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Optimal network electrification plan for operation of battery-electric multiple unit regional trains

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Lab Digital Rail Traffic

Lab Smart Public Transport

Content

- Introduction
- Configuration and Modelling of Battery-Electric Propulsion System
- Optimization Framework for the Intermittent Track Electrification
- Case Study of the Dutch Northern Lines
- Conclusions

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Introduction

- **Non-electrified regional railway networks** require implementation of alternative traction options to meet stringent emission regulations and defined targets.
- **Battery-electric multiple units** offer zero-emission trains operation, requiring only partial track electrification.
- **Research aim: development of a cost-optimal intermittent electrification plan**, as opposed to the conventional continuous electrification approach.
- **Geographical context:** Northern lines in the Netherlands operated by Arriva, the largest regional railway undertaking.

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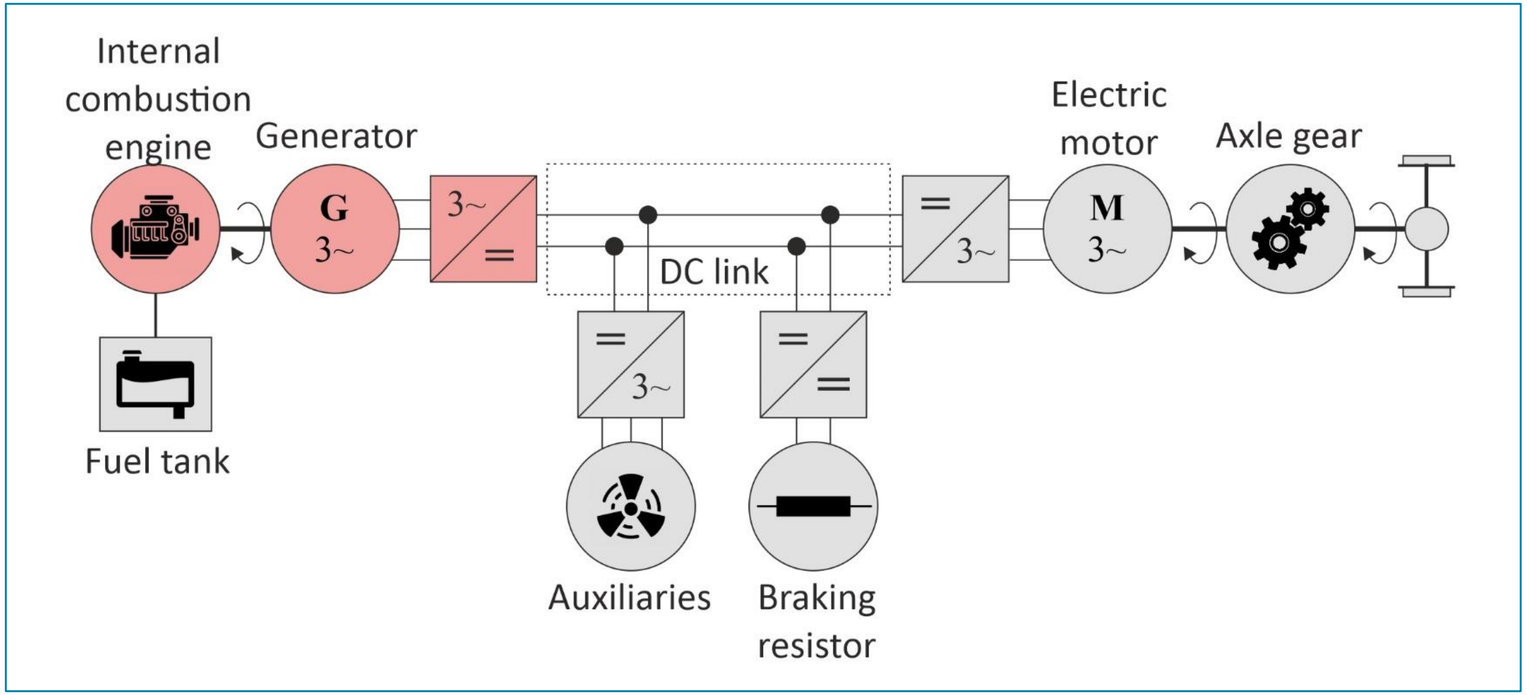
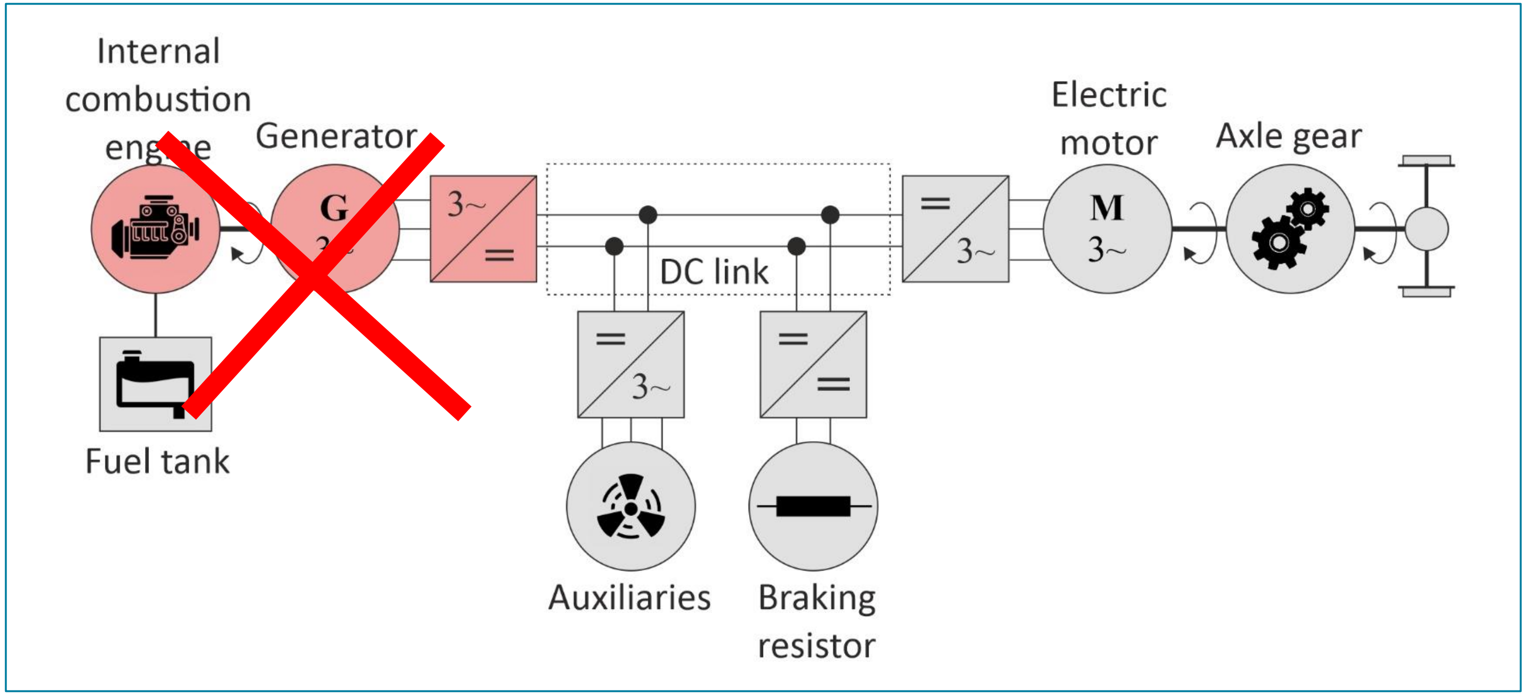
Configuration and Modelling of Battery-Electric Propulsion System

Standard (Diesel-Electric) Propulsion System



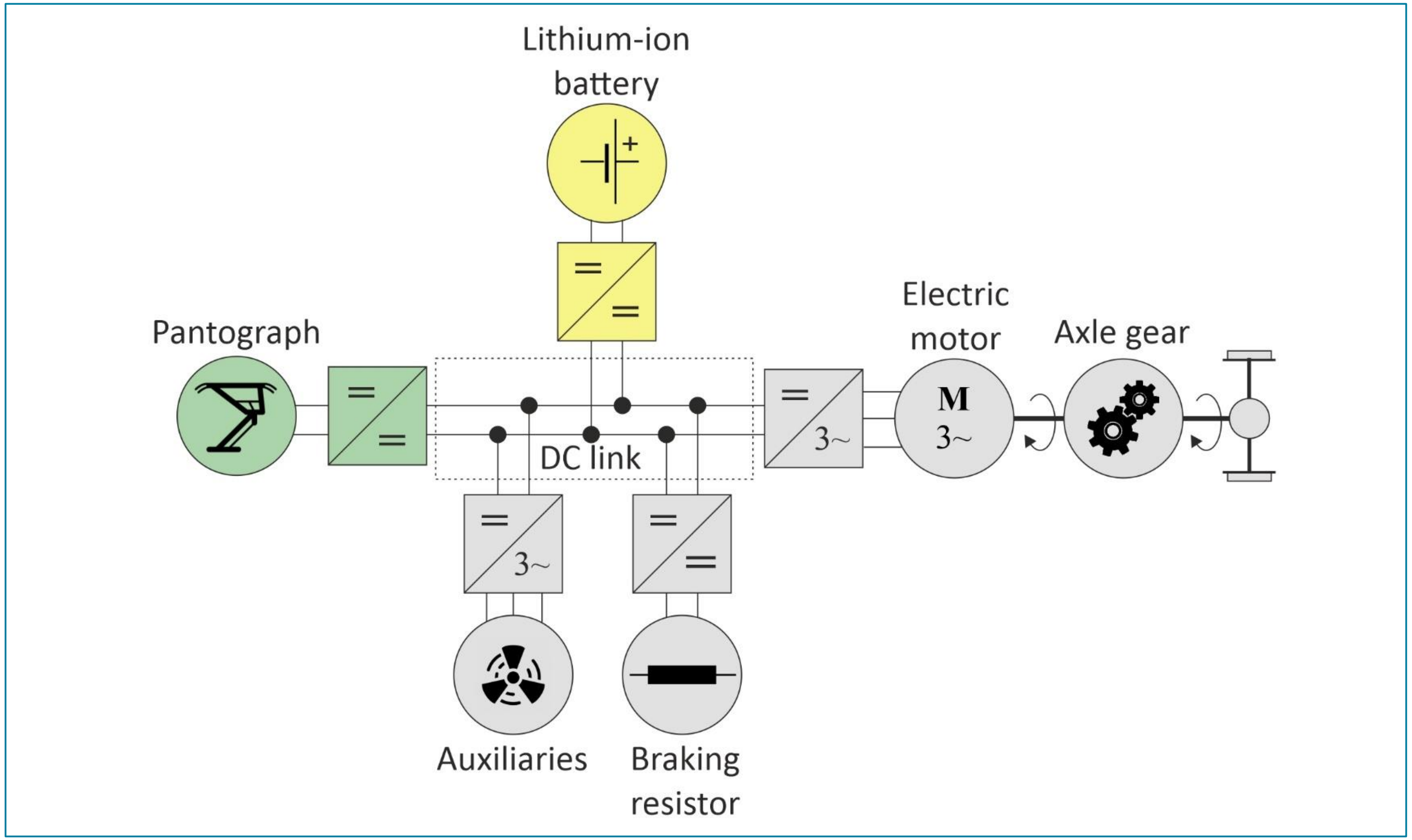
Configuration and Modelling of Battery-Electric Propulsion System

Standard (Diesel-Electric) Propulsion System



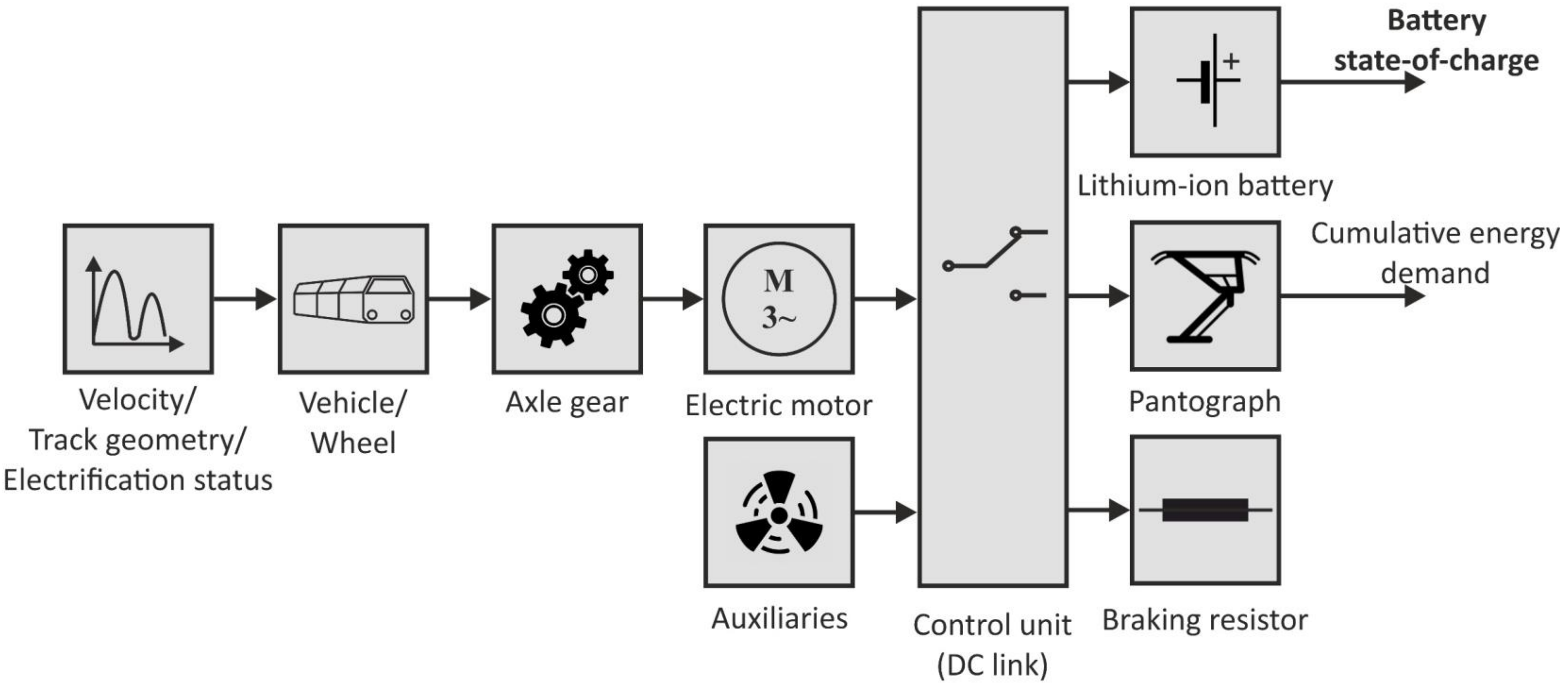
Configuration and Modelling of Battery-Electric Propulsion System

Battery-Electric Propulsion System



Modelling of Battery-Electric Propulsion System

- Backward-looking quasi-static simulation approach
- MATLAB®/Simulink© environment
- OPEUS Simulink toolbox



- Kapetanović, M., Nunez, A., van Oort, N., Goverde, R. (2021). Reducing fuel consumption and related emissions through optimal sizing of energy storage systems for diesel-electric trains. Appl. Energy, 294, 117018 .
- Kapetanović, M., Vajihi, M., Goverde, R.M.P. (2021), “Analysis of Hybrid and Plug-In Hybrid Alternative Propulsion Systems for Regional Diesel-Electric Multiple Unit Trains”, Energies, 14(18), 5920.
- Kapetanović, M., Nunez, A., van Oort, N. and Goverde, R.M.P. (2022), “Analysis of hydrogen-powered propulsion system alternatives for diesel-electric multiple unit regional trains”, J. Rail Transp. Plan. Manag.

