Engine power requirements

Engine and powertrain matching

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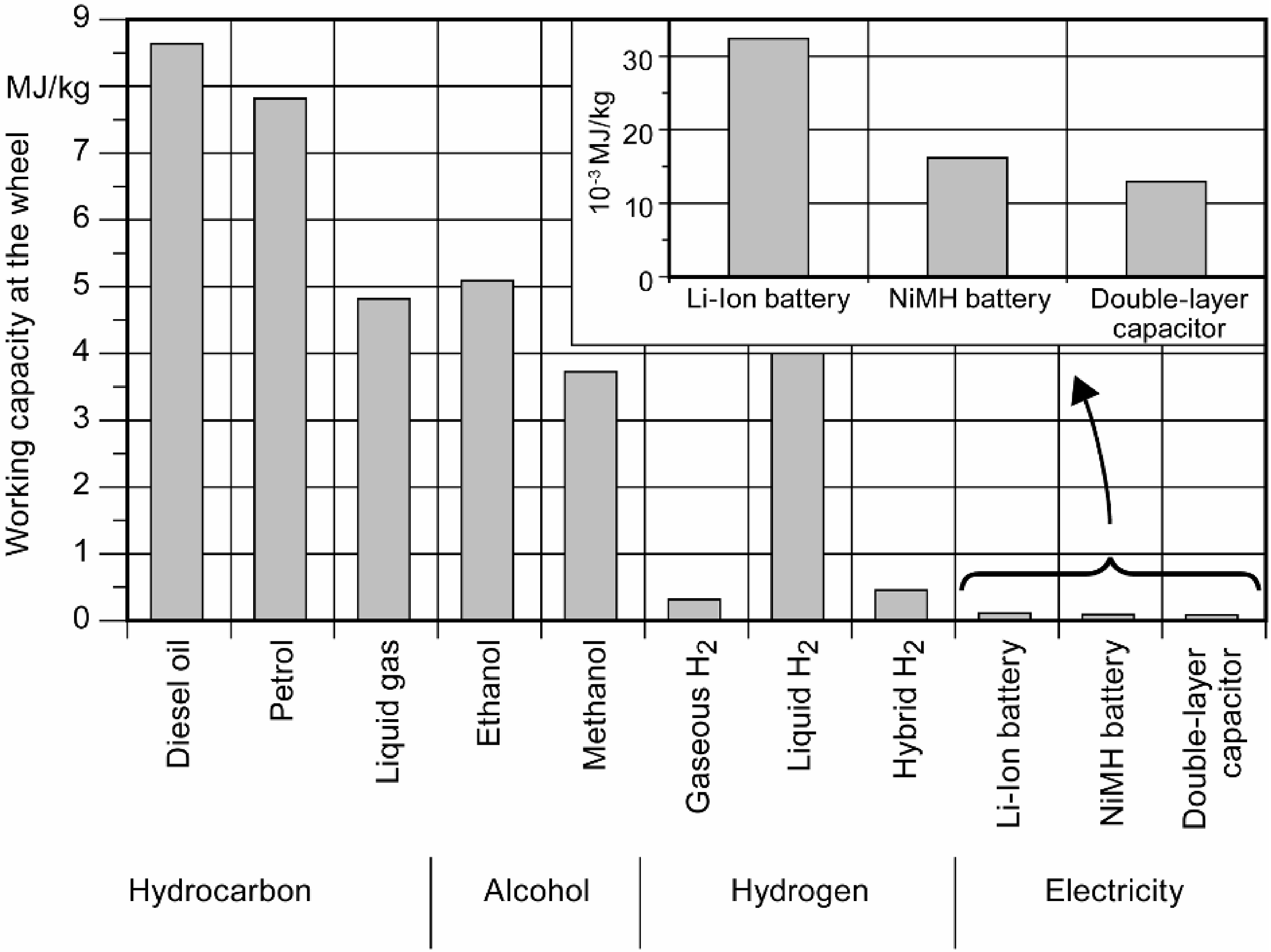
Power Requirement

- **The power requirement at the drive wheels is determined by the driving resistance**
  - **wheel resistance F_R,** $F_{R,Roll} = f_R \; G_R$
    - Wheel resistance comprises the resisting forces acting on the rolling wheel. It is made up of rolling resistance, road surface resistance and slip resistance.
  - **air resistance F_L,** $F_L = \frac{1}{2} \rho_L \; c_W \; A \; v^2$
    - The air resistance is made up of the pressure drag including induced drag (turbulence induced by differences in pressure), surface resistance and internal (through-flow) resistance.
  - **gradient resistance F_{St}** $F_{St} = m_F \; g \; \sin\alpha_{St}$
    - The gradient resistance or downhill force relates to the slope descending force and is calculated from the weight acting at the centre of gravity
  - **acceleration resistance F_a** $F_a = \lambda \; m_F \; a$
    - In addition to the driving resistance occurring in steady state motion (v = const), inertial forces also occur during acceleration and braking.

Power units

- Energy supplies with an energy density as high as possible are desirable.
- The weight of the Energy accumulator is factored in, as is the transmission efficiency.
- Rapid recharging of the energy accumulator and the necessary infrastructure.



Selection of power unit

In selecting a suitable power unit, the following factors must be considered:

- ***operating performance:***

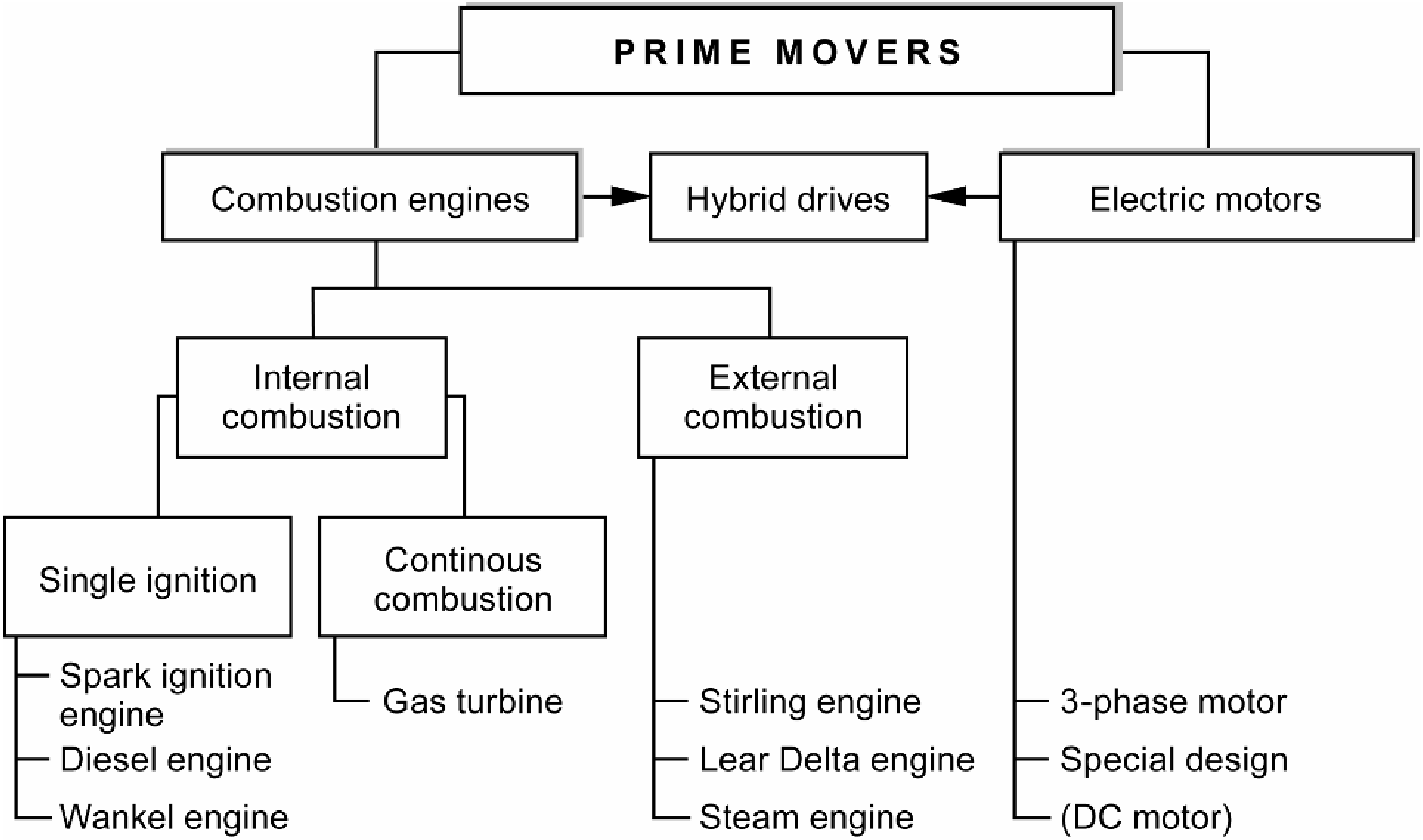
  drive characteristics, ease of control, startability, energy accumulator etc.,

- ***economy***:

  specific energy consumption, specific manufacturing cost etc.

- ***environment friendliness:***

  pollutant emissions, noise, vibration etc.

