UNIVERSITY OF BIRMINGHAM

BCRRE

Railway Power Network Simulation and Optimisation

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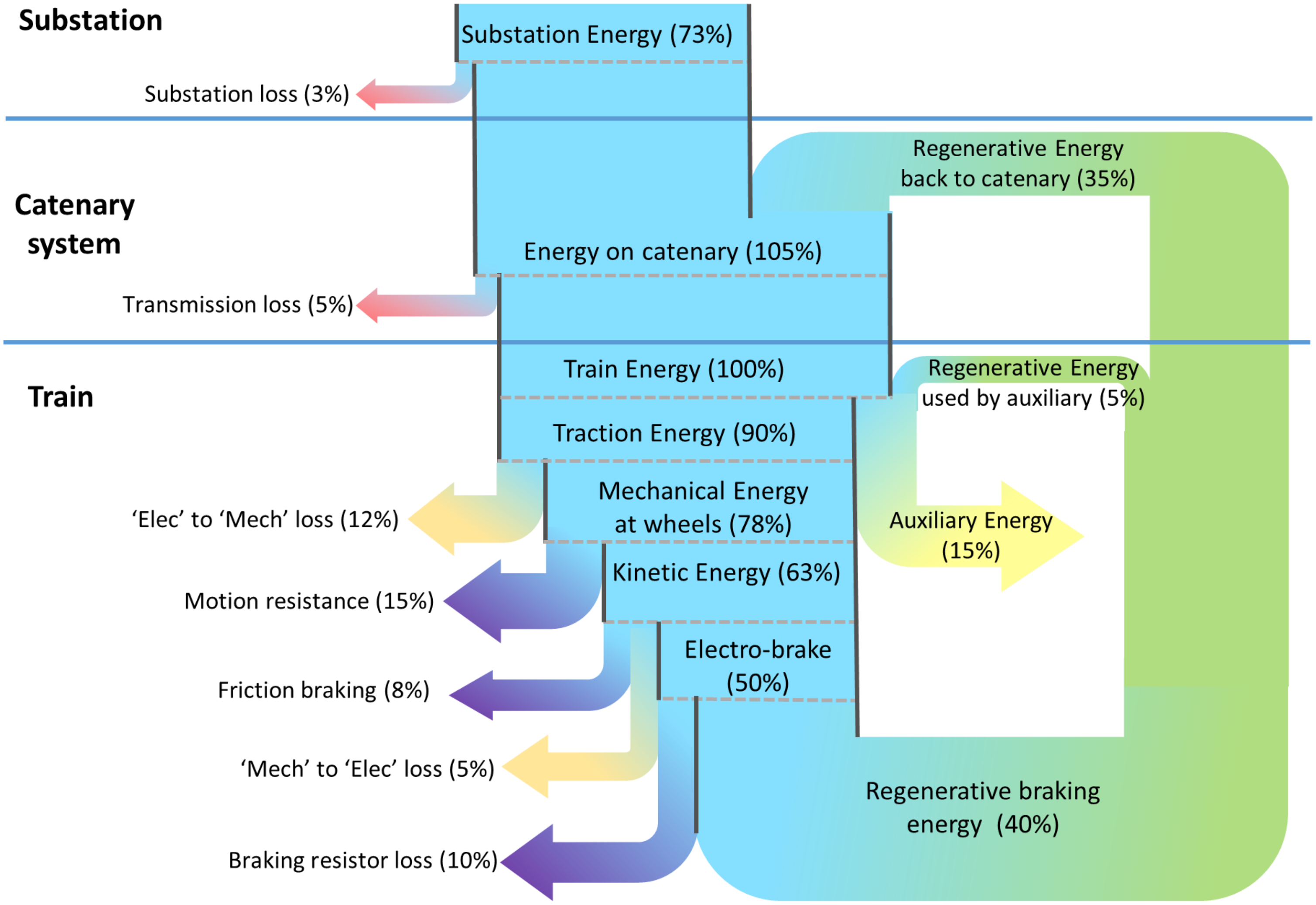
Background

- ☐ Good transport is critical to the economic growth and the success of cities;
- ☐ Energy consumption is becoming a significant concern for modern railway operation;
- ☐ There is an opportunity to improve the energy consumption of the system through analysis, simulation and optimisation of both static and dynamic design parameters.

Contents

- Energy flow in DC rail systems
- Simulation development - Mathematical modelling
- Using the simulator:
  - 1. Understand the rail power systems
  - 2. Energy evaluation
  - 3. Energy optimisation

System Energy Flow Chart



Substation

Substation Energy (73%)

Substation loss (3%)

Catenary system

Regenerative Energy back to catenary (35%)

Energy on catenary (105%)

Transmission loss (5%)

Train

Train Energy (100%)

Regenerative Energy used by auxiliary (5%)

Traction Energy (90%)

Mechanical Energy at wheels (78%)

‘Elec’ to ‘Mech’ loss (12%)

Auxiliary Energy (15%)

Kinetic Energy (63%)

Motion resistance (15%)

Electro-brake (50%)

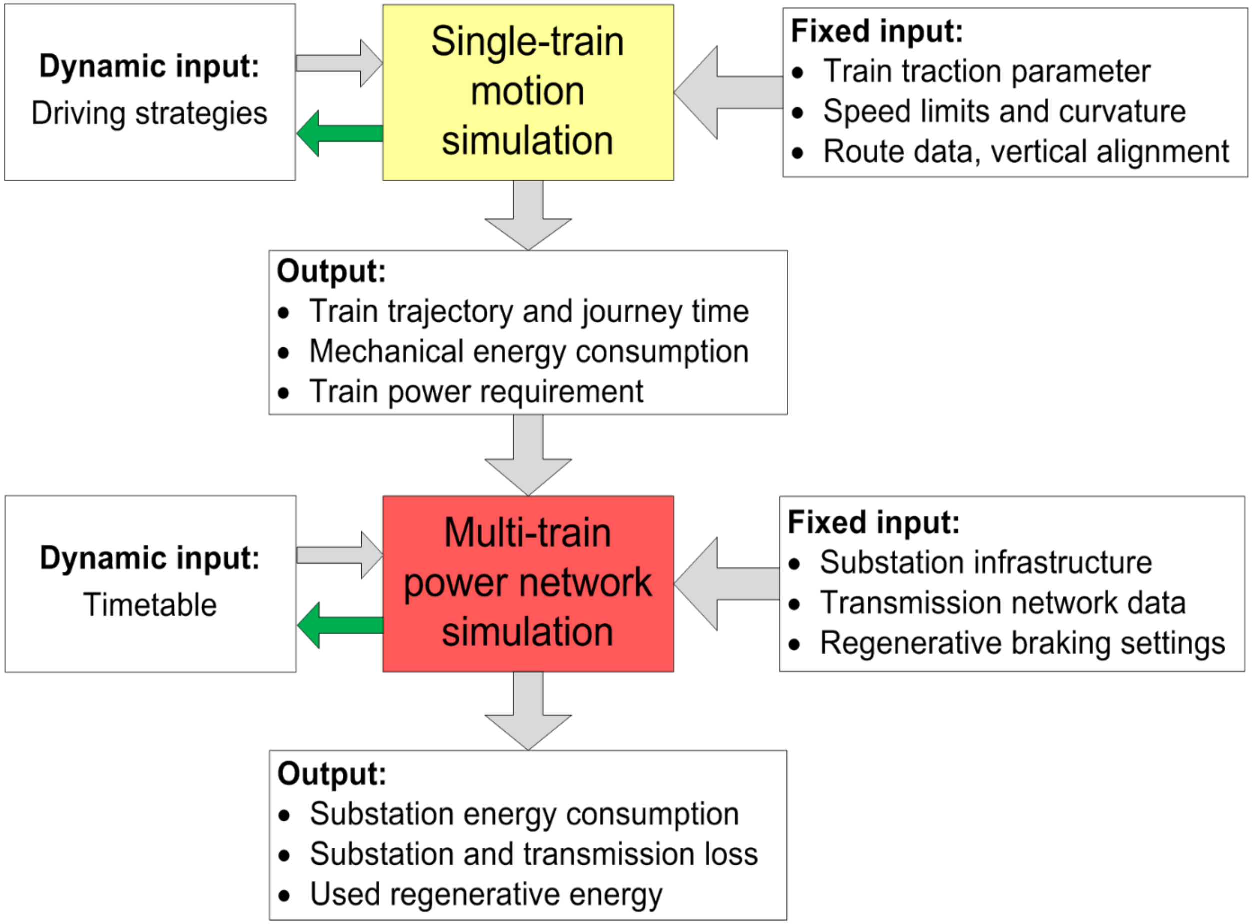
Friction braking (8%)

‘Mech’ to ‘Elec’ loss (5%)

Regenerative braking energy (40%)

Braking resistor loss (10%)

Simulation structure



Dynamic input:
Driving strategies

Single-train motion simulation

Fixed input:
- Train traction parameter
- Speed limits and curvature
- Route data, vertical alignment

Output:
- Train trajectory and journey time
- Mechanical energy consumption
- Train power requirement

