Basics of longitudinal vehicle dynamics

Conference Paper · May 2015

1 author:

Mario Hirz
Graz University of Technology

Automotive Engineering

Focus: Basics of longitudinal vehicle dynamics

Mario Hirz
Institute of Automotive Engineering
Graz University of Technology

Content

1.1 Classification of vehicle dynamics

1.2 Longitudinal vehicle dynamics

- Longitudinal forces and resistances
- Driving power demand
- Internal combustion engines
- Stationary driving force diagram
- Layout processes of different propulsion concepts

1.1 Classification of vehicle dynamics

Longitudinal vehicle dynamics

Topics:
- Driving resistances
- Driving performance
- Acceleration and braking
- Fuel consumption, emissions
- Longitudinal tire slip
- Propulsion layout

Lateral vehicle dynamics

Topics:
- Steering system (e.g. kinematics)
- Cornering, driving agility
- Oversteering, understeering behavior
- Lateral tire behavior

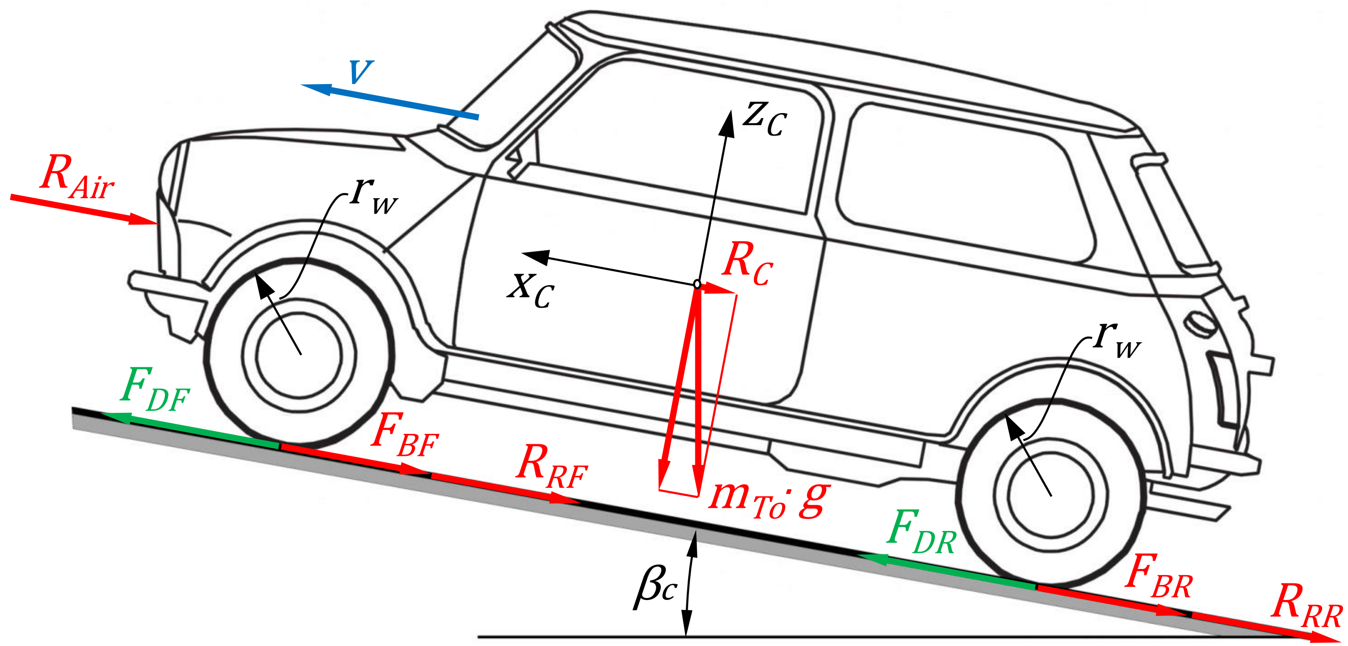
Vertical vehicle dynamics

Topics:
- Axle & suspension system
- Comfort behavior
- Driving in uneven roads

There are several interconnections of the three disciplines.

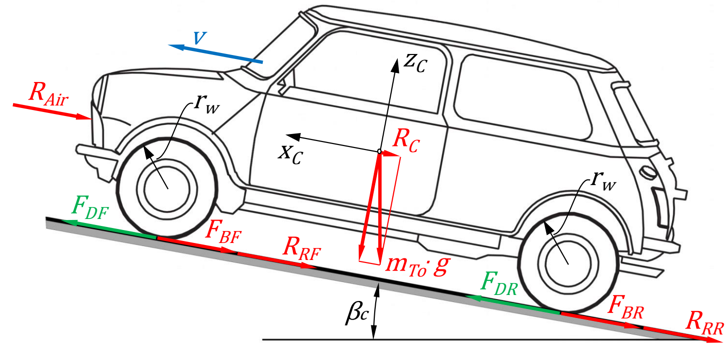
1.2 Longitudinal vehicle dynamics

Longitudinal forces and resistances of a car



F_{DF} and F_{DR} …	driving forces [N]		
F_{BF} and F_{BR} …	braking forces [N]	m_{To} …	total vehicle mass [kg]
R_{RF} and R_{RR} …	rolling resistances [N]	β_C …	climbing angle [deg]
R_{Air} …	aerodynamic drag [N]	v …	vehicle speed [m/s]
R_C …	climbing resistance [N]	r_W …	dynamic wheel radius [m]

1.2 Longitudinal vehicle dynamics



Simplified equation for longitudinal motion under steady state conditions (slip neglected):

$$m^* \, \dot{v} = \frac{M_D - M_B - M_R}{r_W} - R_{Air} - R_C$$

$M_D = (F_{DF} + F_{DR}) \, r_W$ … driving torque [Nm]

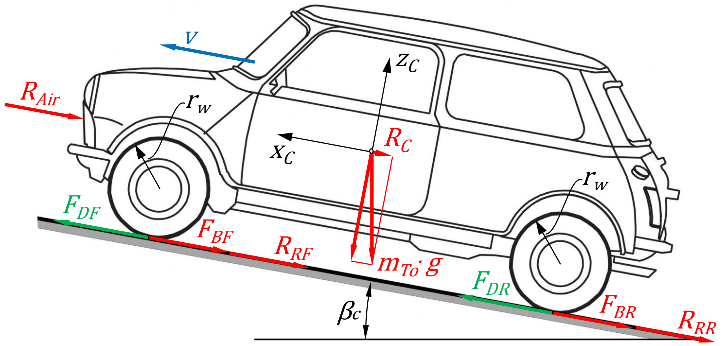
$M_B = (F_{BF} + F_{BR}) \, r_W$ … braking torque [Nm]

$M_R = (R_{RF} + R_{RR}) \, r_W$ … rolling resistance torque [Nm]

$\dot{v}$ … vehicle acceleration [m/s²]

m^* … generalized vehicle mass [kg]

1.2 Longitudinal vehicle dynamics



Vehicle mass and inertia

$$m^* = m_{To} + \frac{\sum I_{Red}}{r_W^2}$$

$$I_{Red} = I_{Axis} + i_{Axis}^2 \left(I_{Trans} + i_{Trans}^2 I_{Eng}\right)$$

I_{Red}	… drivetrain moment of inertia at the driving axle [kgm²]
I_{Axis}	… axis moment of inertia [kgm²]
I_{Trans}	… transmission moment of inertia [kgm²]
I_{Eng}	… engine moment of inertia [kgm²]
i_{Axis}, i_{Trans}	… gear ration @ axis & transmission [-]

Typical gear ratios including axle transmission factor (midsize car):