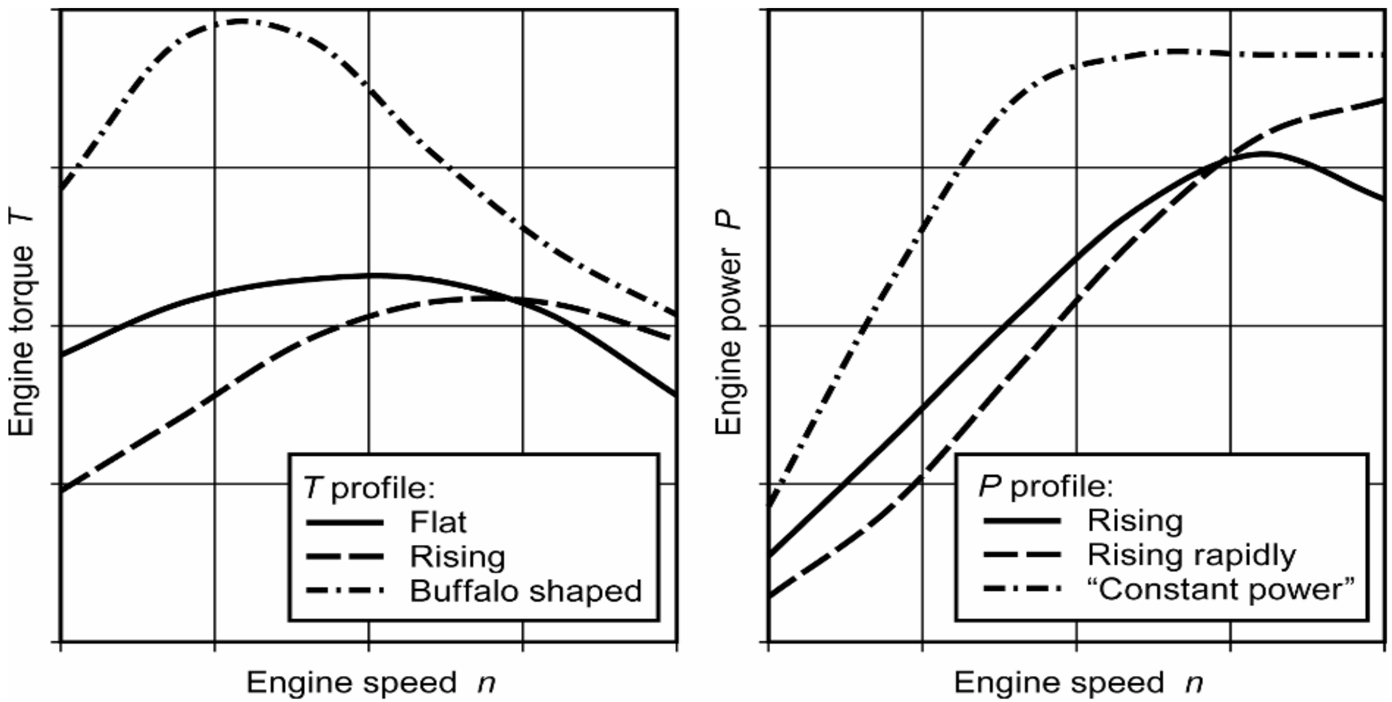

PRIME MOVERS
Combustion engines
Hybrid drives
Electric motors
Internal combustion
External combustion
Single ignition
Continous combustion
Spark ignition engine
Diesel engine
Wankel engine
Gas turbine
Stirling engine
Lear Delta engine
Steam engine
3-phase motor
Special design
(DC motor)

Engine characteristic

*The engine characteristic is a decisive technical consideration in selecting the prime mover, i.e. the **power available at full load across the engine speed range**.*

- There are two typical characteristic curves to describe the engine characteristic

1. the torque/engine speed curve at full load (100% accelerator pedal position)
2. the corresponding full-load power curve (engine characteristic)



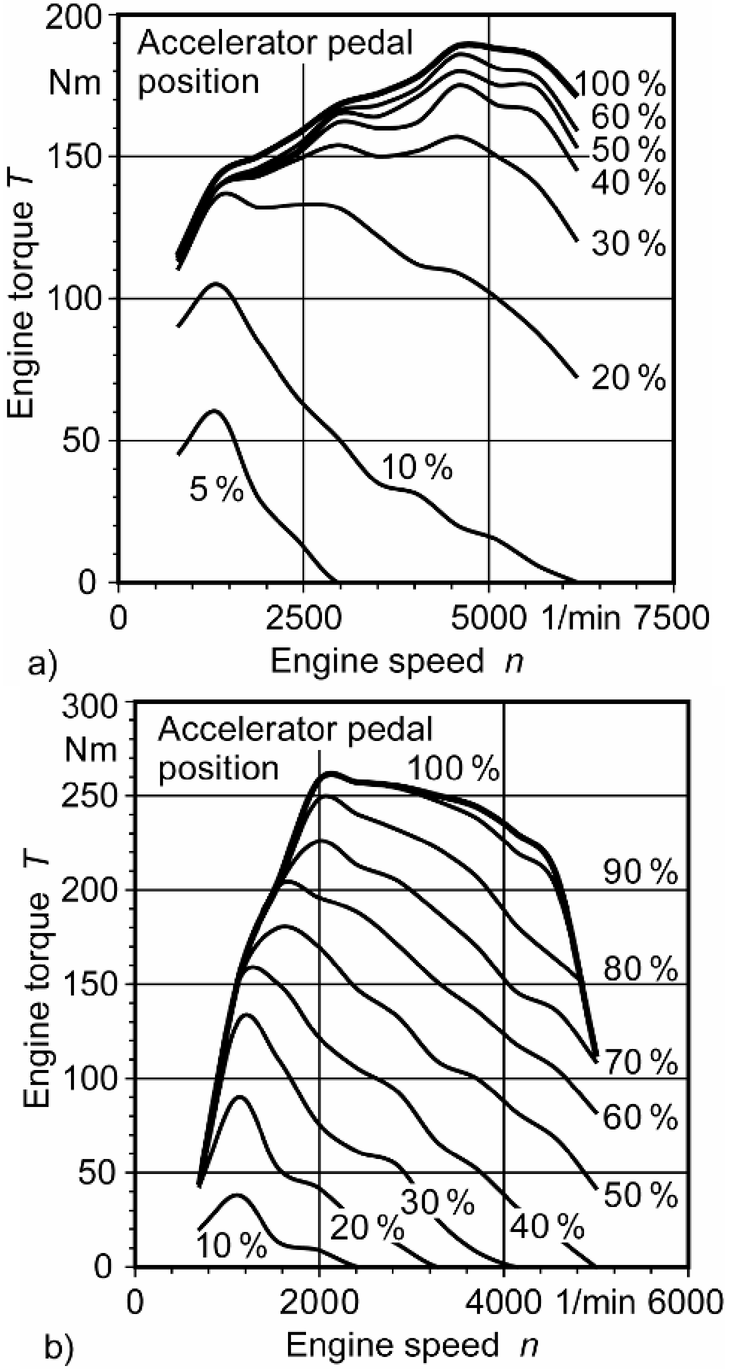
Engine Spread,

- The driver uses the accelerator pedal to indicate the power desired from the engine.
- When the accelerator pedal is fully depressed (100%) this corresponds to the engine full-load curve, and when the accelerator pedal is not depressed (0%), to the thrust characteristic curve.
- The almost equidistant pattern is typical of diesel engines.
- The term “throttle valve angle” is often used instead of “relative accelerator pedal position”.
- A throttle valve angle of 90º then corresponds to the engine full-load line.

The lines for the same accelerator pedal position for the two engines

Spark ignition engine;

turbo diesel engine with intercooler

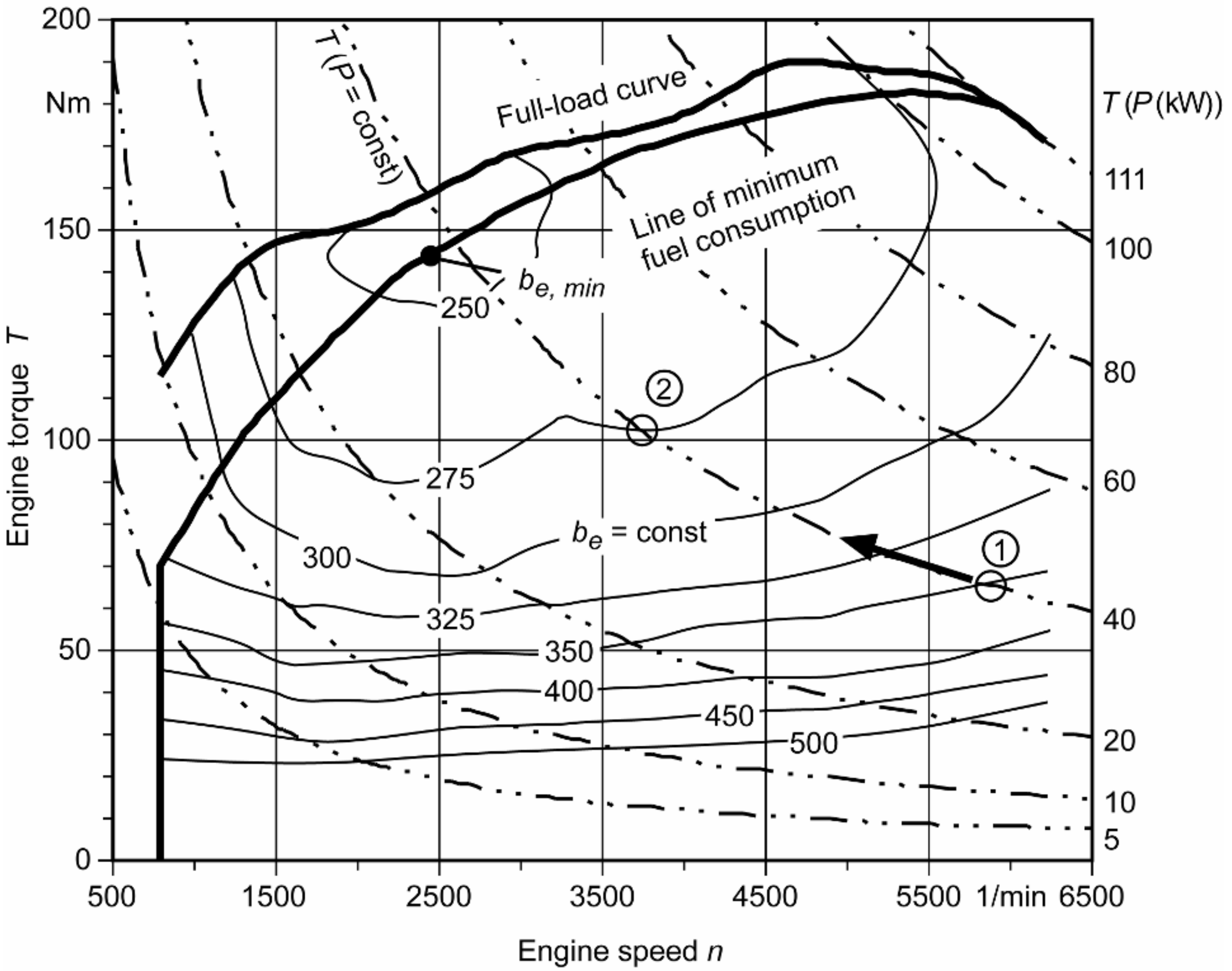


Consumption Map

- the specific consumption b_e is shown in g/kWh, the term “onion diagram”
- There is a minimum consumption $b_{e,min}$ just below the full-load characteristic curve in the lower engine speed range.
- The precise position depends on the engine. *In the case of spark ignition passenger car engines the minimum consumption is around 250 g/kWh*,

