005

Source: http://onlinepubs.trb.org/onlinepubs/sr/sr286.pdf

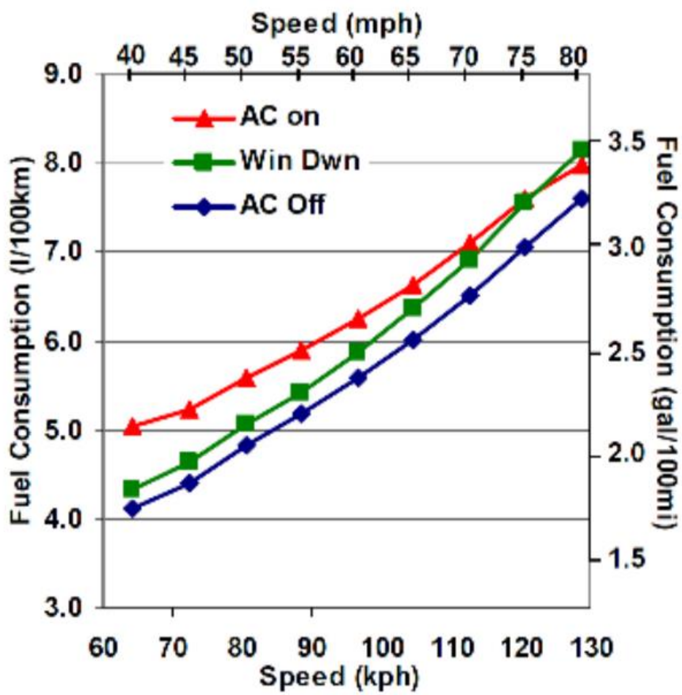
Fuel Economy – Vehicle Resistances

Basic techniques to reduce vehicle resistances:

1. Light weight design: Reduces rolling, grading and acceleration resistance
2. High efficiency tires: Lower rolling resistance
3. Good aerodynamic design: Reduces aerodynamic resistance
   - Shape optimization
   - Exchange wing mirrors with cameras
   - Close the bottom of the car

Fuel Economy – Operating Conditions

Additional load: A/C



Toyota Corolla fuel consumption versus steady state cruising speed

Source: Huff, S., West, B., and Thomas, J., "Effects of Air Conditioner Use on Real-World Fuel Economy," SAE Technical Paper 2013-01-0551, 2013, doi:10.4271/2013-01-0551.

Exterior loading: Roof bike rack

2013 Honda Accord (4-cyl.)	MPG @ 105 km/h
No rack	5.6 l/100km
Empty rack	6.4 l/100km
Empty rack and wind deflector	6.7 l/100km
Rack with two bikes and deflector	8.7 l/100km

Source: http://www.consumerreports.org/cro/news/2013/07/tests-show-bike-racks-can-ruin-your-mileage/index.htm

Fuel Economy – Driving Cycles

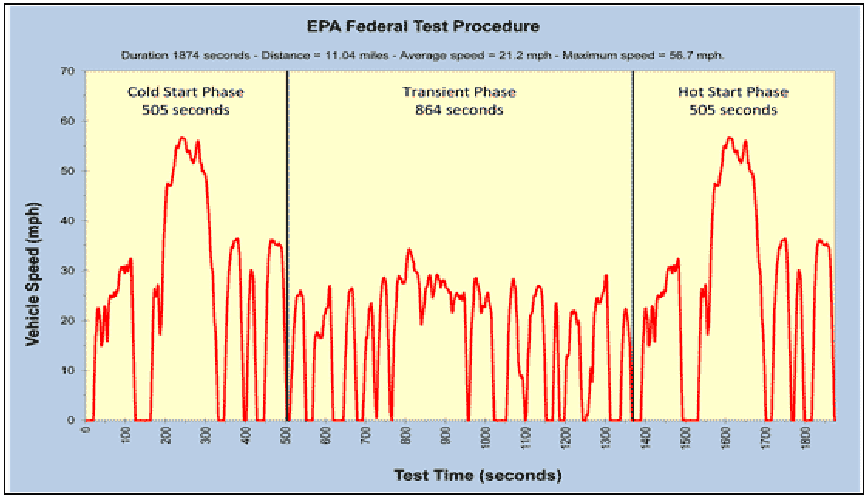
Driving cycle: Driving routines, *cycles* or *schedules*, that specify vehicle speed for each point in time during the laboratory tests

- A realistic and practical test of emissions and fuel economy
- Electrified vehicles: All above and range

