Lecture 2: Vehicle/Driver/Traffic Modeling

Introduction to Traffic Modeling

Prof. Sangyoung Park

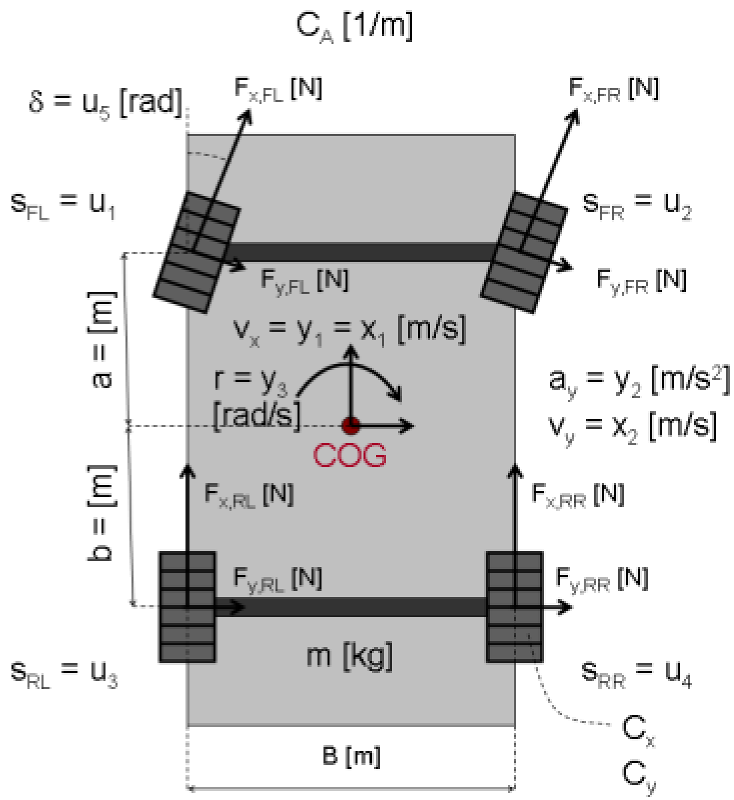
Module ”Vehicle-2-X: Communication and Control“

Contents

- Vehicle Dynamics
- Traffic Models
  - Microscopic
  - Macroscopic
- Driver Behaviors

Vehicle Dynamics

- Study on vehicles in motion
- How the vehicles react to driver inputs on a given road
- Factors
  - Drivetrain and braking
  - Suspension and steering
  - Distribution of mass
  - Aerodynamics
  - Tires



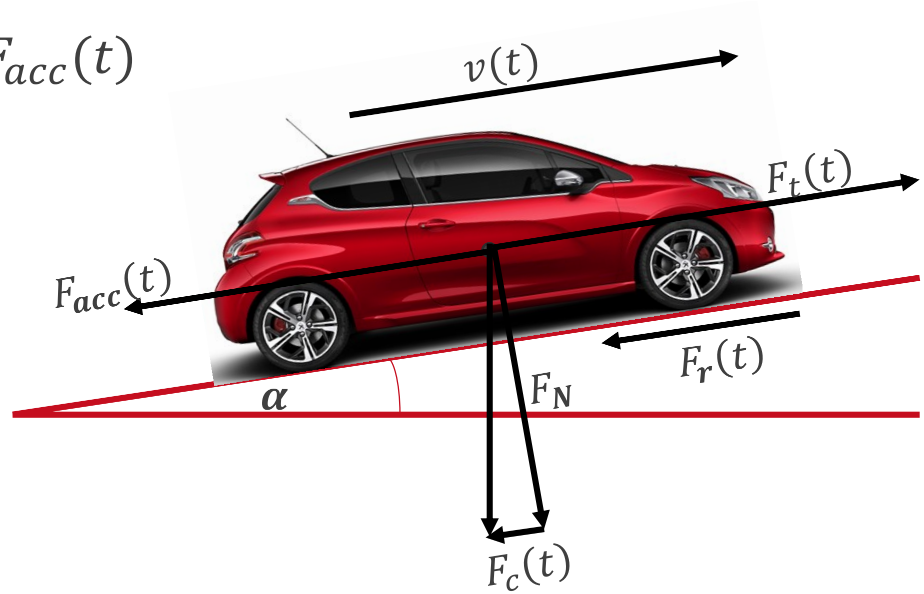
Source: mathworks

Drive Resistance

- $v(t)$: vehicle velocity
- $a(t)$: vehicle acceleration
- m_{tot}: total vehicle mass

Drive Resistance

- $F_t(t) = F_{air}(t) + F_c(t) + F_r(t) + F_{acc}(t)$
- $P_t(t) = F_t(t) \cdot v(t)$



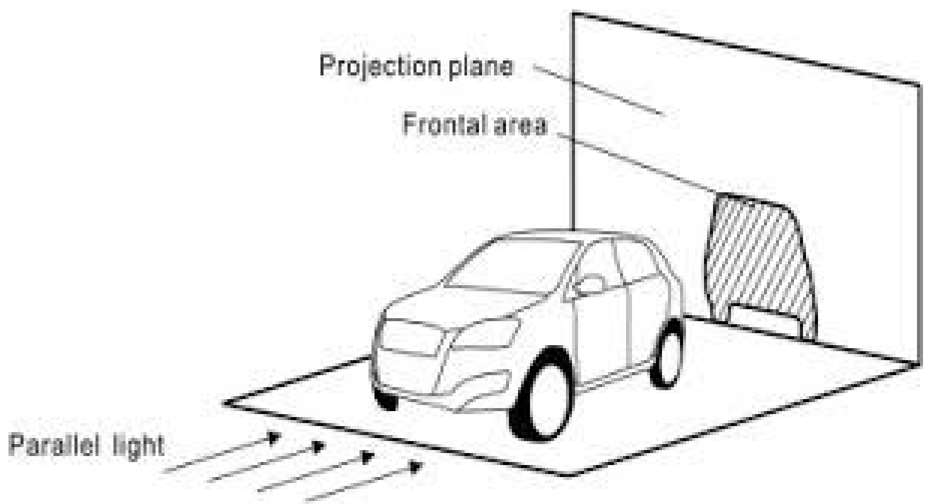
- $F_t(t)$: Traction force
- $F_{air}(t)$: Aerodynamic drag
- $F_c(t)$: Climbing force
- $F_r(t)$: Rolling resistance
- $F_{acc}(t)$: Acceleration force
- $P_t(t)$: Traction power
- $v(t)$: Vehicle velocity

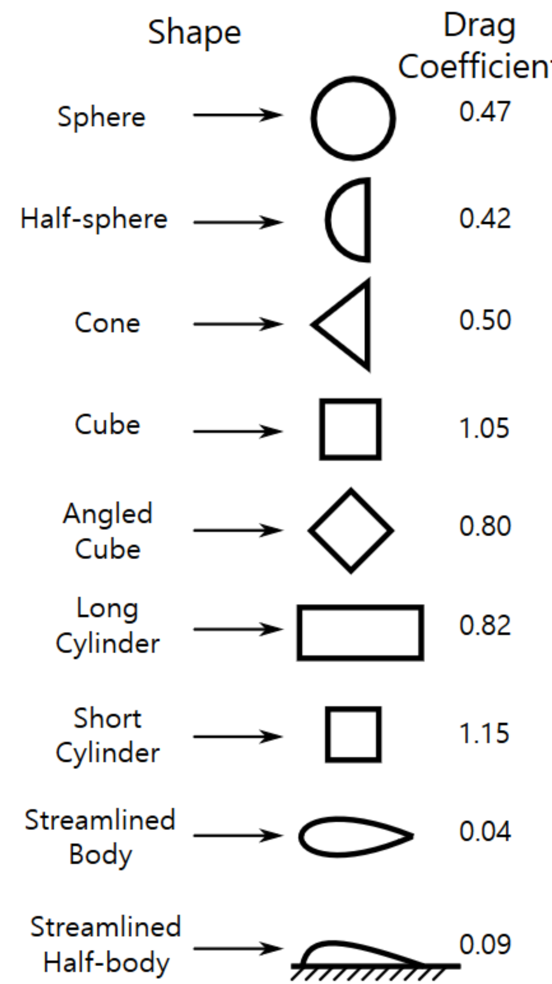
Attention:
$P_t(t) \neq P_{motor}(t)$

Aerodynamic Drag

- $F_{air} = \frac{1}{2}\rho_{air} C_d A v_{rel}^2$

- ρ_{air}: density of air, 1.225 kg/m^3
- C_d: drag coefficient
- A: frontal area
- v_{rel}: relative velocity ($v_{rel} = v_{vehicle} + v_{wind}$)





Measured Drag Coefficients

Aerodynamic Drag

- Drag coefficients of vehicle types

	c_d	A
Passenger vehicle	0.28	1.5-2.8
Transporter	0.35	3.0
Coach (long distance bus)	0.4	7.5
Bus 12 m	0.6	8.3
ICE 3	0.2	9.0

Source: Prof. Voß (2016), Vorlesung Alternative Antriebssysteme und Fahrzeugkonzepte

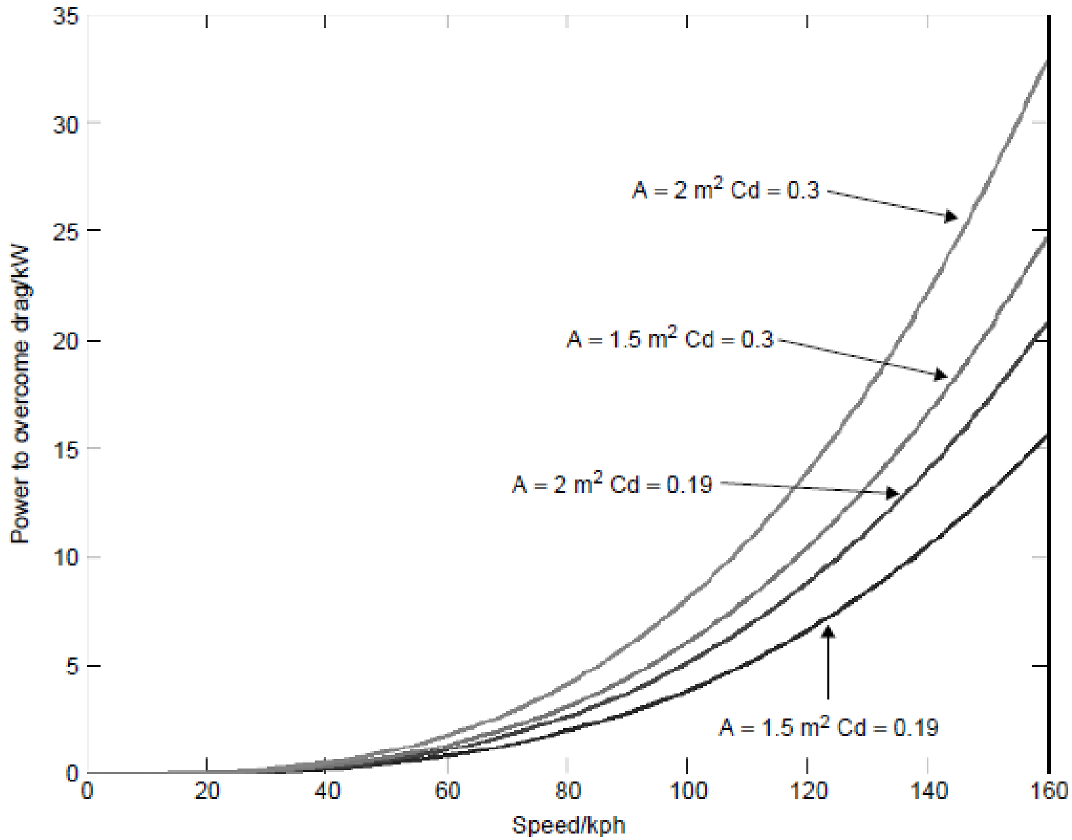
Coach

City bus (12 m)