1st gear: 0.25, 2nd gear: 0.15, 3rd gear: 0.10, 4th gear: 0.075

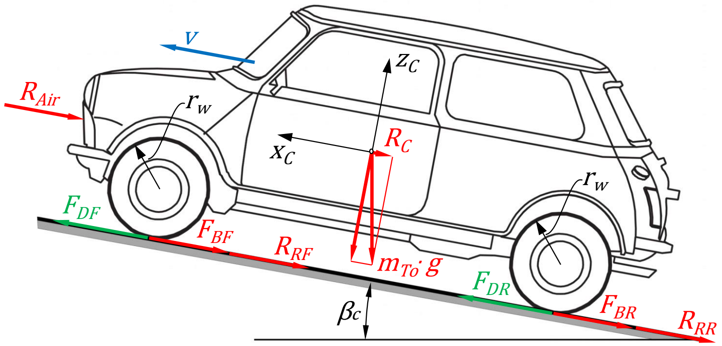
Estimation of the generalized mass *m** for layout purposes:

highest gear: $1.05\, m_{To} < m^* < 1.08\, m_{To}$

lowest gear: $1.25\, m_{To} < m^* < 1.60\, m_{To}$

1.2 Longitudinal vehicle dynamics

Simplified forces, acting at a car in motion



$F_B = (F_{BF} + F_{BR})$ … centralized vehicle braking force [N]

$R_R \approx c_R\, m_{To}\, g\, \cos\beta_c\, \mathrm{sign}(v)$ … rolling resistance [N]

$R_{Air} = {}^1/_2\, c_{Air}\, A_F\, \rho_L\, v\, |v|$ … aerodynamic drag [N]

$R_C = m_{To}\, g\, \sin\beta_c$ … climbing resistance [N]

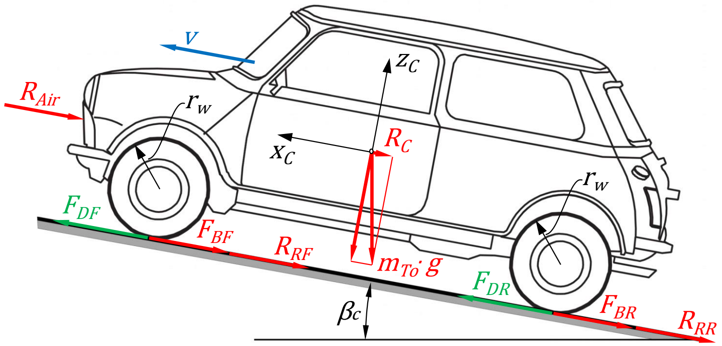
c_R … rolling resistance factor [-] — $c_R \approx 0.01$ for car tires

c_{Air} … aerodynamic resistance factor [-] — $c_{Air} \approx 0.27 – 0.35$ for modern cars

A_F … longitudinal airflow surface [m^2] — $A_F \approx 2 – 4$ m^2 for cars

ρ_L … air density [kg/m^3] — $\rho_L \approx 1.25$ kg/m^3

1.2 Longitudinal vehicle dynamics



Driving power demand

$$P_D = F_D\, v$$

$$P_D = P_E\, \eta$$

F_D	… summarized driving force [N]
P_D	… driving power [W], [kW]
P_E	… engine power [W], [kW]
η	… overall drivetrain efficiency [-]

Estimation:

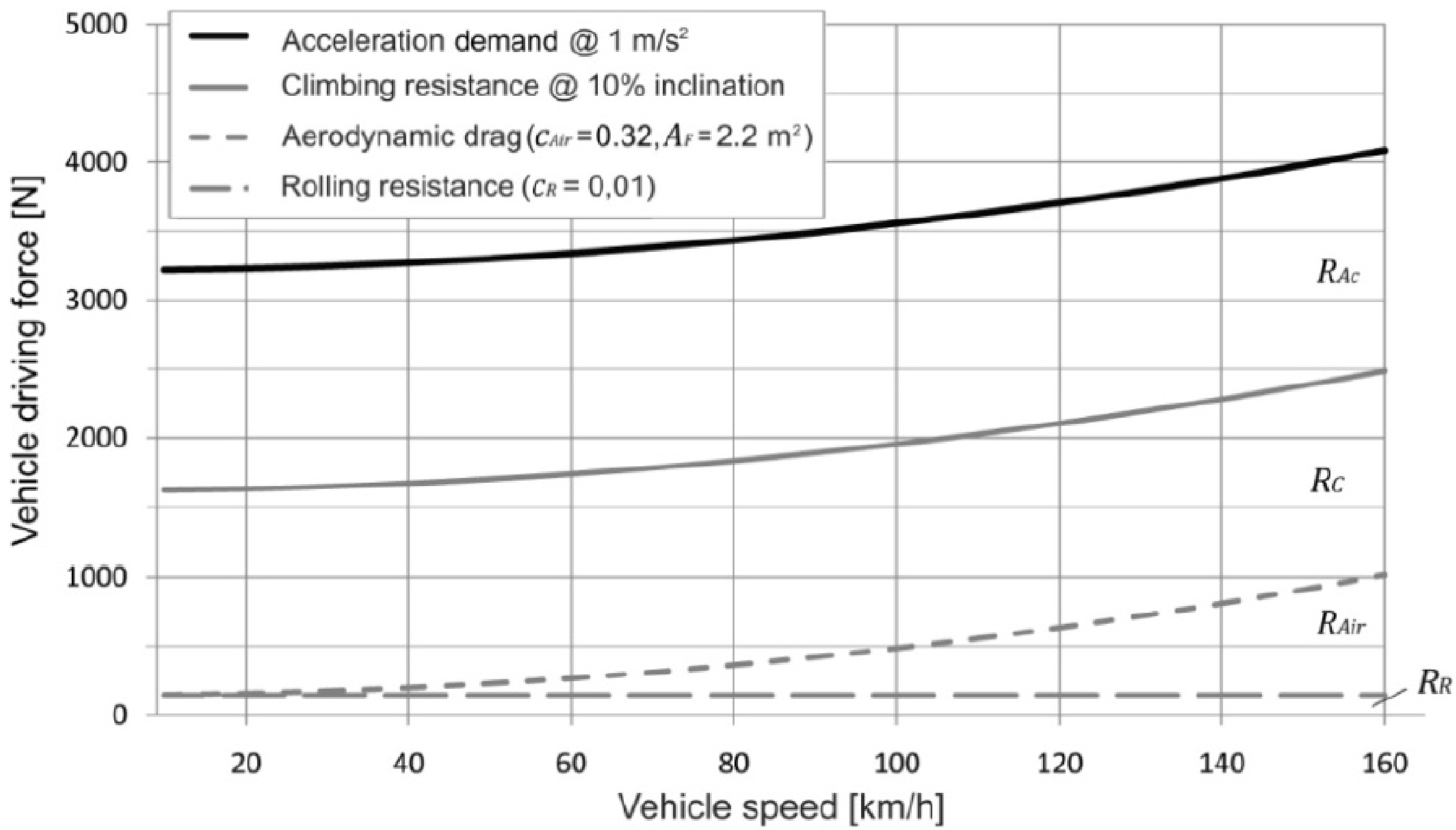
2WD: $0.95 < \eta < 0.98$

4WD: $0.92 < \eta < 0.96$

1.2 Longitudinal vehicle dynamics

Example:

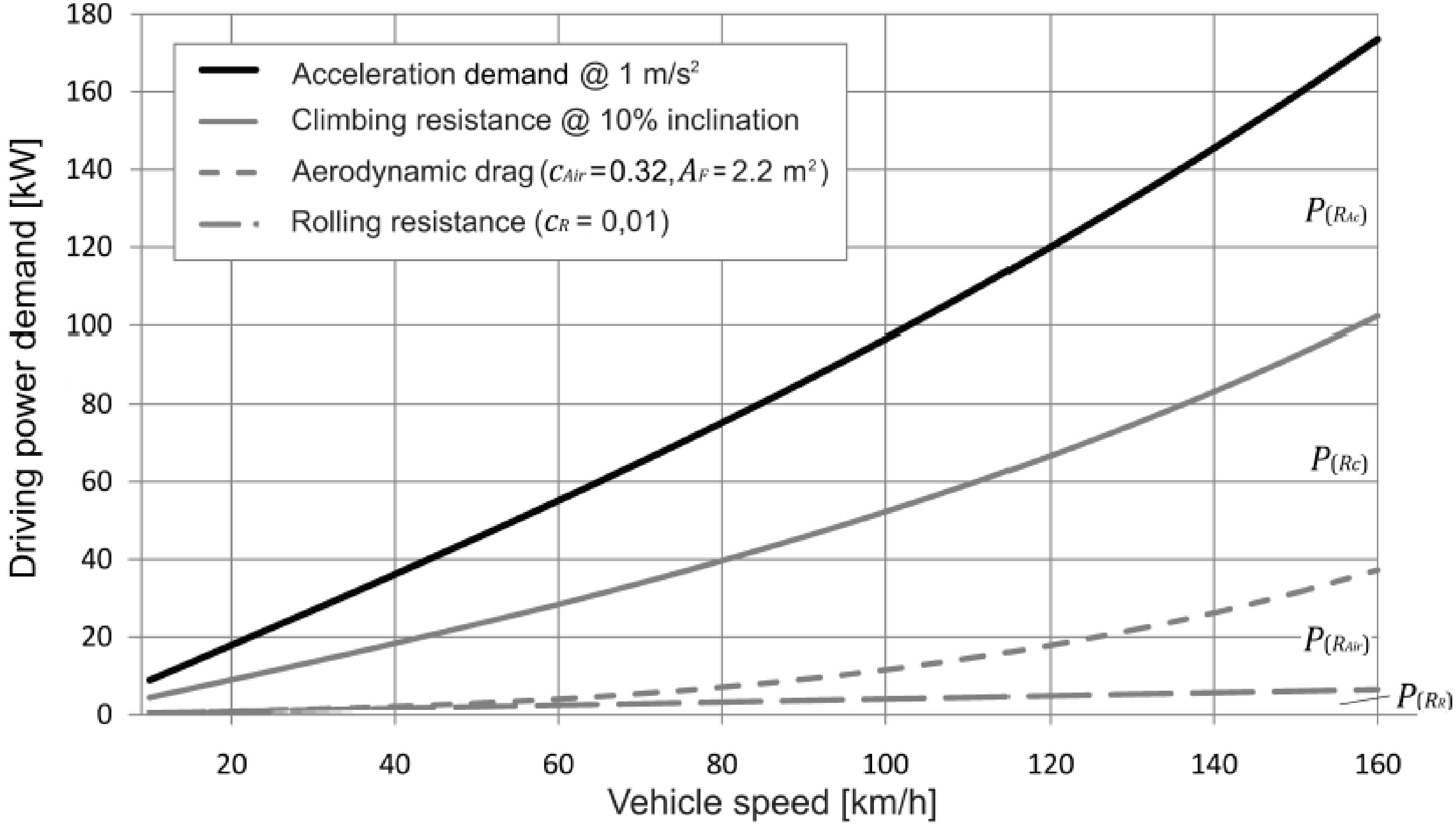
Driving resistances of a compact car (m_{To} = 1500 kg)



1.2 Longitudinal vehicle dynamics

Example:

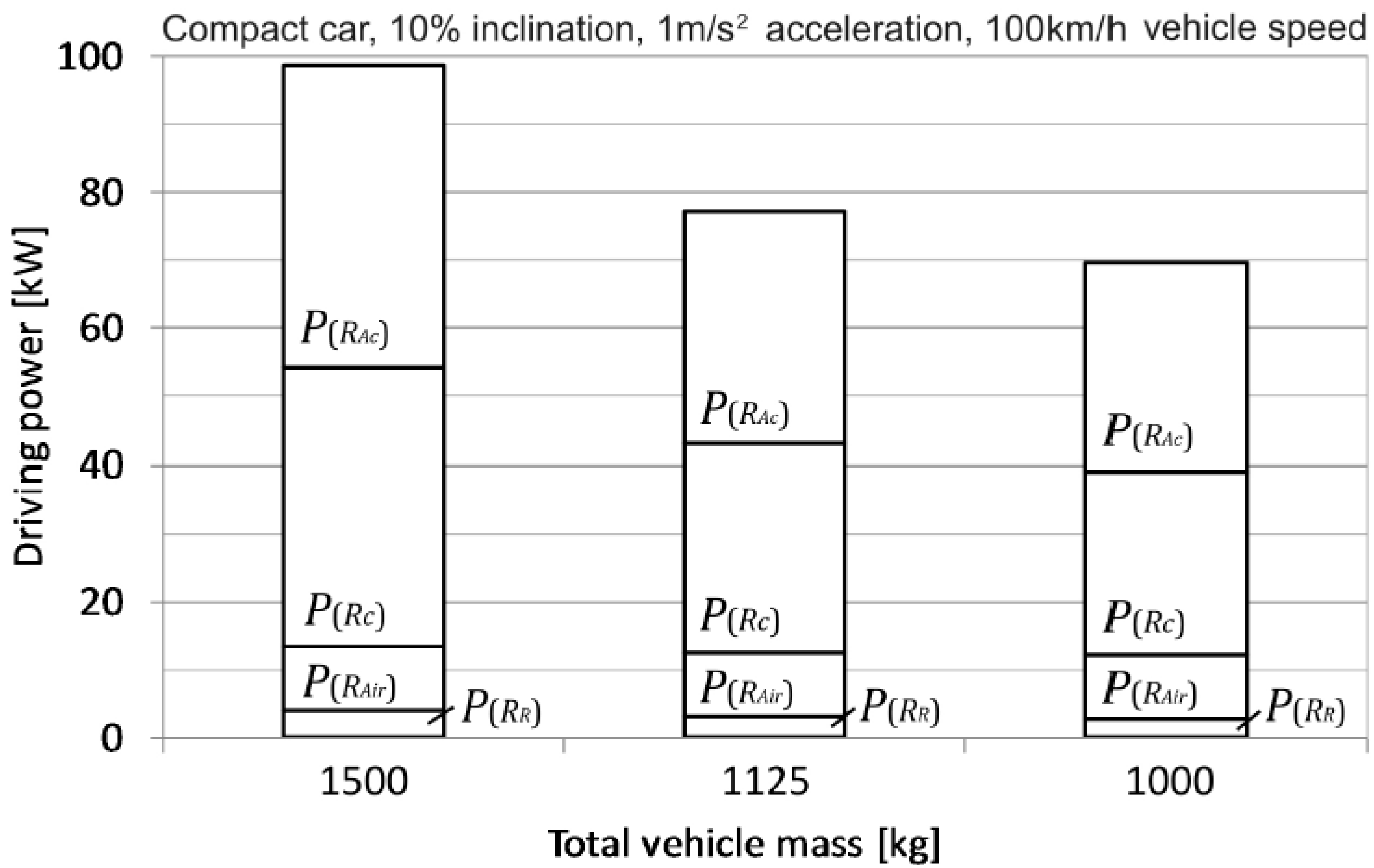
Driving power demand of a compact car (m_{To} = 1500 kg)



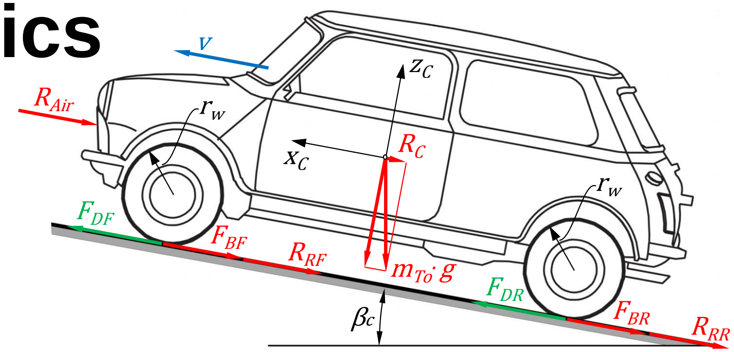
1.2 Longitudinal vehicle dynamics

Example:

Driving power demand distribution for different vehicle masses



1.2 Longitudinal vehicle dynamics



Theoretical maximum speed of a car

$$\frac{P_E \, \eta \, 10^3}{v} = c_R \, m_{To} \, g \, \cos \beta_c + {}^1\!/_2 \, c_{Air} \, A_F \, \rho_L \, v^2 + m_{To} \, g \, \sin \beta_c + m^* \, \dot{v}$$