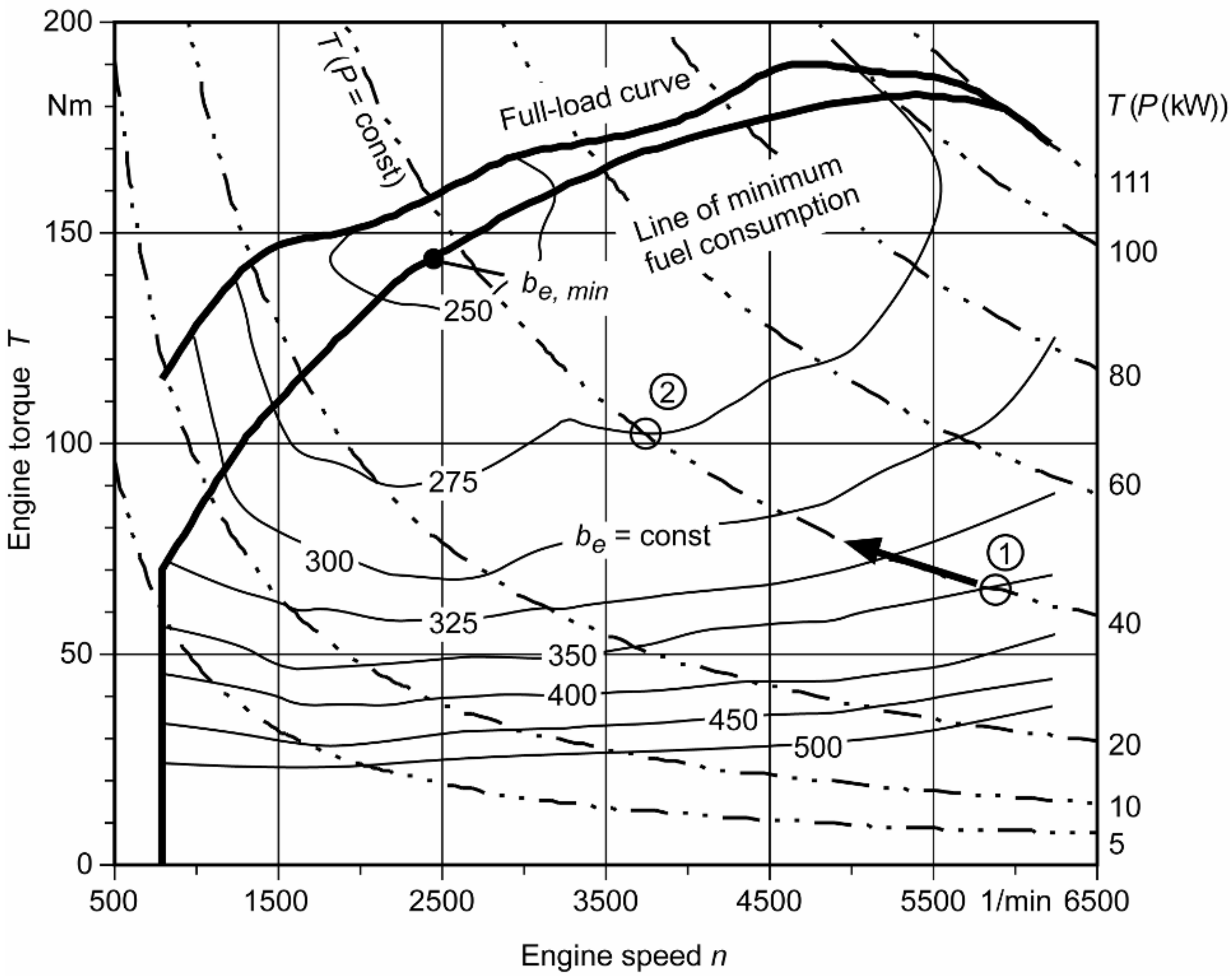
In the engine map the effective average pressure p_{me} in the cylinder is often plotted instead of the engine torque. The following relationship applies

$$p_{me} = \frac{T_M \, 2\pi}{V_H \, i} \quad \text{with} \quad i = \frac{2}{\text{number of strokes}}$$



Consumption Map

- The transmission exploits the fuelefficient areas of the engine performance map.
- Figure shows the contour lines of constant specific fuel consumption b_e (onion curves) as well as the torque/engine speed curves at a constant engine output (demand power hyperbola) $T(P = \text{const})$.
- In this way the same engine output can be achieved at different torque/engine speed values − points *1* and *2* in the engine map − and thus also with different levels of fuel consumption.



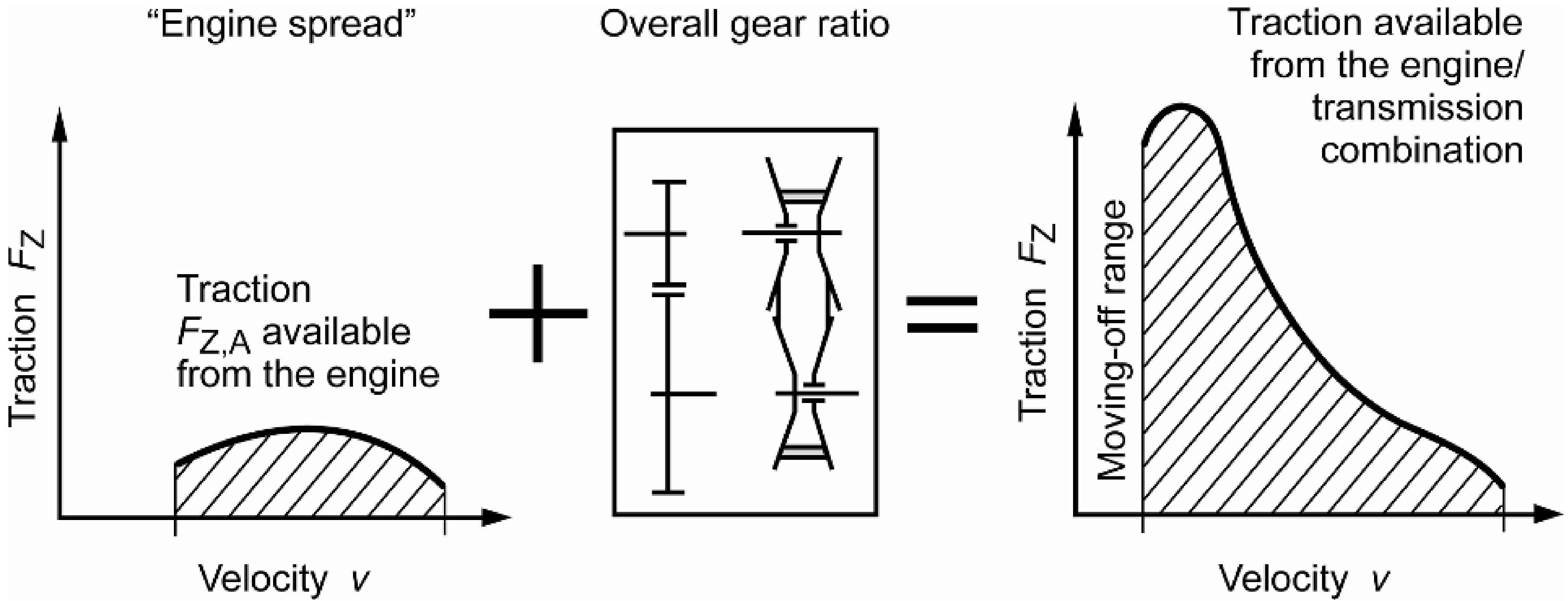
A minimum fuel consumption point can be found on any power hyperbola. The curve passing through these points is the minimum fuel consumption curve.

Powertrain matching

The powertrain components − engine, moving-off element, selector gearbox, final drive etc. − must be “harmoniously” combined

The main optimisation criteria in this process are

- performance,
- fuel consumption,
- emissions and
- comfort.



Traction Diagram

The traction $F_{Z,B}$ required at the drive wheels is made up of the driving resistance forces

$$F_{Z,B} = F_R + F_{St} + F_L + F_a$$

$$F_{Z,B} = m_F\ g\ (f_R\ \cos\alpha_{St} + \sin\alpha_{St}) + \frac{1}{2}\ \rho_L\ c_W\ A\ v^2 + m_F\ \lambda\ a$$

With steady state motion (a = 0) and the approximations mentioned ($\cos \alpha_{St} \approx 1$ and $\sin \alpha_{St} \approx \tan \alpha_{St}$) this simplifies to

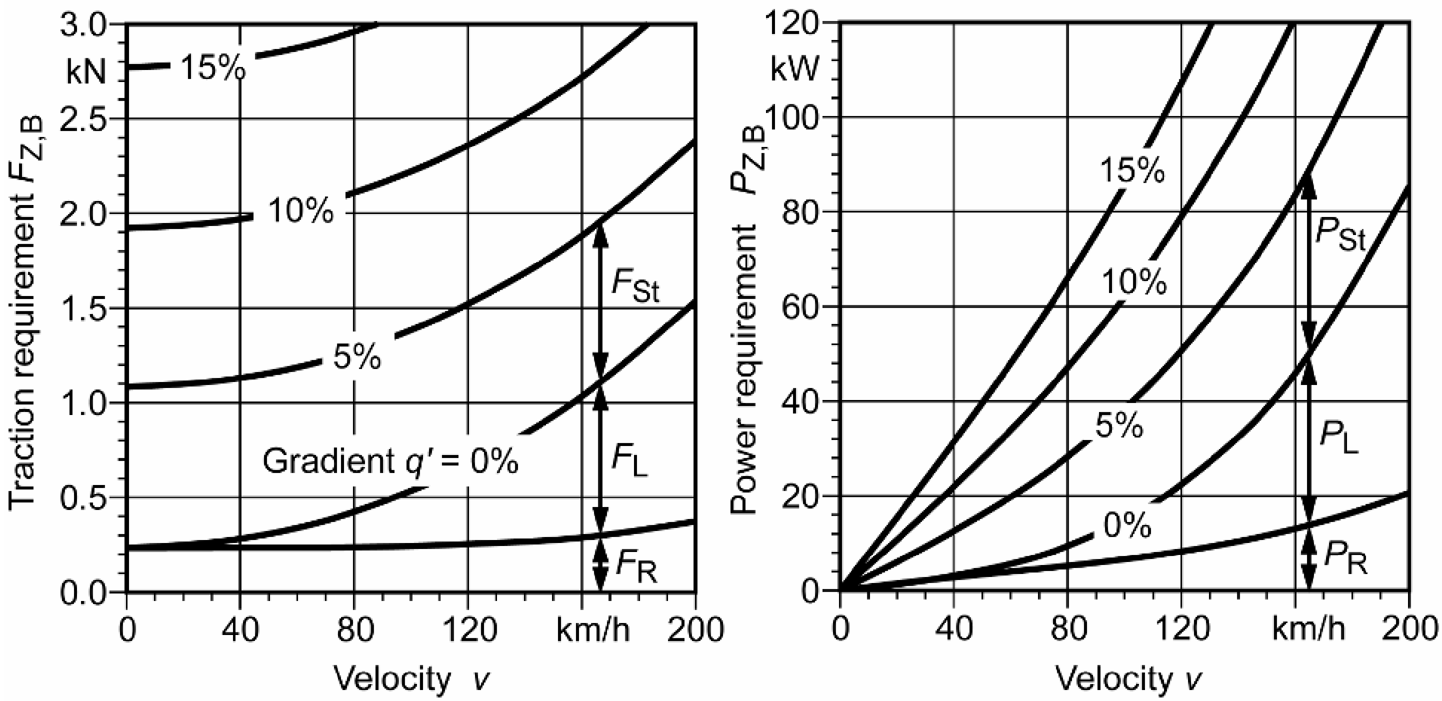
$$F_{Z,B} = m_F\ g\ (f_R + \tan\alpha_{St}) + \frac{1}{2}\ \rho_L\ c_W\ A\ v^2 .$$