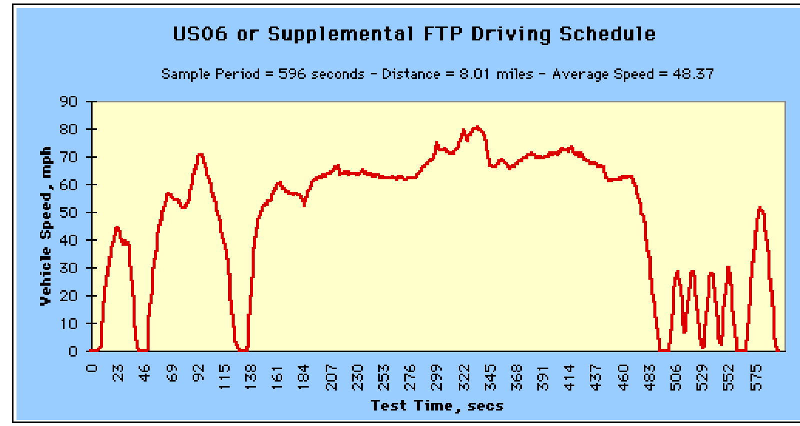
U.S.A.	Europa	Japan	World
• **FTP 72/75 (1978) Urban and highway** • **US06/US03 (2008)**	• **NEDC (1970 and 1997)**	• 10-15 Mode (1983) • **JC08 (2008)**	• **WLTP (2015)**