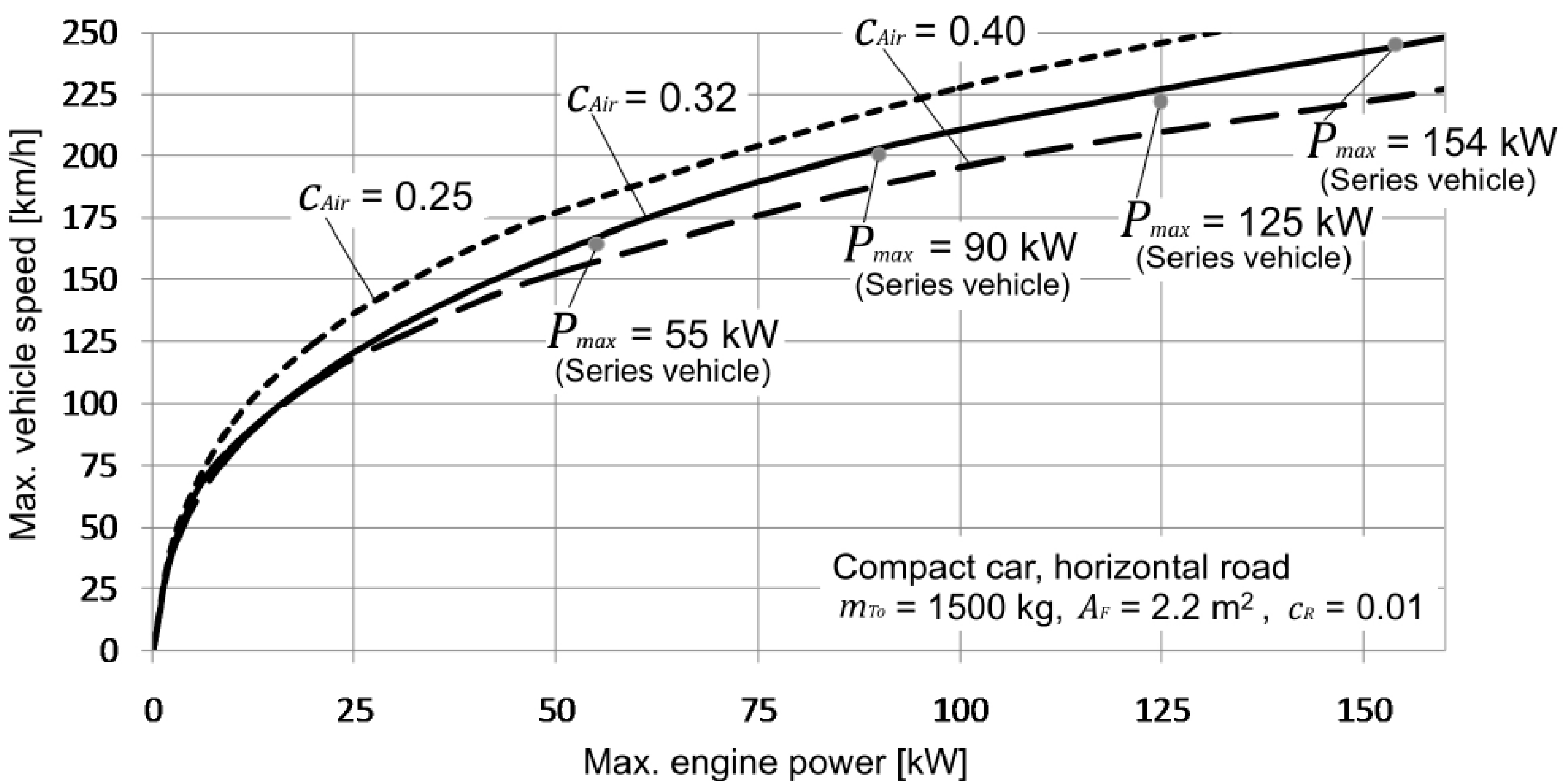
For an estimation of the vehicle maximum speed on a horizontal road, the climbing resistance and the acceleration resistance are set to zero. The engine power demand as a function of the rolling resistance, the aerodynamic drag and the power train efficiency factor can be expressed as

$$P_E = \frac{c_R \, m_{To} \, g}{\eta} \, v + \frac{c_{Air} \, A_F \, \rho_L}{\eta} \, v^3$$

1.2 Longitudinal vehicle dynamics

Example:

**Influence of the aerodynamic resistance factor
on the engine power demand at different vehicle speeds**



1.2 Longitudinal vehicle dynamics

Comparison of internal combustion engine and electric drivetrain

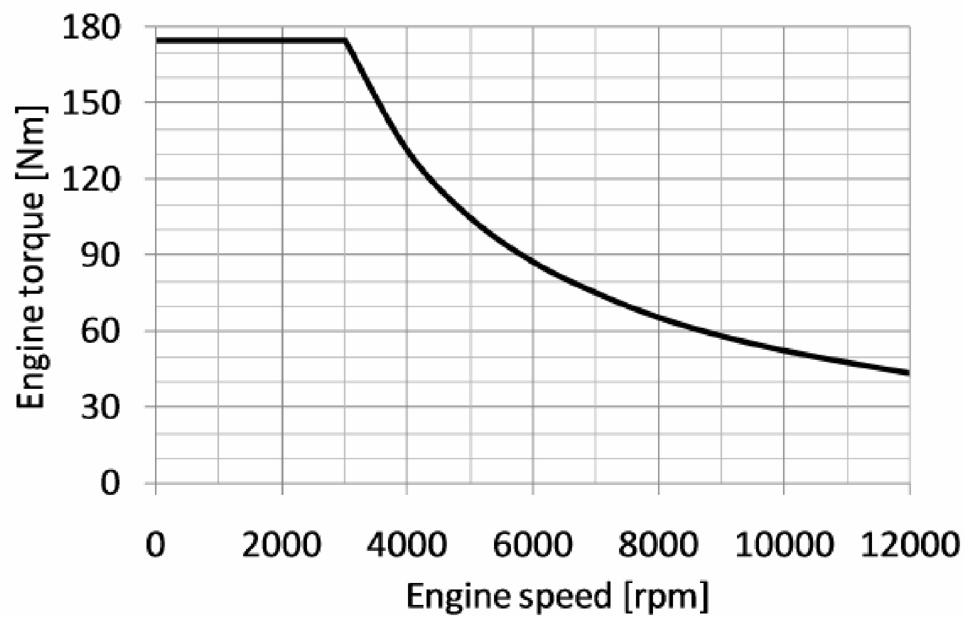
Characteristic figures of a concept vehicle, including the stationary maximum torque output characteristics of a synchronous motor

Analyzed vehicle type:

Concept car based on a mass-production car
Synchronous type electric motor

Vehicle characterisitcs

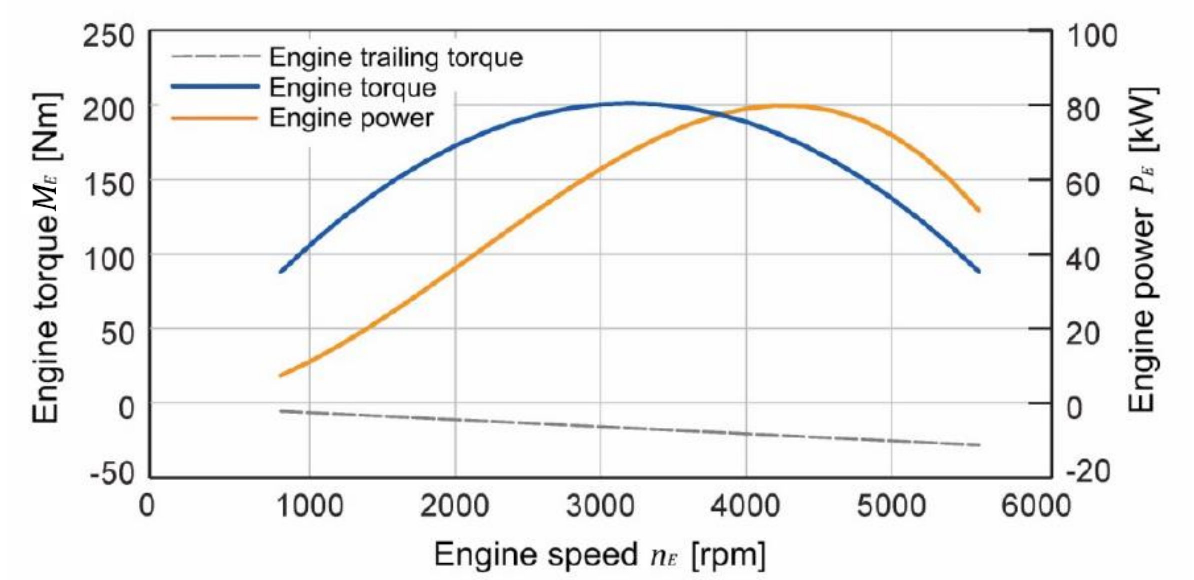
$m_{To} = 1300$ kg
$c_{Air} = 0.32$
$c_R = 0.01$
$A_F = 2.2$ m^2
$P_{El} = 55$ kW
$r_W = 0.315$ m
$i_{total} = 12.05$