This may be used to calculate the power requirement $P_{Z,B}$

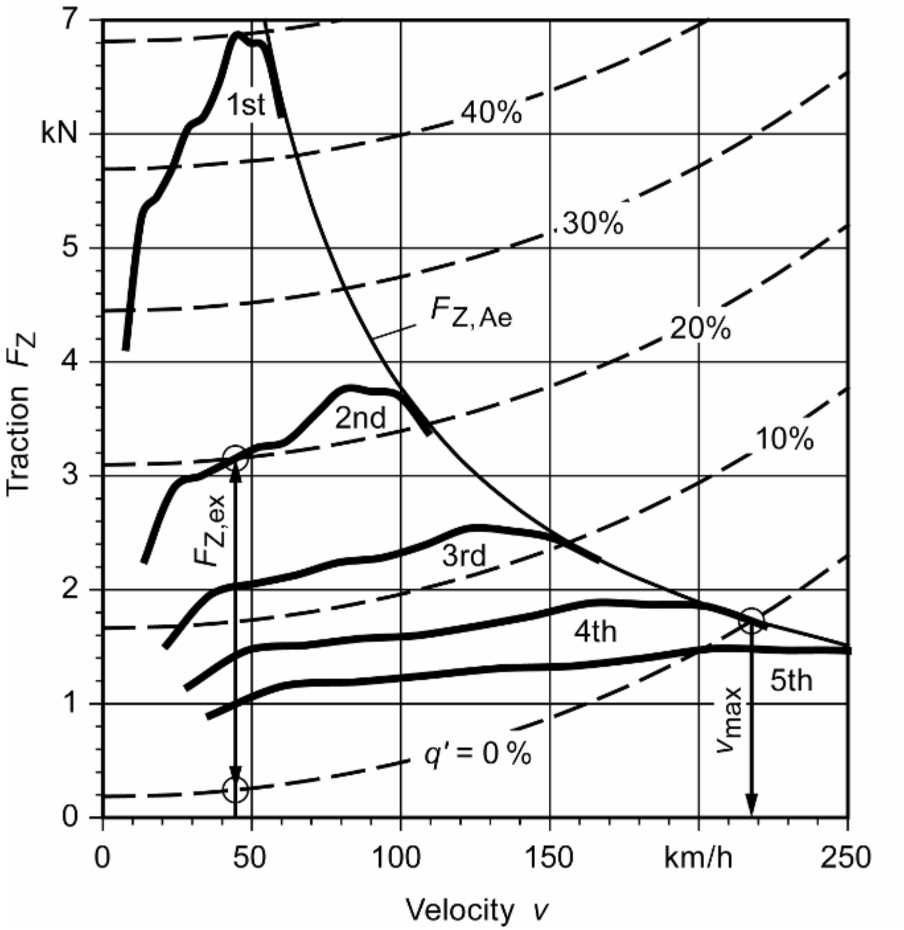
$$P_{Z,B} = F_{Z,B}\ v$$

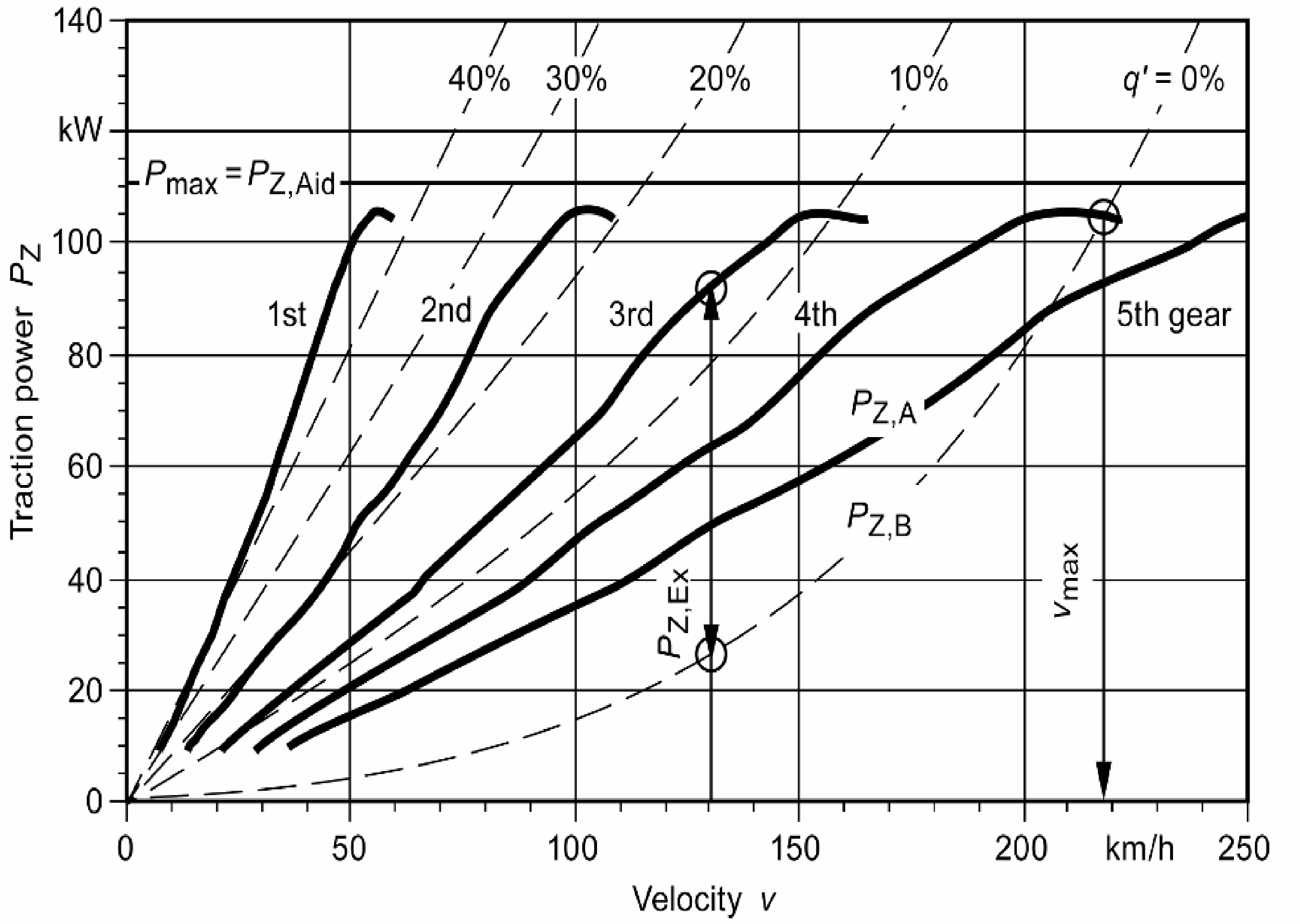
Taking into account the powertrain ratio i_A and the overall powertrain efficiency η_{tot}, the traction $F_{Z,A}$ available at the wheels may be calculated from the engine characteristic curve as follows

$$F_{Z,A} = \frac{P(n_M)}{v}\eta_{tot} = \frac{T(n_M)\ i_A}{r_{dyn}}\eta_{tot} .$$



Traction Diagram





The maximum speed, the maximum climbing performance and excess traction in the various gears can be found from the traction diagram.

Traction Diagram,

Calculation

The maximum speed, the maximum climbing performance and excess traction in the various gears can be found from the traction diagram. The excess traction $F_{Z,Ex}$ is given by the formula

$$F_{Z,Ex} = F_{Z,A} - F_{Z,B} = F_{Z,A} - F_R - F_{St} - F_L - F_a$$

$$= \frac{T(n_M)\, i_A}{r_{dyn}} \eta_{tot} - m_F\, g\,(f_R \cos\alpha_{St} + \sin\alpha_{St}) - \frac{1}{2}\rho_L\, c_W\, A\, v^2 - m_F\, \lambda\, a$$

The traction diagram shows unaccelerated movement, i.e. when a = 0 m/s^2. To interpret the climbing and acceleration performance of a vehicle, the excess power available at the operating point, $F_{Z,Ex}$, can be written in two ways.

climbing performance during unaccelerated movement

$$F_{Z,Ex} = F_{Z,A} - F_R - F_L = m_F\, g \sin\alpha_{St}$$

acceleration performance during movement on the level

$$F_{Z,Ex} = F_{Z,A} - F_R - F_L = m_F\, \lambda\, a$$

Traction Diagram,
Calculation

Determining the Traction Available

1. *Specifying the initial dynamic operating parameters:*
2. *Selecting some characteristic points on the full load curve:*

n_M (1/min)	800	2000	3000	4000	4750	5930	6200
T_M (Nm)	115	150	170	175	189	179	170