ICE 3

Drag Resistance vs Velocity

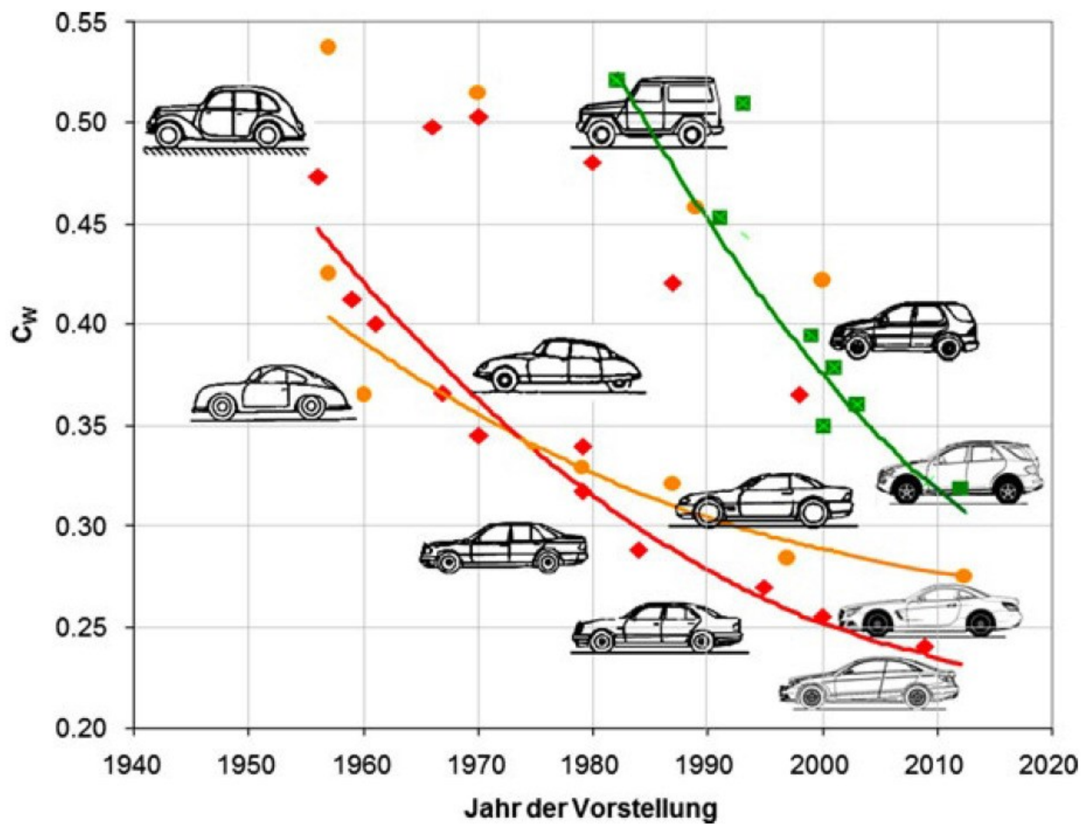
- Power to overcome aerodynamic drag
- Again, $P = F \cdot v$, so what is the relationship between F and v then?



Larminie (2003), Electric Vehicle Technology Explained

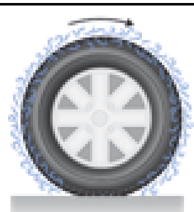
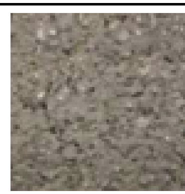
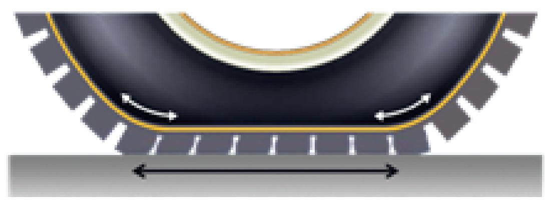
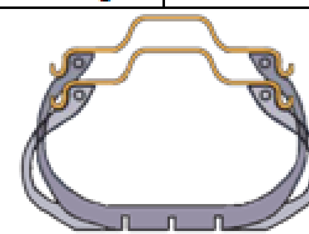
Drag Resistance

- Vehicles‘ shapes have become more aerodynamic over time



Rolling Resistance

- Force resisting the motion when a body “rolls” on a surface
  - Deformation of the tire: Tire gets hot because tire is not perfectly elastic
  - Air circulation: Work is done on the air around the tire
  - Sliippage: Tire gets hot due to friction

What	Surface of tire and air	Tire tread				Sidewall and bottom part	
How	Air circulation	Slippage on ground	Deformation hence dissipation of energy				
			bending	compression	shearing	bending	shearing
							
Contri-bution	< 15%		60 to 70%			20 to 30 %	

Source: http://thetiredigest.michelin.com/michelin-ultimate-energy-tire

Rolling Resistance

- $F_r(\alpha) = C_{rr} m_{tot} g \cdot \cos(\alpha)$, where
  - C_{rr}: Coefficient of rolling resistance
  - m_{tot}: Total vehicle mass
  - g: Standard gravity
  - α: slope angle

Rolling Resistance

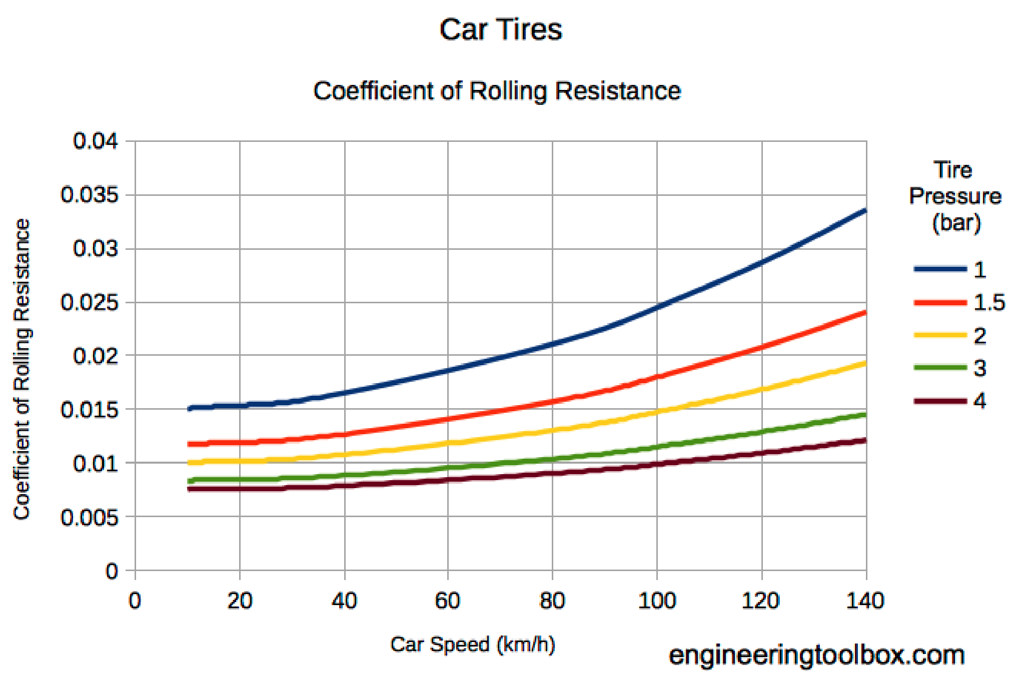
- $F_r(\alpha) = C_{rr} m_{tot} g \cdot \cos(\alpha)$

C_{rr}	Description
0.0003 to 0.0004	Railroad steel on steel rail
0.0022 to 0.0050	Bicycle tires
0.0100 to 0.0150	Ordinary car tires on concrete
0.3000	Ordinary car tires on sand

- How much force is required for rolling a 1000 kg car on concrete?
  - $F_r = 0.01 \times 1000 \times 9.8 = 98\ N$
- On sand?
  - $F_r = 0.3 \times 1000 \times 9.8 = 2{,}940\ N$

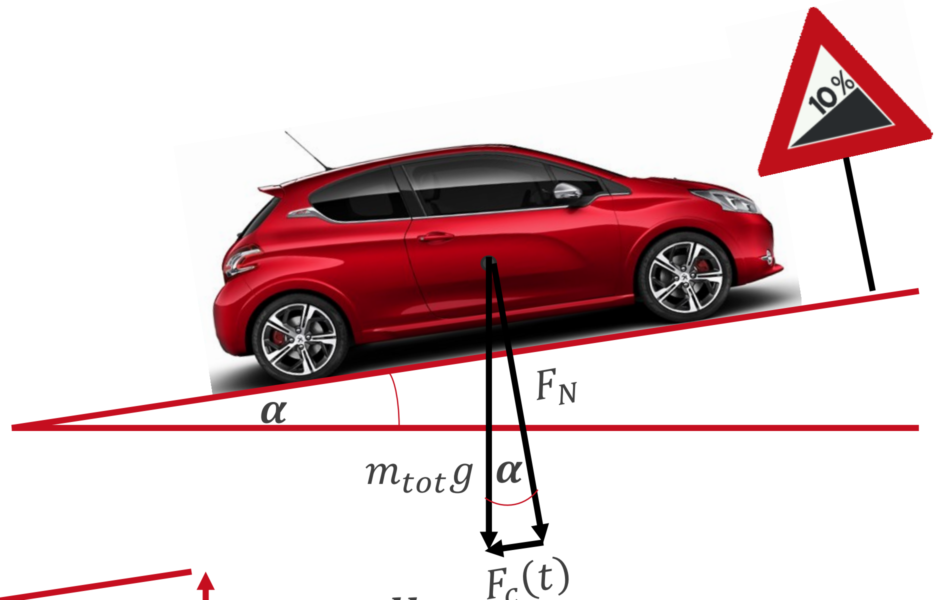
Rolling Resistance

- Other factors
  - Vehicle speed: But not as much as it affects drag
  - Tire pressure: low pressure means more deformation