1.2 Longitudinal vehicle dynamics

Internal combustion engines (ICE)

Schematic stationary engine full load and trailing characteristics



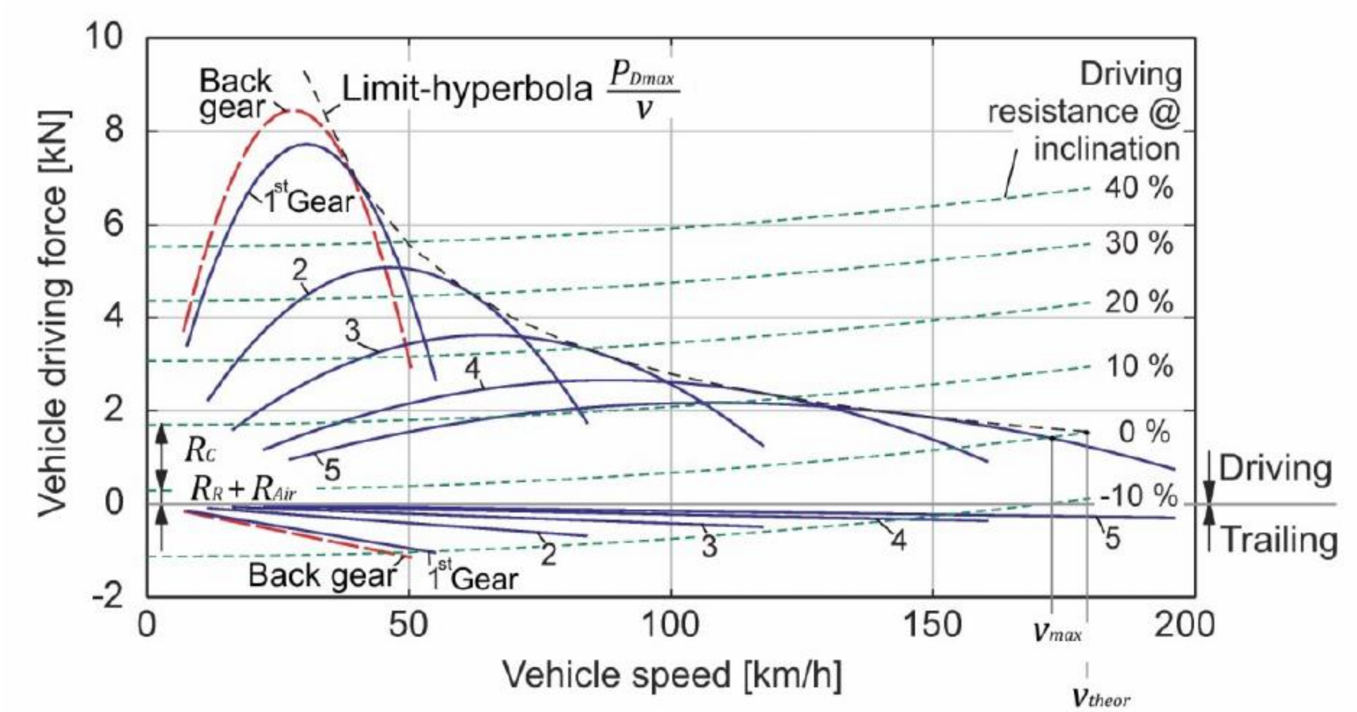
$M_D = \eta\, i_{Trans}\, i_{Axle}\, M_E$ … driving torque [Nm], M_E … engine torque [Nm]

$F_D = M_D / r_W$ … driving force [N]

1.2 Longitudinal vehicle dynamics

Drivetrain with internal combustion engines

Stationary steady state driving force diagram



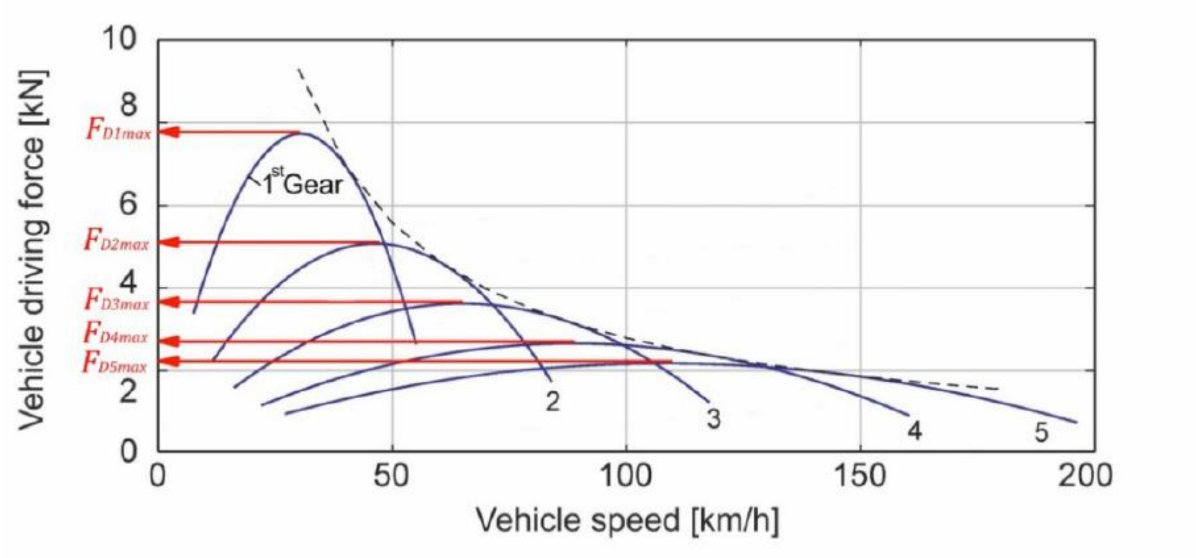
$n_W = n_E / (i_{Trans}\ i_{Axle})$ … wheel speed [rps, rpm], n_E … engine speed [rps, rpm]

$v = 1/30\ (\pi\ n_w\ r_W)$ … vehicle speed [m/s, km/h]

1.2 Longitudinal vehicle dynamics

Drivetrain with internal combustion engines

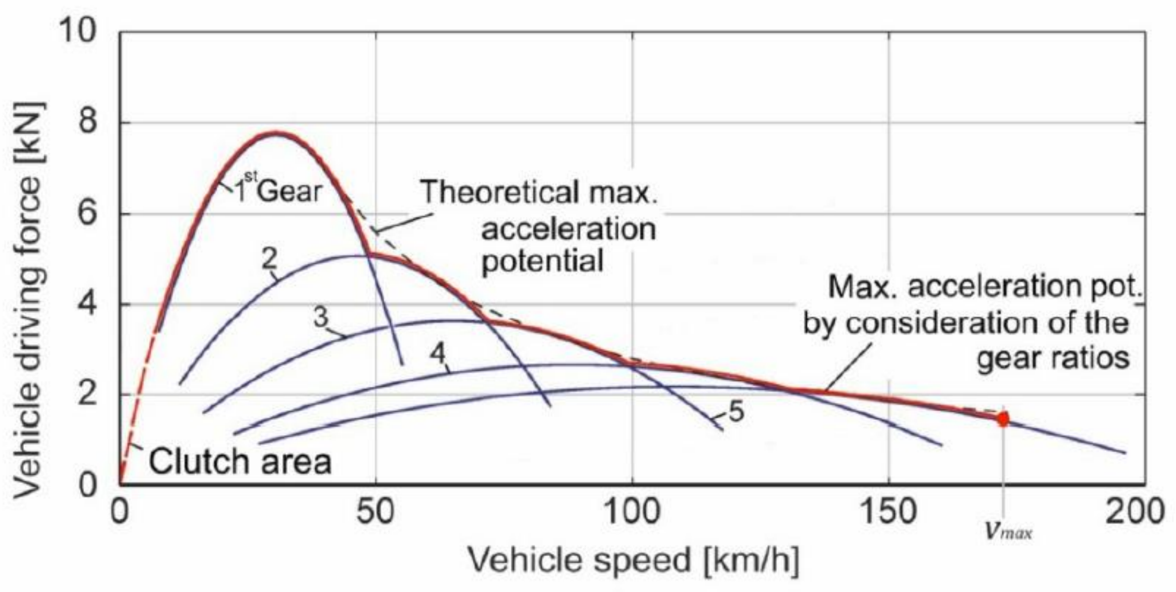
**Example: Stationary steady state driving force diagram,
Climbing force characteristics in each gear**