3. *Calculating the associated gear-dependent speeds and tractions:*

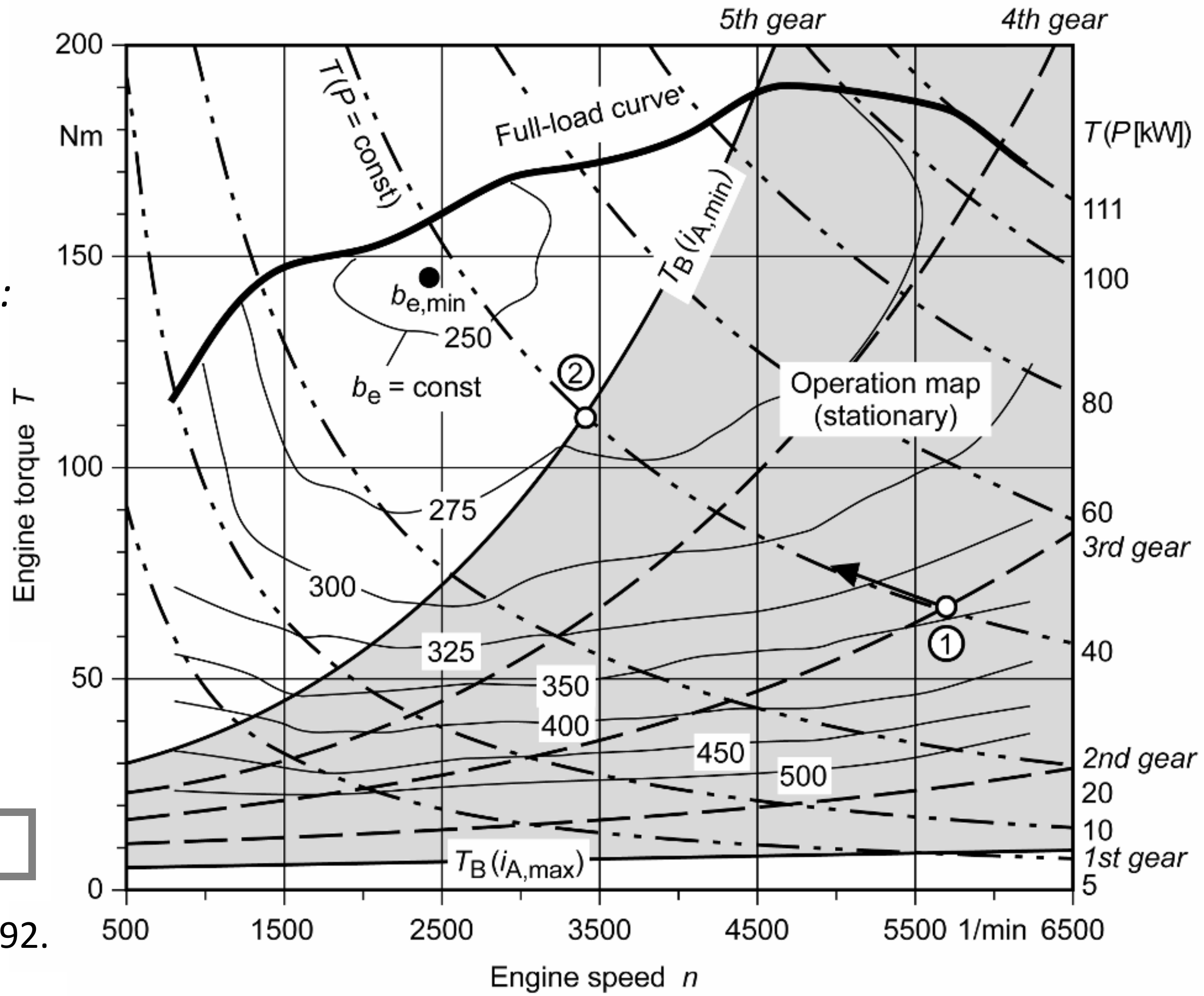
$$v\,(\text{km/h}) = \frac{3.6\,\frac{\pi}{30}\,n_M\,(1/\text{min})\,r_{dyn}}{i_1\,i_E}:$$

v_{1stG} (km/h)	7.6	19.0	28.5	38.0	45.1	56.3	58.9

The powertrain efficiency in 1st gear is assumed to be constant. $\eta_{tot} = 0.92$.

$$F_{Z,A}\ (\text{kN}) = \frac{T(n_M)\,i_E\,i_1}{1000\,r_{dyn}}\,\eta_{tot}:$$

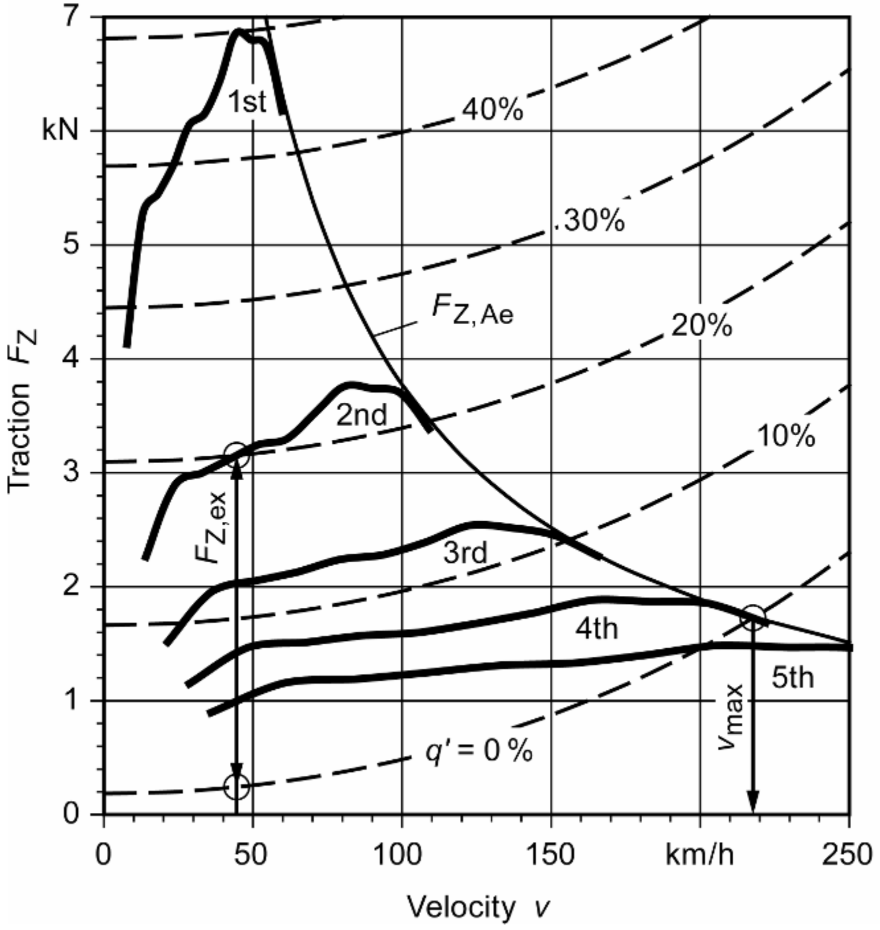
$F_{Z,A1stG}$ (kN)	4.2	5.5	6.2	6.4	6.9	6.5	6.2



Traction Diagram,
Calculation

4. *Entering the traction available/speed values on a diagram:*

$F_{Z,A1stG}$ (kN)	4.2	5.5	6.2	6.4	6.9	6.5	6.2



Traction Diagram,
Calculation

Determining the Driving Resistance Lines

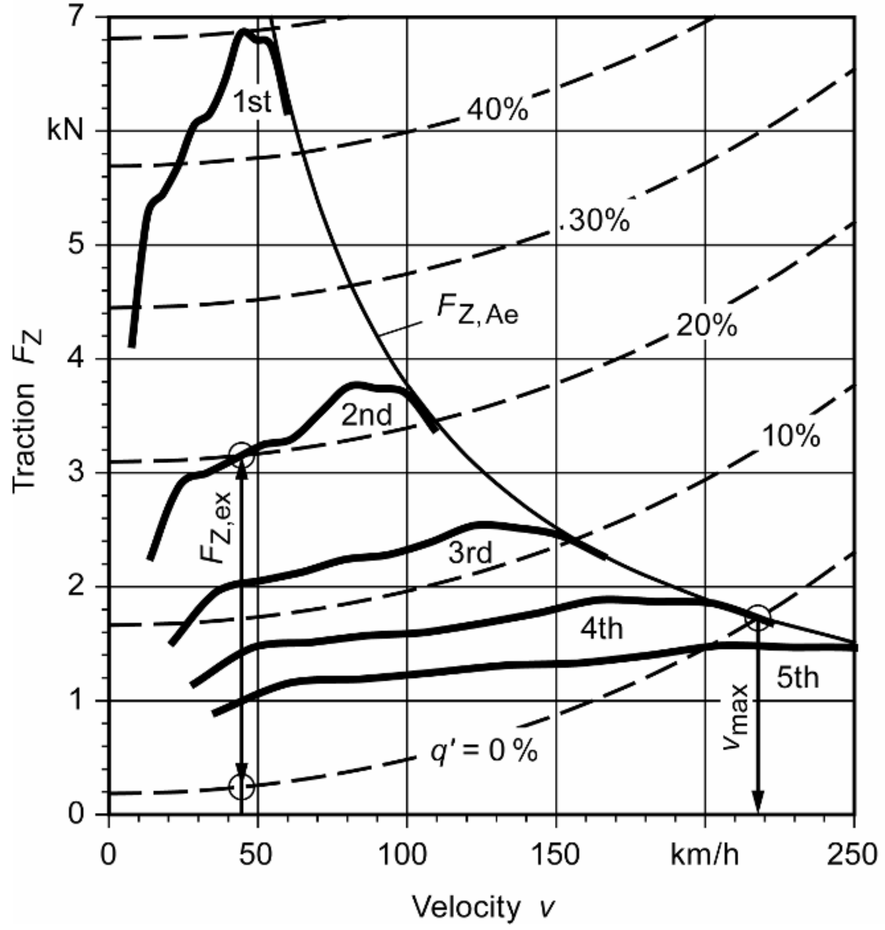
1. *Determining the initial values*
2. *Calculating the traction required at several speeds and gradients*

$$F_{Z,B}\ [\mathrm{kN}] = \frac{1}{1000}\left[m_F\, g\,(f_R \cos\alpha_{St} + \sin\alpha_{St}) + \frac{1}{2}\rho_L\, c_W\, A \frac{v^2\ [\mathrm{km/h}]}{3.6^2}\right]$$

For gradients greater than 10%, the approximations $\cos\alpha_{St} \approx 1$ and $\sin\alpha_{St} \approx \tan\alpha_{St}$ are no longer acceptable. Entering the speed-dependent rolling resistance coefficient f_R gives

v (km/h)	0	50	100	150	200	250
f_R	0.0124	0.0124	0.0131	0.0145	0.0200	0.0330
$F_{Z,B0\%}$ (kN)	0.18	0.26	0.48	0.86	1.45	2.29