Fuel Economy – Driving Cycles in U.S.A

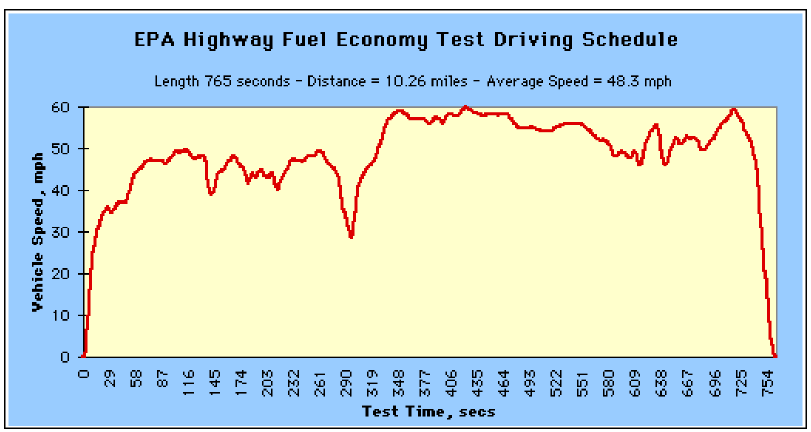
FTP 75 Urban



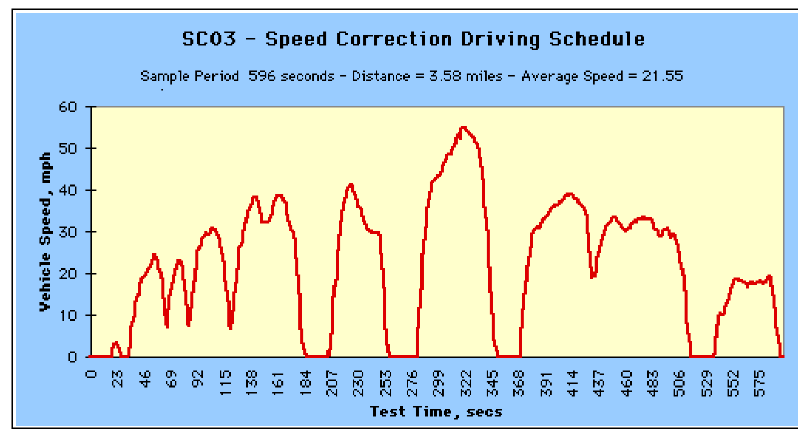
US06 High Speed



FTP 75 Highway



US03 A/C



Fuel Economy – Driving Cycles in U.S.A

	FTP 75 Urban *City*	**FTP 75 Highway** *Highway*	**US06** *High Speed*	**US03** *A/C*	**FTP 75 Urban** *Cold Temp*
Trip Type	Low speeds in stop-and-go urban traffic	Free-flow traffic at highway speeds	Higher speeds; harder acceleration & braking	A/C use under hot ambient conditions	City test w/ colder outside temp.
Top Speed	56 mph	60 mph	80 mph	54.8 mph	56 mph
Average Speed	21.2 mph	48.3 mph	48.4 mph	21.2 mph	21.2 mph
Max. Acc.	3.3 mph/sec	3.2 mph/sec	8.46 mph/sec	5.1 mph/sec	3.3 mph/sec
Distance	11 mi.	10.3 mi.	8 mi.	3.6 mi.	11 mi.
Time	31.2 min.	12.75 min.	9.9 min.	9.9 min.	31.2 min.
Stops	23	None	4	5	23
Idling time	18% of time	None	7% of time	19% of time	18% of time
Engine Startup*	Cold	Warm	Warm	Warm	Cold
Lab temperature	68 ^{o}F–86 ^{o}F			95 ^{o}F	20 ^{o}F
Vehicle A/C	Off	Off	Off	On	Off

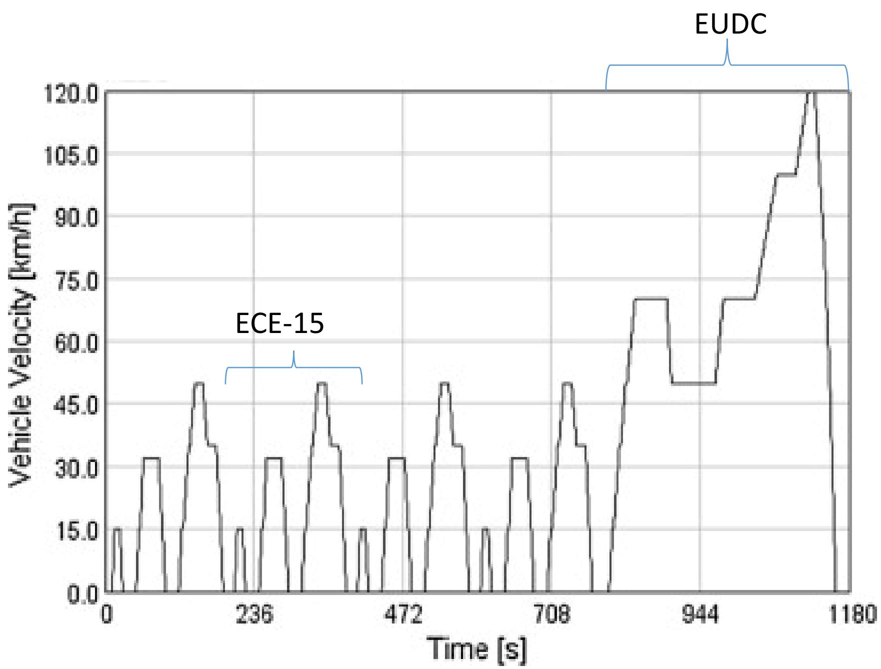
Fuel Economy – Driving Cycles in Europa

NEDC: New European Driving Cycle

- 4 x ECE-15 – European City Cycle
- EUDC – European Urban Driving Cycle

Criticism:

- Inability to represent real-life driving
- Cycle beating: to optimize engine emission performance to the corresponding operating points of the test cycle

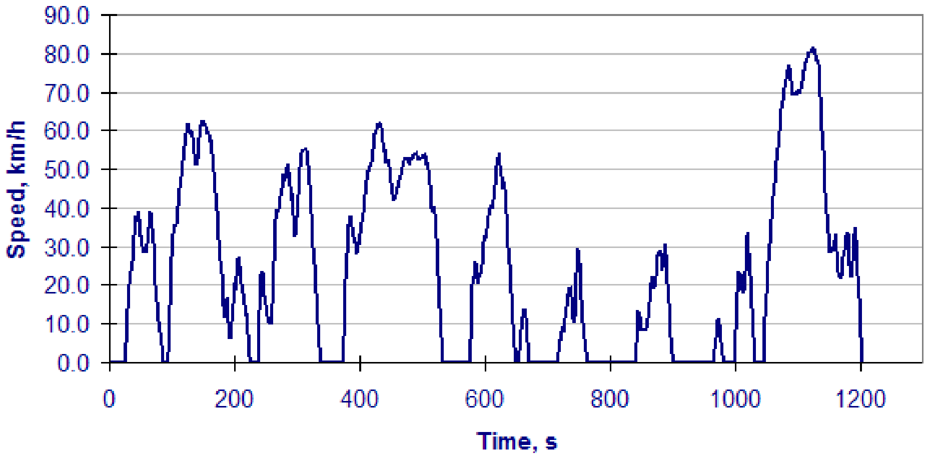


Sources: https://www.dieselnet.com/standards/cycles/ece_eudc.php
https://en.wikipedia.org/wiki/New_European_Driving_Cycle