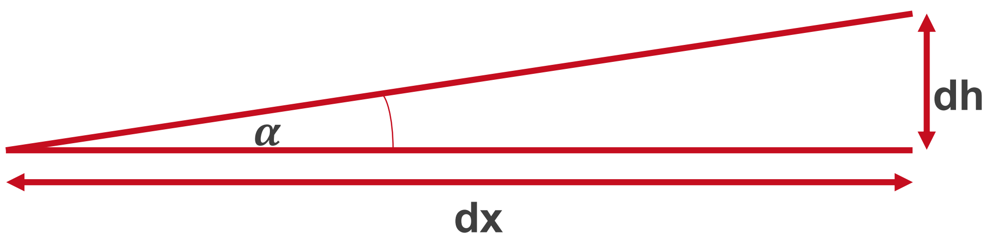


Climbing Resistance

- $F_c(\alpha) = mg \cdot \sin(\alpha)$
- What is 10% in the sign?
- $Slope\ [\%] = \frac{dh}{dx} = \tan(\alpha)$
- 45° is 100% and 5.7° is 10%



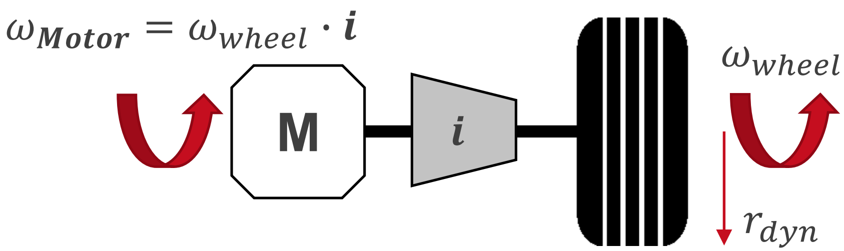
$$\frac{\boldsymbol{dh}}{\boldsymbol{dx}} = \boldsymbol{tan(\alpha)} = \boldsymbol{slope}\ [\%]$$



- The steepest roads in the world are Baldwin Street in Dunedin (38%) , New Zealand and Canton Avenue in Pittsburgh (37%) , Pennsylvania.

Acceleration Force

- $F_{acc} = (m_{vehicle} + m_{acc}) \cdot \dot{v}$
- $m_{vehicle}$: Vehicle mass
- m_{acc}: Equivalent acceleration mass
- Force is being applied to change the motion status of vehicle
- Not all energy is $\frac{1}{2}mv^2$, but also rotational energy in vehicles and engines are there
- The rotational speed should also be changed



Mass inertia of typical wheels
235/65 R17 = 1.7 kgm²
245/55 R18 = 1.9 kgm²

Mass inertia of PSM E-Motor
HVH250 – 115 = 0,086 kgm²
HVH250 – 090 = 0.067 kgm²

Roughly How Much Power?

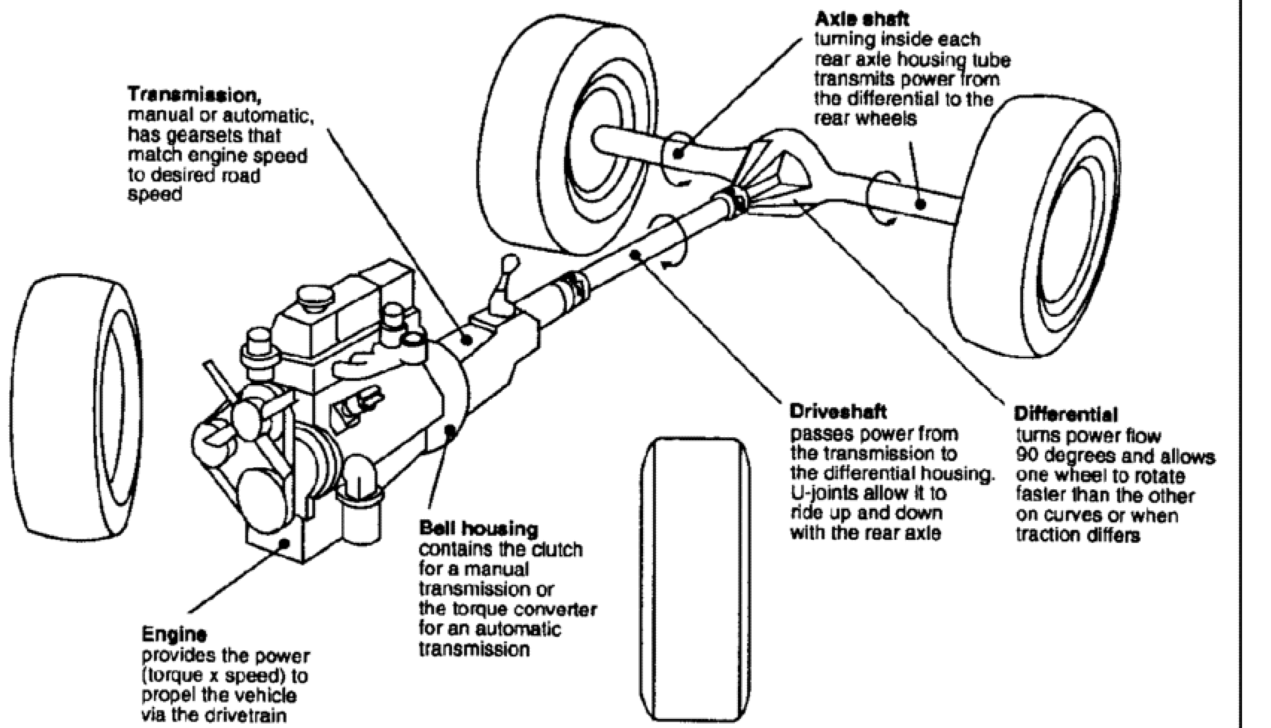
- Acceleration from 0 to 100 kph? ($m = 1600\ kg$)

- Cruising at 60 kph with $C_D A = 0.3 \cdot 2.2\ m^2 = 0.66\ m^2$ and $\rho = 1.2\,\frac{kg}{m^3}$
  - What is the share of aerodynamic drag?

- Cruising at 120 kph?
  - What is the share of aerodynamic drag?

Powertrain

- Powertrain
  - Main components that generate power and deliver it to the road surface, water or air
  - Engine
  - Transmission
  - Drive shafts
  - Differentials



D. Steckberg, „Development of an internal combustion engine fuel map model based on on-board acquisition"

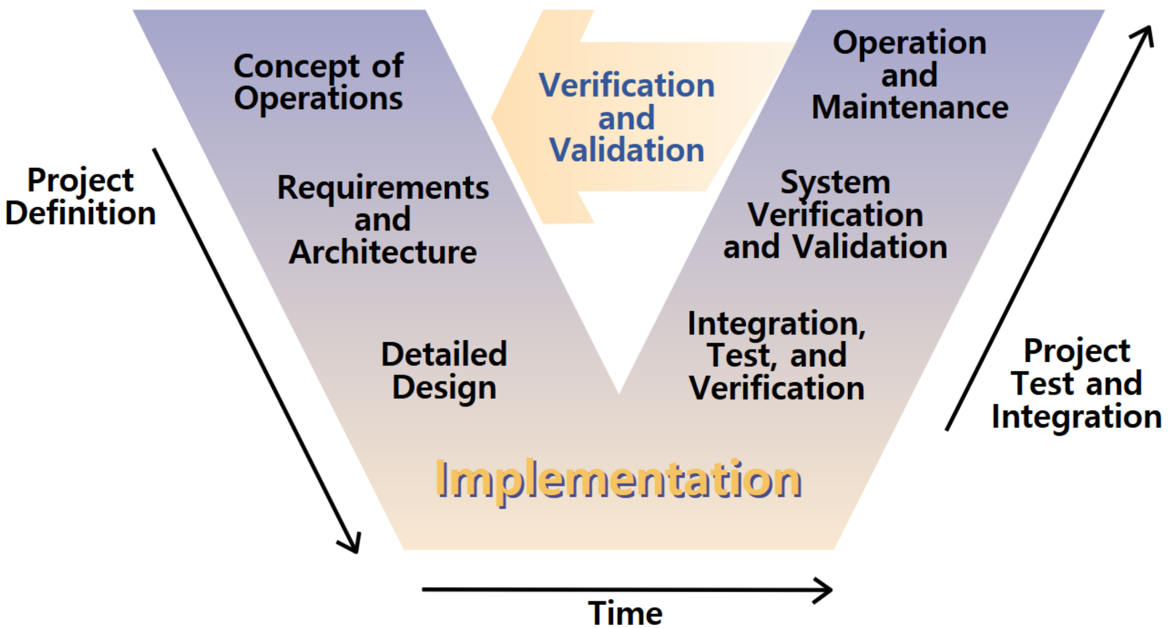
Side Note: Model-Based Design (MBD)

- Why do we talk about models so much?
- A ***mathematical*** and ***visual*** method of addressing problems associated with designing complex control, signal processing, and communication systems (from Wikipedia)
- A system model is at the center of the development process from requirements development, through design, implementation, and testing

- Steps
  - Step 1: modeling a plant
  - Step 2: Analyzing and synthesizing a controller for a plant
  - Step 3: Simulating the plant and controller
  - Step 4: Integrating all these phases by deploying the controller

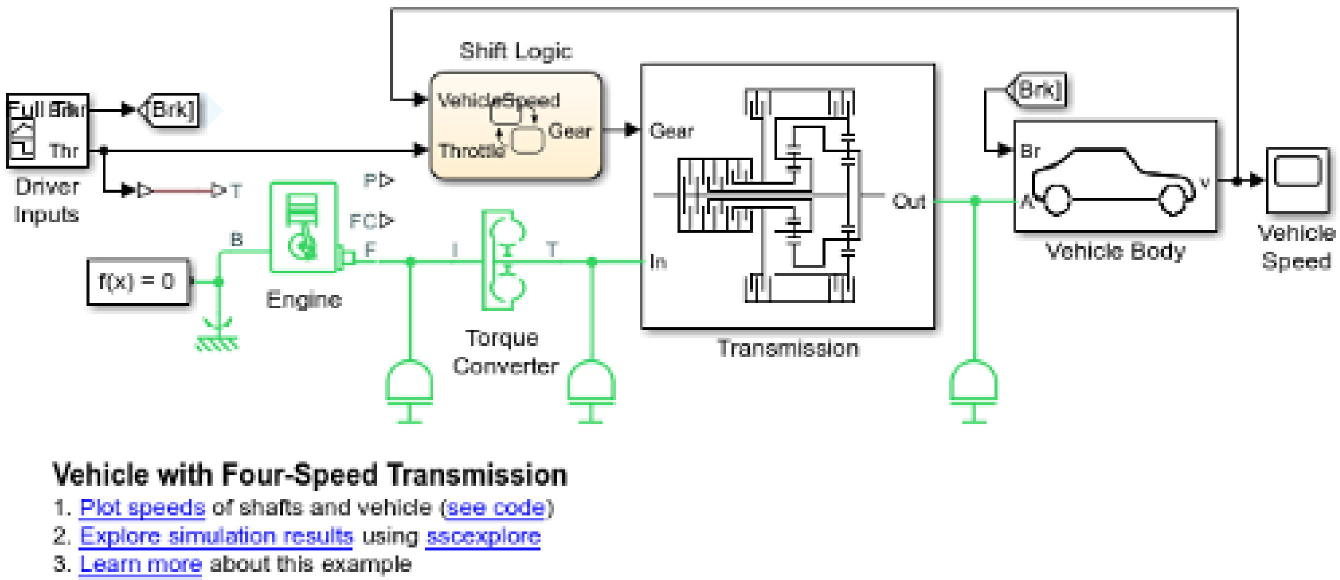
V-Model

- Graphical representation of a systems development lifecycle
- **Left-side:** decomposition of requirements, creation of system specifications,
- **Right side:** Integration of parts and validation
- Correct model is essential in such life cycle!