3. *Entering the traction required/speed values on the diagram:*



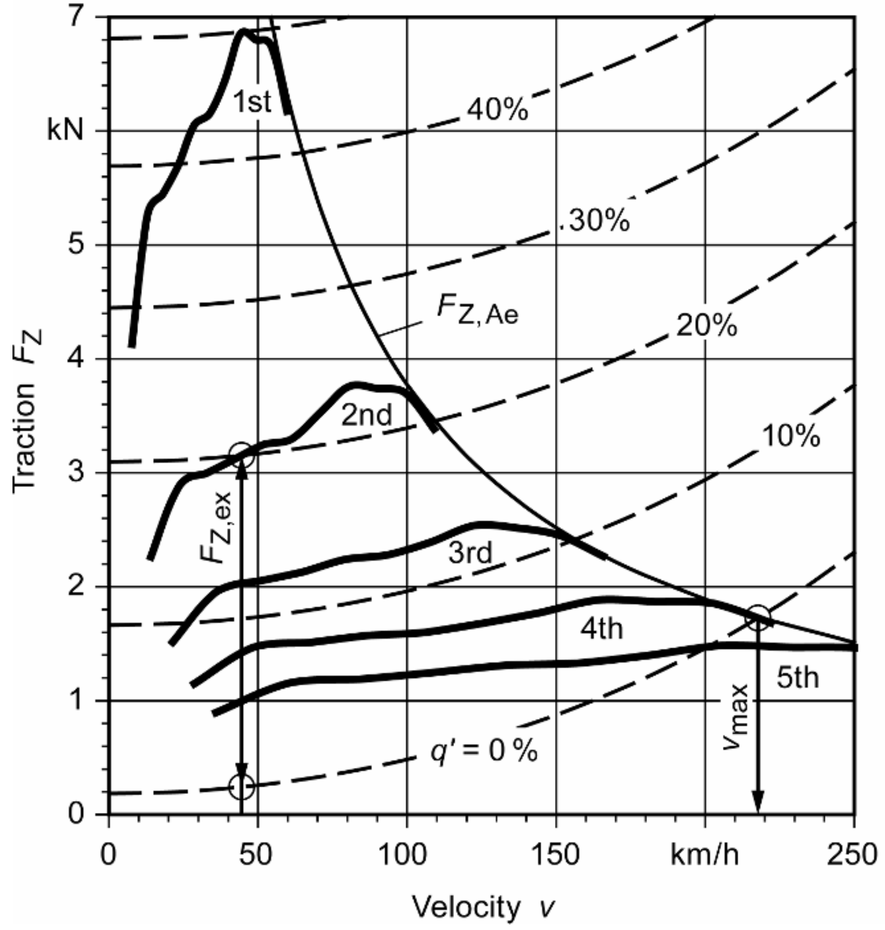
Traction Diagram,
Calculation

Reading of Relevant Data

1. *Maximum speed:*
   The maximum speed of the vehicle on a level surface is achieved in 4th gear, and is approximately 218 km/h. It is found at the intersection of the traction available line and the driving resistance line for *q*' = 0%.

2. *Other performance data:*

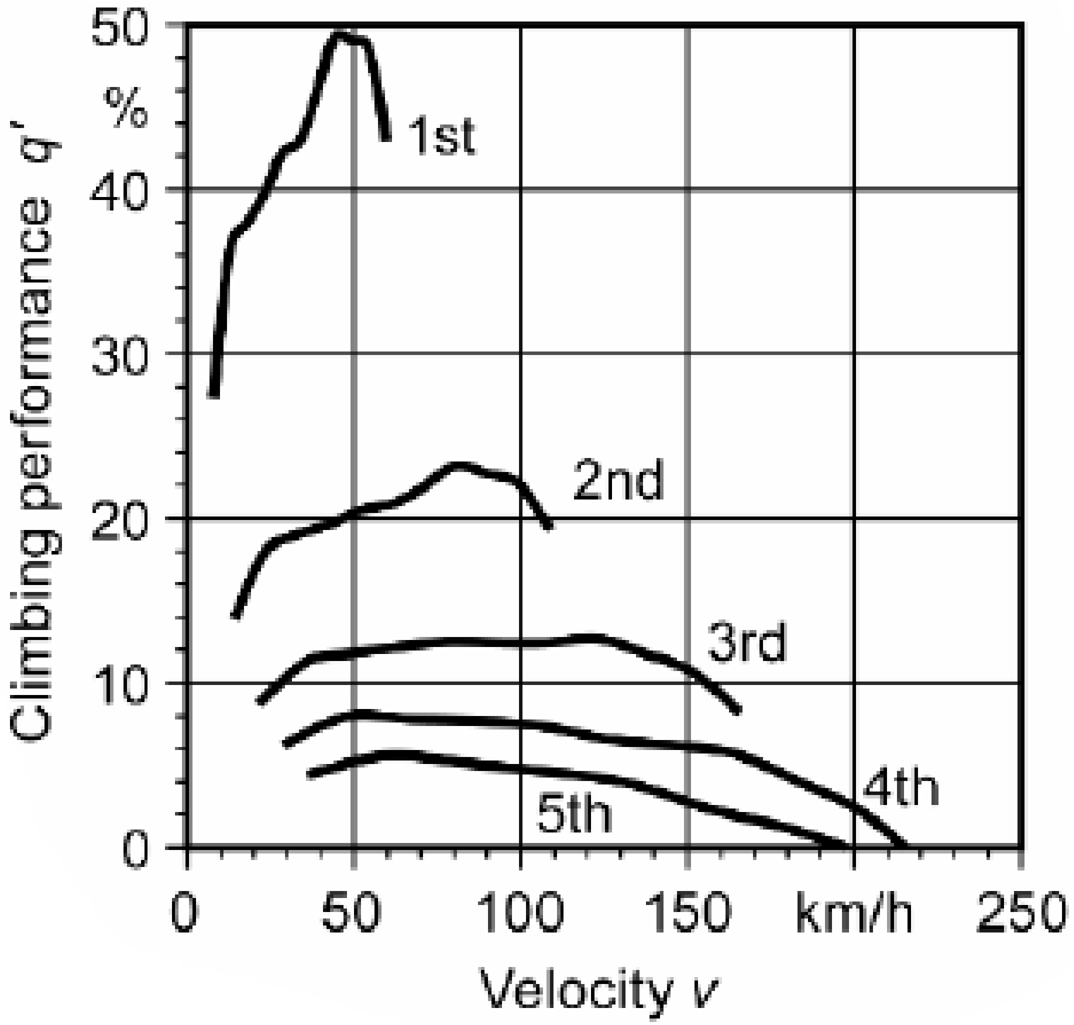
Gear	v (km/h) at		$F_{Z,A}$ (kN) at		$F_{Z,Ex}$ (kN) at		q'_{max} (%) at		a_{max} (m/s²) at	
	T_{max}	T_n	T_{max}	T_n	T_{max}	T_n	T_{max}	T_n	T_{max}	T_n
1	45.8	57.2	6.9	6.5	6.6	6.2	49	46	3.7	3.4
2	83.5	104.3	3.8	3.5	3.3	3.0	23	21	2.0	1.8
3	127.0	158.5	2.5	2.4	1.8	1.4	12	10	1.2	0.9
4	170.1	212.4	1.9	1.8	0.8	0.2	5	1	0.5	0.1
5	213.2	266.1	1.5	1.4	–	–	–	–	–	–



Climbing Performance

- Climbing performance is represented by the gradient resistance.
- Uniform speed (a = 0 m/ss) is assumed when determining climbing performance, so that the entire excess traction $F_{Z,Ex,}$ available to negotiate the gradient.
- The maximum climbing performance is given as

$$\sin \alpha_{\mathrm{St,max}} = \frac{F_{\mathrm{Z,ex}}}{m_{\mathrm{F}}\ g}$$

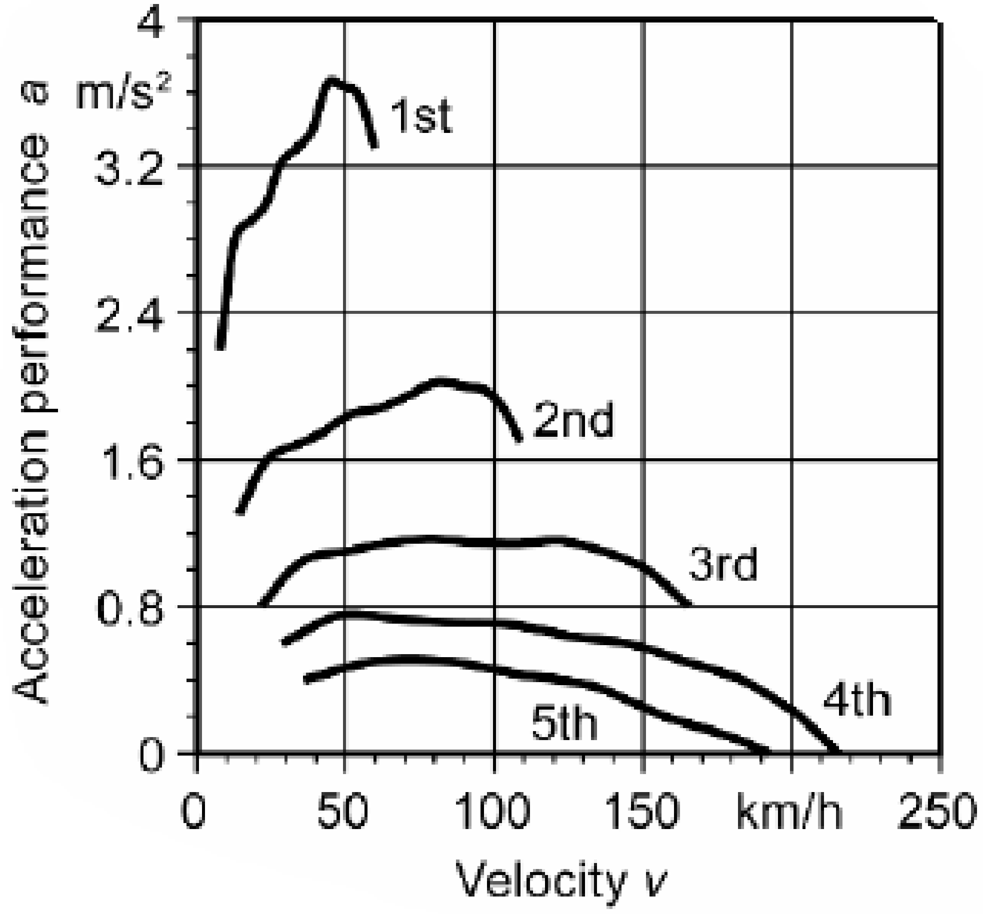


Dependence of climbing performance on gear

Acceleration Performance

- In commercial vehicles the lowest gear is often given a high ratio to give the vehicle good climbing performance, even when fully loaded.
- The coefficient of rotational inertia can thus become very large, with the result that acceleration may be better in second gear than in first.

$$a_{\max} = \frac{F_{\mathrm{Z,Ex}}}{m_{\mathrm{F}}\ \lambda_{\mathrm{n}}}$$



Acceleration performance of the test vehicle

Engine Braking Force

- Fast downhill speeds are required for trucks to achieve high average speeds and hence economic transport
- Attainable downhill speeds are those which can be travelled without acceleration and without activating the service brake (friction brake)

  - ***steady-state braking:***

  preventing unwanted acceleration on downhill runs,
  - ***deceleration braking:***

  reducing speed and stopping if necessary and
  - ***braking at rest:***

  preventing undesired movement of the vehicle at rest

Engine Braking Force

The engine braking power available $F_{B,A}$ is incorporated in the traction diagram in a similar way to the traction available $F_{Z,A}$.