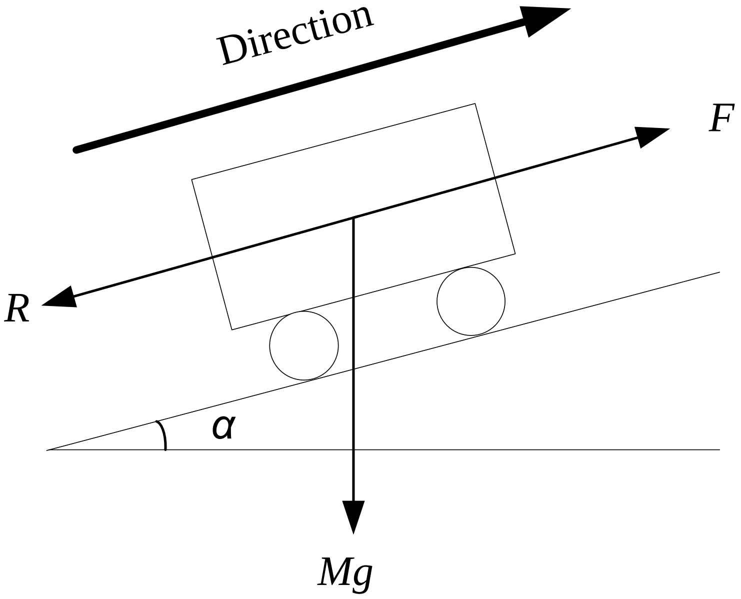
Dynamic input:
Timetable

Multi-train power network simulation

Fixed input:
- Substation infrastructure
- Transmission network data
- Regenerative braking settings

Output:
- Substation energy consumption
- Substation and transmission loss
- Used regenerative energy

Train movement simulation

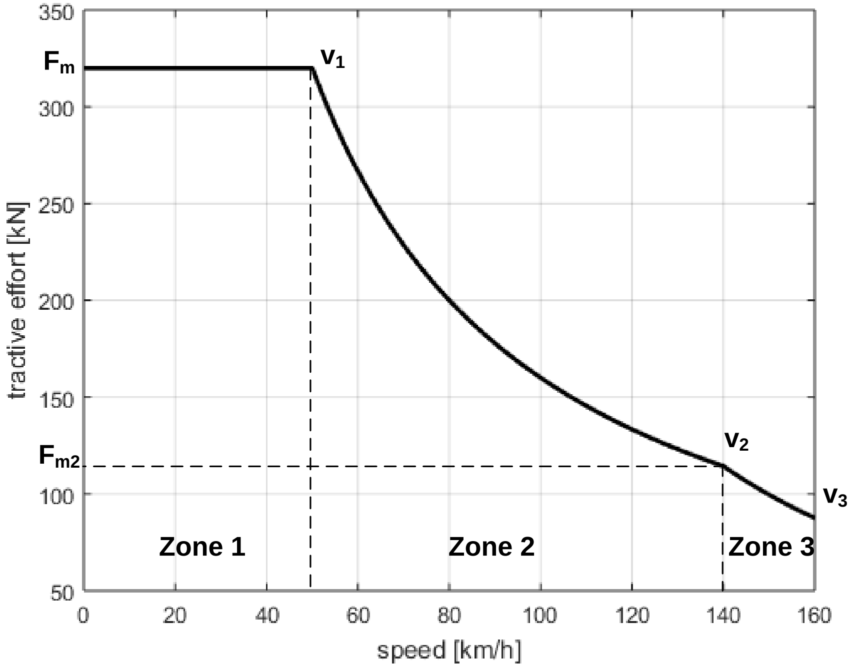


$$M_e \frac{\mathrm{d}^2 s}{\mathrm{d}t^2} = F - Mg\sin(\alpha) - R$$

$$M_e = M_t \times (1 + \lambda_w) + M_l$$

$$R = A + B\frac{\mathrm{d}s}{\mathrm{d}t} + C\left(\frac{\mathrm{d}s}{\mathrm{d}t}\right)^2 + \frac{D}{r}$$

Train movement simulation

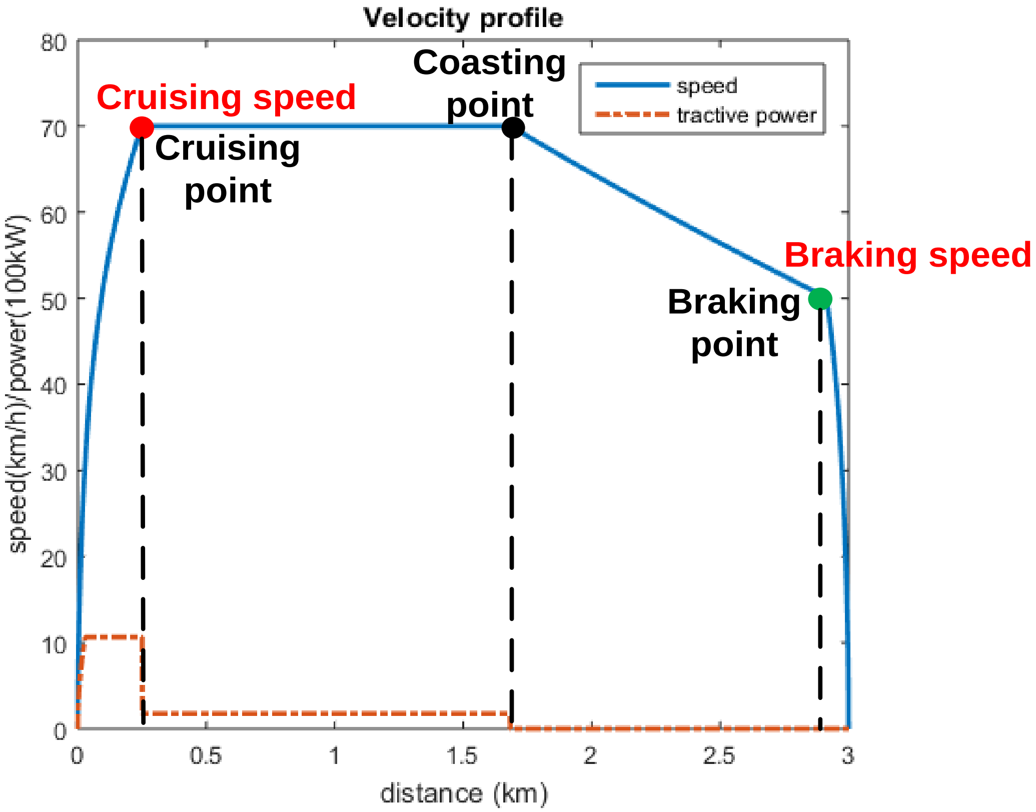


$$F(v) = \begin{cases} F_m & v < v_1 \\ \dfrac{F_m \times v_1}{v} & v_1 < v < v_2 \\ \dfrac{F_{m2} \times {v_2}^2}{v^2} & v_2 < v < v_3 \end{cases}$$