Powertrain Modeling

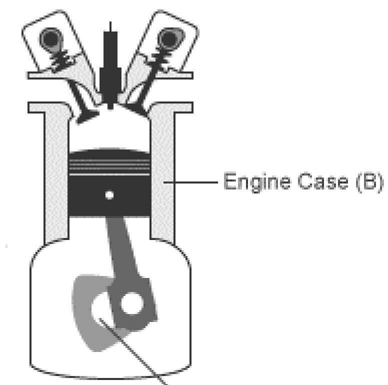
- MATLAB/Simulink example
  - Vehicle with four-speed transmission



Source: Mathworks

Powertrain Modeling: Generic Engine

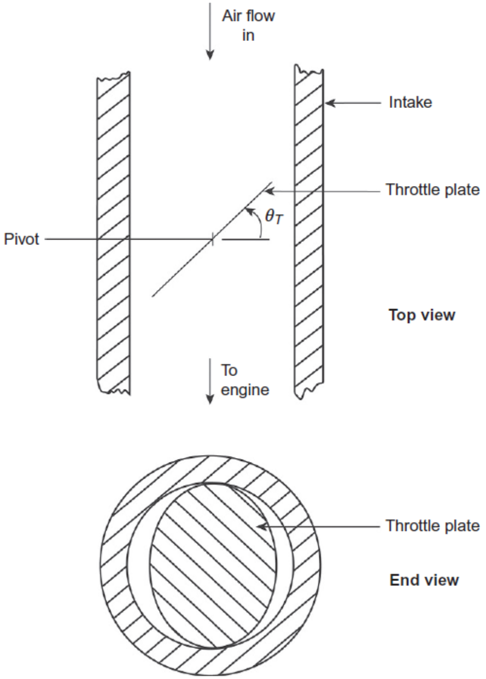
- Generic Engine Model
  - Programmed relationship between ***torque*** and ***speed***
  - Controlled by the throttle signal
- Throttle valve controls the amount of air fed into the engine



Generic engine

Source: mathworks

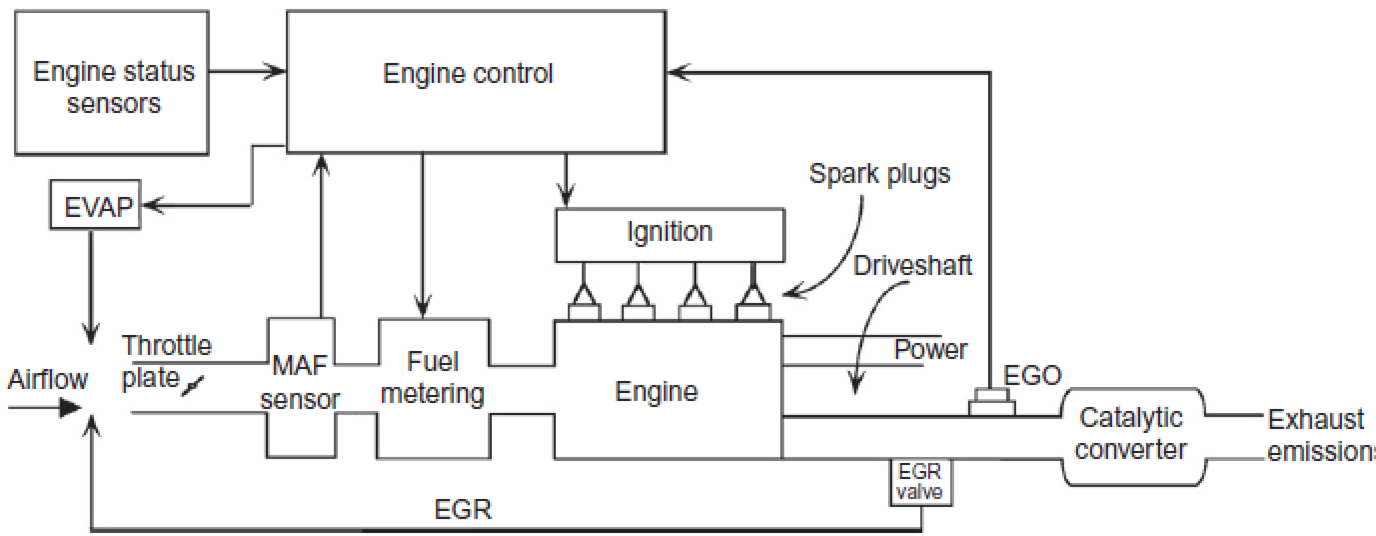
Throttle valve



Source: W. Ribbens, "Understanding automotive electronics"

Powertrain Modeling: Generic Engine

- Rough outline
  - Air inflow is controlled by throttle plate
  - Fuel is mixed with air
  - Electronic engine control controls the ignition



(Gasoline) Engine control diagram

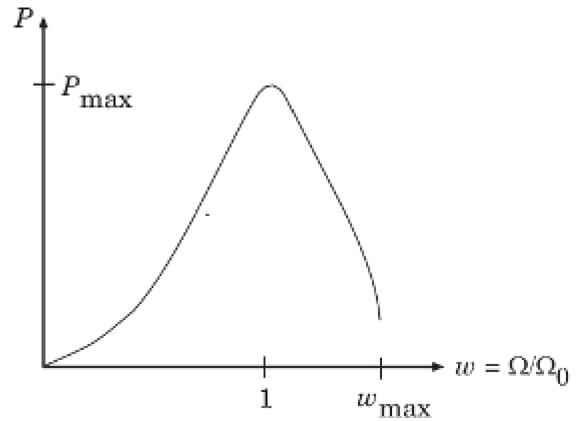
Source: W. Ribbens, "Understanding automotive electronics"

Powertrain Modeling: Generic Engine

- Engine power demand
  - Maximum power available $g(\Omega)$ for a given engine speed Ω
  - Third order polynomial model is often used

- Normalized throttle input signal T specifies the actual engine power P
  - A fraction of the maximum power in a steady-state engine speed
  - $P(\Omega, T) = T \cdot g(\Omega)$
  - Engine torque is $\tau = P/\Omega$

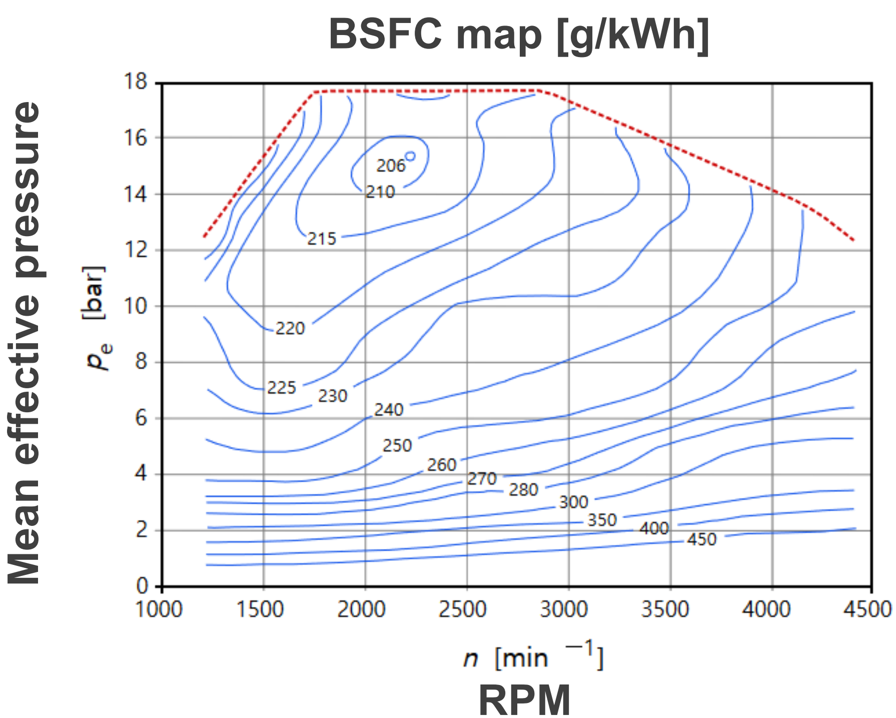
- There is minimum speed
  - Stall speed usually 500 RPM



Engine power demand

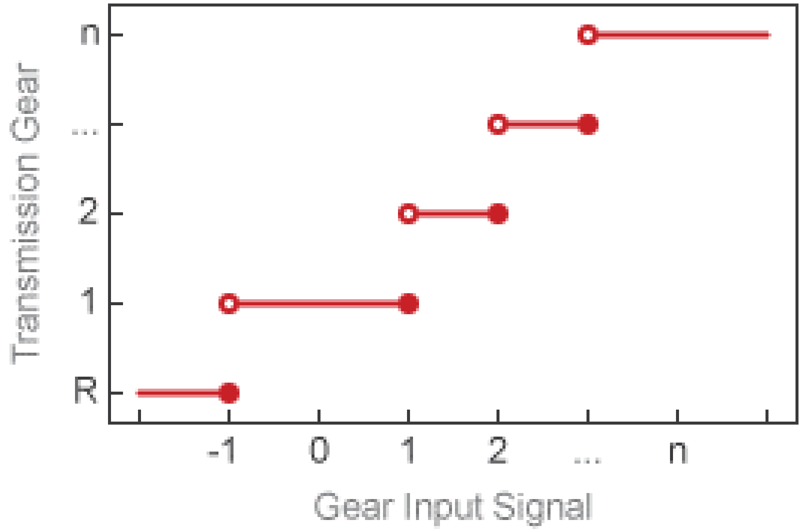
Powertrain Modeling: Generic Engine

- Fuel consumption model?
  - Constant per revolution?
  - As a function of speed and torque? Brake-specific fuel consumption (BSFC)]
  - $BSFC = \frac{r}{P}$, where r is the fuel consumption rate (gram/sec), and $P = \tau\Omega$