Characteristics	FTP 75	NEDC
Distance	17.7028 km	10.9314 km
Total time	1872 s	1180 s
Idle time	18 %	23 %
Avg. speed (incl. stops)	34.12 km/h	33.35 km/h
Avg. speed (excl. stops)		43.10 km/h
Maximum speed	90 km/h	120 km/h
Avg. acc.	1.5 m/s^2	0.506 m/s^2

Fuel Economy – Driving Cycles in Japan

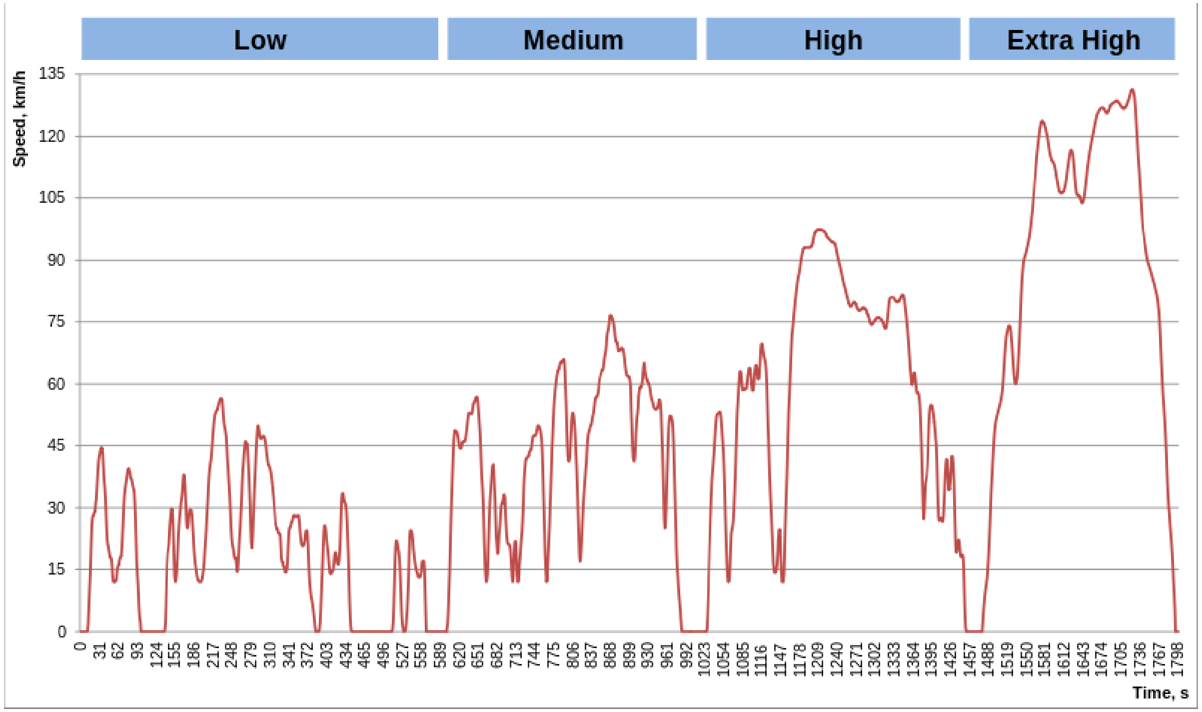
JC08



Characteristics	FTP 75	JC08
Distance	17.7028 km	8.171 km
Total time	1872 s	1204 s
Idle time	18 %	29.7%
Avg. speed (incl. stops)	34.12 km/h	34.8 km/h
Avg. speed (excl. stops)		24.4 km/h
Maximum speed	90 km/h	81.6 km/h
Avg. acc.	1.5 m/s^2	

Source: https://www.dieselnet.com/standards/cycles/jp_jc08.php

Fuel Economy –Worldwide Harmonized Light Vehicles Test Procedures (WLTP)



Criticism:

- Still unrealistically slow
  Cycle: 0-30mph (~50kph) time is 15 seconds
  Most western European drivers accelerate 0-30mph (~50kph) in 5 to 10 seconds
- No hill climbing