$$F_{m2} = \frac{F_m \times v_1}{v_2}$$

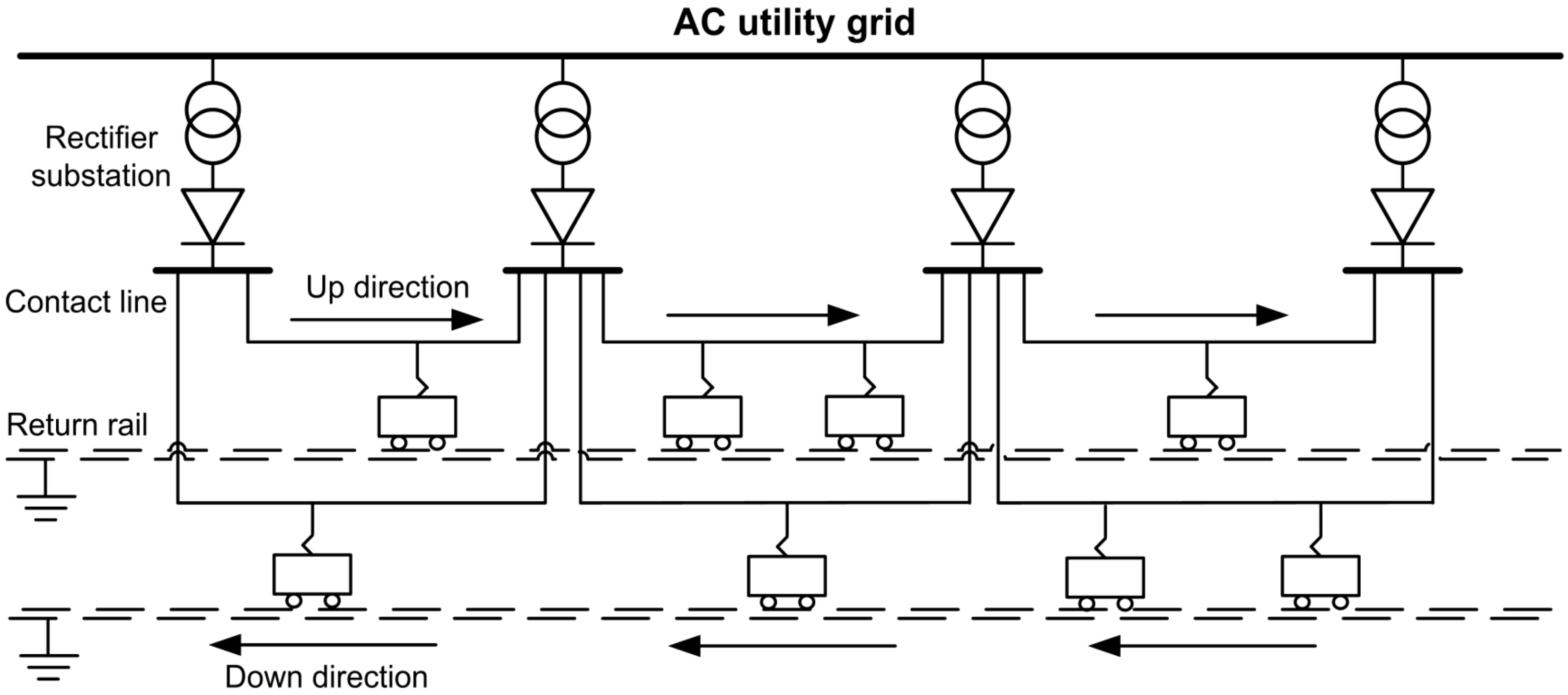
$$P_{me\_max} = F_m \times v_1$$

Train movement simulation

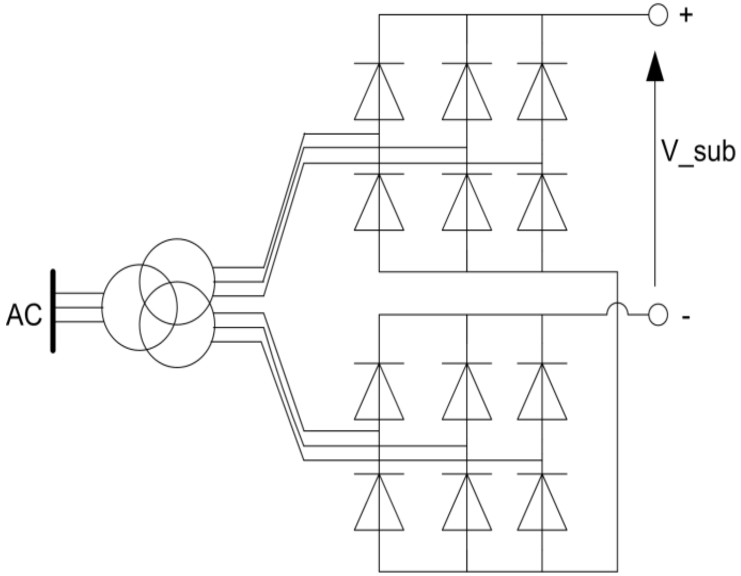


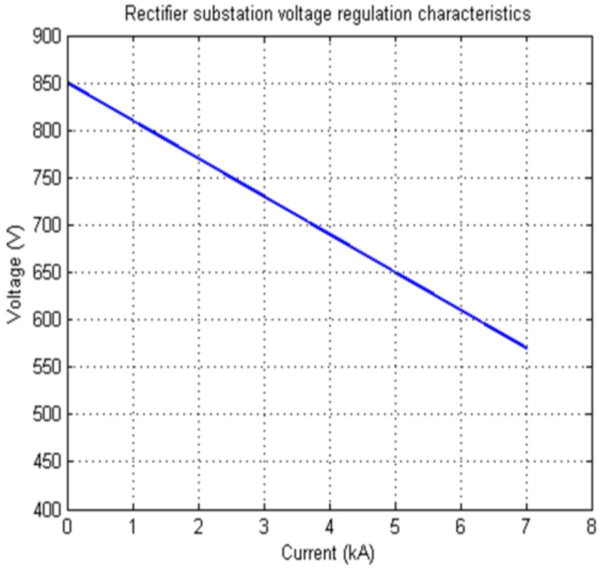
Motoring	$\begin{cases} F > Mg\sin(\alpha) + R \\ a = \dfrac{F - Mg\sin(\alpha) - R}{M_e} \end{cases}$
Cruising	$\begin{cases} F = Mg\sin(\alpha) + R \\ a = 0 \end{cases}$
Coasting	$\begin{cases} F = 0 \\ a = \dfrac{-Mg\sin(\alpha) - R}{M_e} \end{cases}$
Braking	$\begin{cases} F < 0 \\ a = \dfrac{F - Mg\sin(\alpha) - R}{M_e} \end{cases}$