Powertrain Modeling: Transmission

- Simpler to model
  - Dog clutch, cone clutch, disk friction clutch
- Efficiency?
  - $\eta_c = C_{sr}C_{tr}$, where the RHS are speed ratio and torque ratios

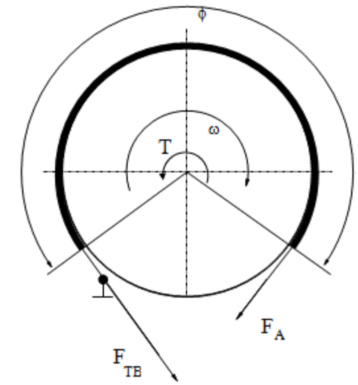


Powertrain Modeling: Differentials

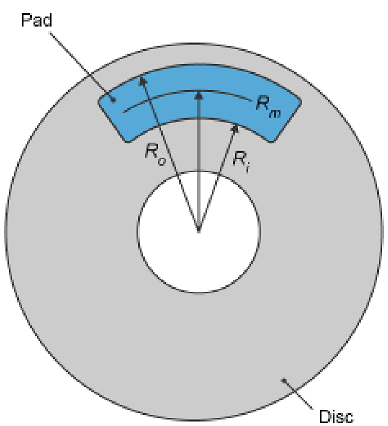
- Differentials
  - Gear arrangement that permits power from engine to be transmitted to a pair of driving wheels diving the force equally between them
  - Gear train with three shafts that has the property that the rotational speed of one shaft is the average of the others
  - Allows the wheels to follow paths of different lenghts when turning a corner of traversing an uneven road
  - https://www.youtube.com/watch?v=rxHjKoB2vn4
- Planetary gear

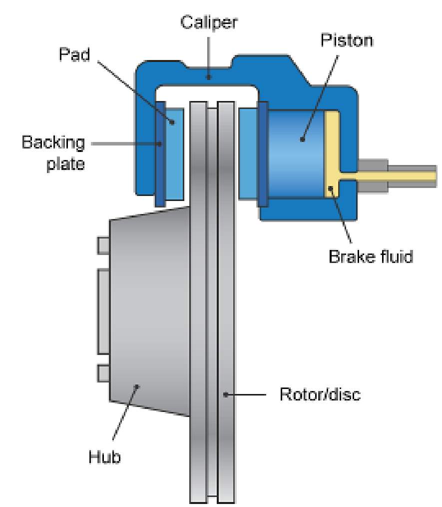
Brake Modeling

- Band brakes
  - High torque at cost of low precision (chain-saw, go-kart)



- Disc brakes
  - Braking torque
  - $T_{br} = F_{br} R_m = \mu_k P A_{tot} R_m = \mu_k P \frac{\pi D_b^2 N}{4} R_m$, when $\Omega \neq 0$
  - $T = \frac{\mu_s P \pi D_b^2 R_m N}{4}$, when $\Omega = 0$
  - Where
  - D_b is the area of an oil piston
  - N is the number of pistons
  - μ_k kinetic friction coef.
  - P brake oil pressure
  - R_m mean effective radius (axle-midline of brake calipers)





Tires

- Non-slipping
  - $V_x = r_w \Omega$, where V_x is velocity, r_w is tire radius, and Ω is angular velocity
- Slip
  - $V_{sx} = r_w \Omega - V_x$, where V_{sx} is the wheel slip velocity
  - Wheel slip is $\mathrm{k} = \frac{V_{sx}}{|V_x|}$, $k = -1$ for perfect sliding, 0 for perfect rolling
- Deformation
  - Because of the deformation, tire-road contact turns at slightly different angular velocity Ω'

Drive cycles - Passenger Cars and Light-duty Trucks

- NEDC

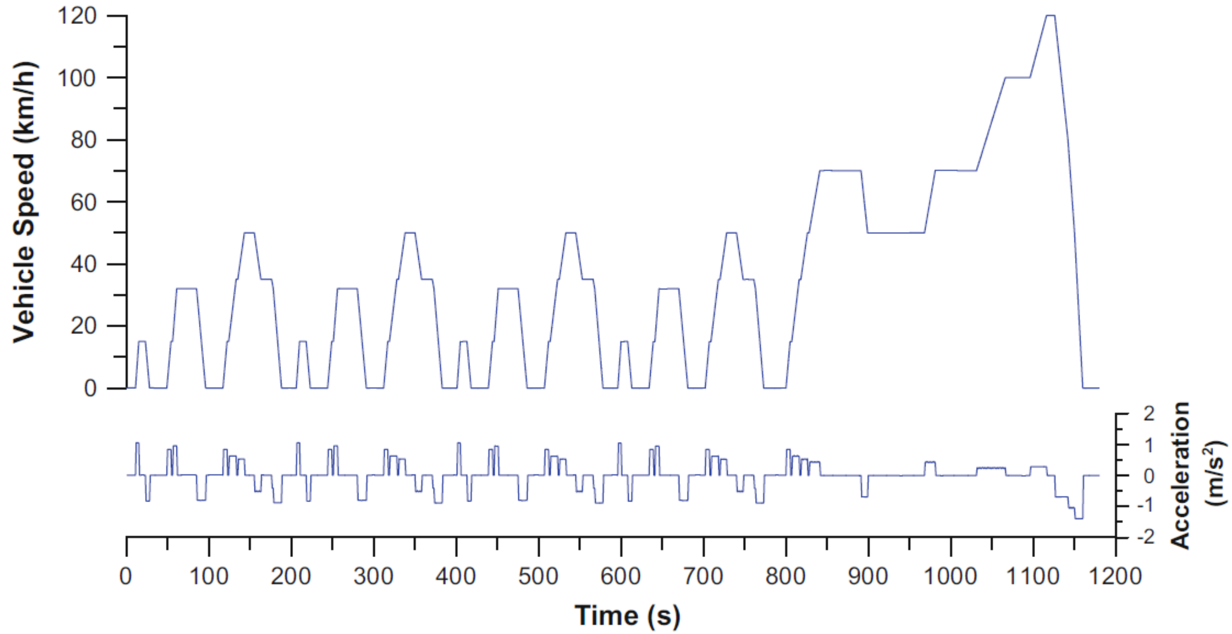


Fig. A.1 Vehicle speed and acceleration versus time of the European NEDC

Distance [m]	11,000	Duration [s]	1180
Idling time [%]	24	Average speed [km/h]	34
Cruising time [%]	40	Maximum speed [km/h]	120
Acceleration time [%]	21	Number of stops	14

Source: Giarkoumis

Drive cycles - Passenger Cars and Light-duty Trucks

- WLTC

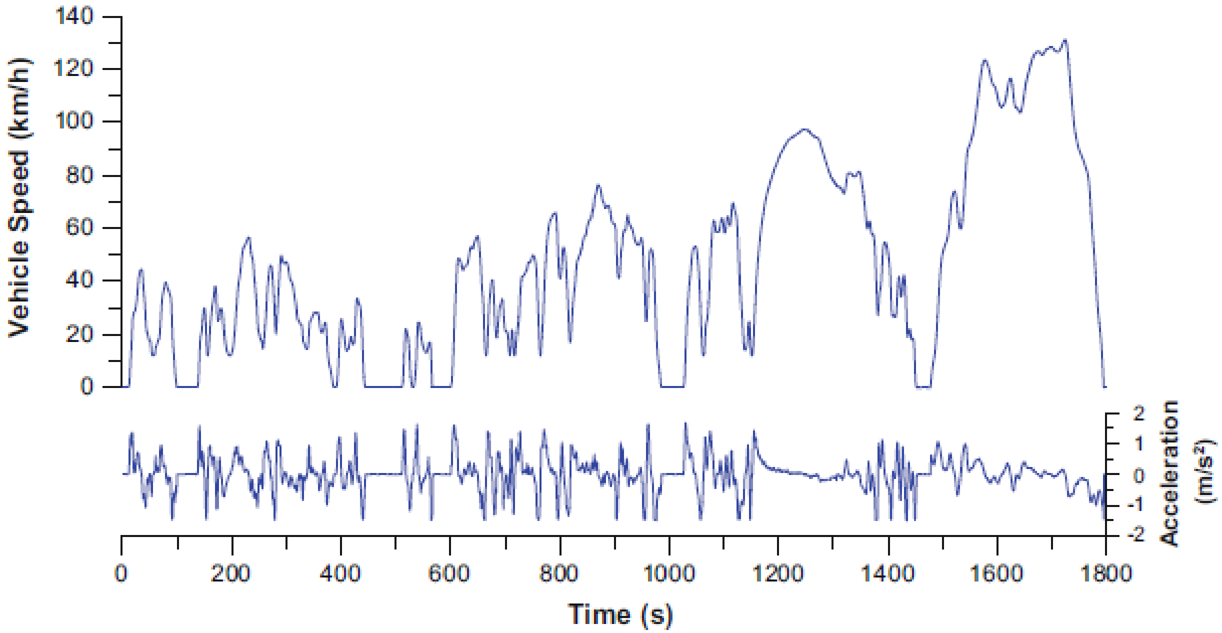


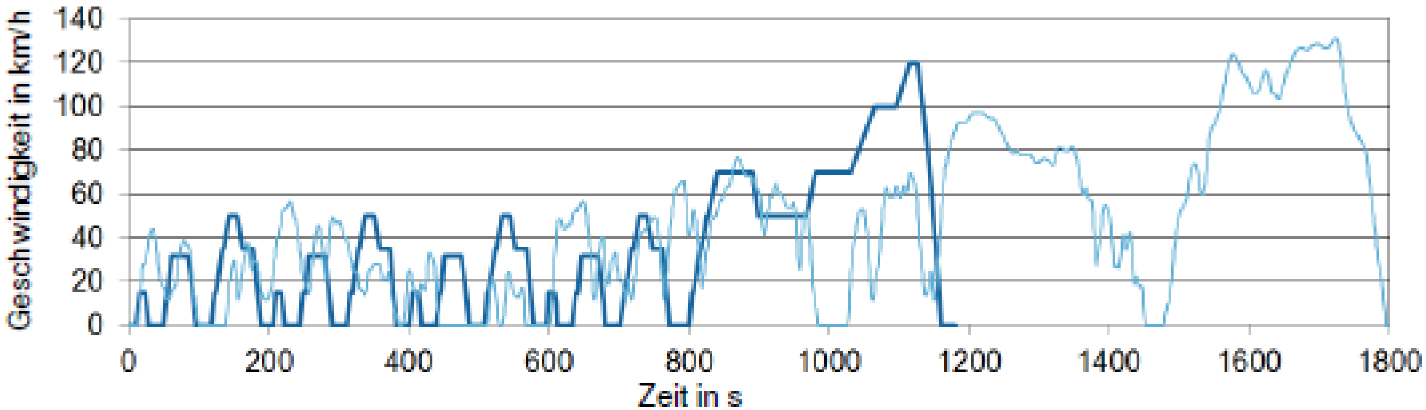
Fig. A.25 Vehicle speed and acceleration versus time of the WLTC Class 3-2