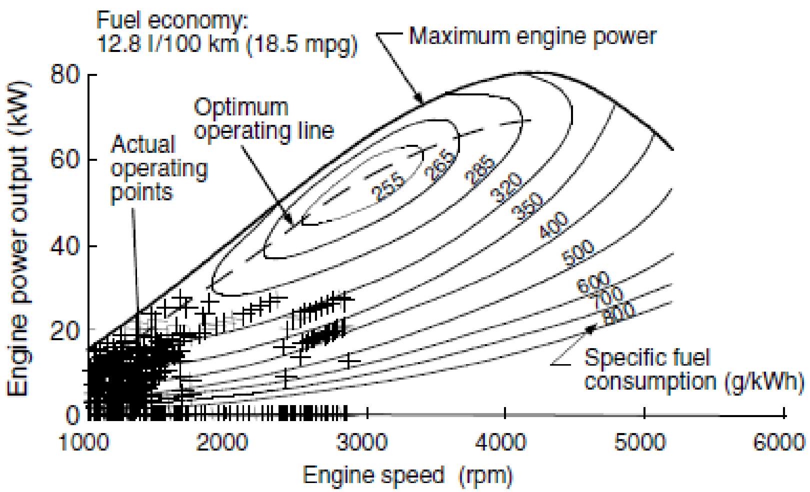
https://en.wikipedia.org/wiki/Worldwide_harmonized_Light_vehicles_Test_Procedures

Fuel Economy –Worldwide Harmonized Light Vehicles Test Procedures (WLTP)

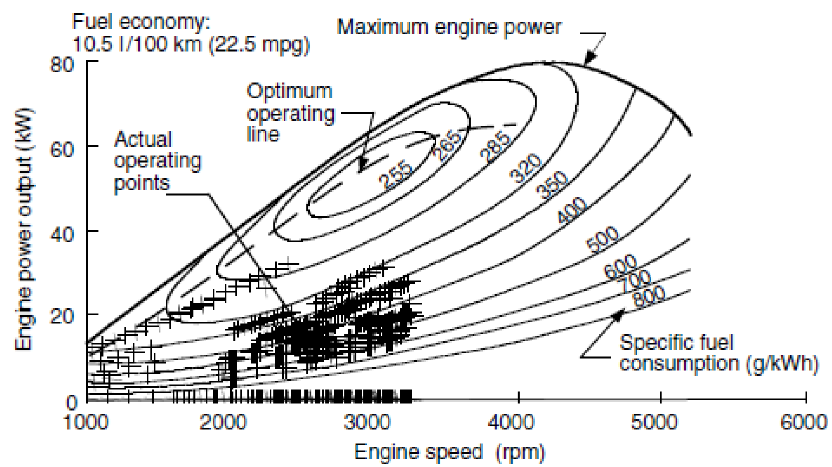
Characteristics	NEDC	FTP 75	WLTP
Distance	10.9314 km	17.7028 km	23.262 km
Total time	1180 s	1872 s	1800 s
Idle time	23 %	18 %	13.4 %
Avg. speed (incl. stops)	33.35 km/h	34.12 km/h	46.5 km/h
Avg. speed (excl. stops)	43.10 km/h		53.8 km/h
Maximum speed	120 km/h	90 km/h	131.3 km/h
Avg. acc.	0.506 m/s^2	1.5 m/s^2	1.6 m/s^2

Fuel Economy – Driving Cycles Frequently Operating Points

Fuel economy and engine operating points in EPA FTP75 overlapped on engine fuel consumption characteristics map



Urban drive cycle



Highway drive cycle

Links

Anti-lock Brake System ABS:

https://www.youtube.com/watch?v=hwwXukJaTlM

How electronic stability control works:

https://www.youtube.com/watch?v=MCRLKRluk1w

Automobile News:

https://www.autonews.com/

More Videos:

Wings and Spoilers; Lift and Drag | How It Works

The Differences Between Understeer & Oversteer And How To Combat Them

Advertisement of the week:

VW Golf 5 mit DSG Werbung

Textbooks:

Reading Assignment: Chapter 2: Vehicle Fundamentals of Ehsani, M. and Gao, Y. and Emadi, A., **“**Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, 2nd Edition, CRC Press LLC, 2009.

- Ehsani, M. and Gao, Y. and Emadi, A., **“**Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, 2nd Edition, CRC Press LLC, 2009.
- Larminie, J. and Lowry J., “Electric Vehicle Technology Explained”, 2nd edition, John Wiley & Sons, 2012.
- Mi, C. and Masrur, M. A. and Gao, D. W., “Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives”, John Wiley & Sons, May 23, 2011.