1.2 Longitudinal vehicle dynamics

Drivetrain with internal combustion engines

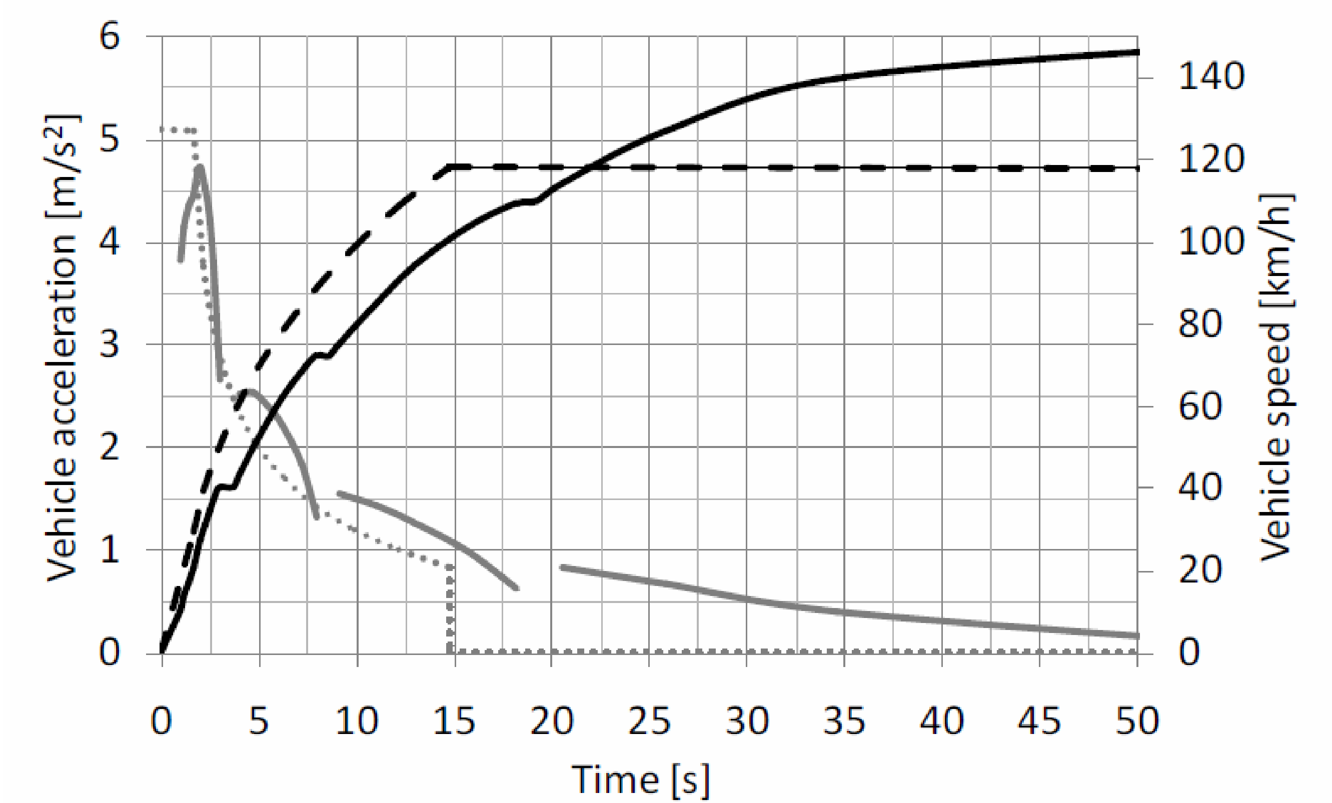
Example: Stationary steady state driving force diagram,
Maximum acceleration potential across the entire drive train operating range



1.2 Longitudinal vehicle dynamics

Comparison of ICE and Electric drivetrain

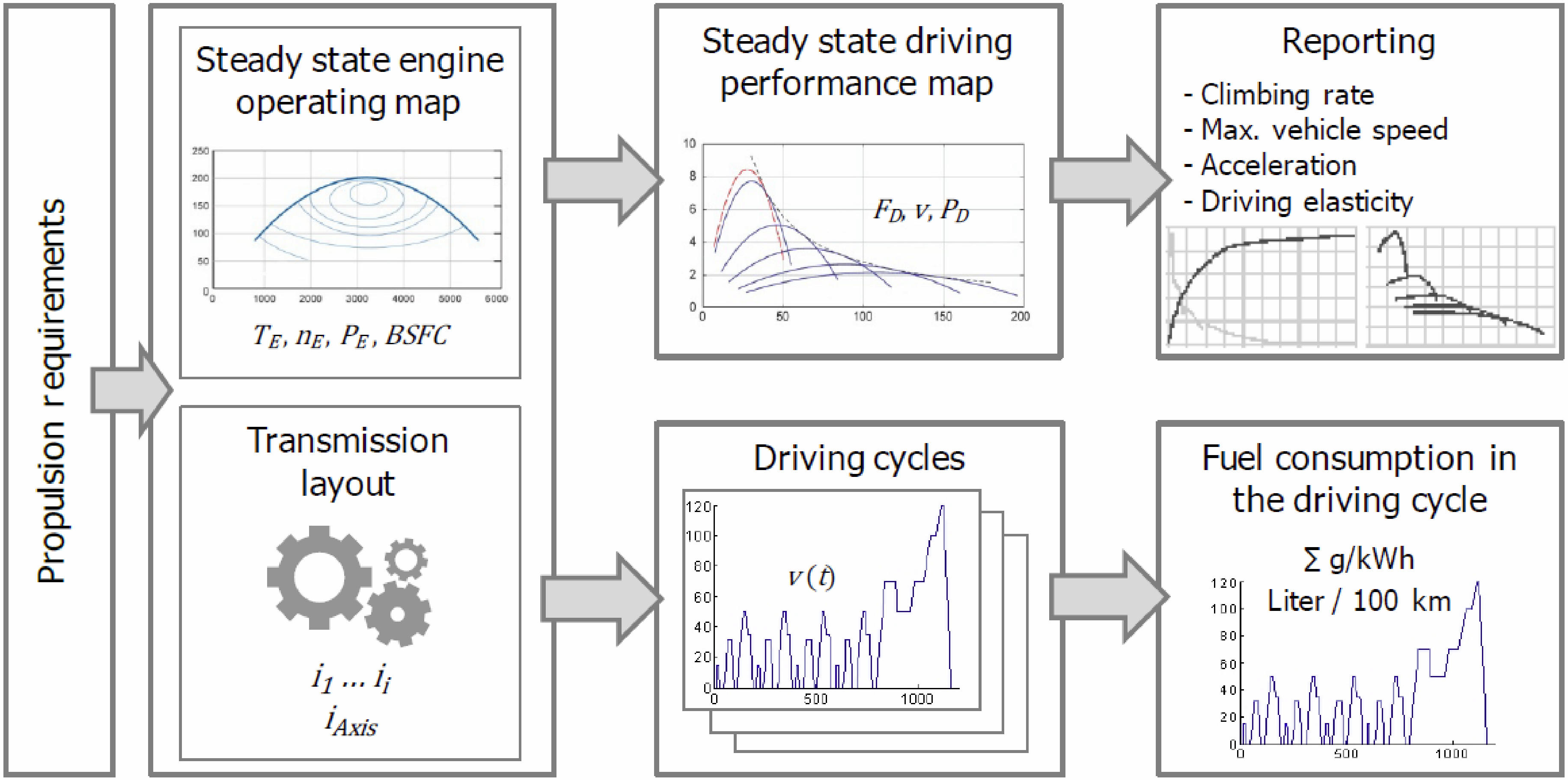
Acceleration comparison of a concept vehicle driven by two different propulsion technologies