Distance [m]	23266	Duration [s]	1800
Idling time [%]	13	Average speed [km/h]	47
Cruising time [%]	4	Maximum speed [km/h]	131
Acceleration time [%]	44	Number of stops	8

- WLTC = Worldwide Harmonized Light-Duty Vehicles Test Cycle
- WLTP = Worldwide Light-Duty VehiclesTest Procedure

Introduced Sept. 2017

Comparicon of NEDC and WLTC (NEFZ und WLTP)



Source: 16. VDA Technischer Kongress, BMW, 2014 and Delphi 2014

	NEDC	WLTC	Modification
Distance [m]	11,000	23266	+ 100%
Duration [s]	1180	1800	+ 50%
Idling time [%]	24	13	- 50%
Cruising time [%]	40	4	More dynamic
Acceleration time [%]	21	44	
Number of stops	14	8	
Average speed [km/h]	34	47	+ 40%
Maximum speed [km/h]	120	131	+ 10%

Consequences
- Closer to real driving cycle
- Higher CO2 emissions
- Higher energy consumption
- Lower electric range

Drive cycles - Passenger Cars and Light-duty Trucks

- FTP 75

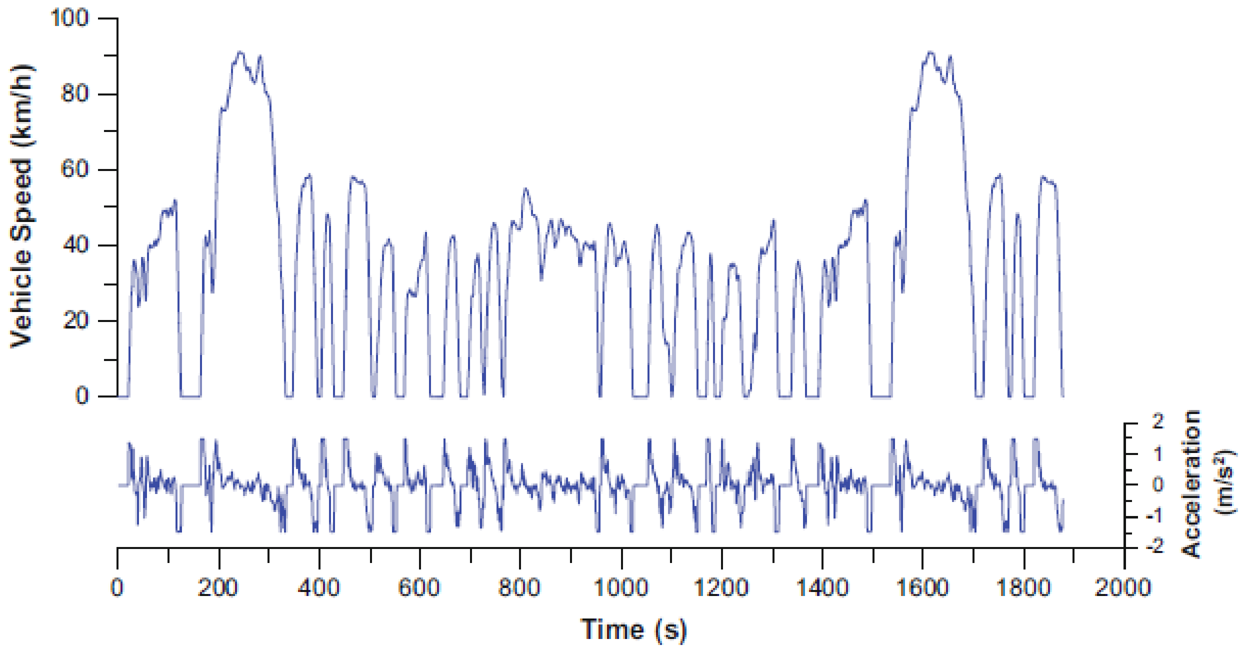


Fig. A.9 Vehicle speed and acceleration versus time of the U.S. FTP-75

Distance [m]	17769	Duration [s]	1877
Idling time [%]	18	Average speed [km/h]	47
Cruising time [%]	8	Maximum speed [km/h]	91
Acceleration time [%]	39	Number of stops	19

Drive cycles – Heavy Duty Vehicles

- Braunschweig

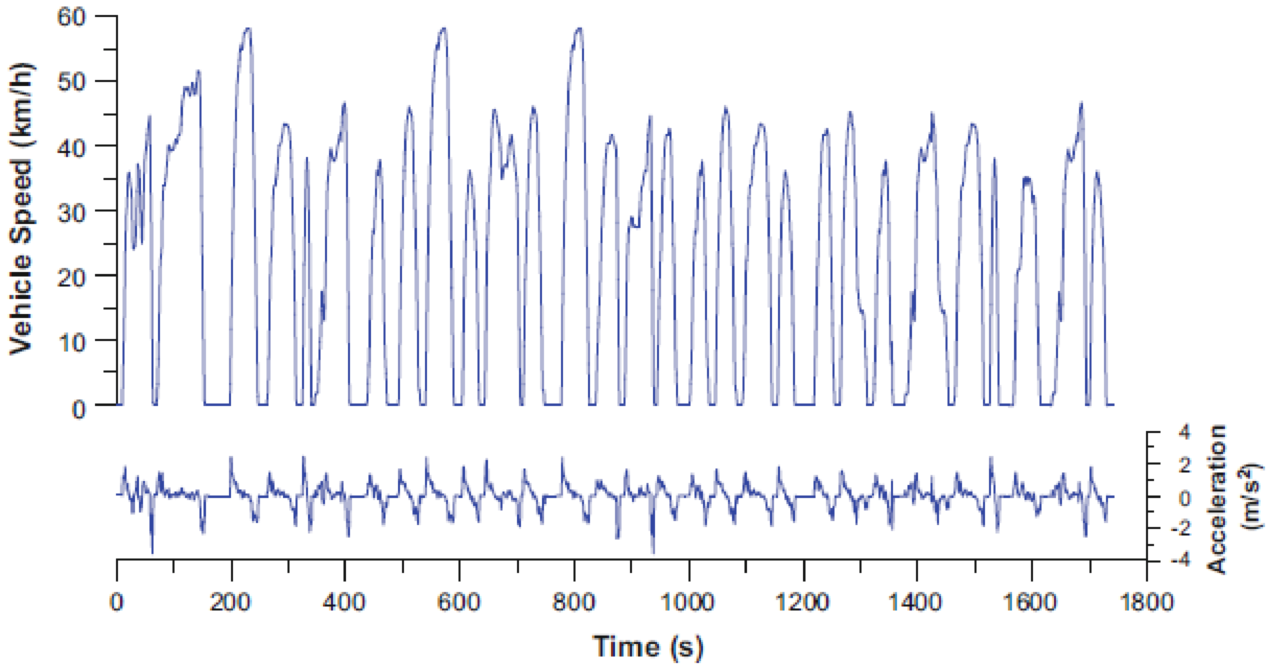


Fig. A.34 Vehicle speed and acceleration versus time of the Braunschweig cycle

Distance [m]	10873	Duration [s]	1740
Idling time [%]	24	Average speed [km/h]	23
Cruising time [%]	6	Maximum speed [km/h]	58
Acceleration time [%]	40	Number of stops	8

Contents

- Microscopic traffic modeling
  - *„Single vehicle-driver units, so the dynamic variables of the models represent microscopic properties like the position and velocity of single vehicles“ – Wikipedia*
- Macroscopic traffic modeling
  - It is a mathematical traffic model that formulates the relationships among traffic flow characteristics like density flow, mean speed of a traffic stream, etc.

Macroscopic Traffic Model

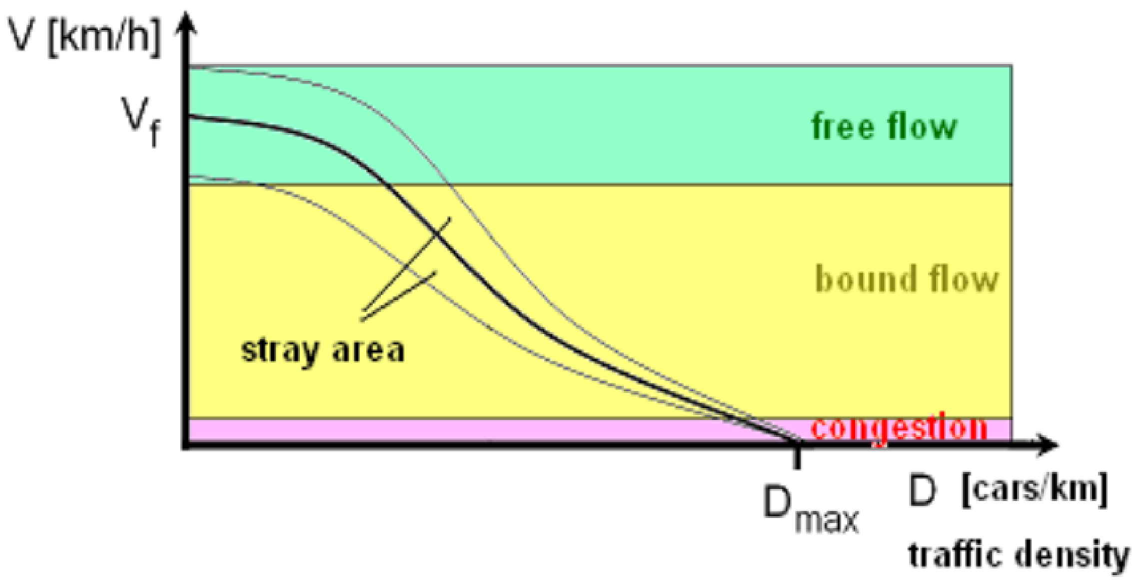
- Fundamental diagram of traffic flow
  - Relationship between traffic flux (vehicles/hour) and the traffic density (vehicles/km)
  - Primary tool for graphically displaying traffic flow information
  - Comprises three different graphs
    - Flow-density
    - Speed-flow
    - Speed-density
  - Flow: cars/h
  - Speed: km/h
  - Density: ?