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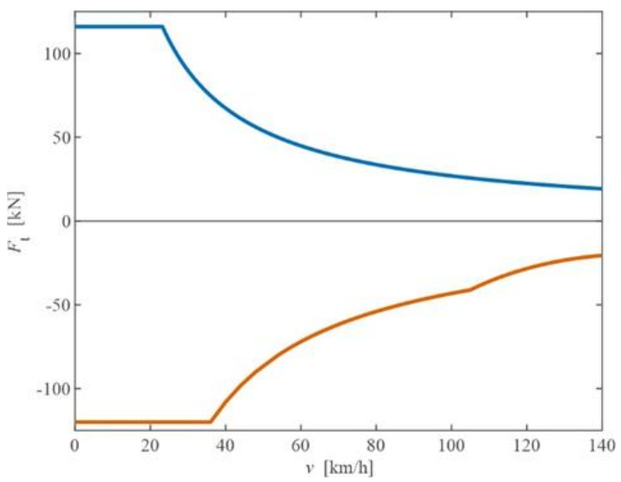
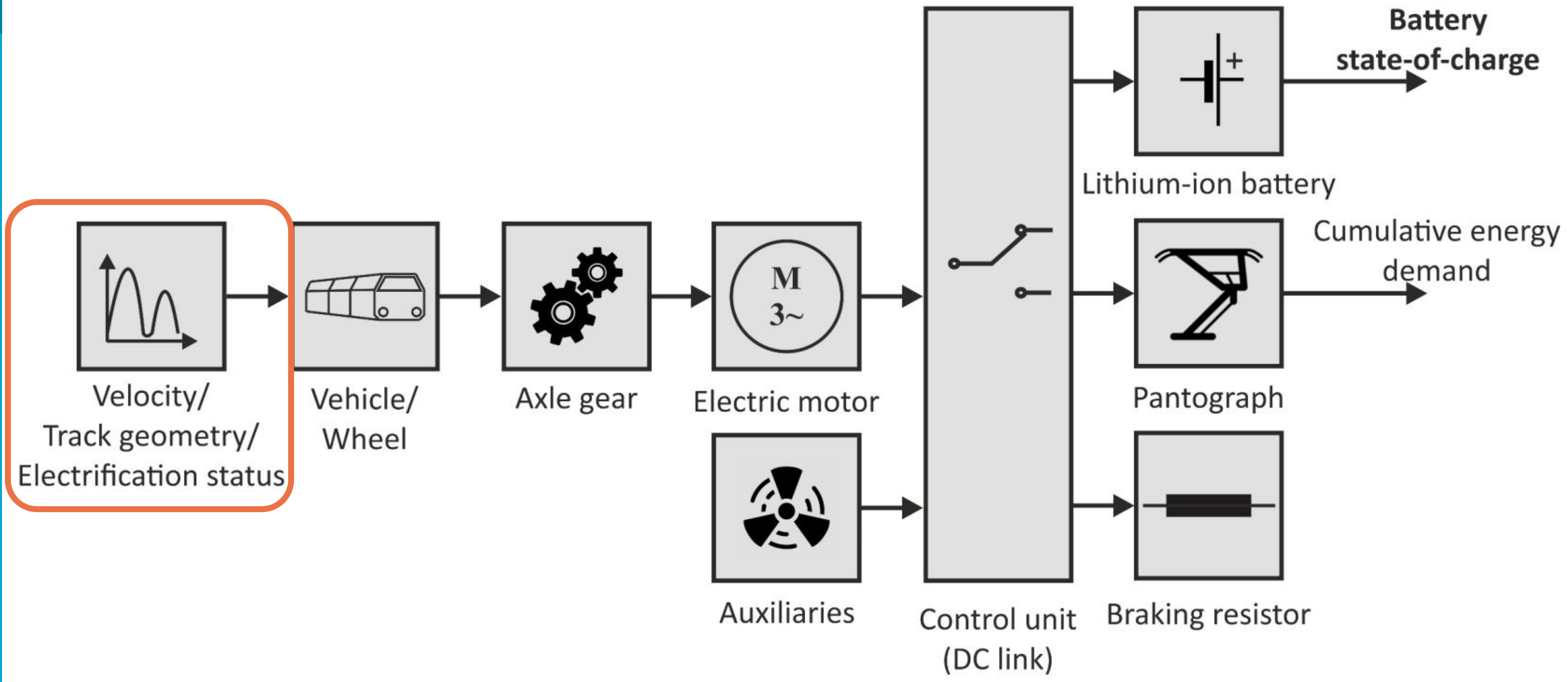
Main inputs of the simulation model:

- **Vehicle parameters**
- **Track geometry**
- **Electrification status**
- **Velocity profile** (complying with the timetable, speed limits, vehicle weight, and maximum tractive effort)

Tractive effort vs. velocity curve:



Modelling of Battery-Electric Propulsion System



Modelling of Battery-Electric Propulsion System

Vehicle/Wheel

Tractive/braking effort at the wheel:

$$F_\mathrm{w}(v(t)) = m_\mathrm{v} \cdot a(t) + R_\mathrm{v}(v(t)) + R_\mathrm{g}\left(\gamma(s(t))\right) + R_\mathrm{C}\left(\phi(s(t))\right)$$

with

$$R_\mathrm{v}(v(t)) = r_0 + r_1 \cdot v(t) + r_2 \cdot v(t)^2$$

$$R_\mathrm{g}\left(\gamma(s(t))\right) = m_\mathrm{V} \cdot g \cdot \sin\left(\gamma(s(t))\right)$$

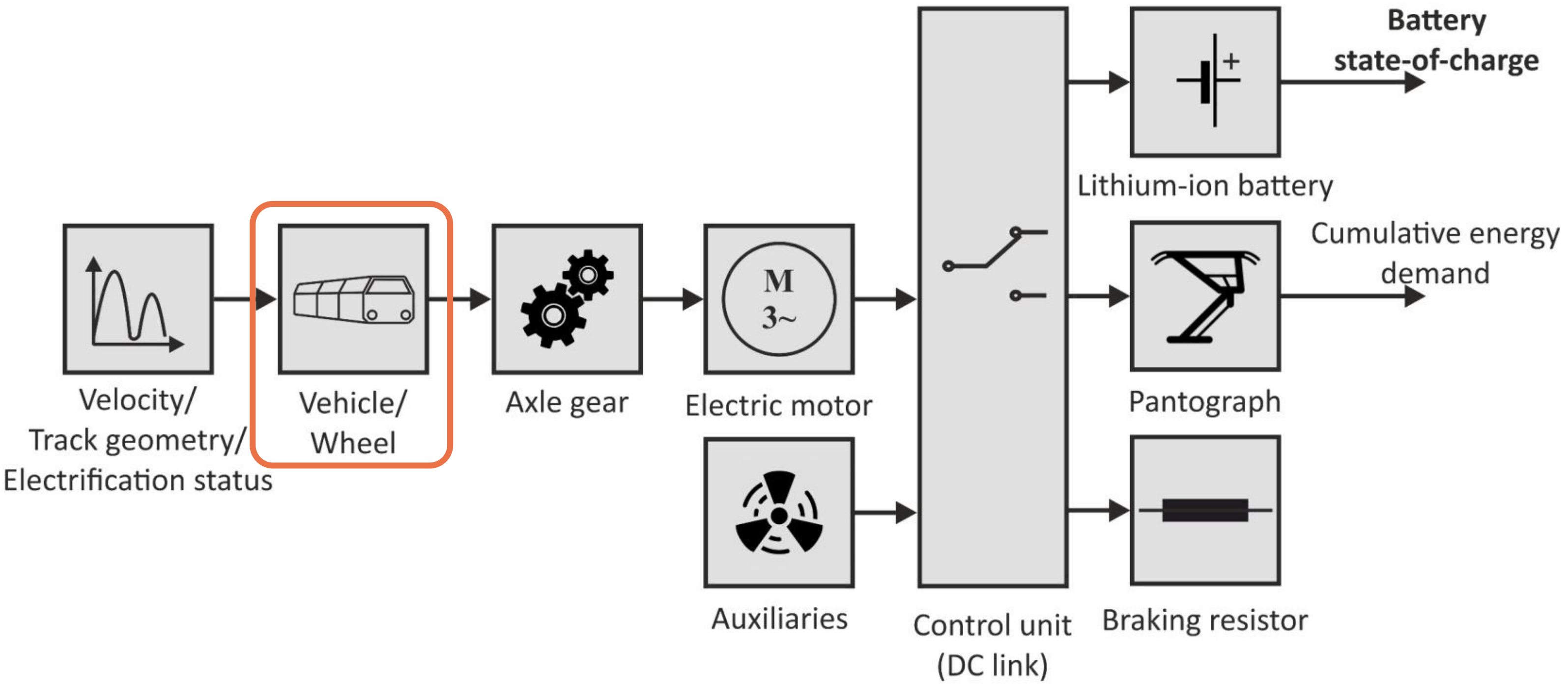
$$R_\mathrm{C}\left(\phi(s(t))\right) = \begin{cases} m_\mathrm{V} \cdot \dfrac{4.91}{\phi - 30} & if\ \phi < 300\ \mathrm{m} \\ m_\mathrm{V} \cdot \dfrac{6.3}{\phi - 55} & if\ \phi \geq 300\ \mathrm{m} \end{cases}$$

Torque at the wheel:

$$T_\mathrm{w}(t) = F_\mathrm{w}(t) \cdot \frac{d_\mathrm{w}}{2}$$

Rotational speed of the wheel:

$$\omega_\mathrm{w}(t) = 2 \cdot \frac{v(t)}{d_\mathrm{w}}$$



Axle Gear

Torque and rotational speed at the mechanical input of the axle gear:

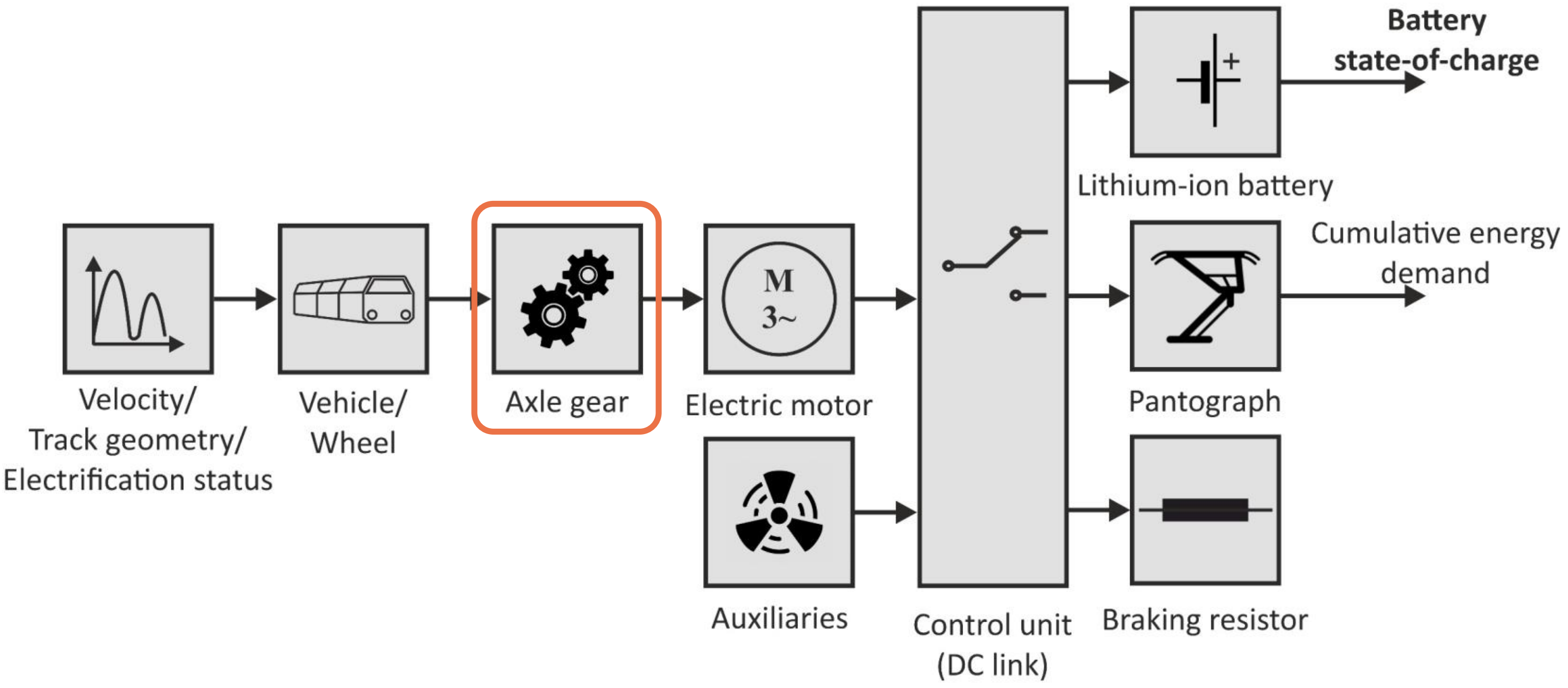
$$T_{EM}(t) = \begin{cases} \dfrac{T_W(t)}{i_{ag} \cdot \eta_{ag}} & if\ T_W \geq 0 \\ \dfrac{T_W(t) \cdot \eta_{ag}}{i_{ag}} & if\ T_W < 0 \end{cases}$$

$$\omega_{EM}(t) = \omega_W(t) \cdot i_{ag}$$

where

$$i_{ag} = const.$$

$$\eta_{ag} = const.$$



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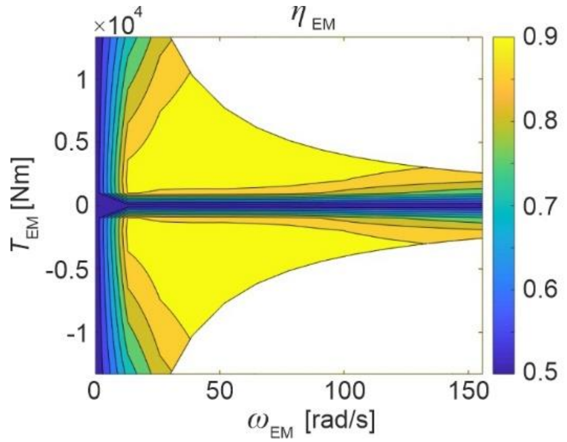
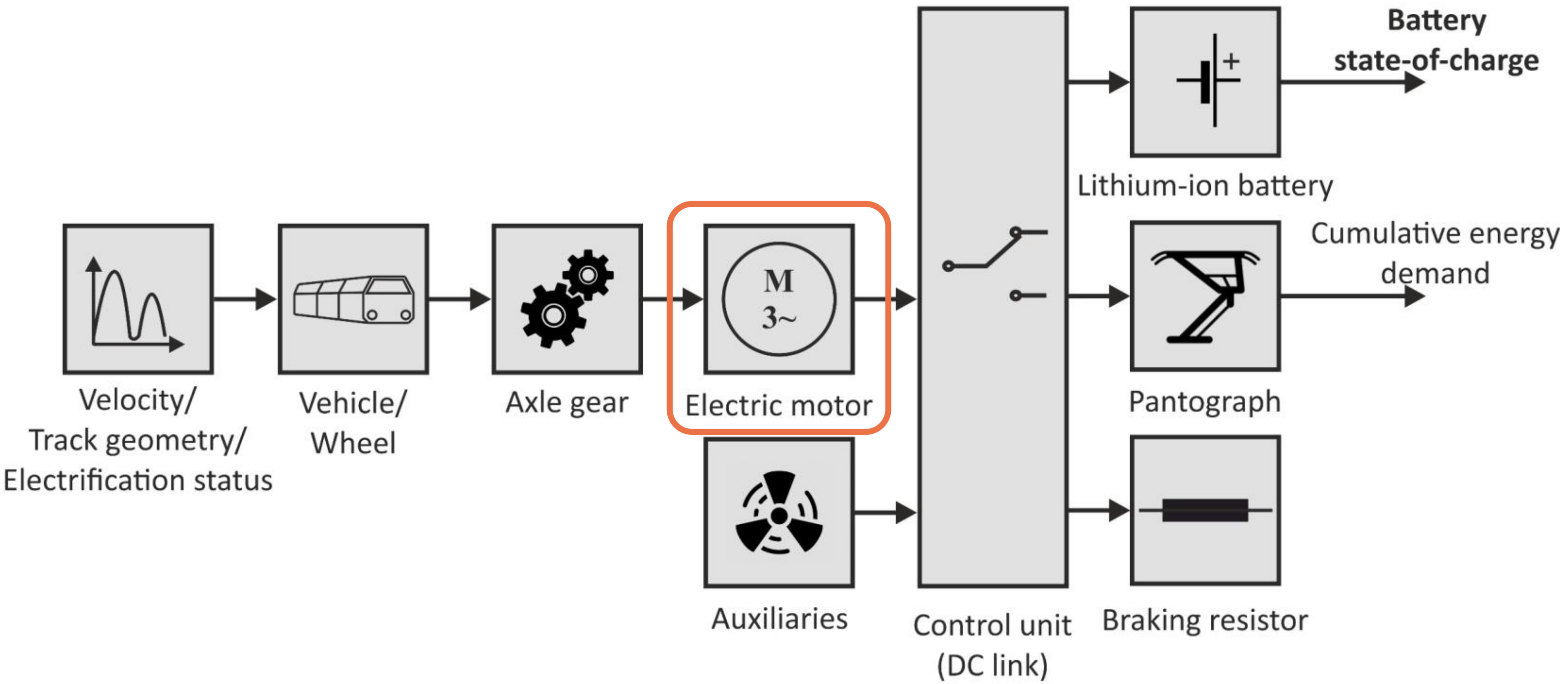
Electric Motor