Power network simulation



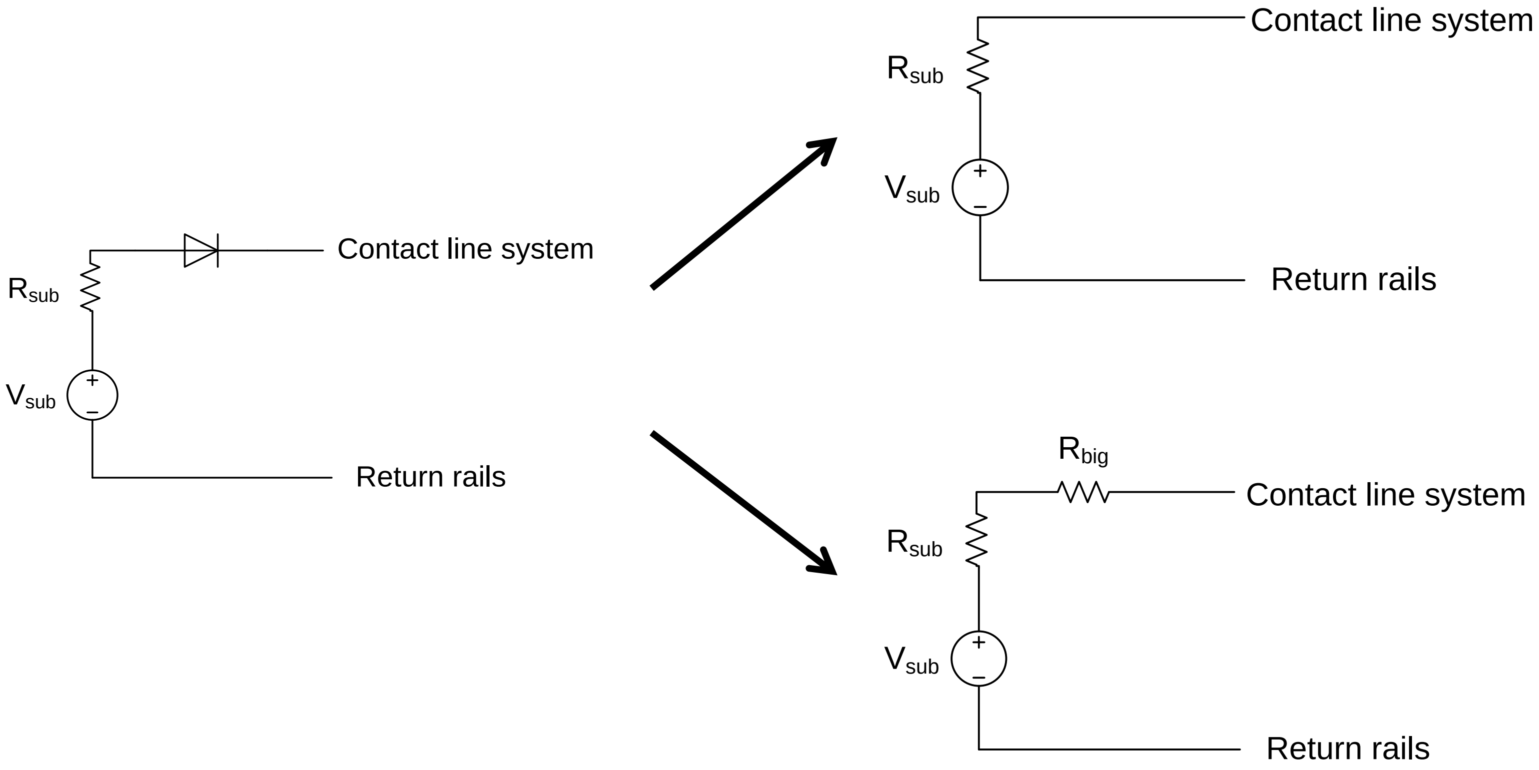
Rectifier substation



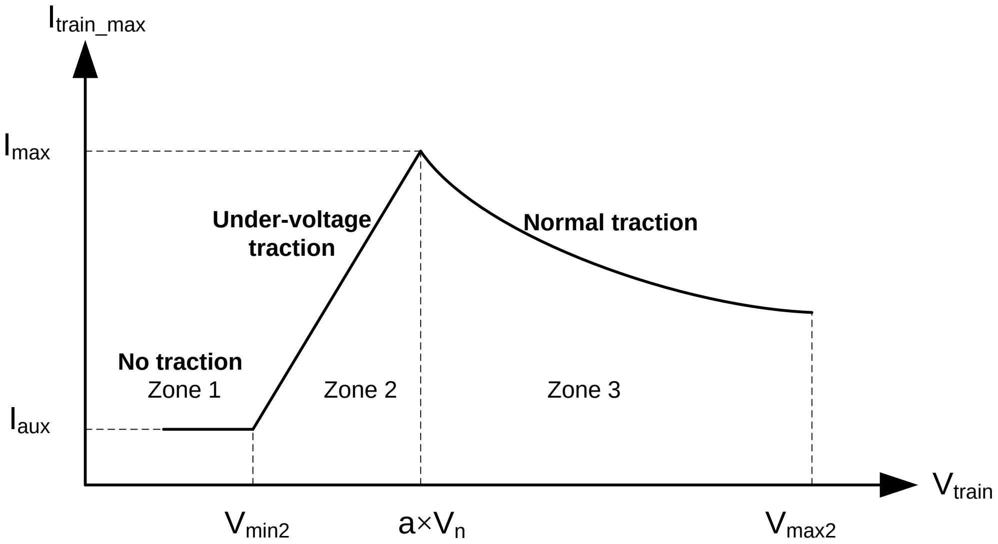


$$V_{sub} = V_{\text{no−load}} - R \times I_{sub}$$

Rectifier substation circuit

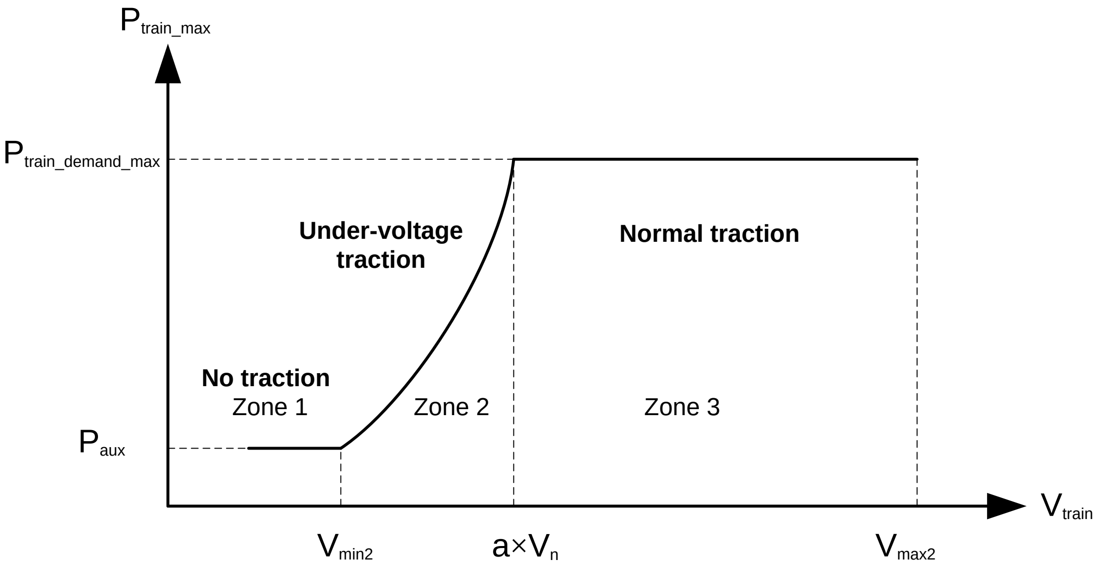


Traction train current limit



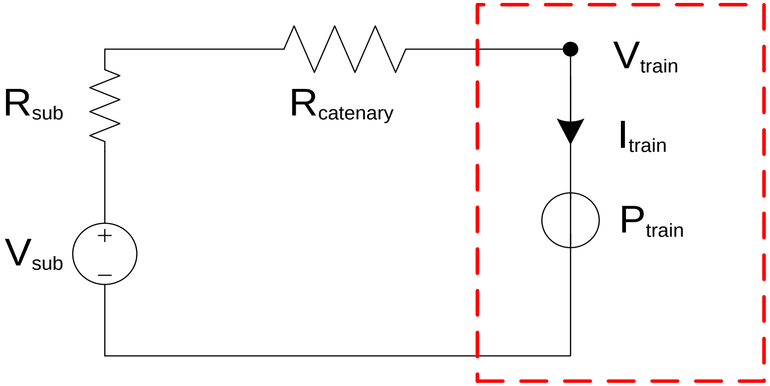
$$I_{train\_max} = \begin{cases} I_{aux} & if\ V_{train} \leq V_{min2} \\ \dfrac{V_{train} - V_{min2}}{r_{trac\_eq}} + I_{aux} & if\ V_{min2} < V_{train} \leq a \times V_n \\ \dfrac{P_{train\_demand\_max}}{V_{train}} & if\ V_{train} > a \times V_n \end{cases}$$

Traction train power limit

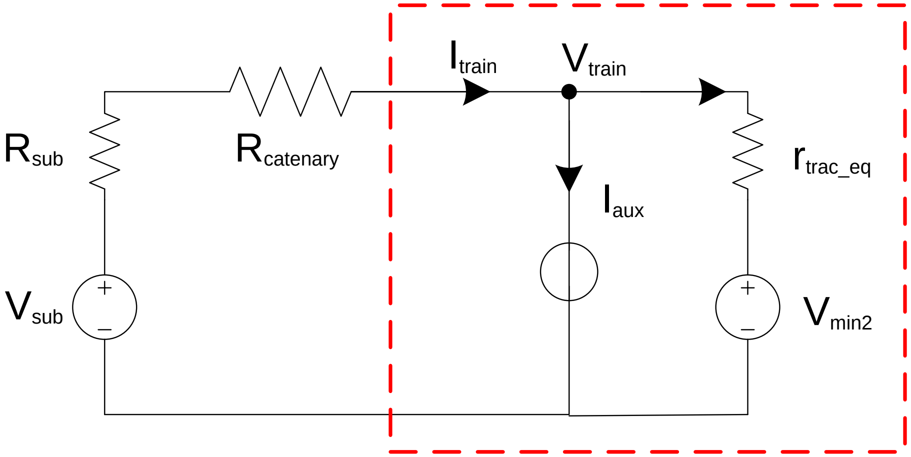


$$P_{train\_max} = \begin{cases} P_{aux} & if\ V_{train} \leq V_{min2} \\ \dfrac{(V_{train} - V_{min2}) \times V_{train}}{r_{trac\_eq}} + P_{aux} & if\ V_{min2} < V_{train} \leq a \times V_n \\ P_{train\_demand\_max} & if\ V_{train} > a \times V_n \end{cases}$$

Traction train circuit limit



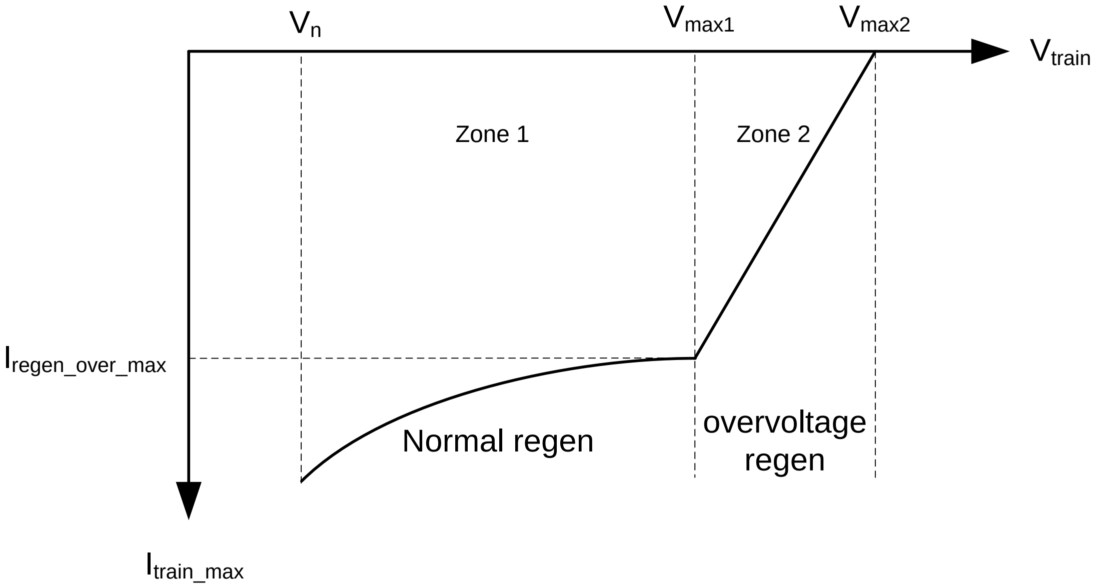
$$P_{train\_demand} = P_{train} = I_{train} \times V_{train}$$



$$P_{train\_demand} > P_{train} = I_{train} \times V_{train}$$

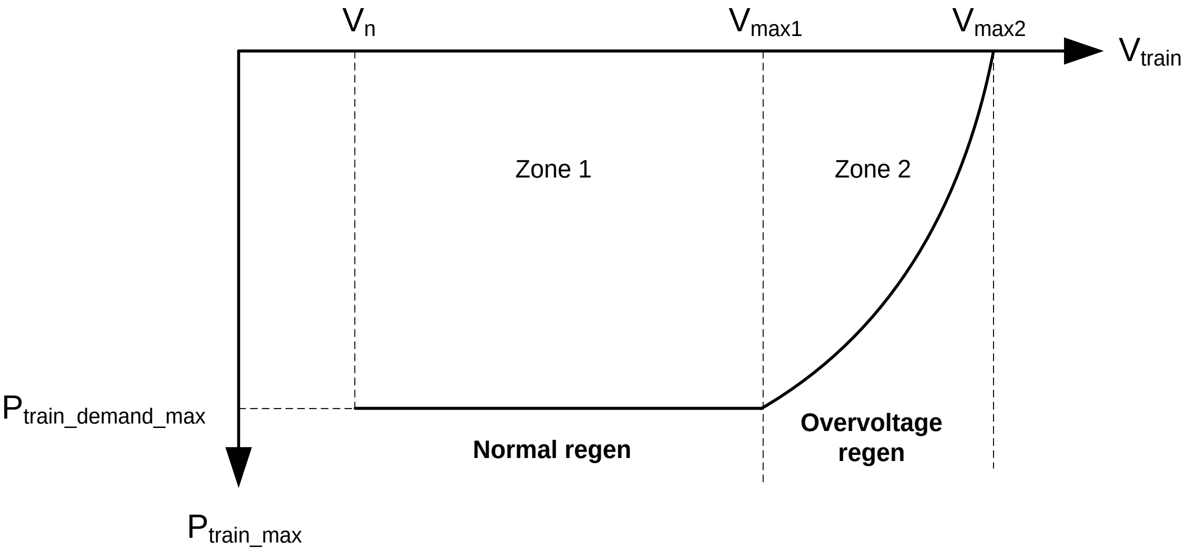
$$I_{train} = I_{aux} + \frac{V_{train} - V_{min2}}{r_{trac\_eq}}$$