Power flow in overrun conditions is from the wheels to the engine. Whereas the traction diagram is calculated from the full load characteristic curve of the engine when power flow is from the engine to the road

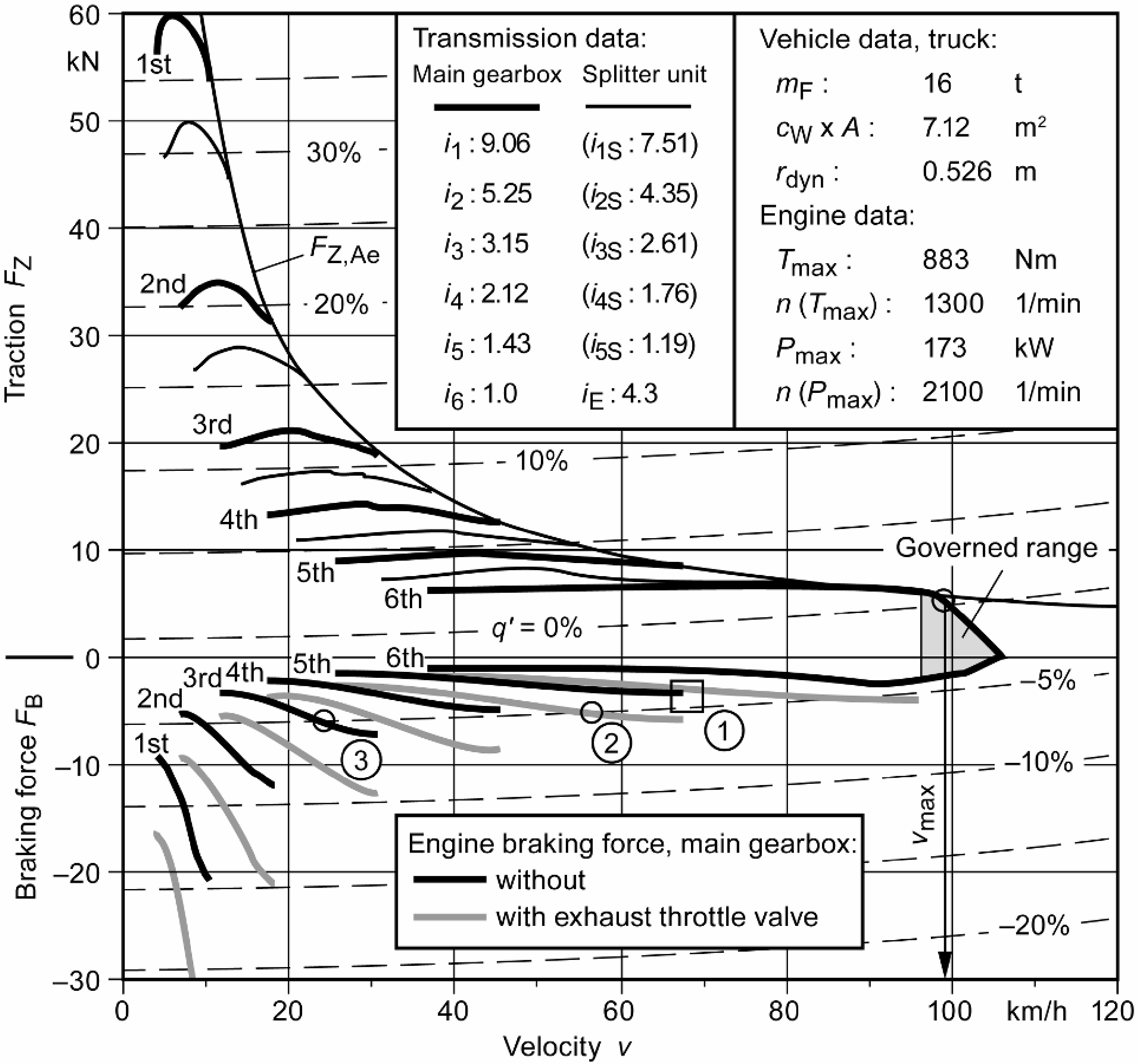
If the variation in the powertrain efficiency η_{tot} = f (ratio, speed, torque) is taken into account in calculating engine braking force, then it must be remembered that the ratio is defined in the direction of power flow. That means that in overrun conditions "the ratio is reversed".

$$F_{Z,A} = \frac{T(n_M)\left(\frac{n_M}{n_R}\right)}{r_{dyn}} \eta_{tot} = \frac{T(n_M)\, i_A}{r_{dyn}} \eta_{tot}$$

$$F_{B,A} = \frac{T(n_M)}{r_{dyn}\, \eta_{tot} \left(\frac{n_R}{n_M}\right)} = \frac{T(n_M)\, i_A}{r_{dyn}\, \eta_{tot}}$$

Engine Braking Force

- Engine braking force in 5th gear without an exhaust throttle is not adequate to prevent acceleration when travelling down a 5% slope **(Point *1*);**
- this is made possible by using an engine brake in 5th gear **(Point 2).**
- Without an exhaust throttle the vehicle would have to travel down the slope in 3rd gear at a lowerspeed (**Point 3).**

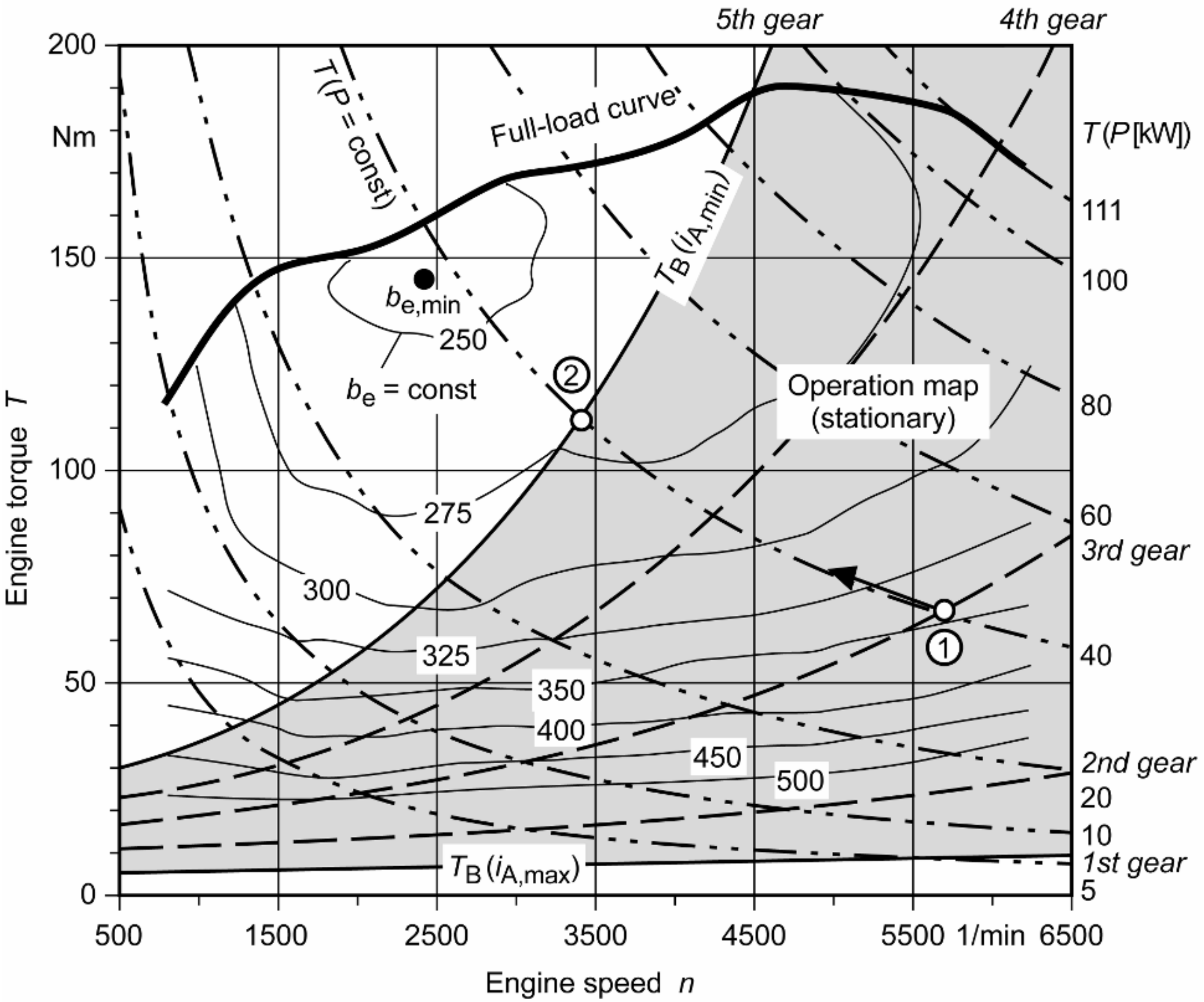


Fuel Consumption

The fuel consumption of a vehicle is expressed either as

- consumption per distance travelled b_s in l /100 km
- consumption per unit time b_t in g/h.