Electric power:

$$P_{EM}(t) = \begin{cases} \dfrac{T_{EM}(t) \cdot \omega_{EM}(t)}{\eta_{EM}\left(T_{EM}(t), \omega_{EM}(t)\right)} & if\ T_{EM} \geq 0 \\ T_{EM}(t) \cdot \omega_{EM}(t) \cdot \eta_{EM}\left(T_{EM}(t), \omega_{EM}(t)\right) & if\ T_{EM} < 0 \end{cases}$$

Efficiency map:

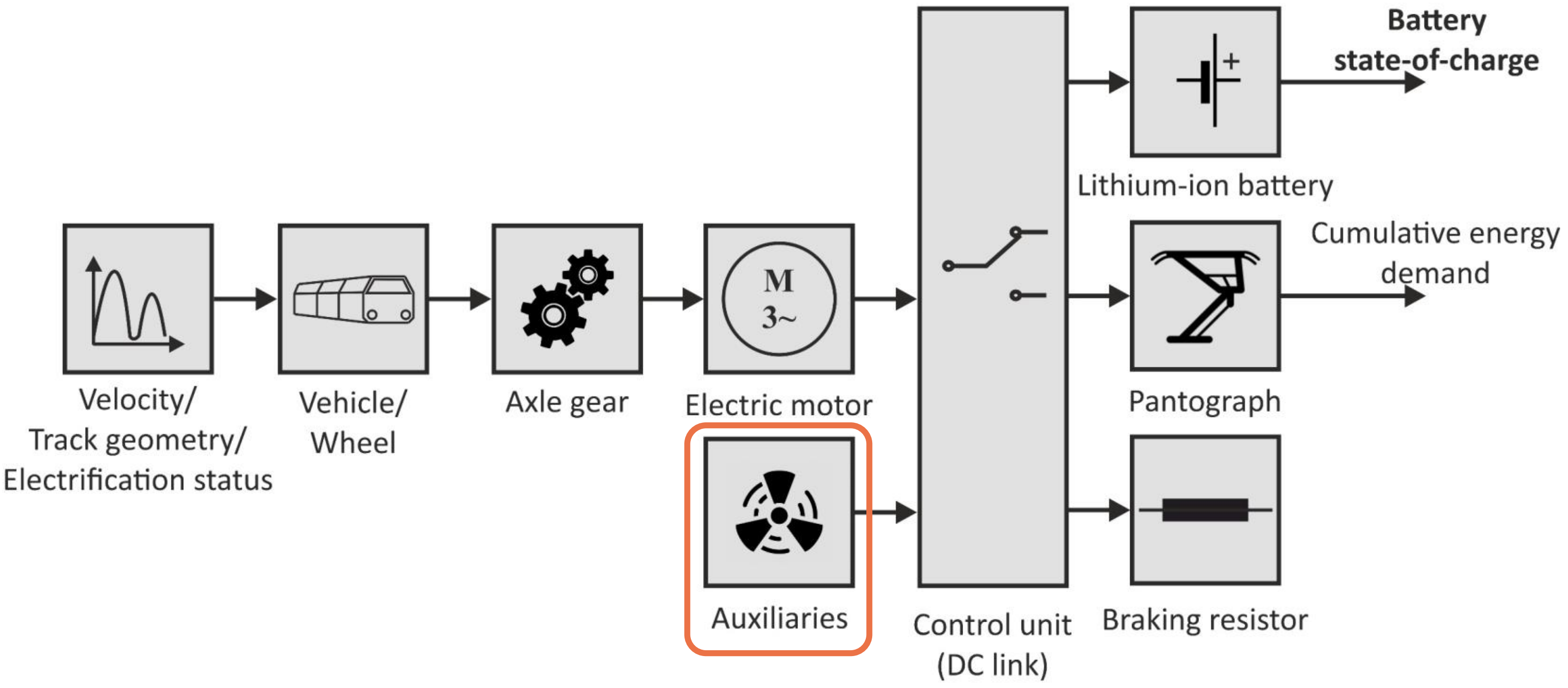




Auxiliaries

Total auxiliary systems' power:

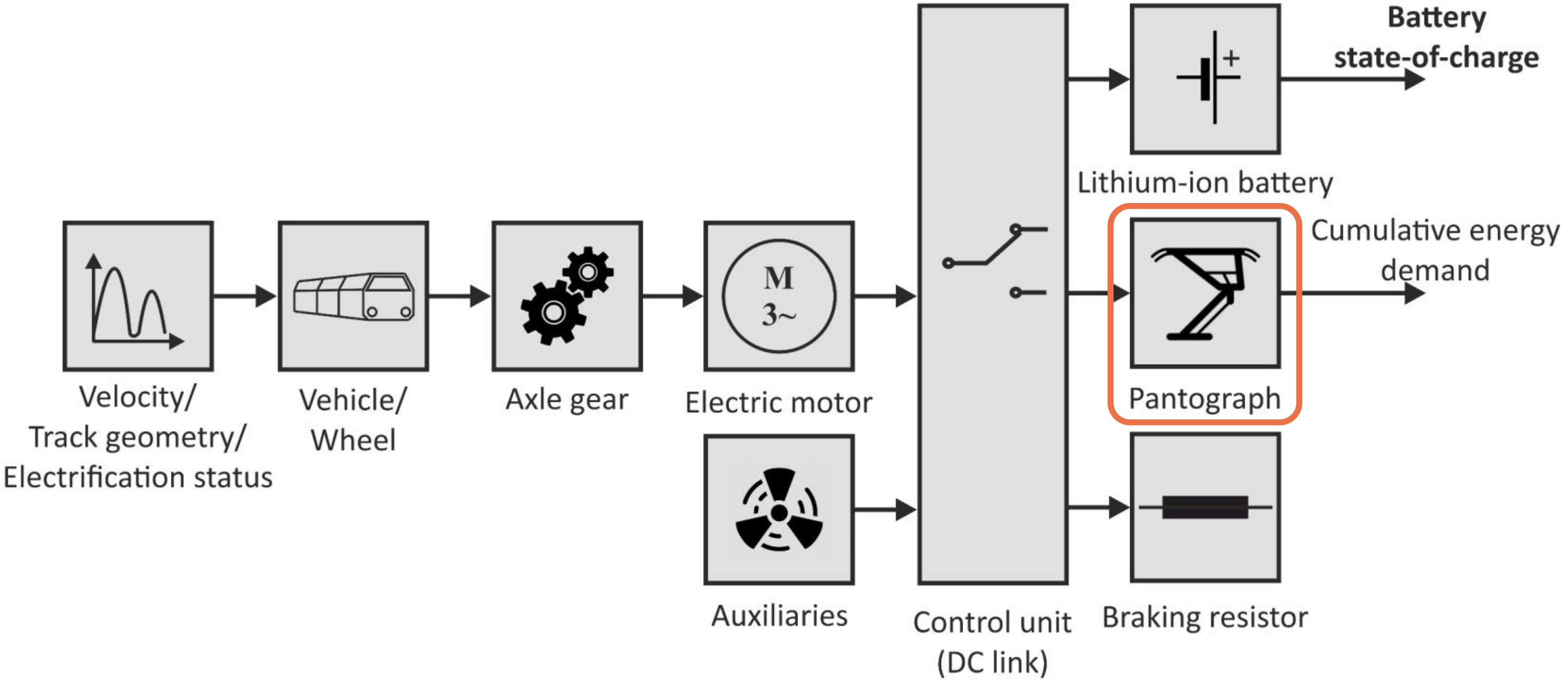
$$P_{\mathrm{aux}}(t) = P_{\mathrm{aux,const}} + p_{\mathrm{cool}} \cdot |P_{\mathrm{EM}}(t)|$$



Pantograph

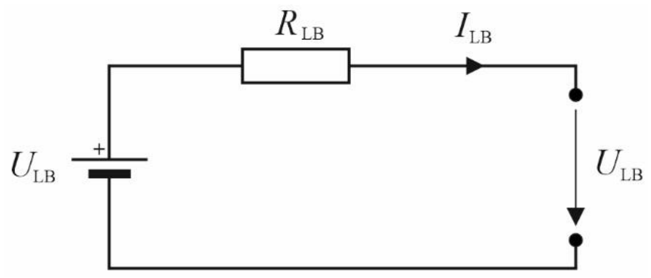
Cumulative electrical energy use:

$$E_{\text{pan}}(t) = \int_0^t P_{\text{pan}}(\tau)d\tau$$

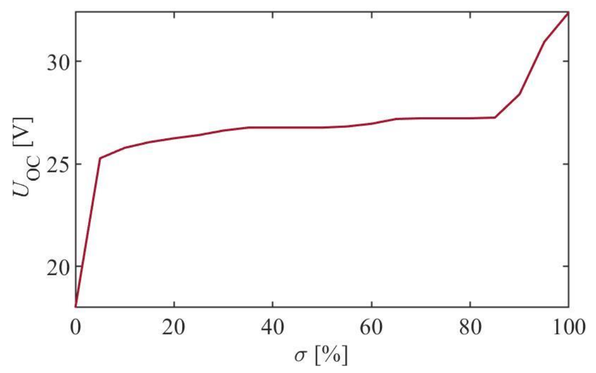


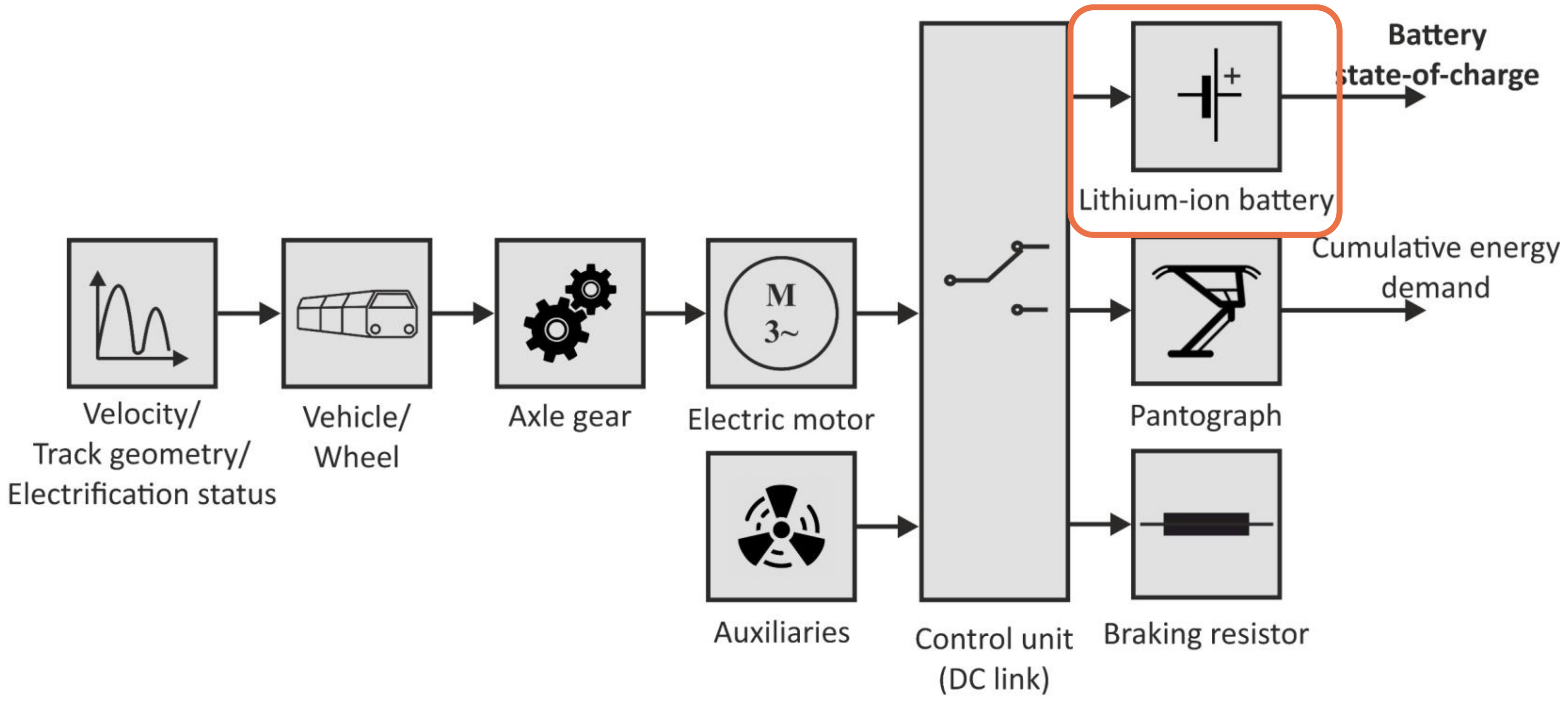
Lithium-ion Battery

Equivalent electrical circuit:



Open circuit voltage as a function of state-of-charge:





Lithium-ion Battery

Current:

$$I_{LB}(t) = \frac{U_{OC}\left(\sigma_{LB}(t)\right) - \sqrt{U_{OC}\left(\sigma_{LB}(t)\right)^2 - 4 \cdot P_{LB}(t) \cdot R_{LB}\left(I_{LB}(t)\right)}}{2 \cdot R_{LB}\left(I_{LB}(t)\right)}$$

Terminal voltage:

$$U_{LB}(t) = U_{OC}\left(\sigma_{LB}(t)\right) - R_{LB}\left(I_{LB}(t)\right) \cdot I_{LB}(t)$$

State-of-charge (SoC):

$$\sigma_{LB}(t) = \sigma_{LB}(0) - \frac{1}{Q_{LB}} \cdot \int_0^t I_{LB}(\tau) d\tau$$

Maximum discharging/charging power:

$$P_{LB}^{max}(t) = \left(U_{OC}\left(\sigma_{LB}(t)\right) - R_{LB}^{dch} \cdot I_{LB}^{max}(t)\right) \cdot I_{LB}^{max}(t)$$

$$P_{LB}^{min}(t) = \left(U_{OC}\left(\sigma_{LB}(t)\right) - R_{LB}^{ch} \cdot I_{LB}^{min}(t)\right) \cdot I_{LB}^{min}(t)$$