Braking train current limit



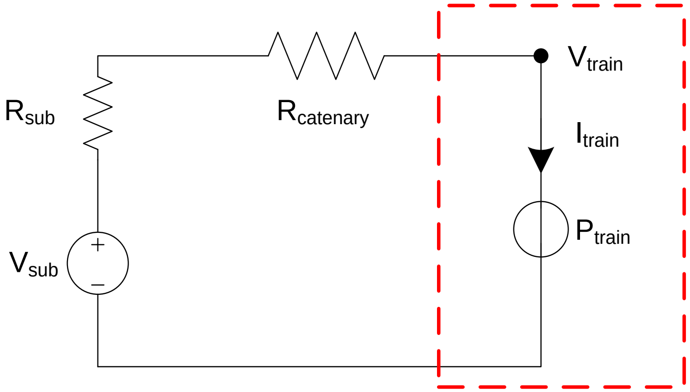
$$I_{train\_max} = \begin{cases} \dfrac{P_{train\_demand\_max}}{V_{train}} & if\ V_{train} \le V_{max1} \\ \dfrac{V_{train} - V_{max2}}{r_{brake\_eq}} & if\ V_{max1} < V_{train} \le V_{max2} \end{cases}$$

Braking train power limit

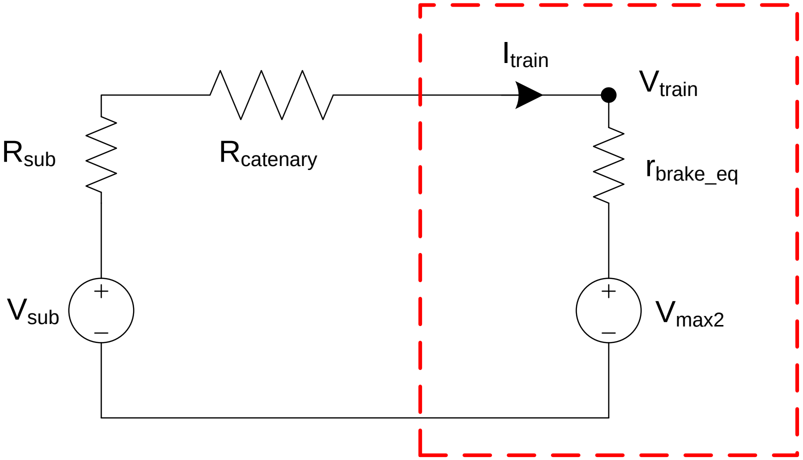


$$P_{train\_max} = \begin{cases} P_{train\_demand\_max} & if\ V_{train} \leq V_{max1} \\ \dfrac{(V_{train} - V_{max2}) \times V_{train}}{r_{brake\_eq}} & if\ V_{max1} < V_{train} \leq V_{max2} \end{cases}$$

Braking train circuit



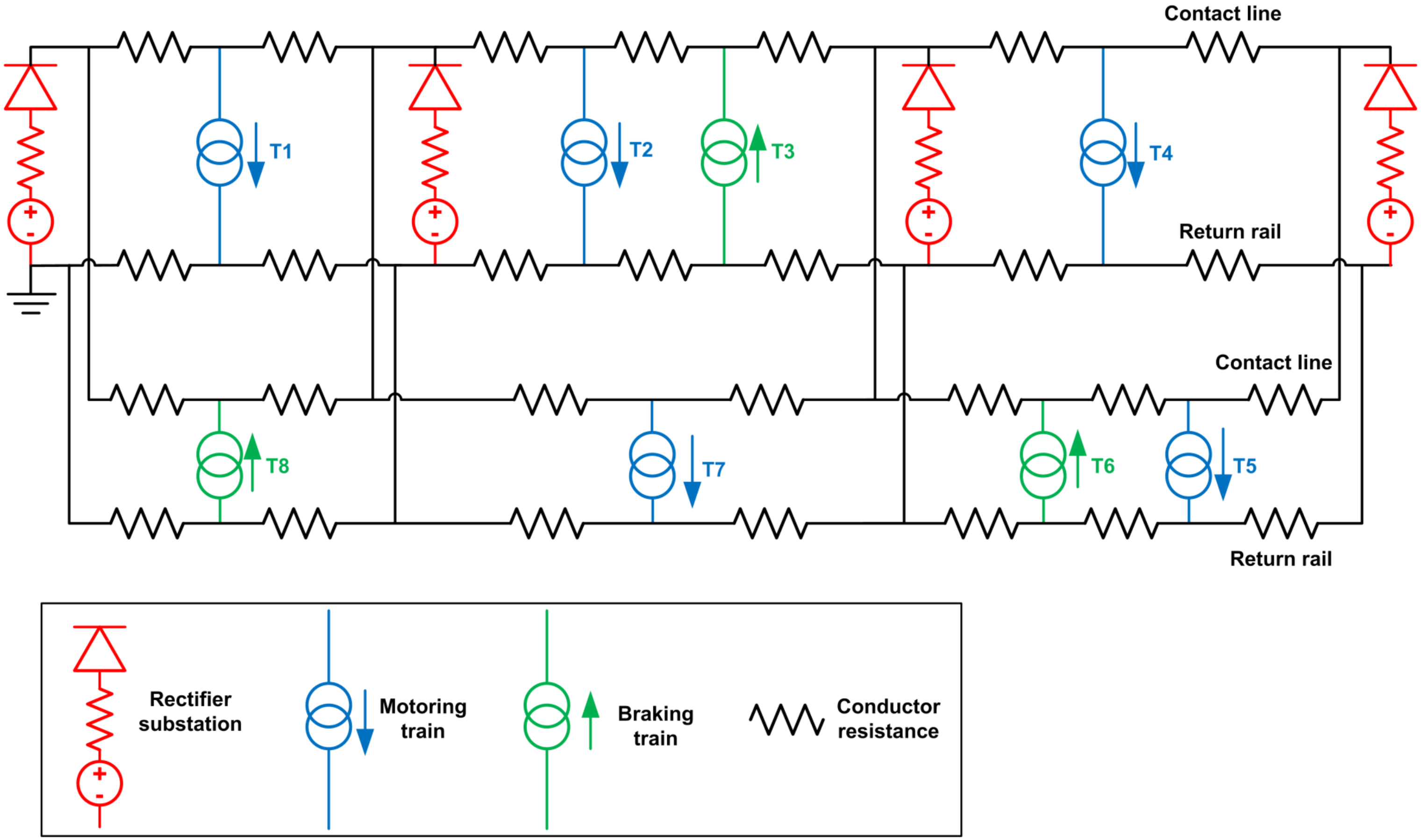
$$P_{train\_demand} = P_{train} = I_{train} \times V_{train}$$



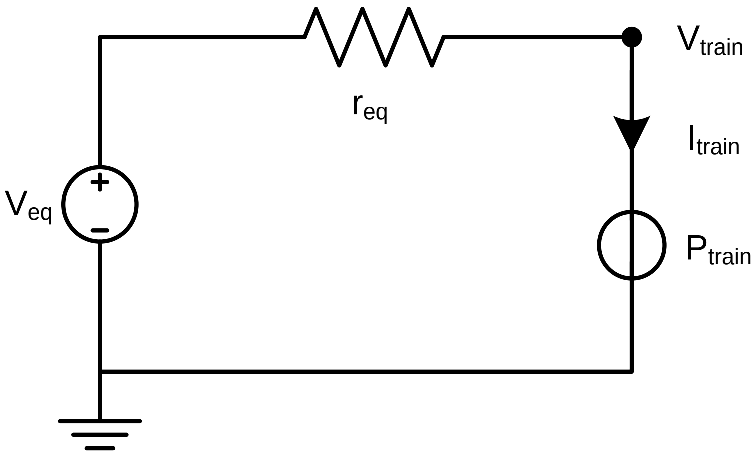
$$\left|P_{train\_demand}\right| > |P_{train}| = |I_{train} \times V_{train}|$$

$$I_{train} = \frac{V_{train} - V_{max2}}{r_{brake\_eq}}$$

Equivalent circuit



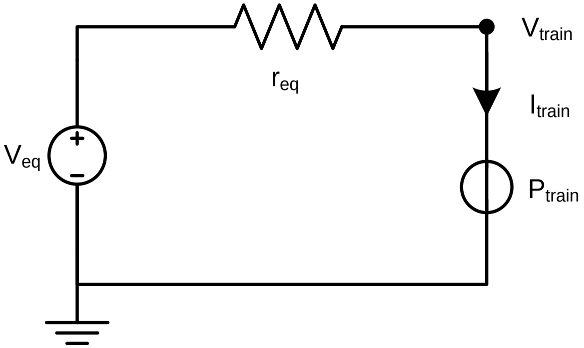
Traditional power flow solver



- $P_t = \frac{(V_{eq} - V_t)}{r_{eq}} \times V_t$
- P_t is known
- V_t ?