$$\boldsymbol{Q = D \cdot V}$$

Flow = Speed * Density

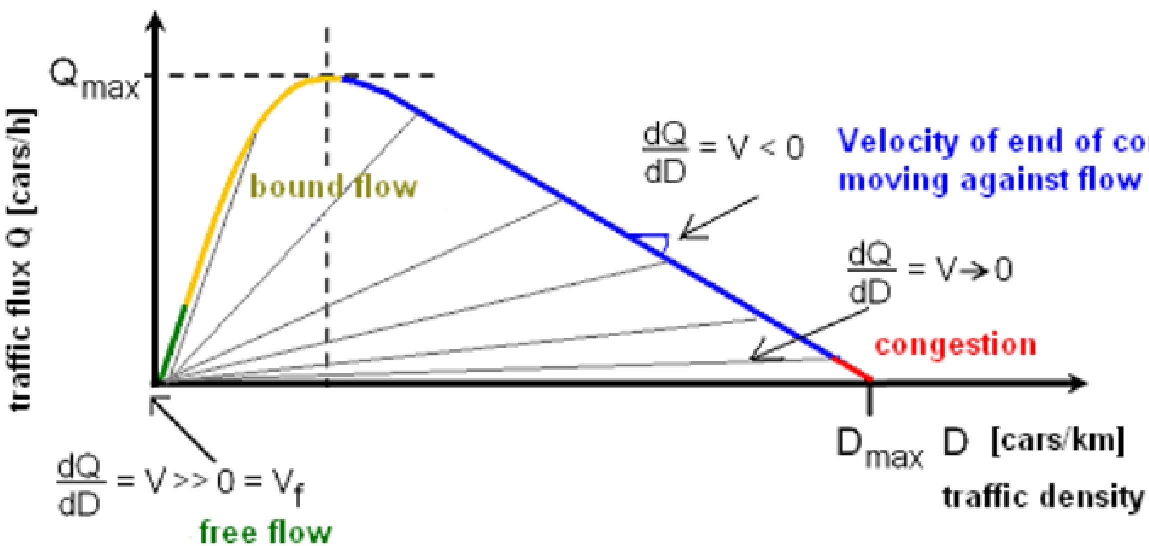
Macroscopic Traffic Model

- Speed-density
  - The denser the traffic (cars/km), slower the speed
    - Could you drive fast at a very small inter-vehicle distance?
  - V_f: Free flow speed
  - D_{max}: Jam density



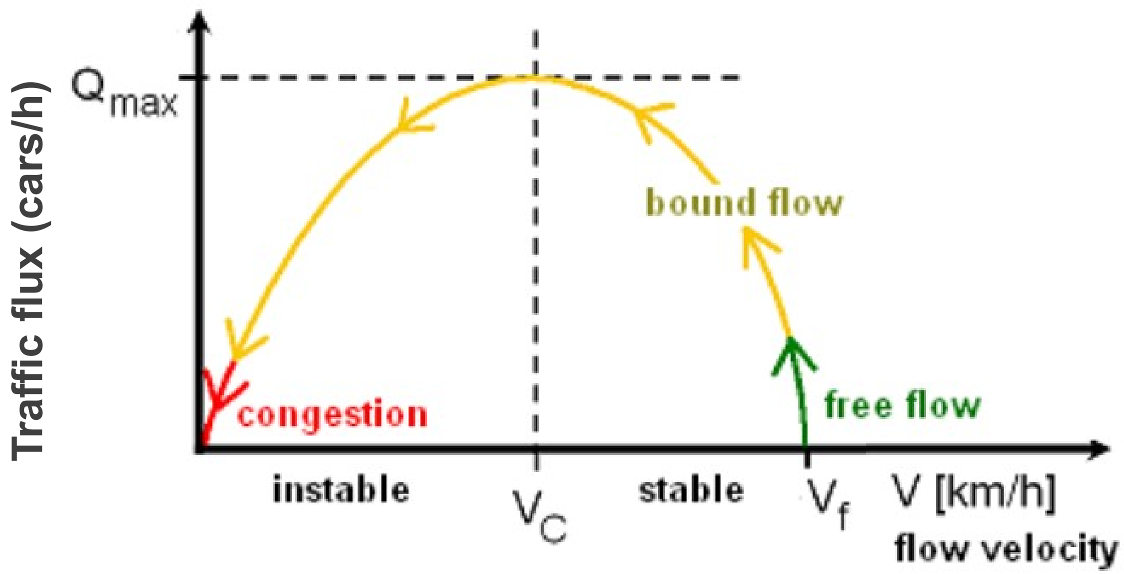
Macroscopic Traffic Model

- Flow-Density
  - If the car density is small, flow is small because number of cars is small
  - If the density is large, flow is small because flow velocity (km/h) is small
  - The „apex“ is the capacity of the segment of the road
  - There exists an optimal traffic density
  - „Wave speed“ (w): slope of the stable region



Macroscopic Traffic Model

- Flow-speed graph
  - There exist two flows
  - V_C: Critical speed

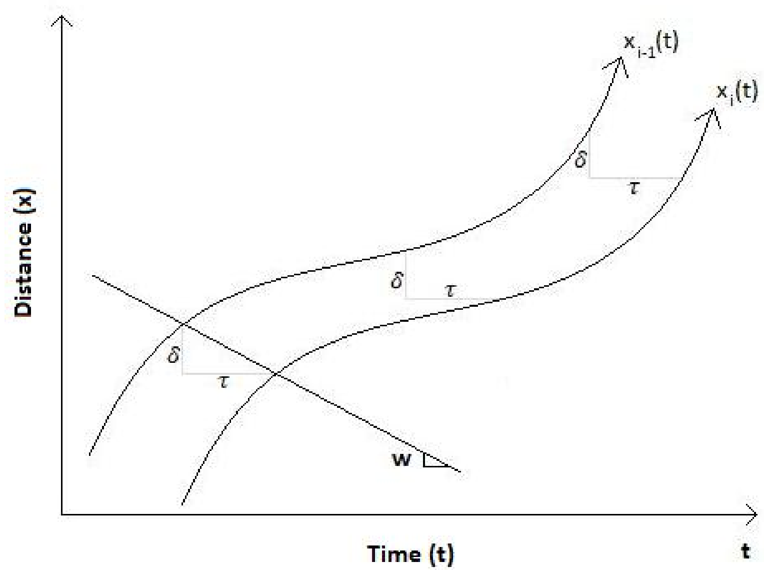


Macroscopic Traffic Model

- Some key terms used in the model
- Stability?
  - If one of the vehicles brake, does this result in persistent stop-and-go?
  - **Free:** less than 12 vehicles per mile are on a road
  - **Stable:** between 12 and 30 vehicles per mile per lane
  - **Unstable:** more than 30 vehicles per miles per lane
  - **Jam density:** Traffic stops! (more than 185-250 vehicles per mile per lane)
  - Remember the congestion in the ring road from the first lecture?
  - The numbers are „empirical“ (not causal from mathematical derivations)

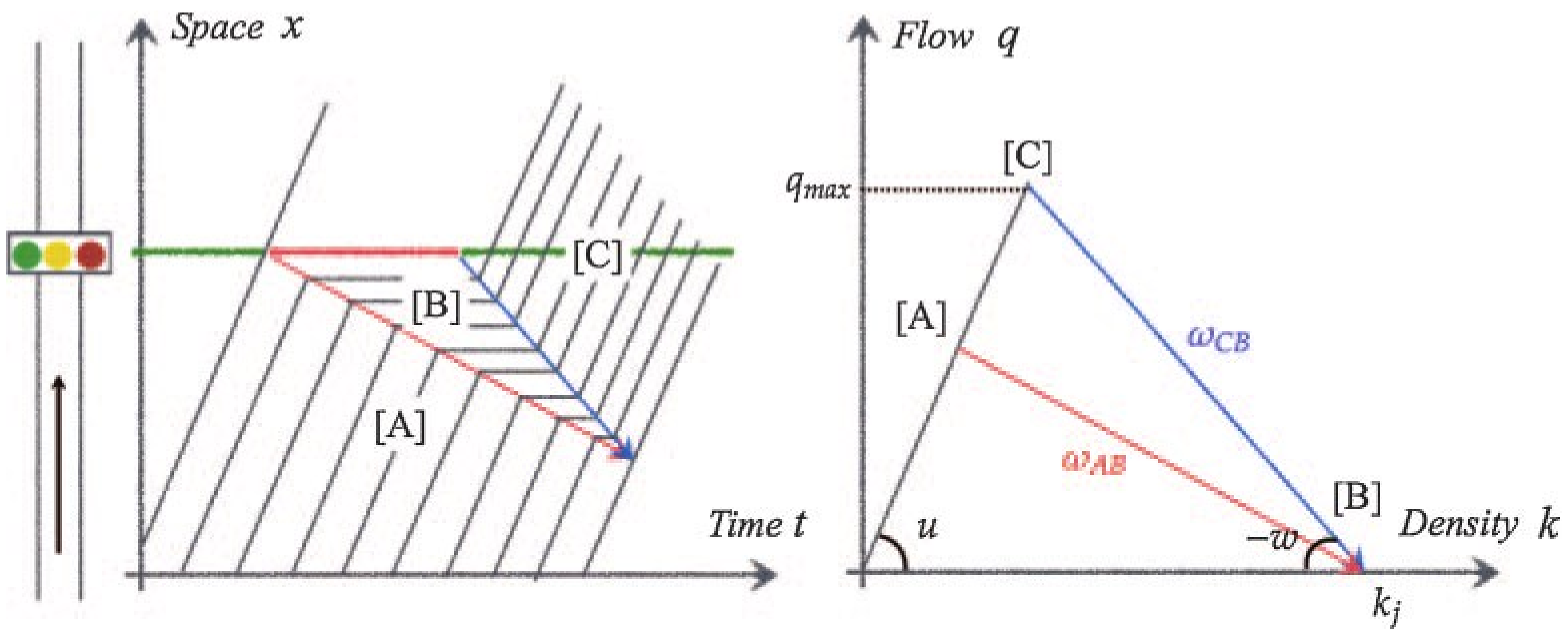
Microscopic Traffic Model

- Newell‘s car following model
  - It assumes that the vehicles will maintain the minimum time and space gap
  - But why?
  - If you assume each vehicle follows the same trajectory, you can move the trajectory of a vehicle in parallel in distance (by δ) and time (by τ)
- In time-space diagram,
  - $s_A = v_A\tau + \delta$, where τ is time separation and δ is space separation
  - Why is it called time and space gap?
  - Imagine large v_A and 0
  - Shockwave speed $w = \frac{\delta}{\tau}$
  - But why?