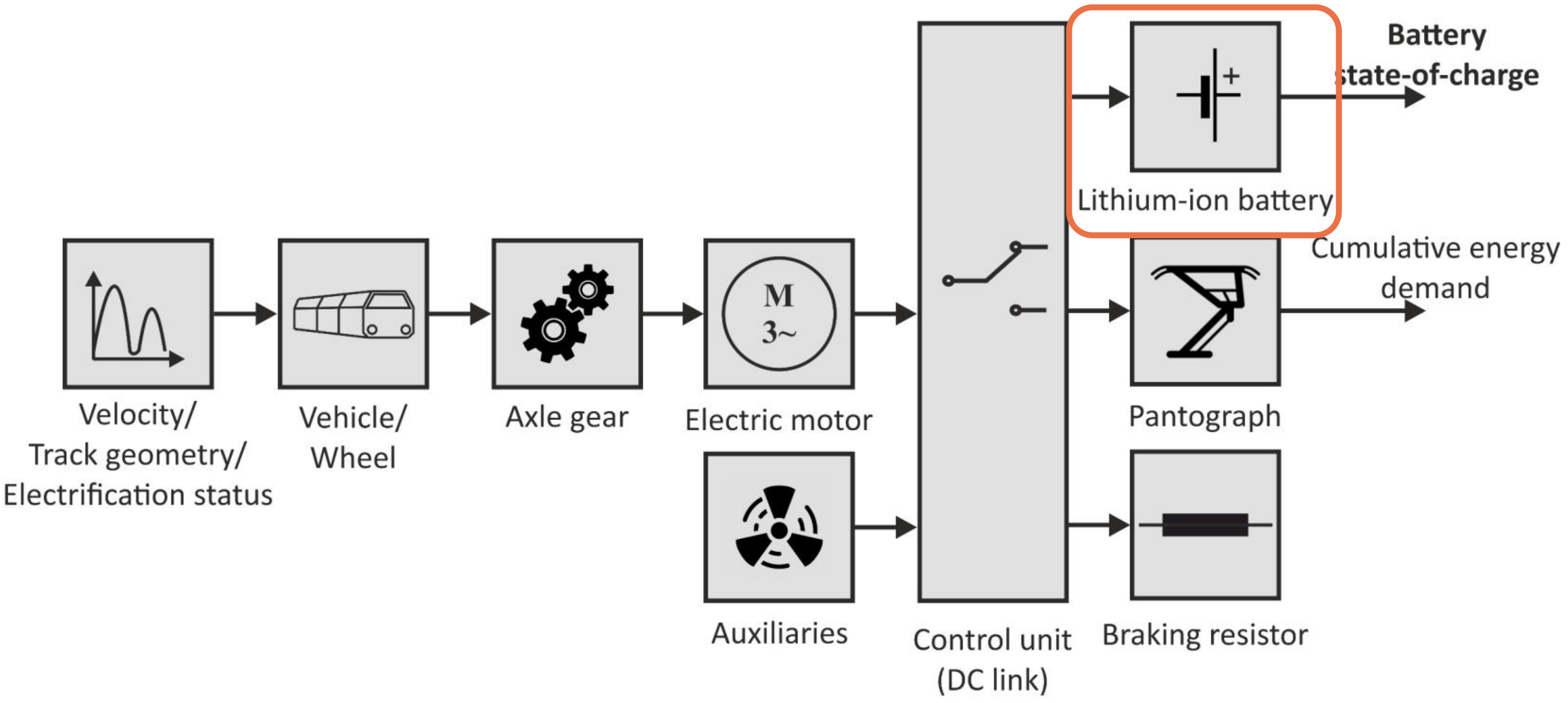
with

$$I_{LB}^{max}(t) = \min\left\{\frac{U_{OC}(\sigma_{LB}(t)) - U_{LB}^{min}}{R_{LB}^{dch}}, \frac{\left(\sigma_{LB}(t) - \sigma_{LB}^{min}\right) \cdot Q_{LB}}{\Delta t}, I_{LB}^{max,dch}(t)\right\}$$

$$I_{LB}^{min}(t) = \max\left\{\frac{U_{OC}(\sigma_{LB}(t)) - U_{LB}^{max}}{R_{LB}^{ch}}, \frac{\left(\sigma_{LB}(t) - \sigma_{LB}^{max}\right) \cdot Q_{LB}}{\Delta t}, I_{LB}^{max,ch}(t)\right\}$$

$$I_{LB}^{max,dch}(t) = \begin{cases} I_{LB}^{peak,dch} & if\ t_{cnt}^{dch}(t) < t_{peak}^{dch} \\ I_{LB}^{cont,dch} & if\ t_{cnt}^{dch}(t) \geq t_{peak}^{dch} \end{cases}$$

$$I_{LB}^{max,ch}(t) = \begin{cases} I_{LB}^{peak,ch} & if\ t_{cnt}^{ch}(t) < t_{peak}^{ch} \\ I_{LB}^{cont,ch} & if\ t_{cnt}^{ch}(t) \geq t_{peak}^{ch}. \end{cases}$$



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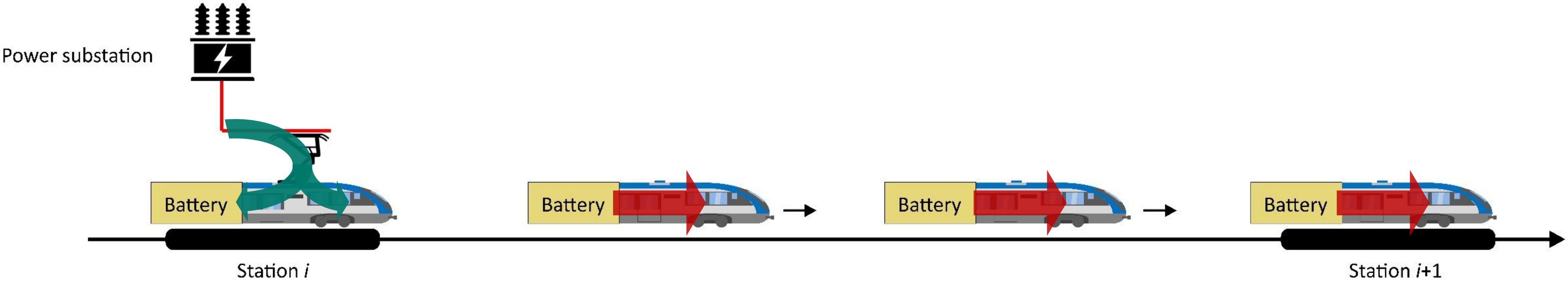
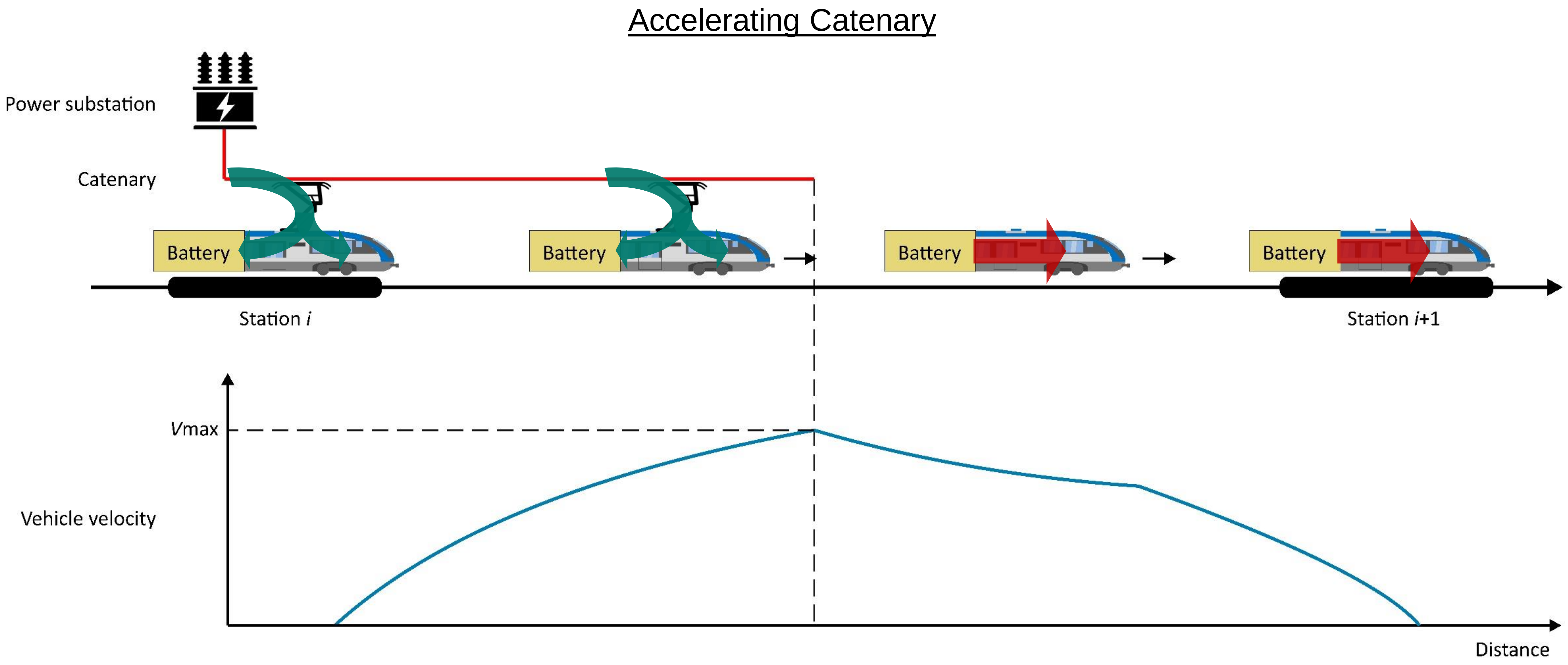
Electrification Alternatives

<u>Charging Station</u>



Electrification Alternatives



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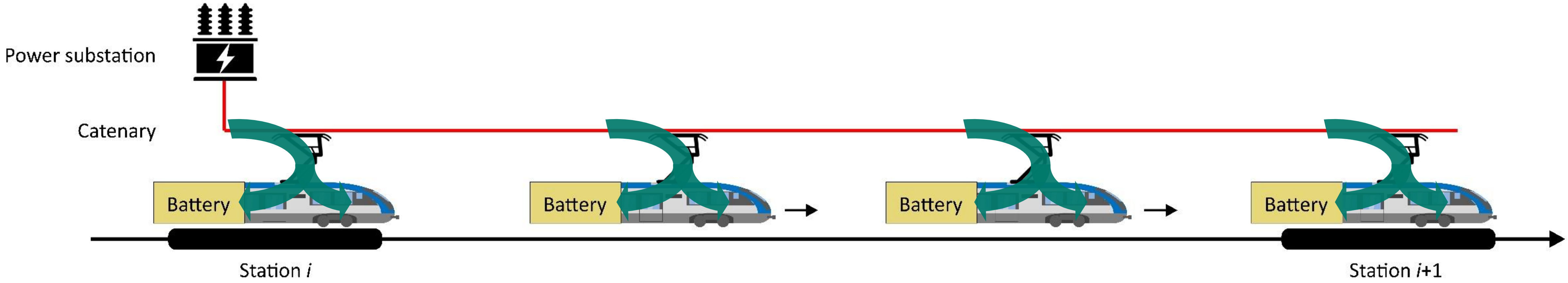
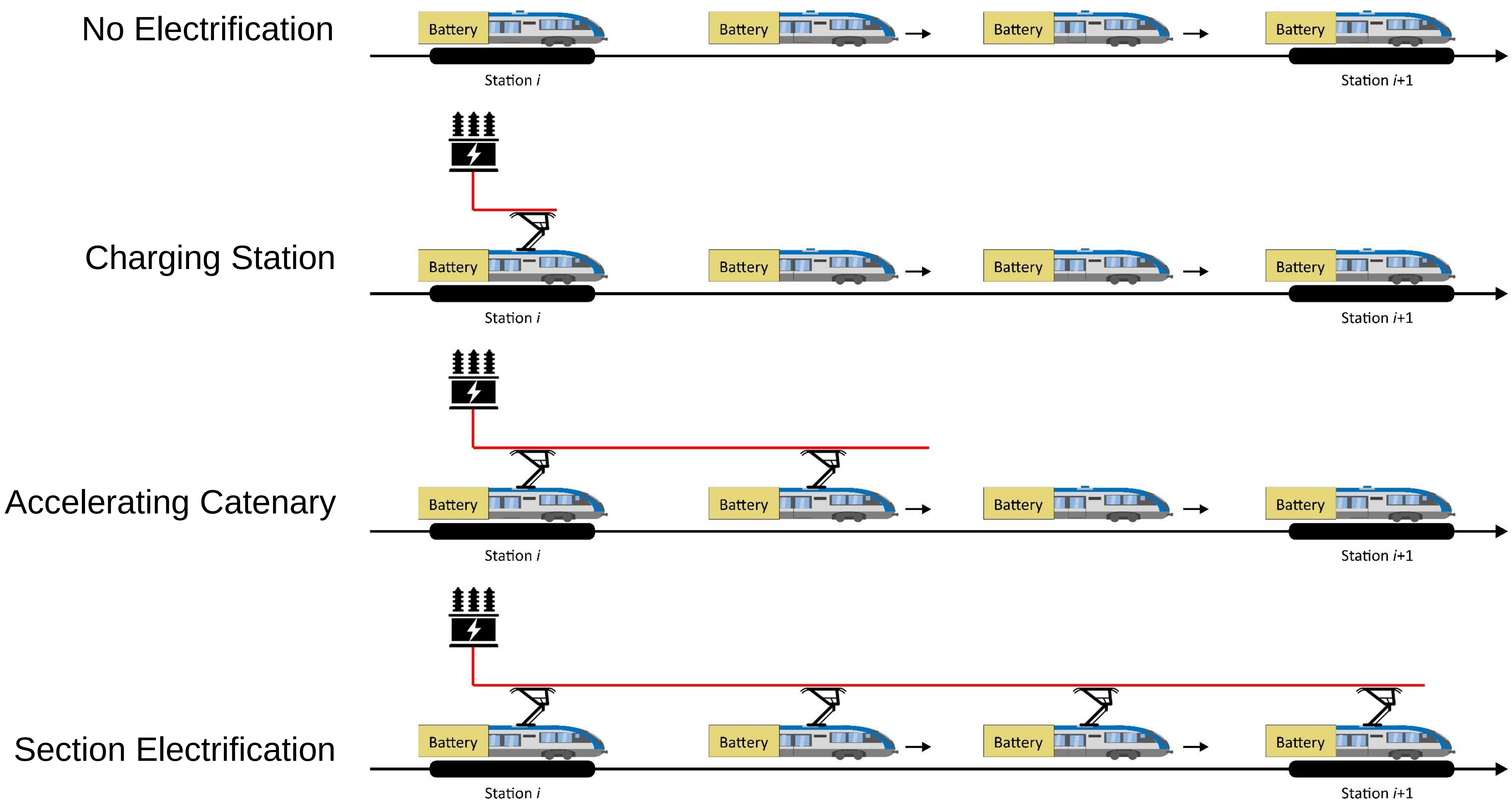
Electrification Alternatives

Section Electrification



Electrification Alternatives



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Optimization Framework for the Intermittent Track Electrification

The objective is to minimize **capital cost of electrification**, by assigning one of the electrification options to each track section, while complying with the required vehicle range (i.e. maintaining battery SoC above lower threshold):