- Newton-Raphson iterative method
- Point-Jacobi method
- Zollenkopf's bifactorisation
- Incomplete Cholesky Conjugate Gradient

Current-vector iterative method



- Step 1: Initialise all the train voltage

$$V_{train\_n}{}^{(0)} = V_{sub}$$

- Step 2: Calculate the train current at next iteration

$$I_{train\_n}^{(1)} = \frac{P_{train\_demand\_n}}{V_{train\_n}{}^{(0)}}$$

- Step 3: Update nodal voltages by nodal analysis

$$\left[V^{(1)}\right] = [Y]^{-1} \times \left[I^{(1)}\right]$$

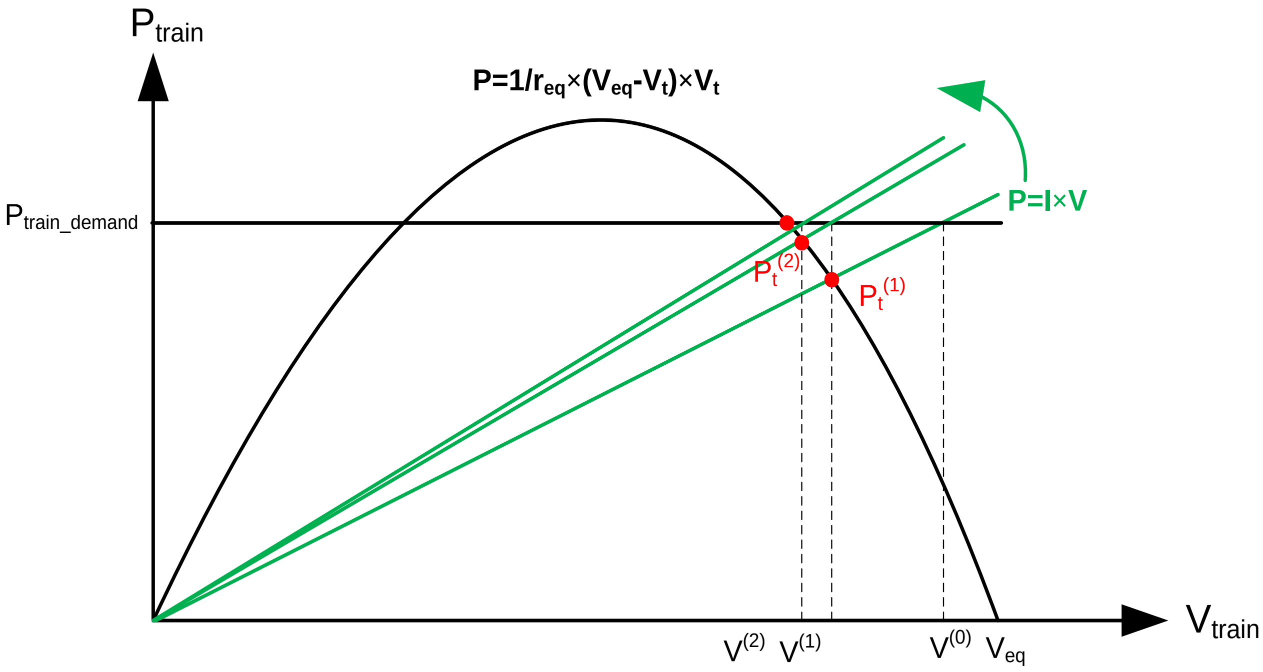
$$V_{train\_n}^{(1)} = V_{eq\_n} - r_{eq\_n} \times I_{train\_n}{}^{(1)}$$

- Step 4: Calculate train power at this iteration

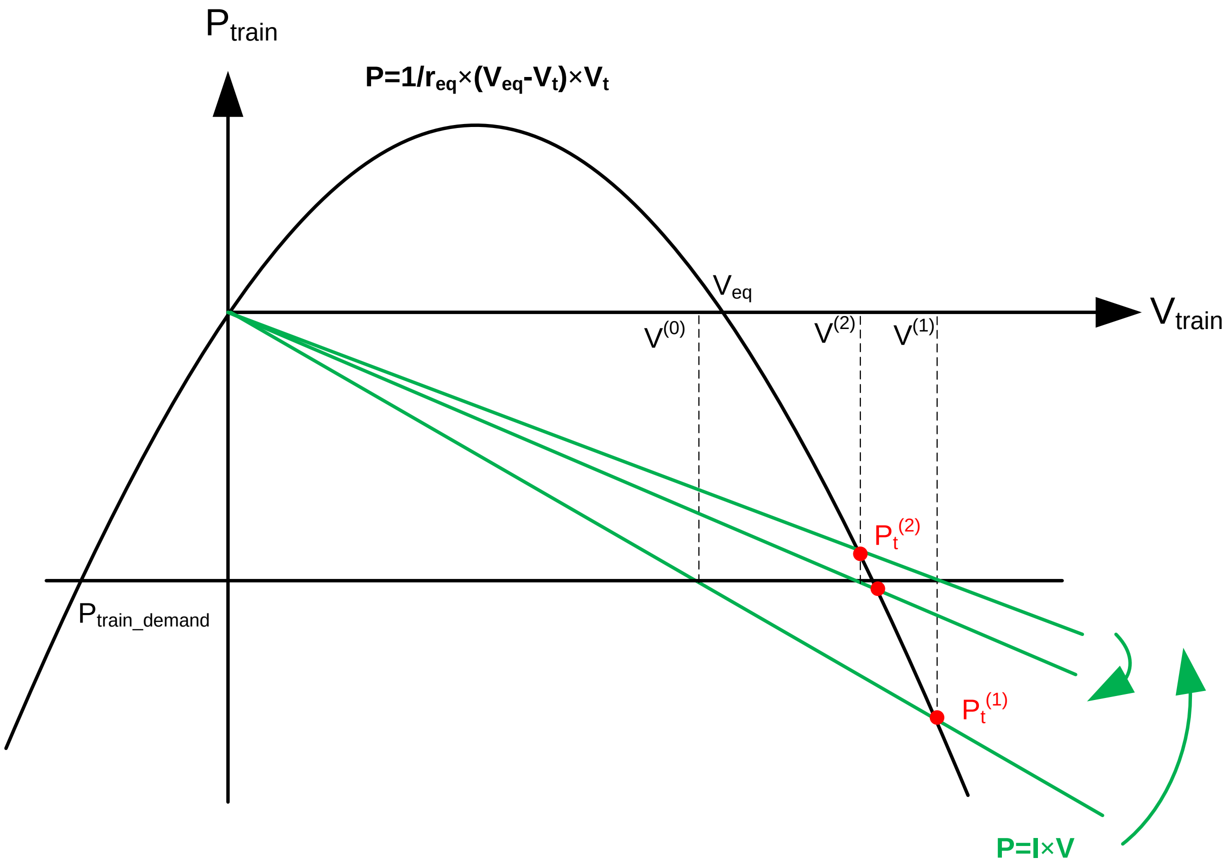
$$P_{train\_n}{}^{(1)} = V_{train\_n}{}^{(1)} \times I_{train\_n}{}^{(1)}$$

- Step 5: Criteria check . If not, repeat the above steps.