Microscopic Modeling

- What exactly are shockwaves?
  - Shock wave is basically the movement of the point that demarcates the two stream conditions: Hence the red and blue slopes
- Typical shockwaves propagation
  - Forward wave speed
  - Backward wave speed

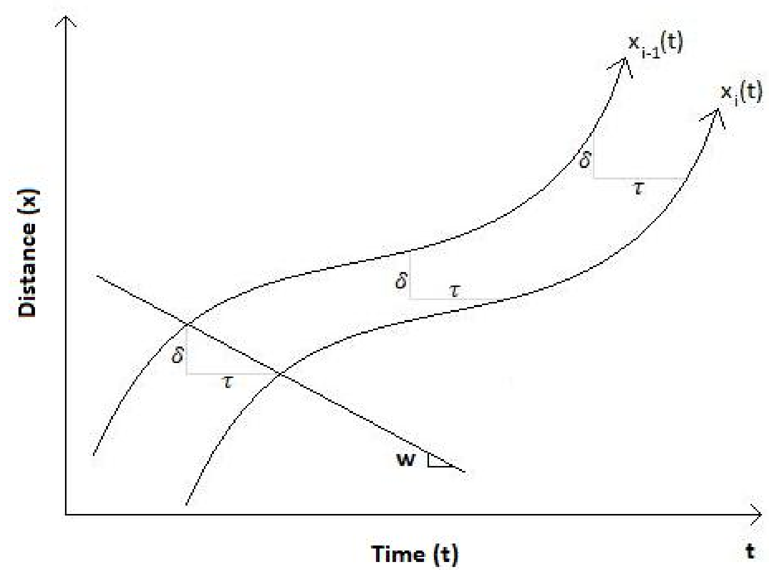


Microscopic Modeling

- Shockwave is also equivalent to the slope between two points in flow-density diagram
- Why?
  - Let‘s say there‘s a shockwave demarcated by two different streams v_A, q_A, and k_A (velocity, flow, and density), v_B, q_B, and k_B
  - Let‘s assume shockwave speed is w
  - Relative speeds of two streams to the shockwave are $v_A - w$ and $v_B - w$
  - The number of vehicles passing through the demarcation line are $(v_A - w)k_A$ and $(v_B - w)k_B$, which of course have to be the same as cars don‘t disappear or appear at the demarcation line
$$(v_A - w)k_A = (v_B - w)k_B$$
  - If you subsitute $q = v \cdot k$, arrange by w
$$w = \frac{q_A - q_B}{k_A - k_B}$$

Microscopic Traffic Model

- In time-space diagram,
  - $s_A = v_A \tau + \delta$, where τ is time separation and δ is space separation
- $k_A = 1/s_A$, where k_A is the density at traffic state A and s_A is spacing
- From flow-density graph, $w = \frac{(q_A - 0)}{(k_j - k_A)} = \frac{k_A v_A}{k_j - k_A}$, if you re-arrange
- $k_A = (k_j w)/(v_A + w)$, where k_j is the jam density, w is the wave speed
- So, $\tau = 1/(w k_j)$ and $\delta = 1/k_j$
- Separation is independent of the speed of the leading vehicle



Microscopic Traffic Model

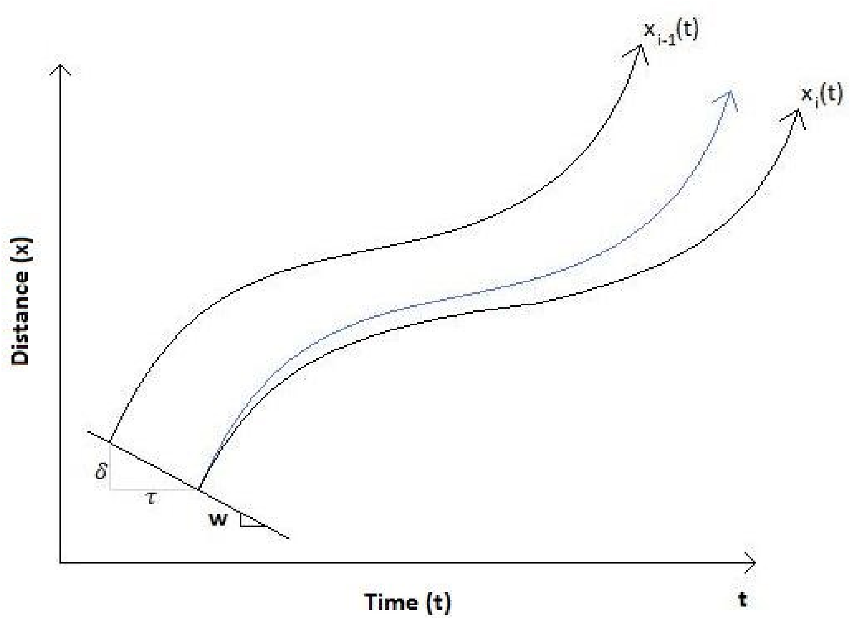
- Then, the location of vehicle i at time t will be
- $x_i(t) = \min(x_A^F(t), x_A^C(t))$,
- Where
- $x_A^F(t) = x_i(t-\tau) + v_f \cdot \tau$, is the position of vehicle under free-flow
- $x_i^C(t) = x_{i-1}(t-\tau) - \delta$, is the position of vehicle under congested conditions

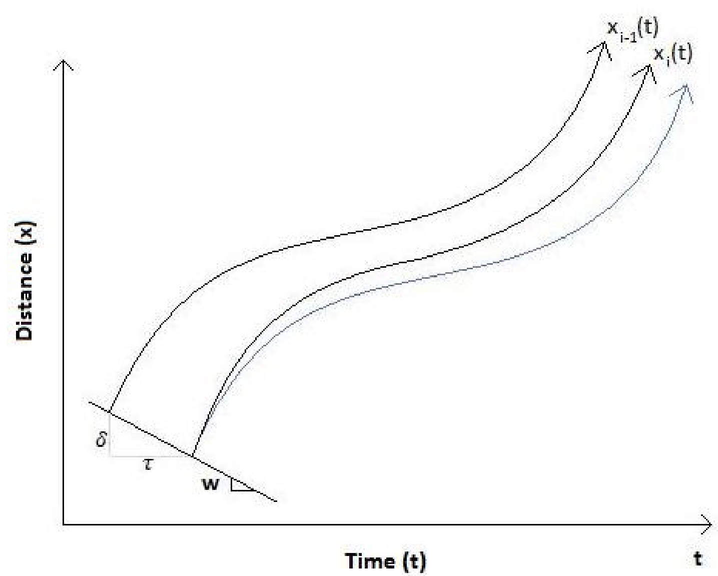
Microscopic Modeling

- However, in reality, the spacing of vehicles is not perfectly maintained by human drivers
- Car following models
  - Use of partial differential equations describing the complete dynamics of the vehicles' positions
  - Simplest model determines the acceleration of the vehicle α considering the velocity of the preceding vehicle α-1
    - $\ddot{x}_\alpha(t) = \dot{v}_\alpha(t) = F\big(v_\alpha(t), s_\alpha(t), v_{\alpha-1}(t)\big)$
  - The simplest control would be
    - $\dot{v}_\alpha(t+T) = \kappa_i[v_{i-1}(t) - v_i(t)]$
    - Which means you adjust acceleration proportional to the speed difference with the preceding vehicle every time period T

Microscopic Modeling

- Driver aggressiveness
- More on this in the „control“ part later





Microscopic Modeling

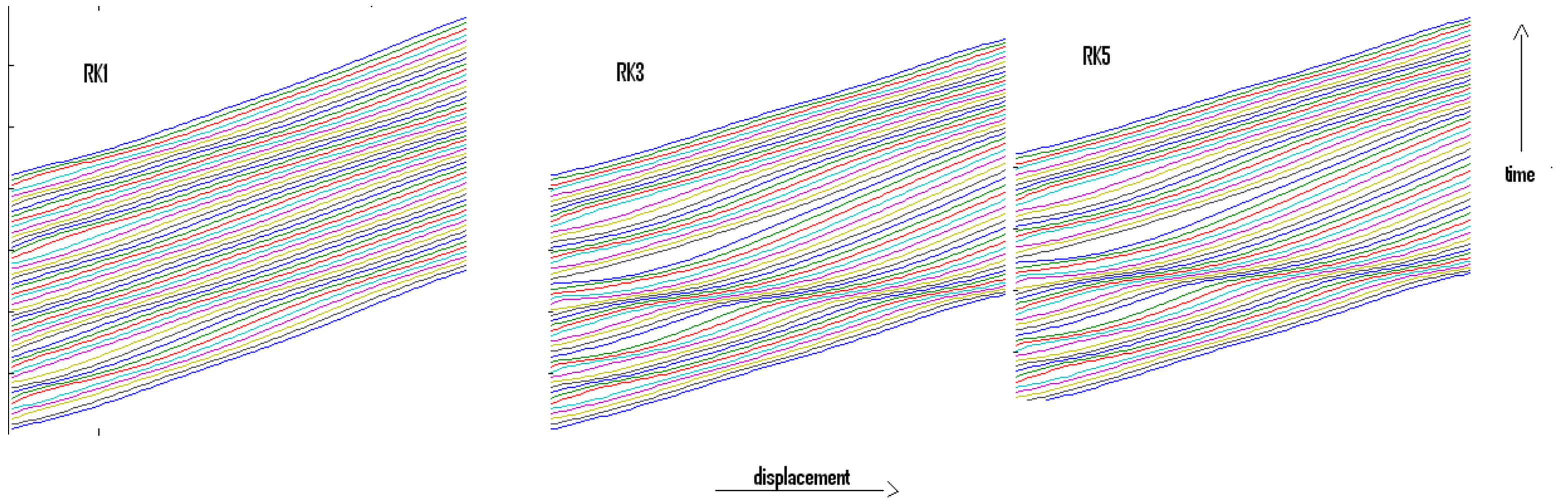
- Intelligent driver model (IDM)
  - Free road behavior + behavior at high approaching rates

Free road behavior **Interaction**

  - $\ddot{x}_\alpha = \frac{dx_\alpha}{dt} = v_\alpha$
  - $\dot{v}_\alpha = \frac{dv_\alpha}{dt} = a\left(\boxed{1 - \left(\frac{v_\alpha}{v_0}\right)^\delta} - \boxed{\left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2}\right)$
  - With $s^*(v_\alpha, \Delta v_\alpha) = s_0 + \mathrm{v}_\alpha \mathrm{T} + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}}$,
  - v_α is the desired velocity at free traffic
  - s_0 is the minimum spacing
  - T is the minimum desired headway
  - a is the maximum acceleration
  - b is the comfortable braking deceleration

Microscopic Modeling

- Example result for IDM
  - Ring road of 50 vehicles where the first vehicle is following the 50th vehicle



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