$$C = C_{\mathrm{PS}} + C_{\mathrm{CAT}}$$

Power substations cost

$$C_{\mathrm{PS}} = n_{\mathrm{PS}} \cdot c_{\mathrm{PS}}$$

Unit cost for 1.5kV DC (3MVA): 0.9M€

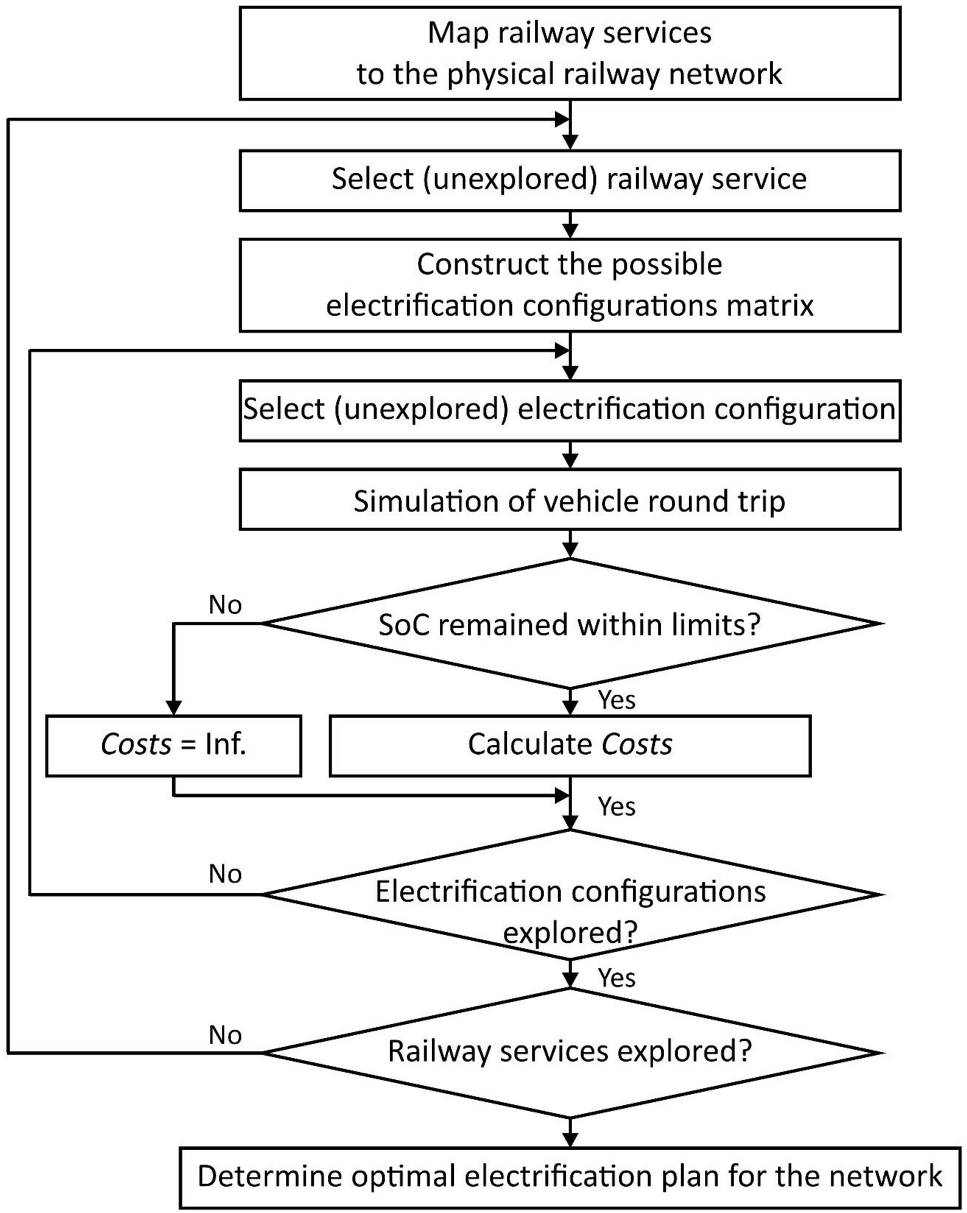
Maximum track coverage: 10km

Catenary cost

$$C_{\mathrm{CAT}} = l_{\mathrm{CAT}} \cdot c_{\mathrm{CAT}}$$

Unit cost for 1.5kV DC: 0.2M€/km

Optimization Framework for the Intermittent Track Electrification



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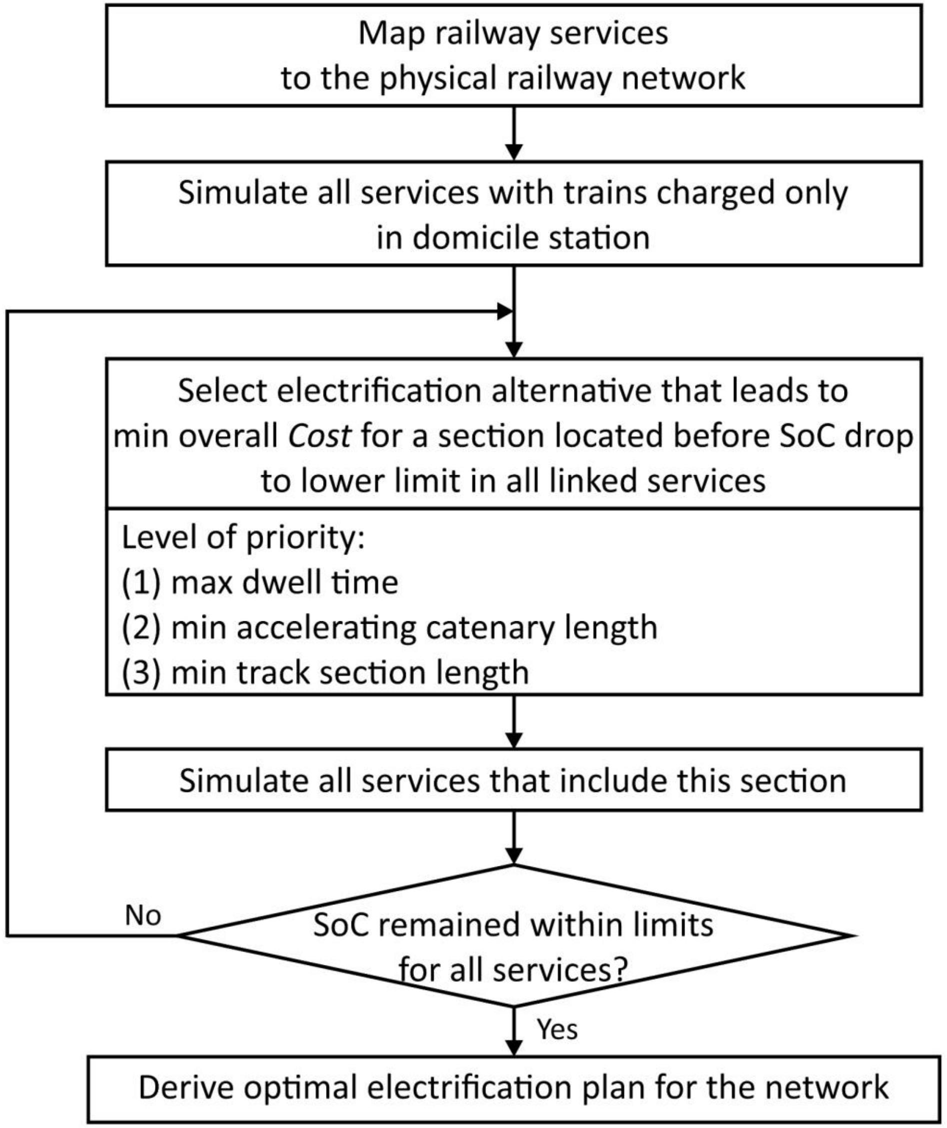
Optimization Framework for the Intermittent Track Electrification



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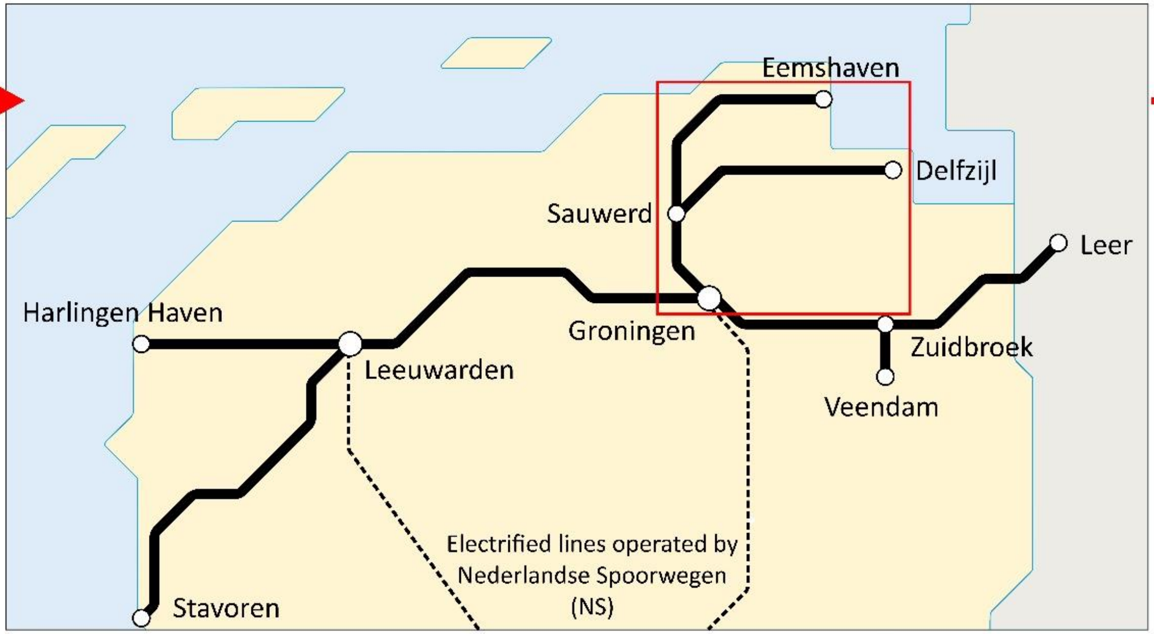
Case Study of the Dutch Northern Lines

Stadler WINK multiple unit

Parameter	Unit	Value
Vehicle		
Tare weight	t	*Confidential*
Rotating mass factor	%	*Confidential*
Maximum passengers capacity	-	*Confidential*
Davis equation coefficient (constant term)	N	*Confidential*
Davis equation coefficient (linear term)	N/(km/h)	*Confidential*
Davis equation coefficient (quadratic term)	$N/(km/h)^2$	*Confidential*
Powered wheel diameter	m	0.87
Axle gear ratio	-	*Confidential*
Axle gear efficiency	%	*Confidential*
Maximum velocity	km/h	140
Maximum acceleration	m/s^2	*Confidential*
Maximum deceleration	m/s^2	*Confidential*
Maximum (starting) tractive effort	kN	*Confidential*
Maximum power at the wheel	kW	748
EM rated power	kW	*Confidential*
Maximum auxiliary systems power	kW	*Confidential*
Lithium-ion battery system		
Number of battery packs	-	10
Nominal capacity	Ah	*Confidential*
Minimum/maximum continuous current	A	*Confidential*
Minimum/maximum pulse current	A	*Confidential*
Allowed time for pulse current	s	*Confidential*
Minimum/maximum voltage	V	*Confidential*
Internal resistance	Ω	*Confidential*
Minimum/maximum state-of-charge (SOC)	%	10/90
Energy content	kWh	*Confidential*

Case Study of the Dutch Northern Lines



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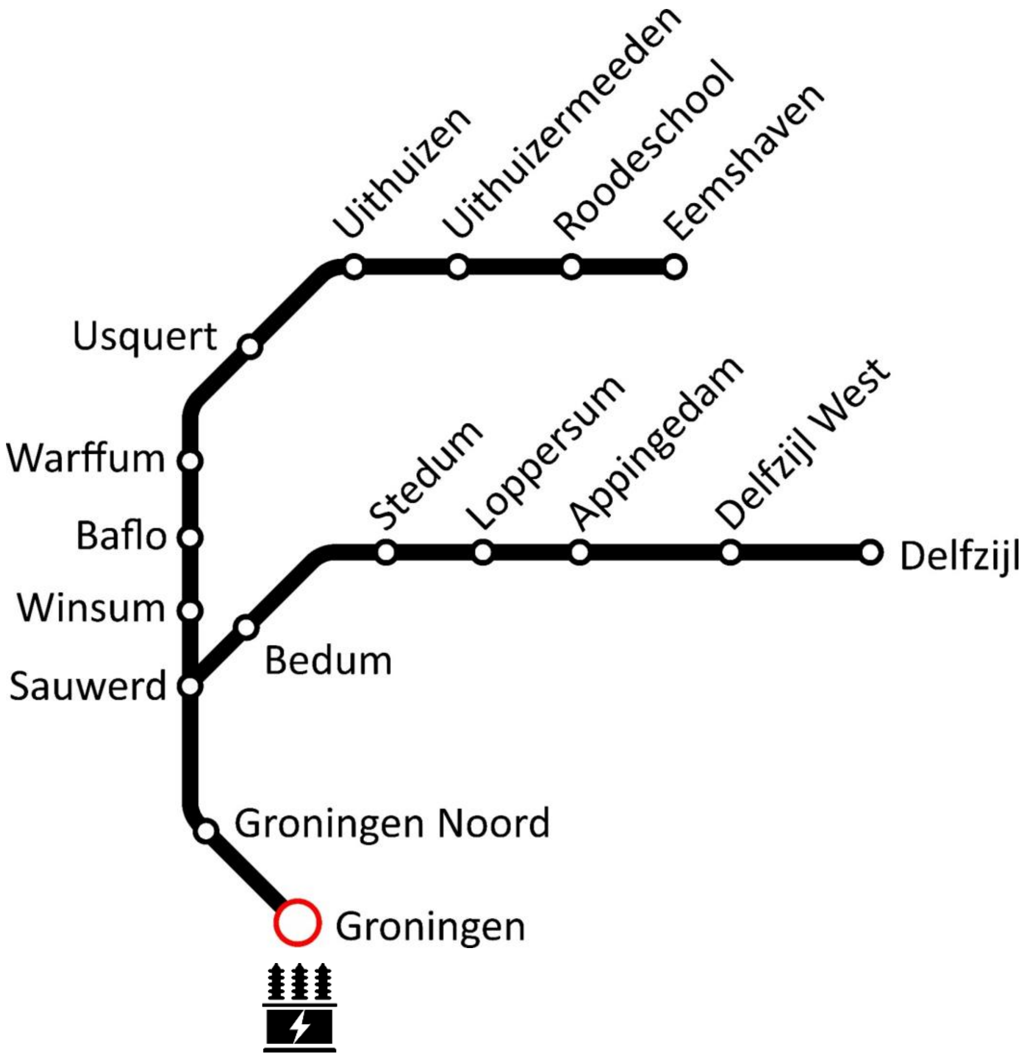
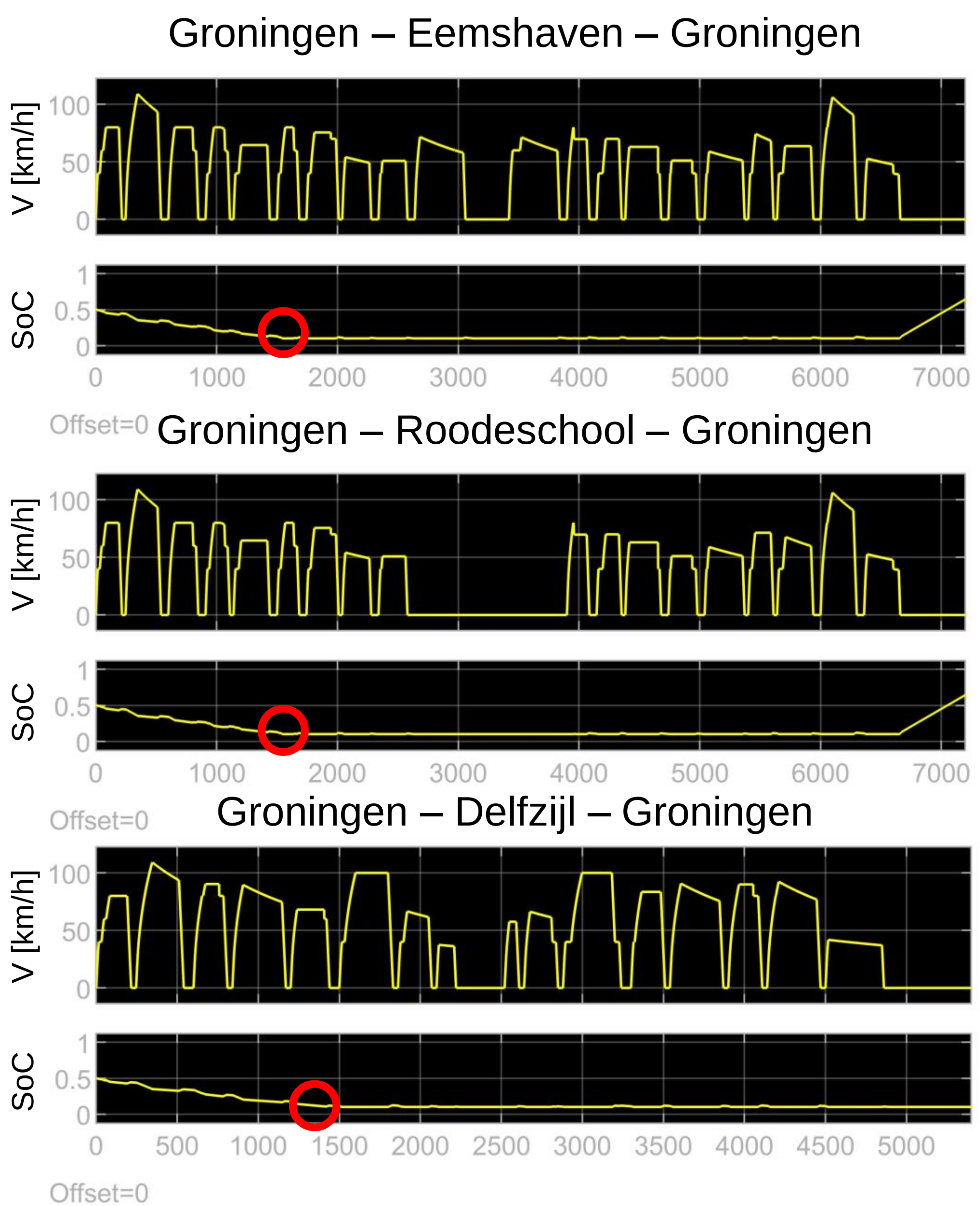
Case Study of the Dutch Northern Lines