1.2 Longitudinal vehicle dynamics

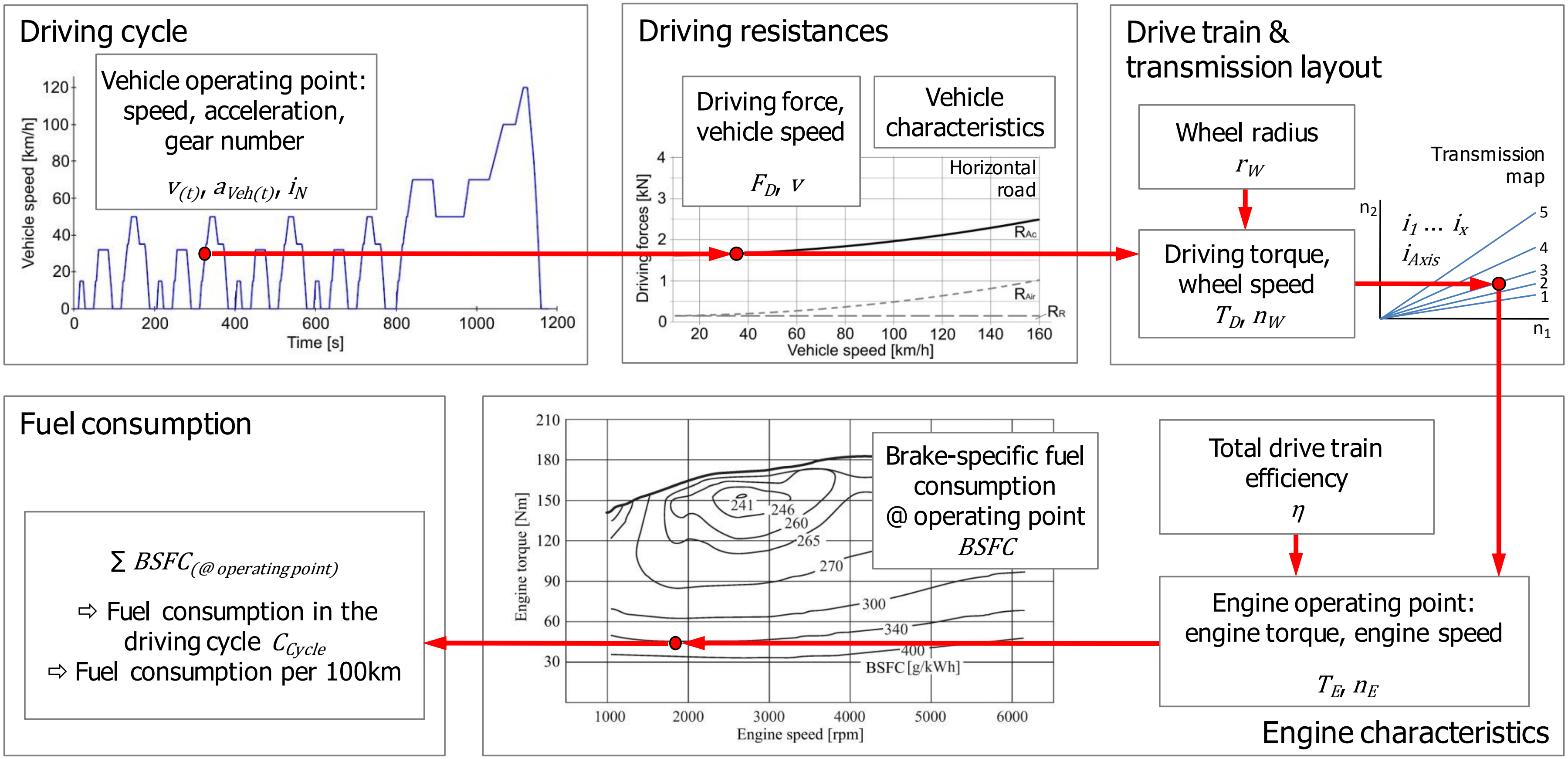
Drivetrain with internal combustion engines

Schematic layout process of an ICE and an appropriate gearbox



1.2 Longitudinal vehicle dynamics

Drivetrain with internal combustion engines, parameters of simulation

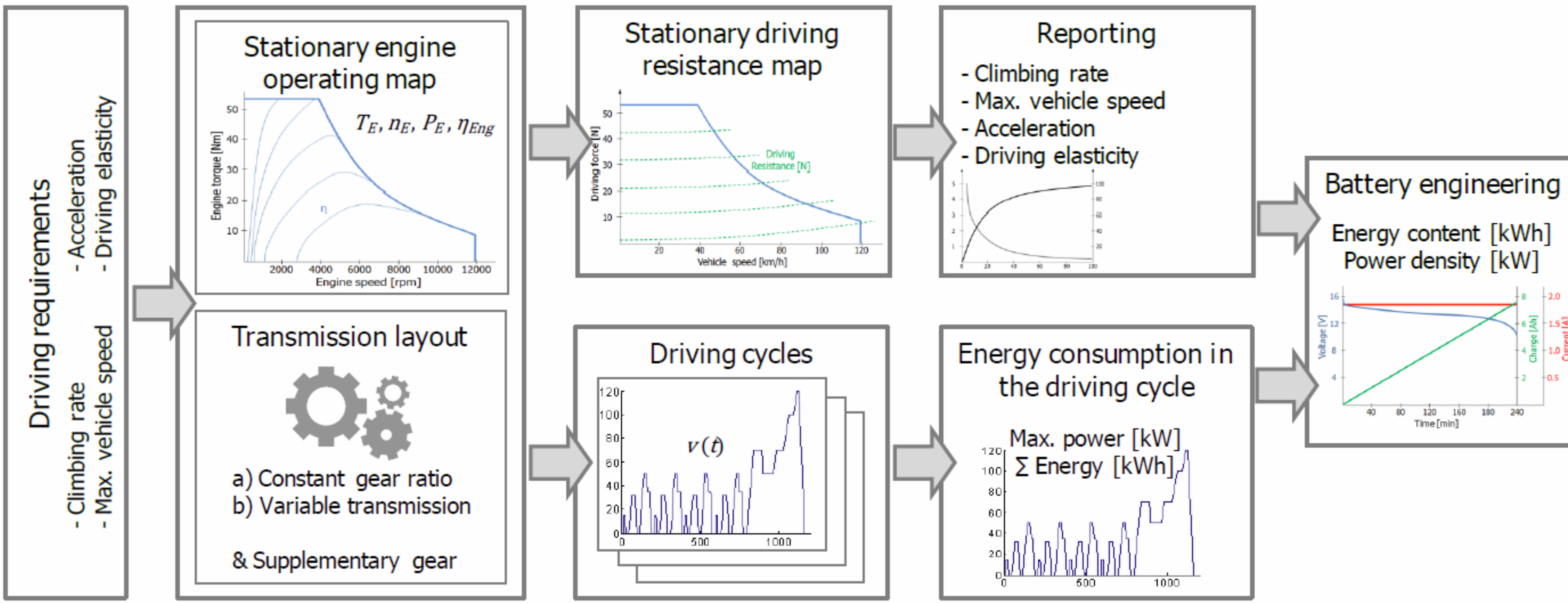


$v_{(t)}$ …	vehicle speed [m/s]	n_1 …	transmission initial speed [rpm]	C_{Cycle} …	driving cycle fuel consumption [l]
$a_{Veh(t)}$ …	vehicle acceleration [m/s^2]	n_2 …	transmission output speed [rpm]	C_{100km} …	fuel consumption per 100 km [l/100km]
t …	cycle time [s]	$i_1 \dots i_x$ …	transmission gear ratios [-]	m_F …	fuel mass [kg]
i_N …	gear number [-]	i_{Axis} …	axis transmission gear ratio [-]	P_E …	engine power output [kW]
F_D …	vehicle driving force [N]	T_E …	engine torque [Nm]	ρ_F …	fuel density [kg/l]
r_W …	wheel radius [m]	n_E …	engine speed [rpm]	D_{cycle} …	cycle distance [km]
T_D …	driving torque [Nm]	η …	power train efficiency factor [-]	K_1 …	CO_2 conversion factor for gasoline [kg/l]
n_W …	wheel speed [rpm]	$BSFC$ …	brake-specific fuel consumption [g/kWh]	K_2 …	CO_2 conversion factor for diesel [kg/l]