Traction train power flow



Braking train power flow



Piecewise nonlinear circuit solver

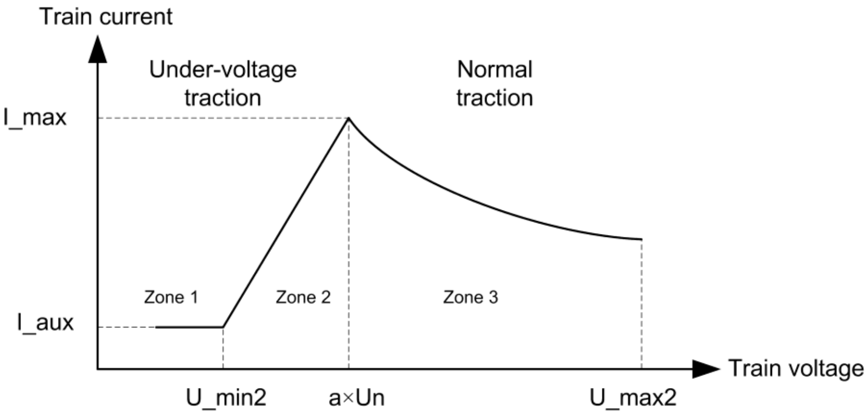


Fig.1 Train current limitation in traction

- ☐ Traction train model
- ☐ Under-voltage traction
- ☐ Normal traction

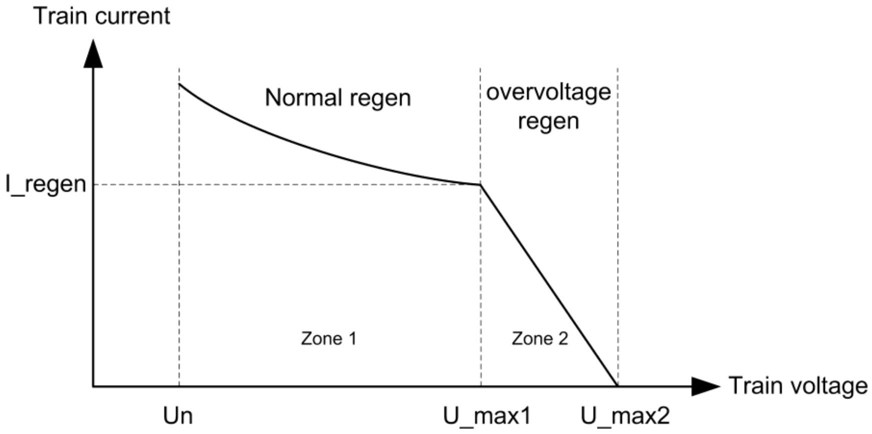
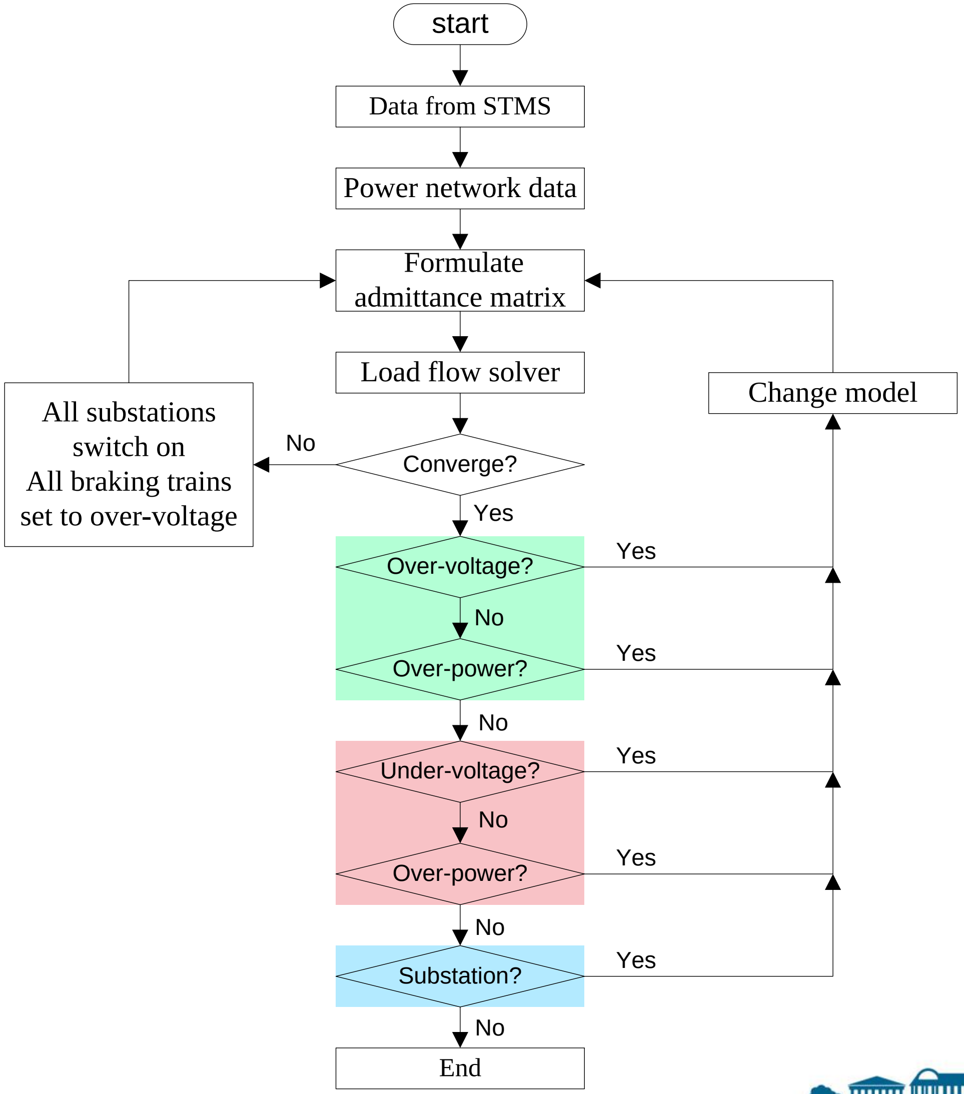


Fig.2 Train current limitation in regeneration

- ☐ Regen train model
- ☐ Normal regen
- ☐ Over-voltage regen

Load solver structure



start

Data from STMS

Power network data

Formulate admittance matrix

Load flow solver

Converge?

No

All substations switch on
All braking trains set to over-voltage

Yes

Over-voltage?

Yes

Change model

No

Over-power?

Yes

No

Under-voltage?

Yes

No

Over-power?

Yes

No

Substation?

Yes

No

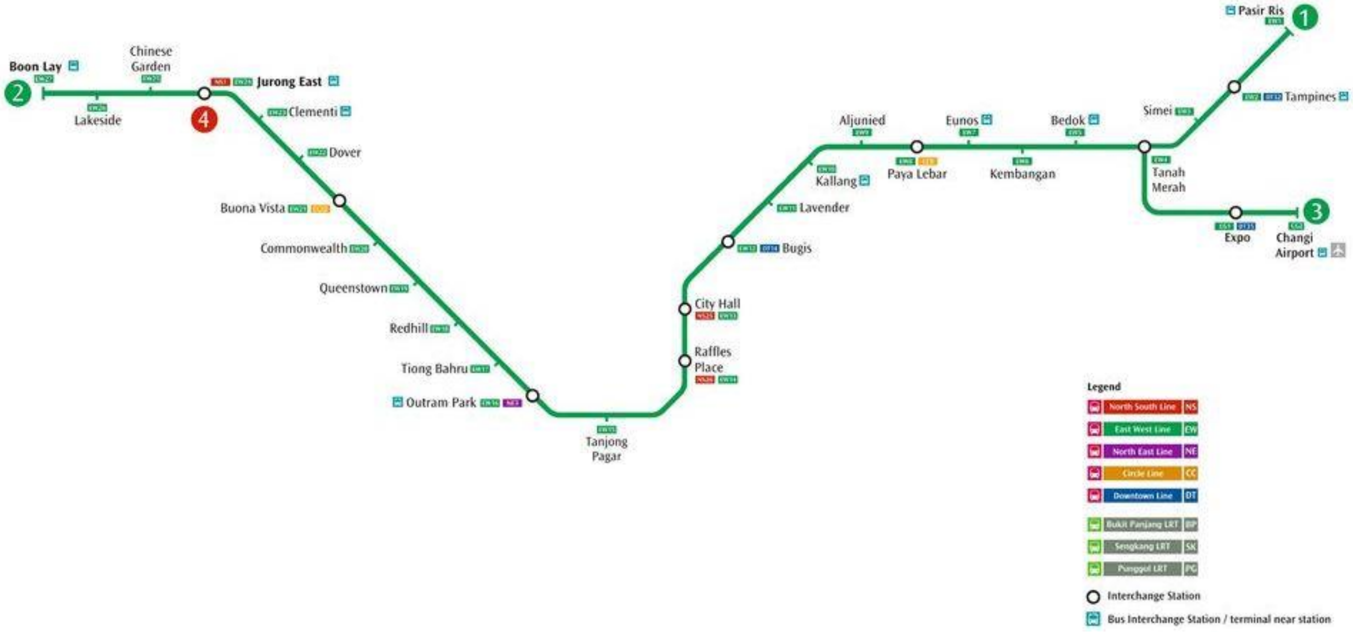
End

Using the simulator

- To apply the University of Birmingham Multi-Train Simulator at existing or expected rail routes to assist the understanding of the existing power supply network system performance：
  - Normal operation;
  - Energy consumption;
  - Shut down a traction power substation (TPSS);
  - Short circuit;
- The developed simulation will be further used to optimise the train driving and operation systems for energy saving or delay reduction.

SMRT East West MRT line

- East West MRT line is a suburb commuter railway line;
- Connecting from Boon Lay to Airport or Pasir Ris, total length 29km, 750V third-rail power supply system;
- The line is equipped with 23 substations, 8 tie stations and 2 stations without DC-link connection