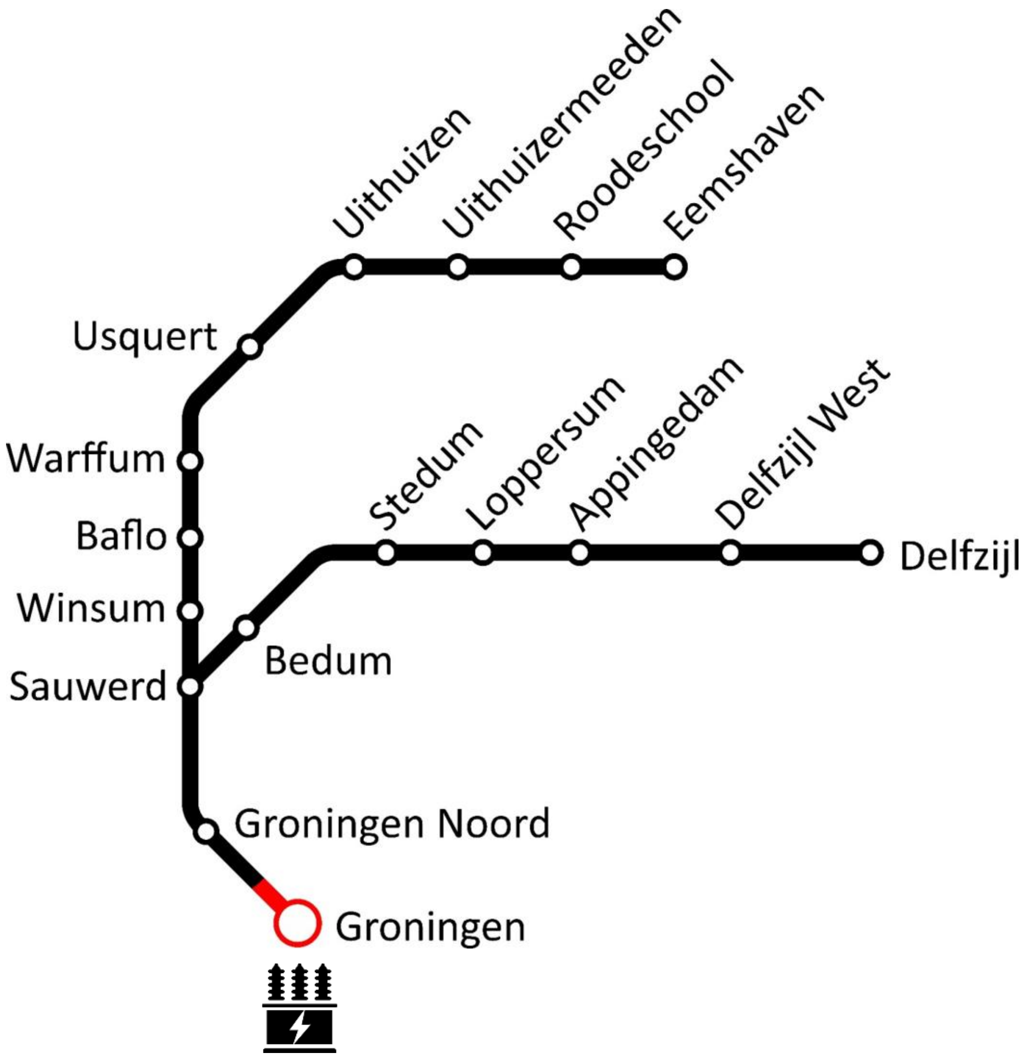
Iter. 1

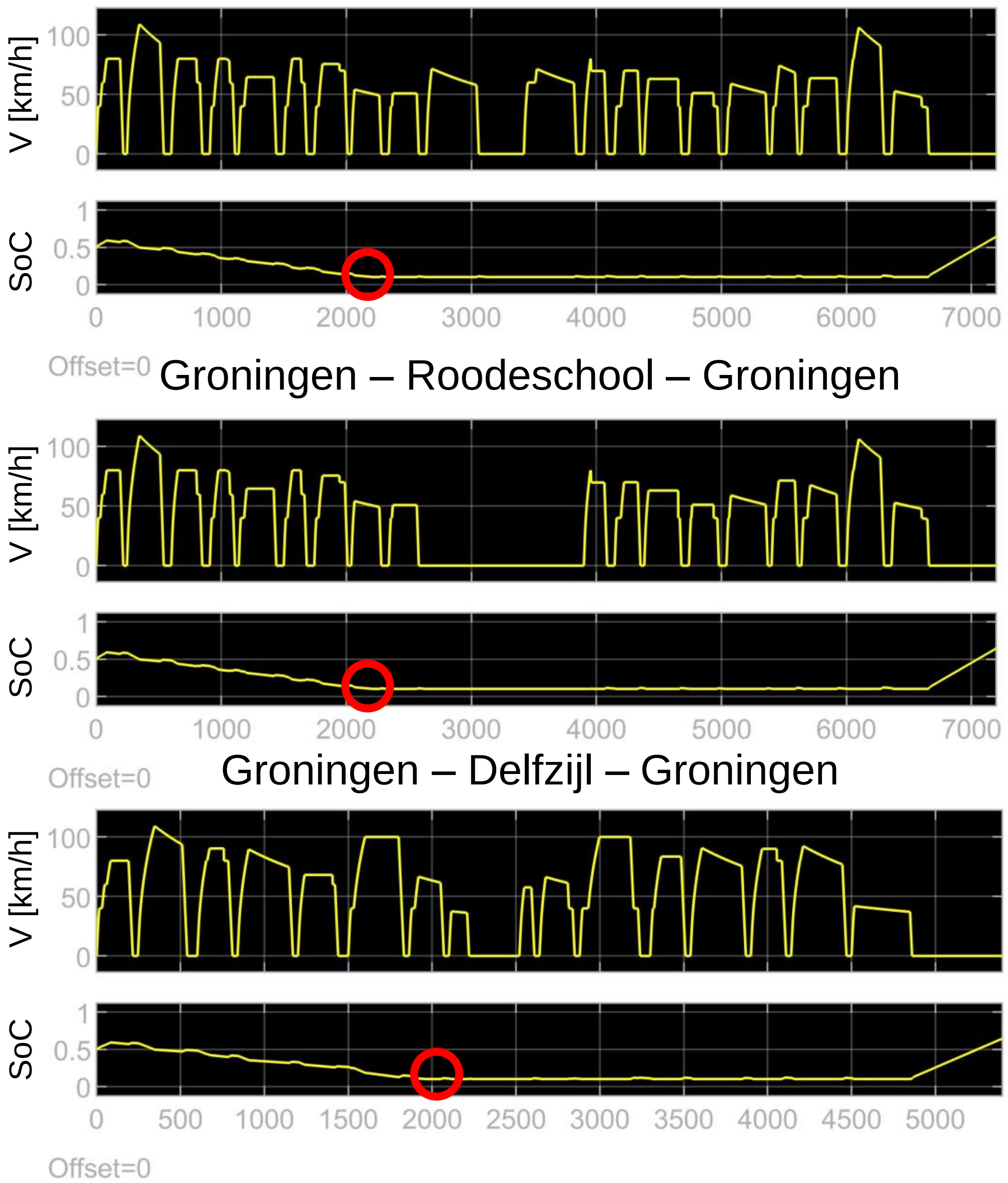




Case Study of the Dutch Northern Lines

Iter. 2





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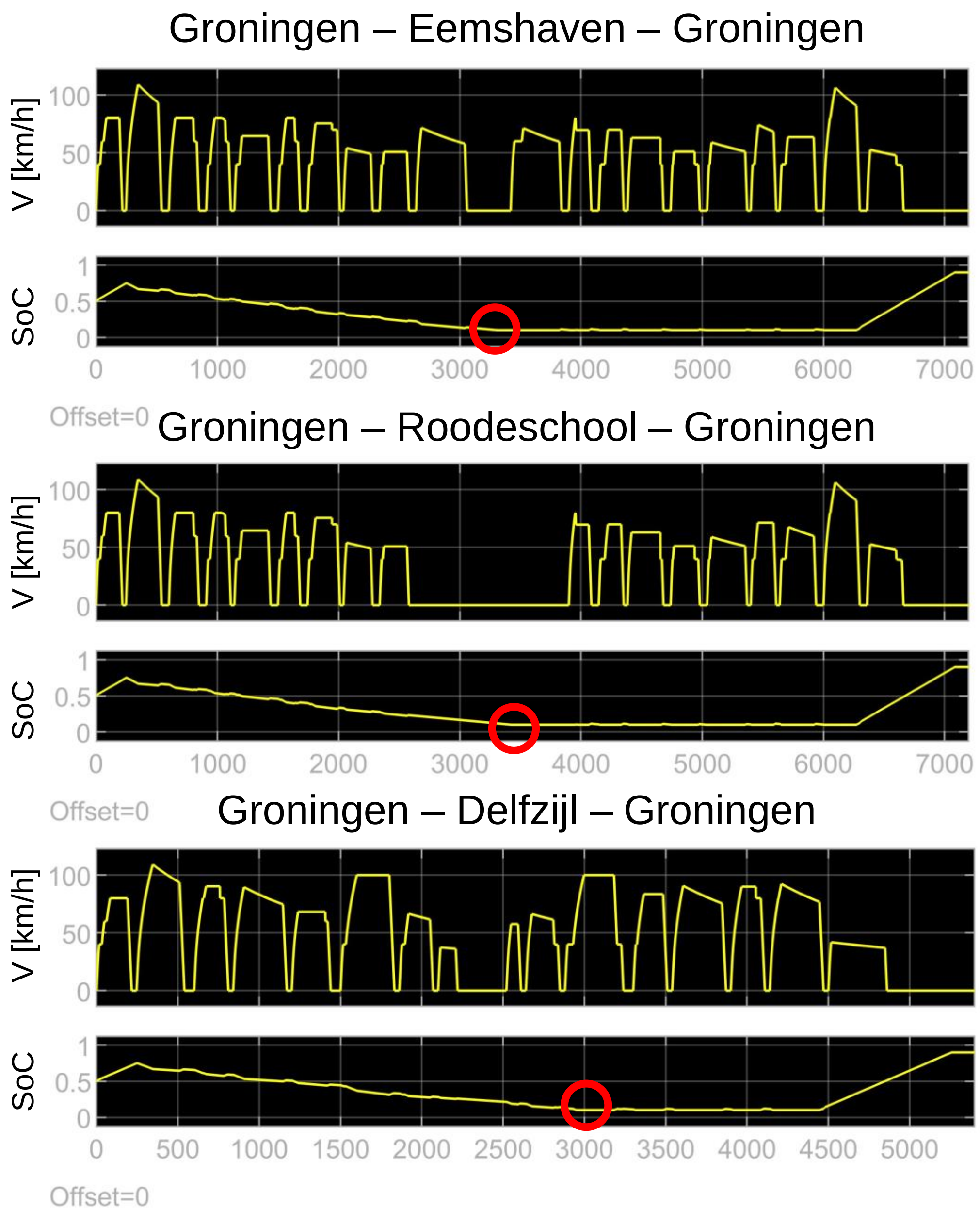

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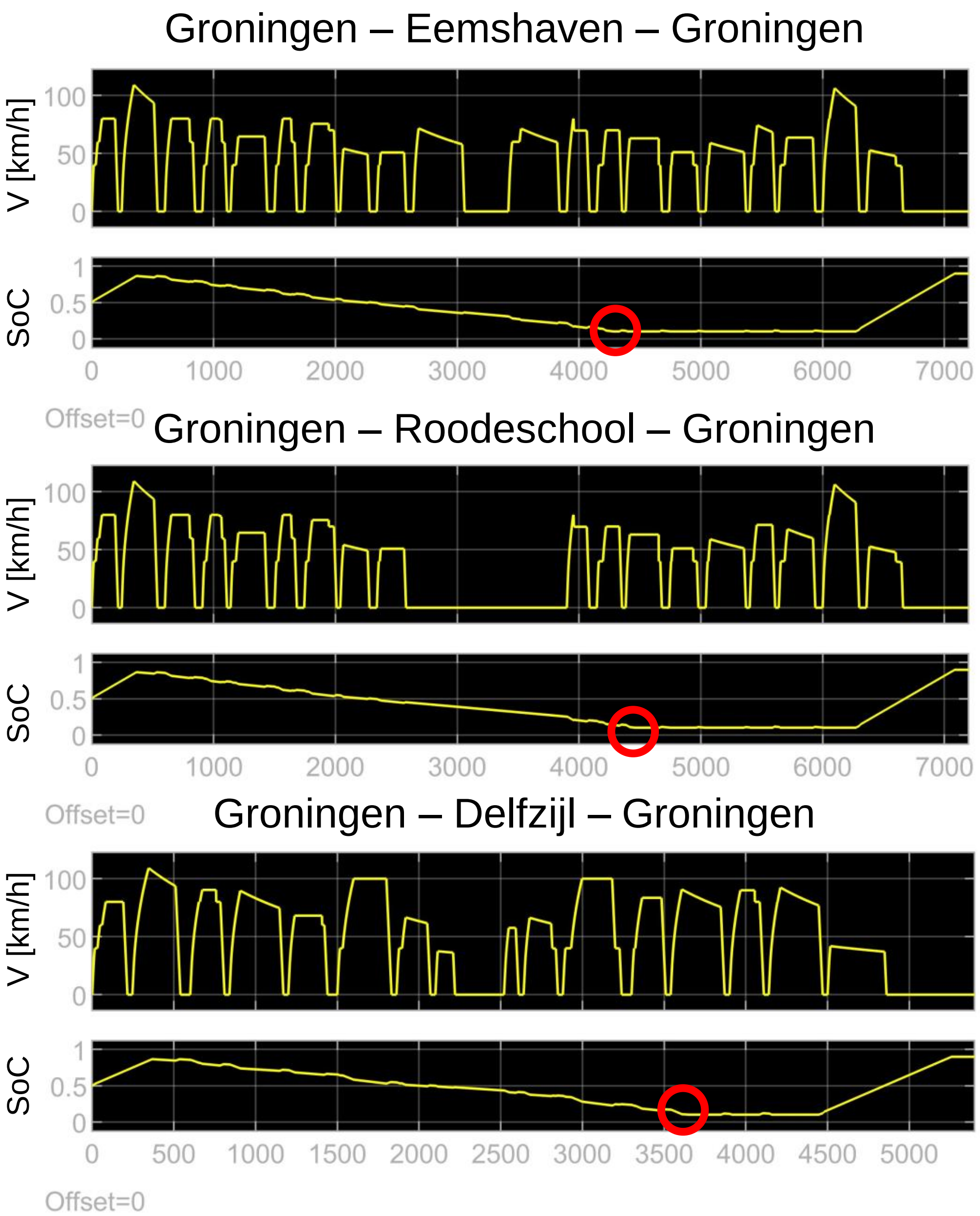