1.2 Longitudinal vehicle dynamics

Electric drivetrain layout

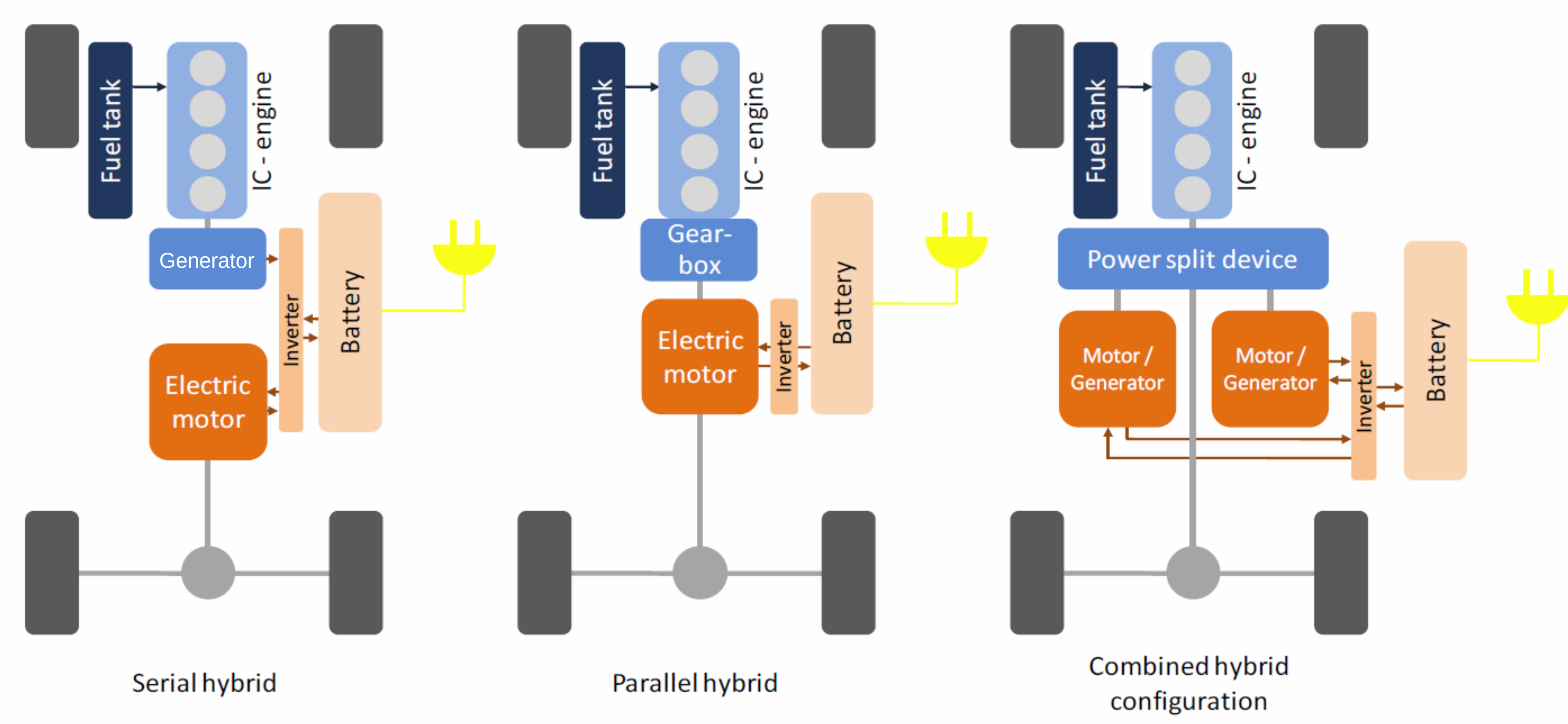
Schematic layout process of an electric drivetrain



1.2 Longitudinal vehicle dynamics

Excurse: Hybrid drivetrain layout

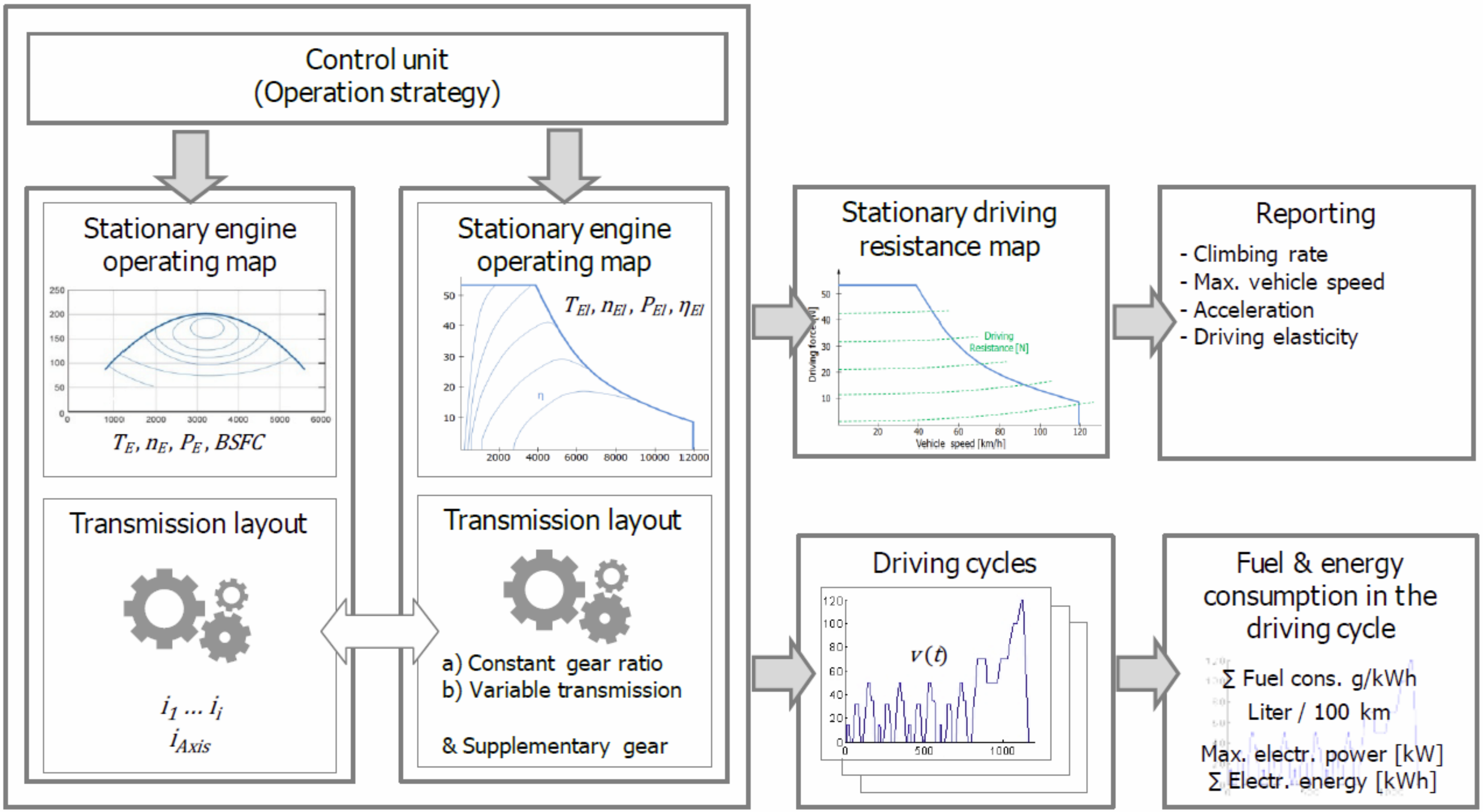
Schemata of hybrid drive train configurations



1.2 Longitudinal vehicle dynamics

Excurse: Hybrid drivetrain layout

Schematic layout process of y hybrid drivetrain



fine