- The specific fuel consumption b_e at any momentary operating point may be read off the engine performance map
- This requires the engine speed n_M and the associated engine torque $T(n_M)$



The engine speed is calculated from the road speed

$$n_M = \frac{v\, i_A}{2\pi\, r_{dyn}}$$

The engine torque required $T_{Z,B}(n_M)$ is calculated from the traction required at the wheels and the powertrain efficiency

$$T_{Z,B}(n_M) = \frac{F_{Z,B}\, r_{dyn}}{i_A} \frac{1}{\eta_{tot}}$$

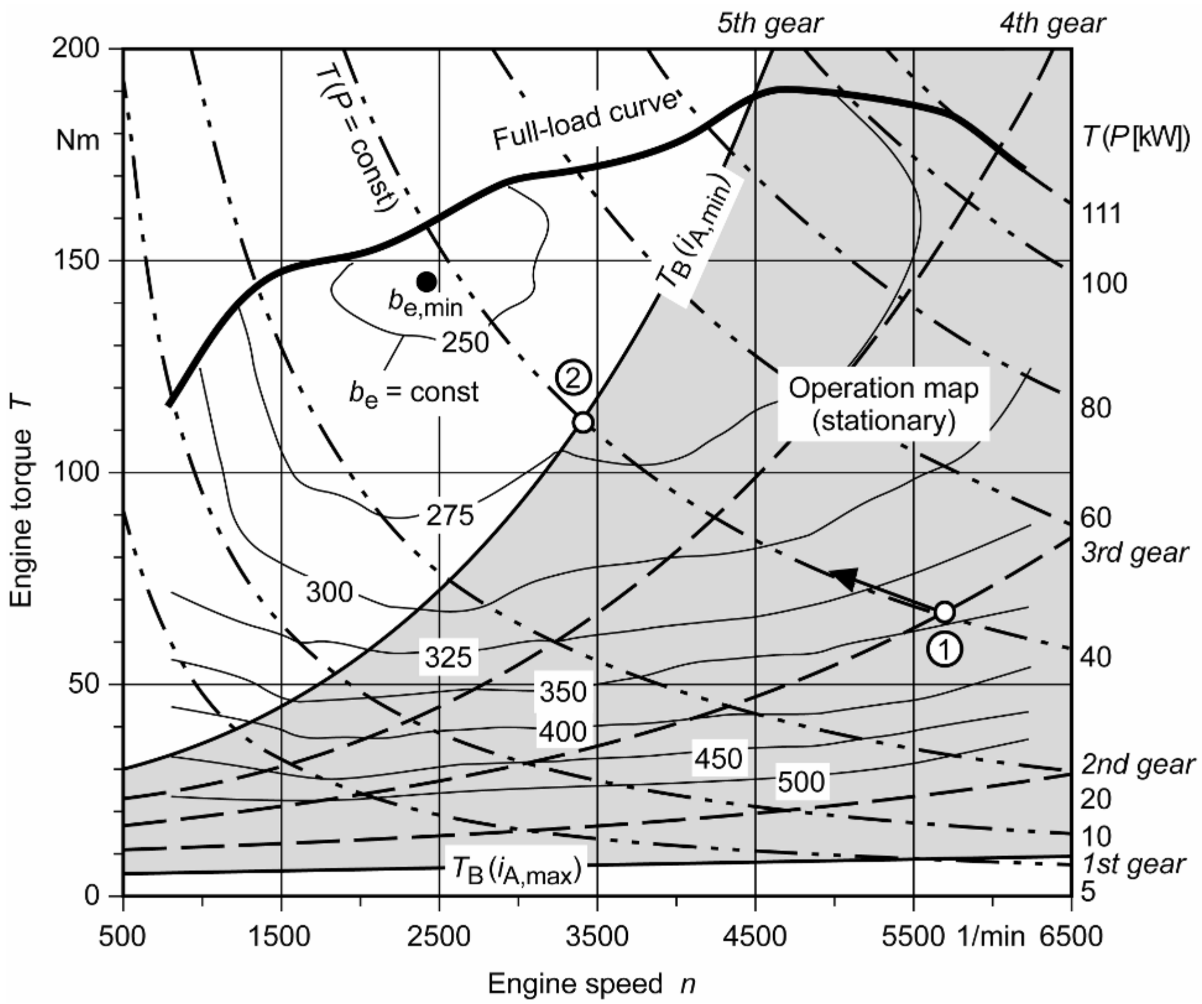
The fuel consumption per unit distance

$$b_s = \frac{b_e\, P(n_M)}{\rho_{fuel}\, v} = \frac{b_e\, F_{Z,B}}{\rho_{fuel}\, \eta_{tot}}$$

Fuel Consumption

Calculation

- Constant speed of 150 km/h
- Given that f_R = 0.0145
- ρ_L = 1.199 kg/m3,
- the traction requirement at the wheels is 862 N.
- powertrain efficiency of ηtot = 0.92 (assumed constant)
- If the vehicle travels at this speed in 3rd gear, then operating point *1* shows a specific fuel consumption *b*e ≈ 350 g/kWh
- petrol density of ρ_{fuel} = 755 g/*l*



$$b_s = \frac{350\left(\frac{\text{g}}{\text{kWh}}\right)40\,(\text{kW})}{755\left(\frac{\text{g}}{l}\right)150\left(\frac{\text{km}}{\text{h}}\right)} = 0.124\left(\frac{l}{\text{km}}\right) = 12.4\left(\frac{l}{100\,\text{km}}\right).$$

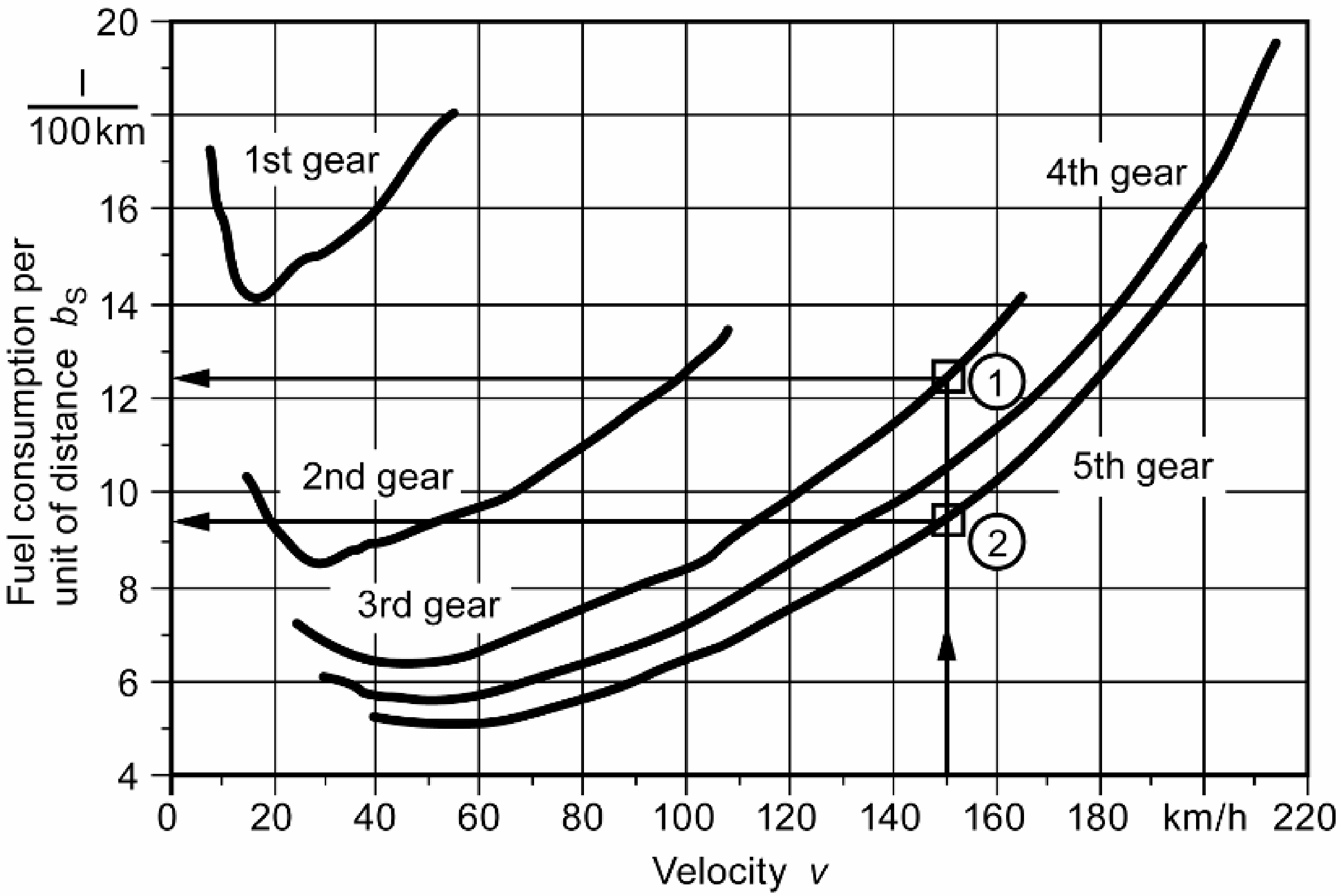
Driving in 5th gear (operating point *2*), b_e ≈ 270 g/kWh.

$$b_s = \frac{270\left(\frac{\text{g}}{\text{kWh}}\right)862\left(\text{N} = \frac{\text{Ws}}{\text{m}} = \frac{\text{kWh}}{\text{km}\,3600}\right)}{755\left(\frac{\text{g}}{l}\right)0.92} = 0.093\left(\frac{l}{\text{km}}\right) = 9.3\left(\frac{l}{100\,\text{km}}\right)$$

Fuel Consumption

Calculation

- The driver can thus have a decisive effect on fuel consumption by the gear selection and the timing of gearshifts.
- In each gear there is a speed at which fuel consumption is optimal.
- Because air resistance increases as the square of speed, the power requirement, and thus fuel consumption, increases rapidly at high speed.



Fuel consumption related to gear for the vehicle

Fuel Consumption

Reduction

- **Optimising the efficiency of the internal combustion engine,** in particular by reducing part-load consumption.
- **Appropriate engine performance characteristics**, i.e. the vehicle must be neither over-powered nor under-powered.
- **Reducing driving resistance**, for example rolling resistance and drag.
- **Reducing the power draw of accessories** such as servo pumps, air conditioning etc.
- **Improving the efficiency of the transmission**. This relates principally to continuously variable transmissions, which includes torque converters.
- **Traffic management systems** to reduce stationary periods.
- **Improved driving**. Intelligent control systems, which protect the driver against his own misjudgement. There are many factors involved in determining how far this "usurping" of control can go.

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