Case Study of the Dutch Northern Lines

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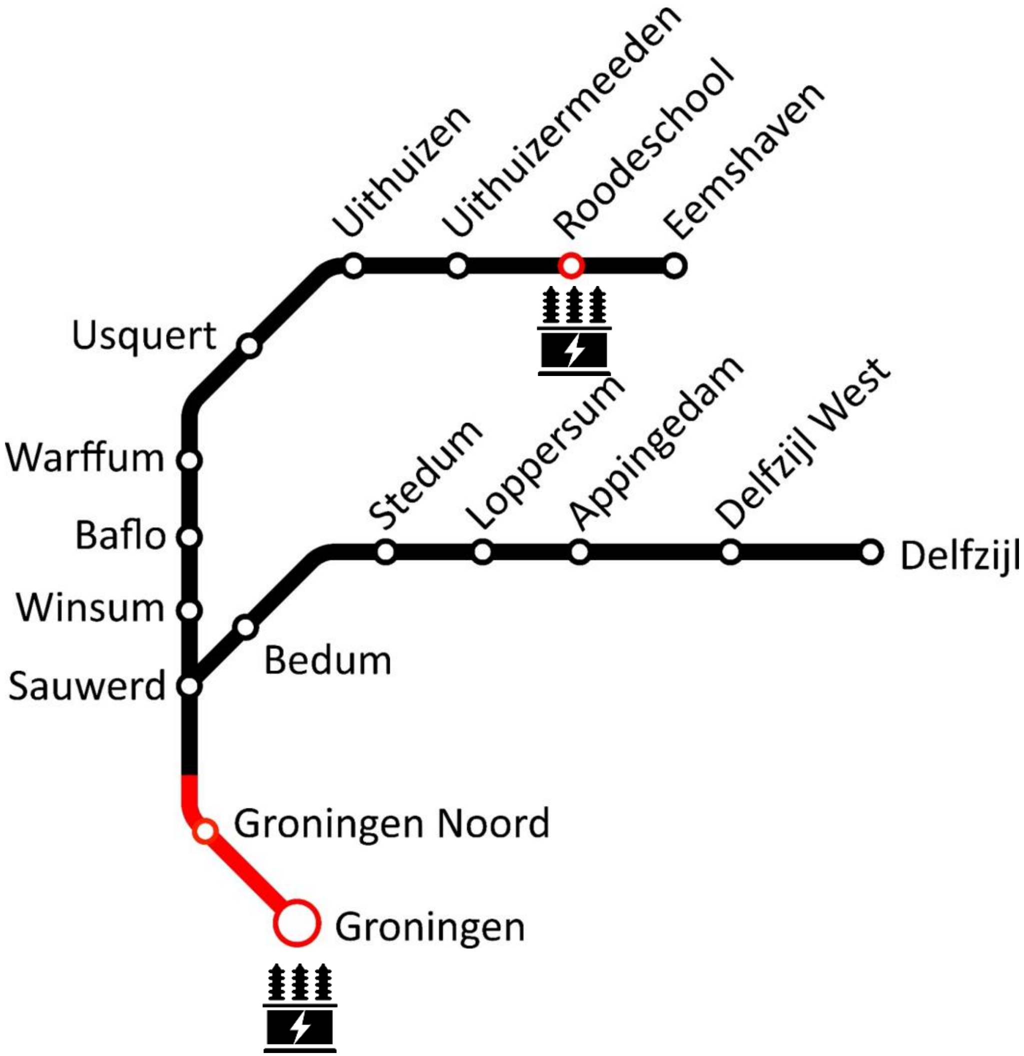
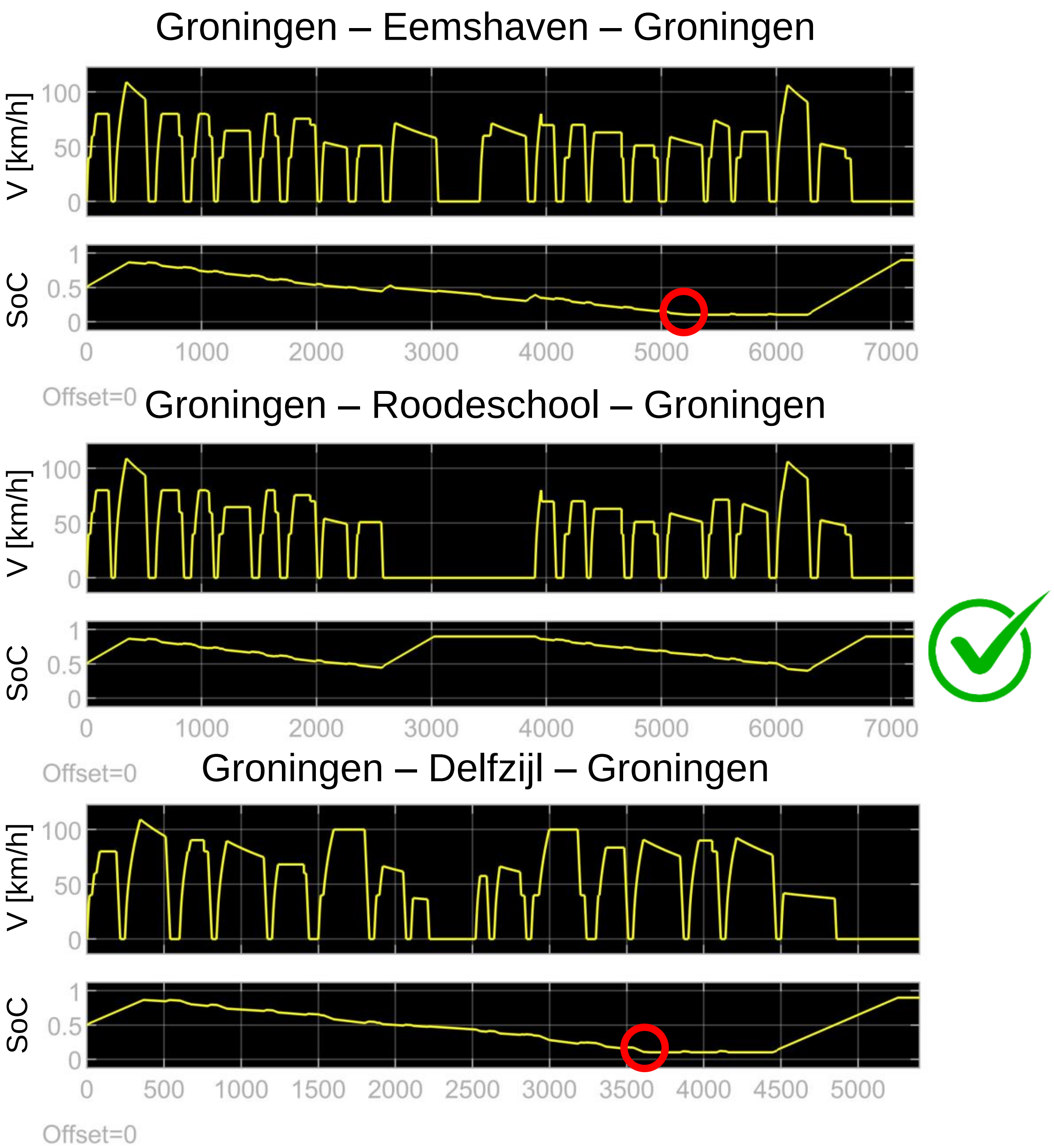
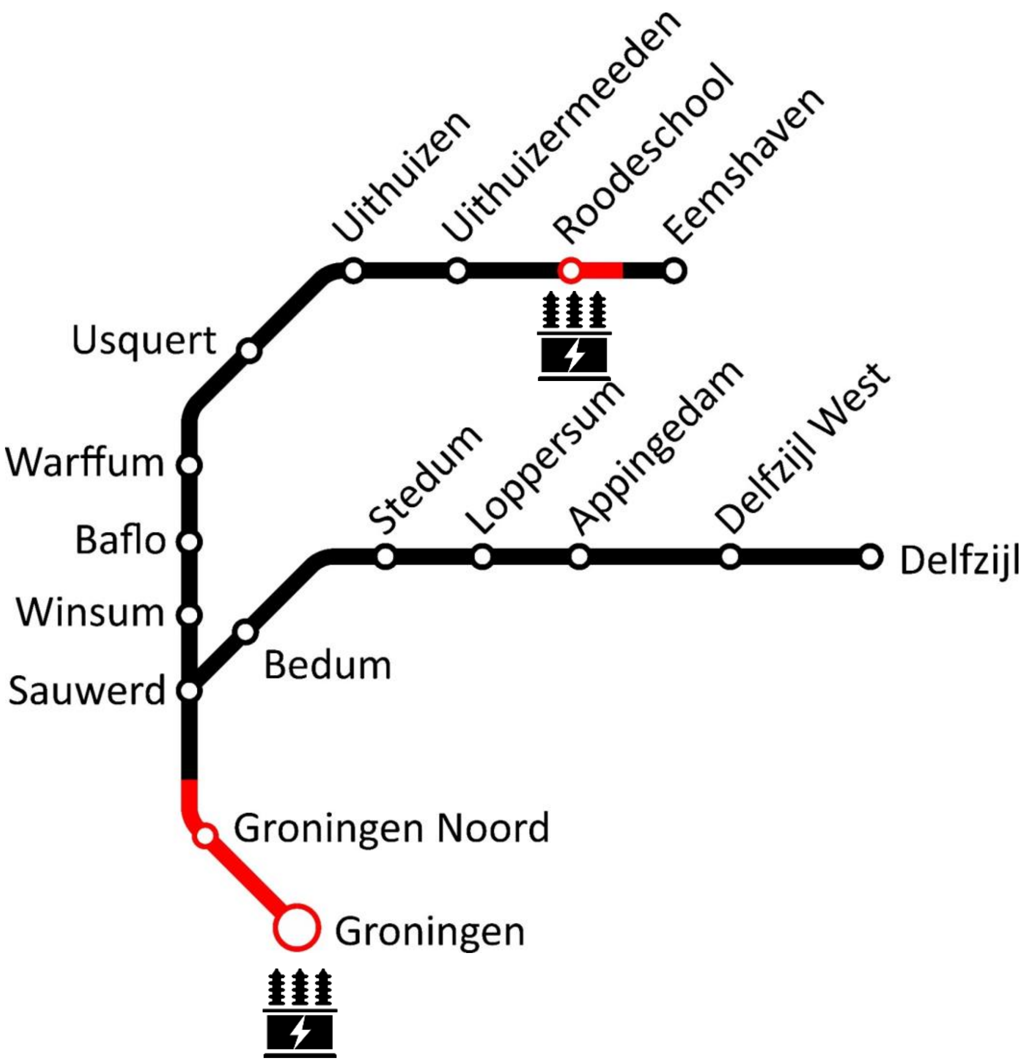
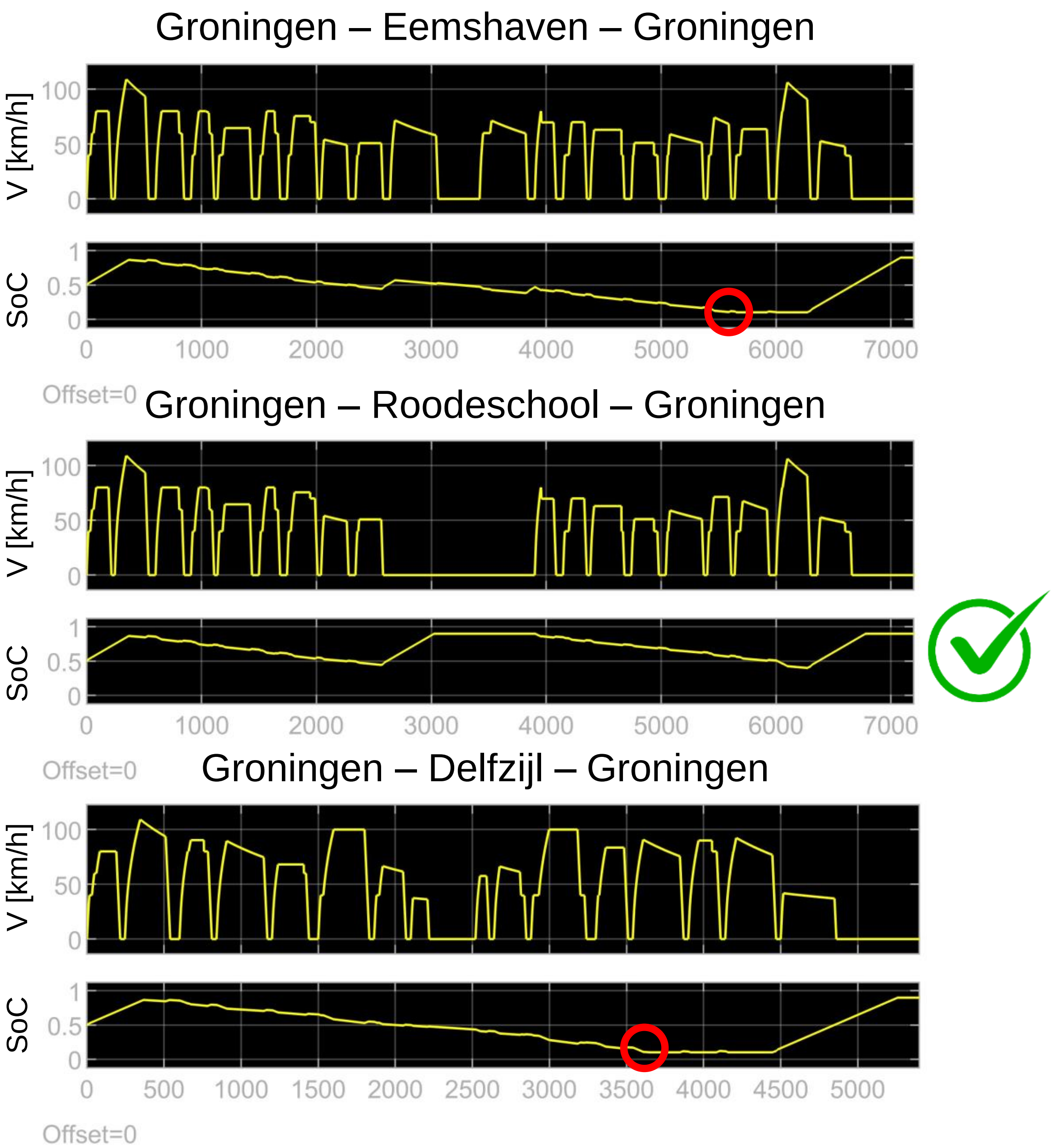




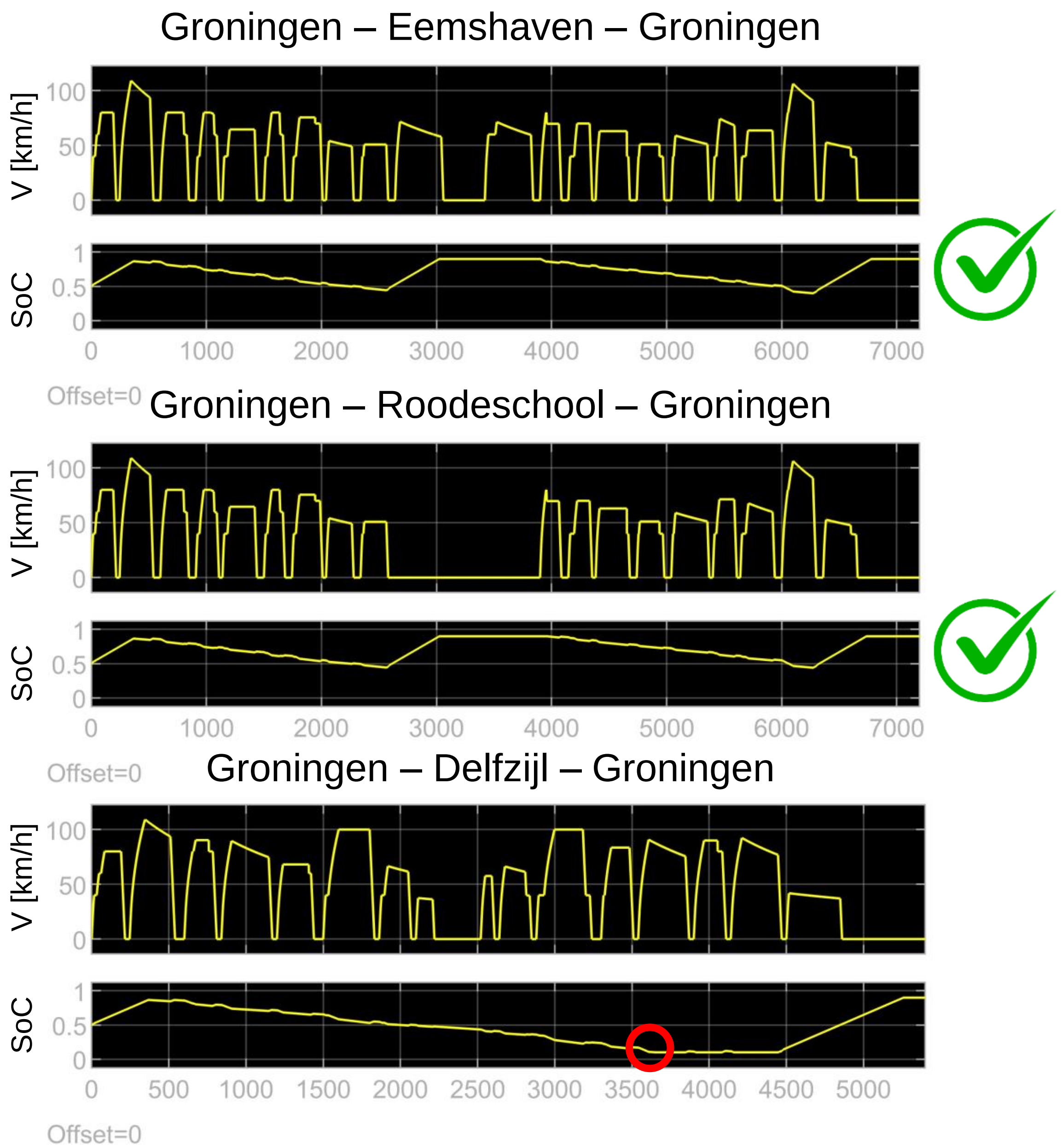
Case Study of the Dutch Northern Lines

Iter. 6



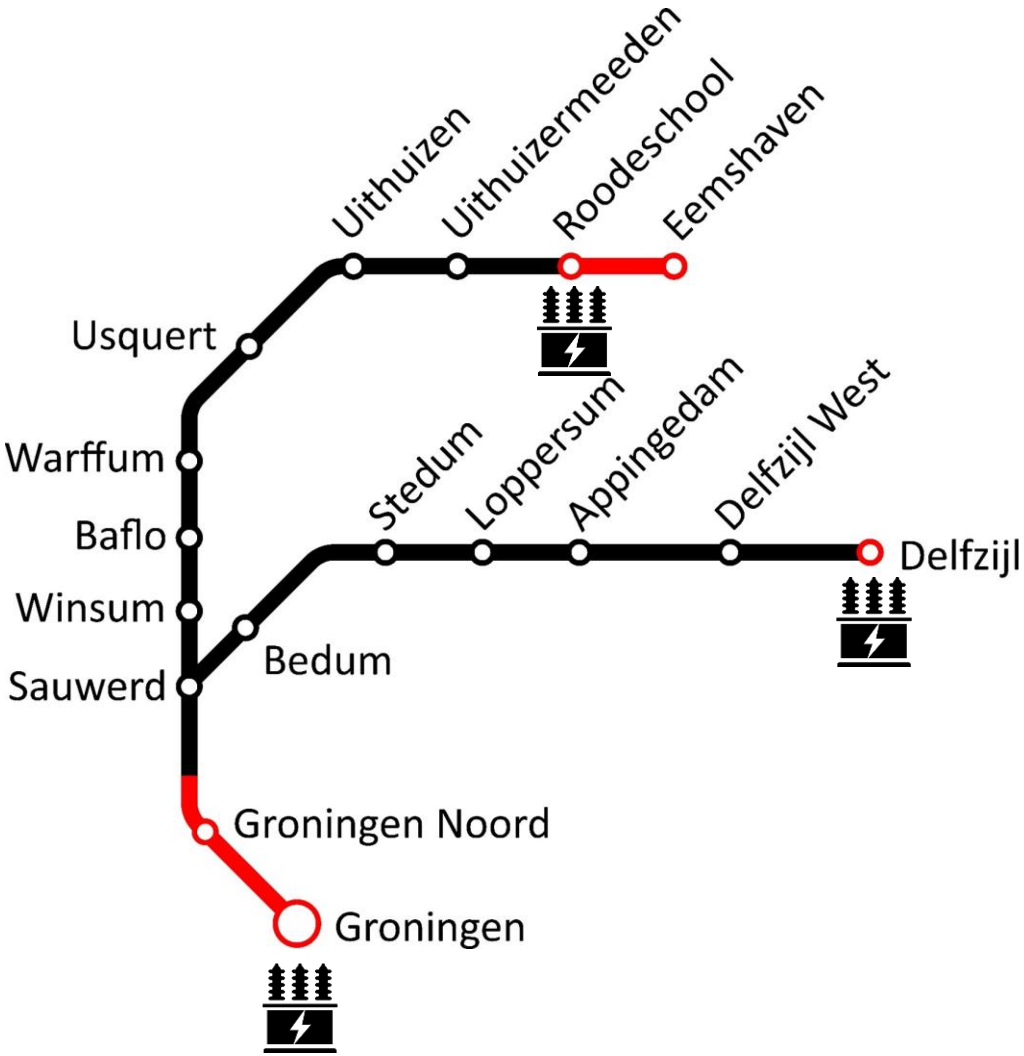


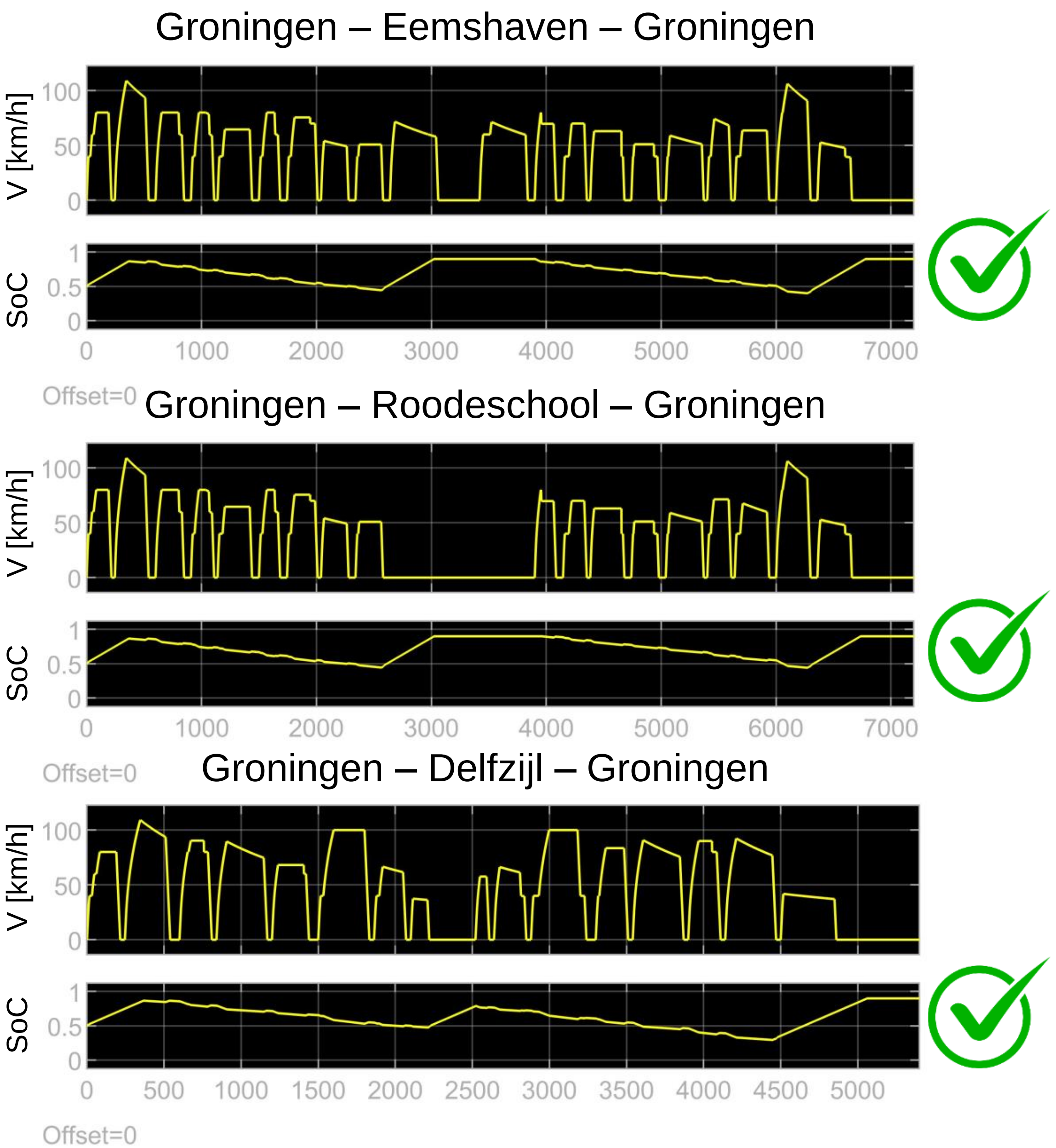
Case Study of the Dutch Northern Lines



Case Study of the Dutch Northern Lines

Iter. 8





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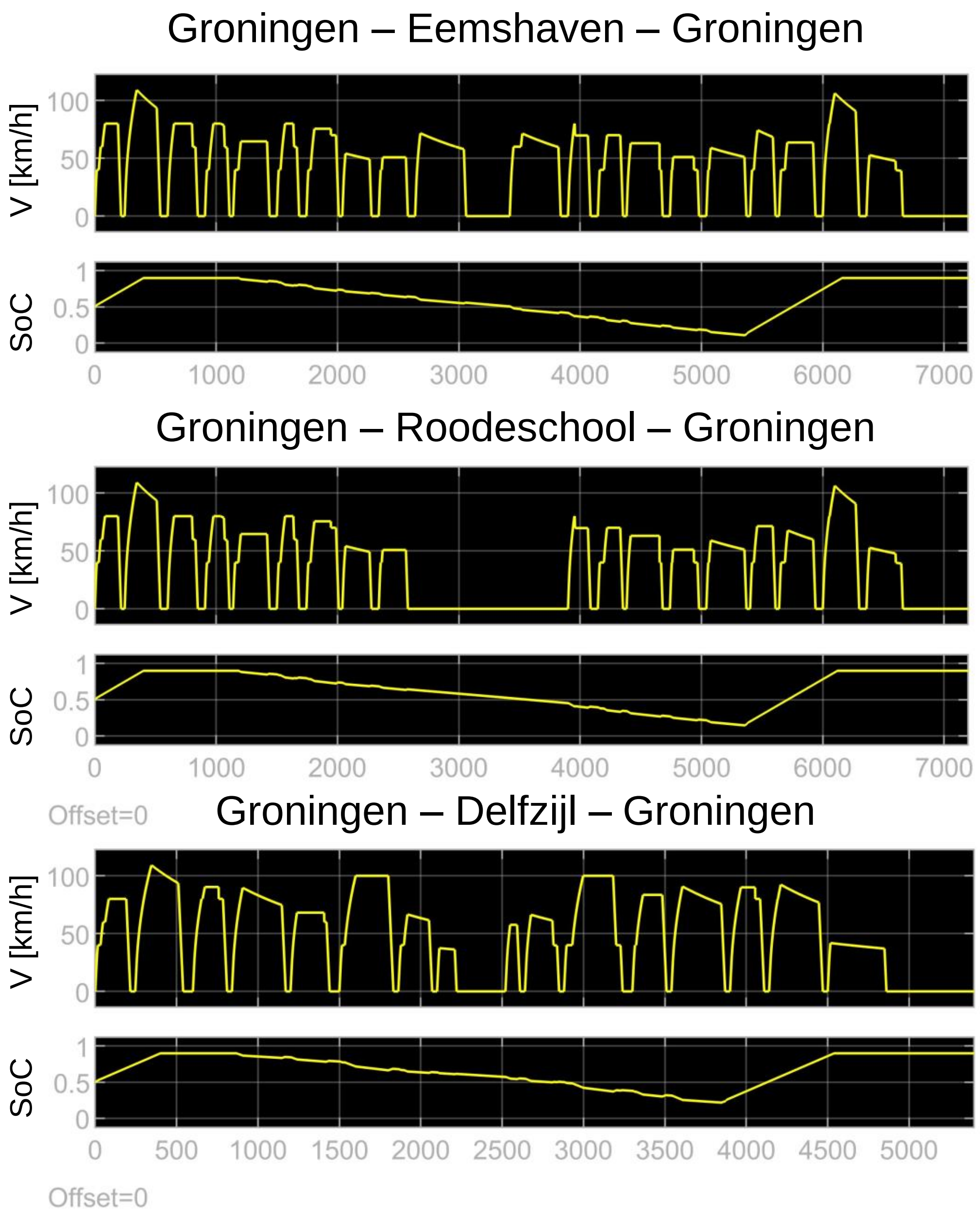
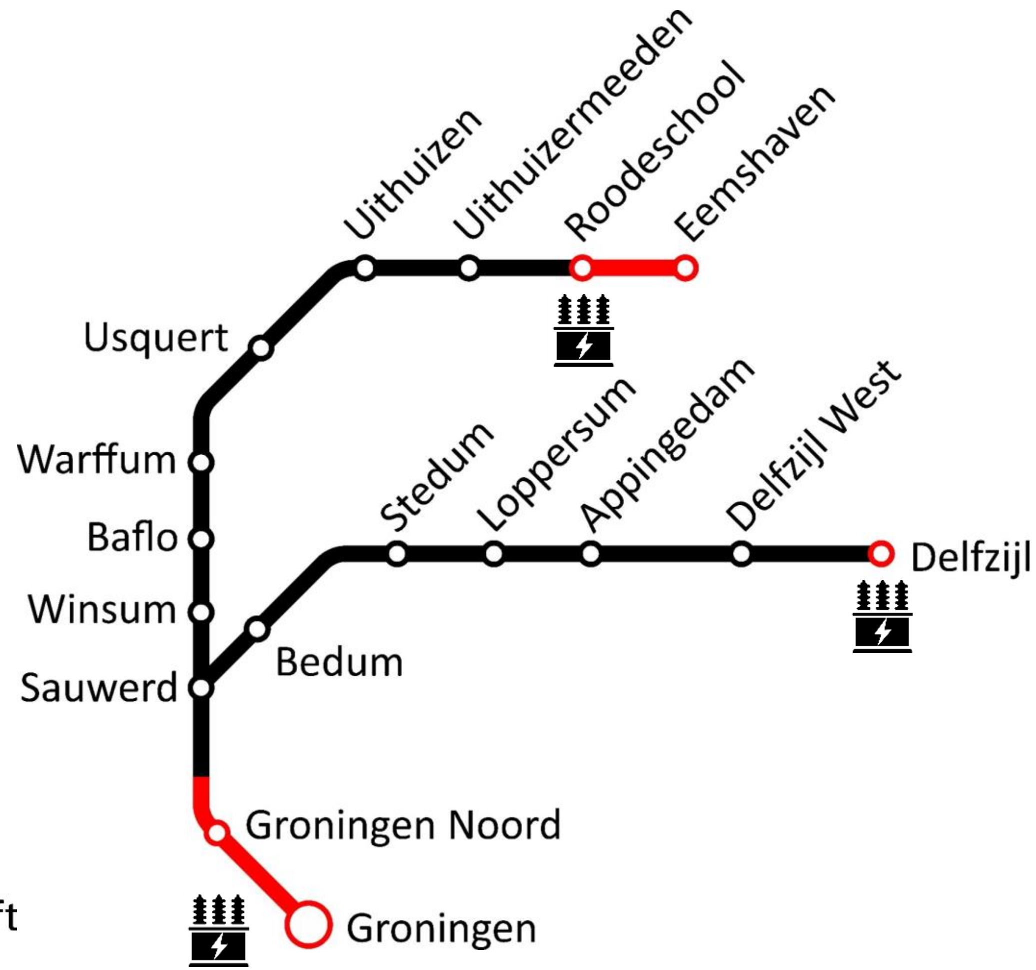


Case Study of the Dutch Northern Lines

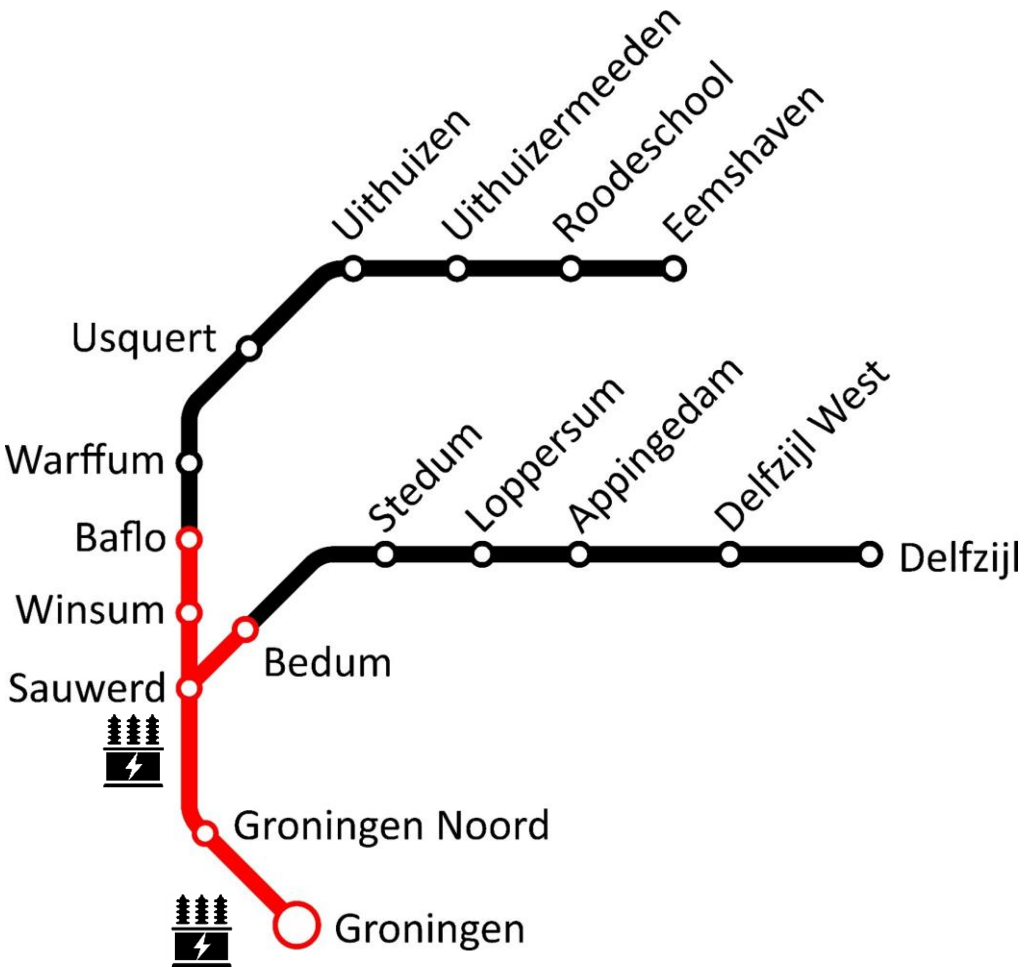
Intermittent partial electrification

Electrified track: 10.807 km
Number of power substations: 3
Total cost: 4.8614 mil. €



Continuous partial electrification

Electrified track: 18.934 km
Number of power substations: 2
Total cost: 5.5868 mil. €



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Conclusions

- **Powertrain simulation models** can be effectively exploited in strategic transportation planning and capital investments optimization frameworks.
- **Intermittent electrification** could lead to significantly lower capital cost for the required railway network electrification compared to the continuous electrification approach.

- Extensions of the present research:
  - ✓ Further investigation on the variability of used parameters in a **sensitivity analysis**.
  - ✓ Incorporation of operation and maintenance costs in a comprehensive **life cycle costs analysis**.
  - ✓ Extension of the approach with other electrification alternatives.

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Questions?

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