Speed trajectory

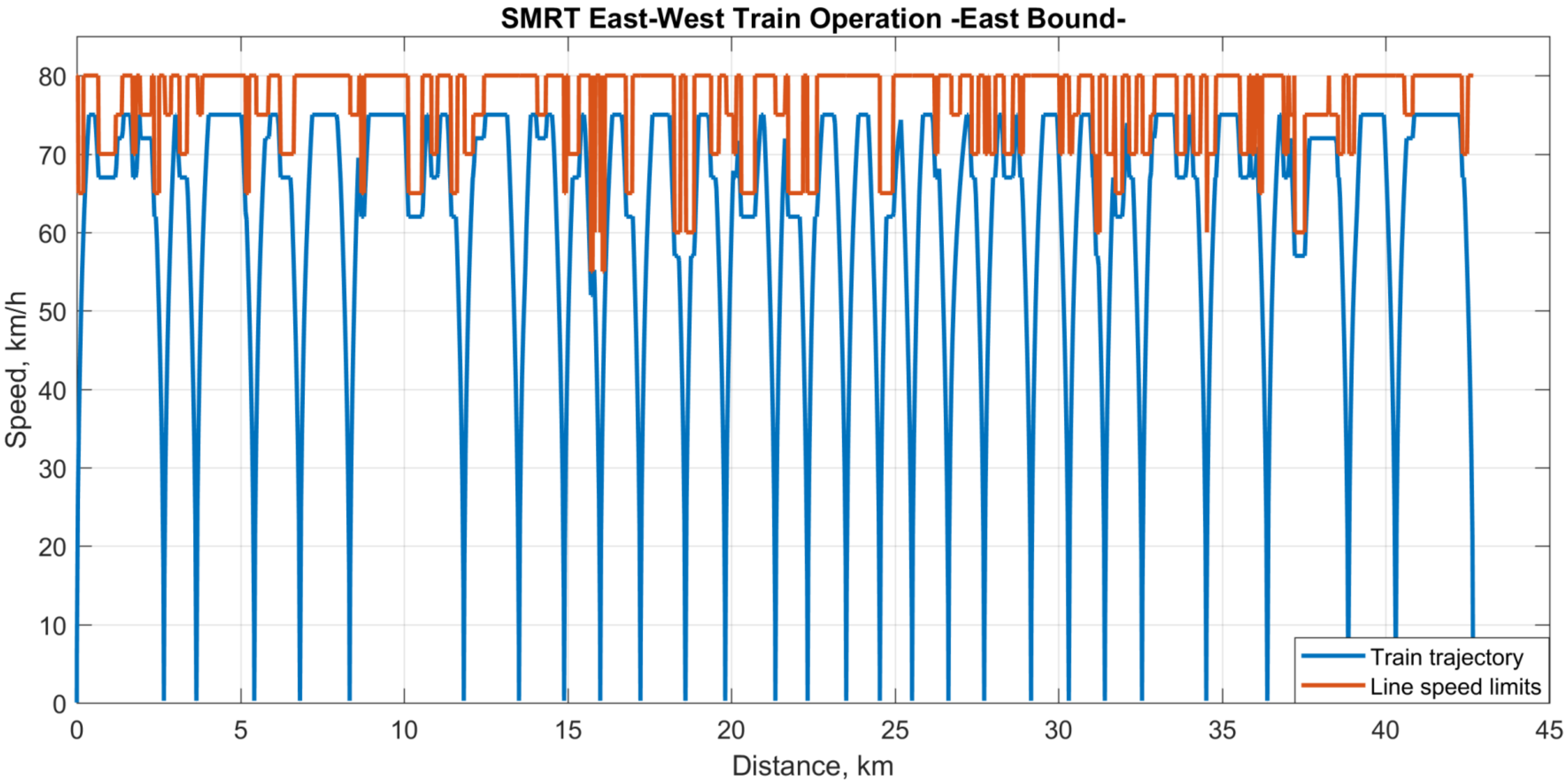
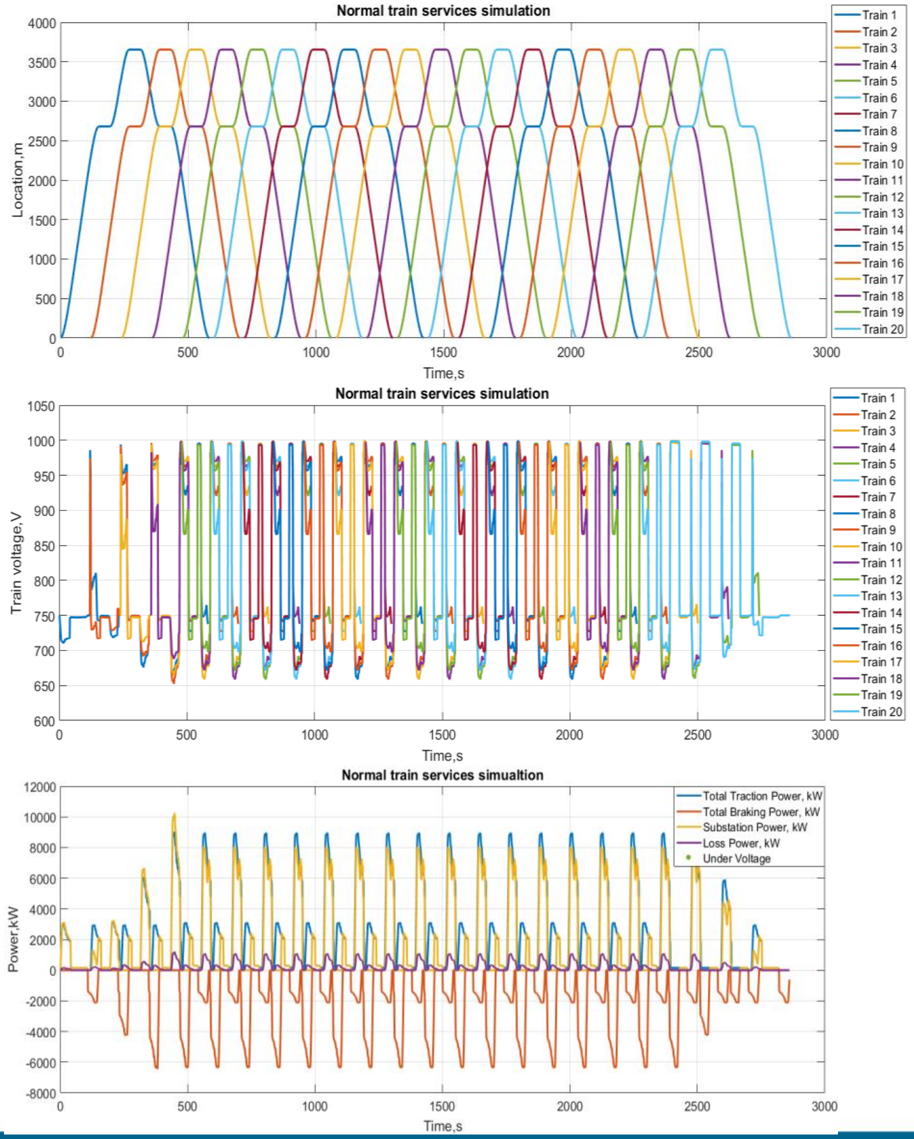


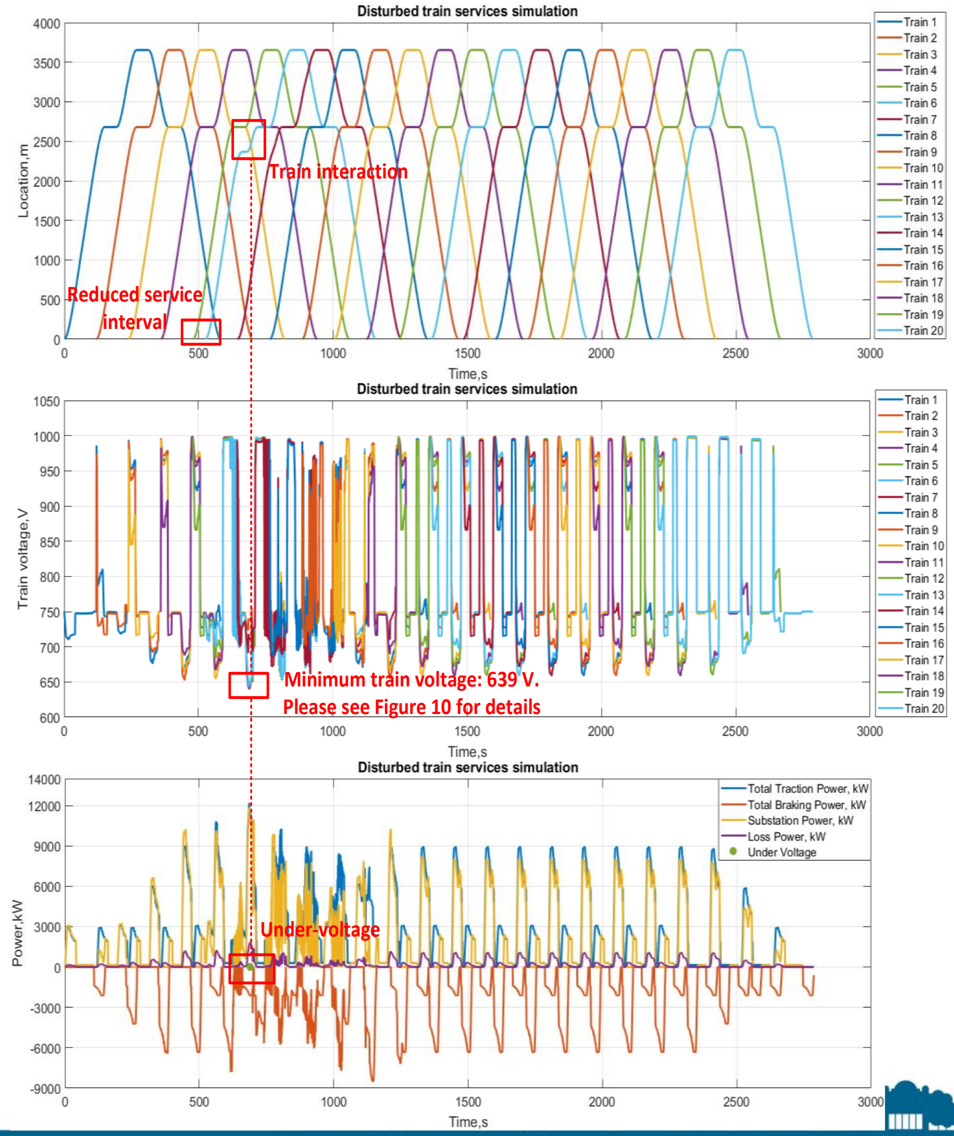
Figure SMRT East-West Train Operation -East Bound-

Normal operation VS disturbed operation


Normal train services simulation

Normal train services simulation

Normal train services simualtion


Disturbed train services simulation

Train interaction

Reduced service interval

Disturbed train services simulation

Minimum train voltage: 639 V. Please see Figure 10 for details

Disturbed train services simulation

Under-voltage

Under-voltage operation

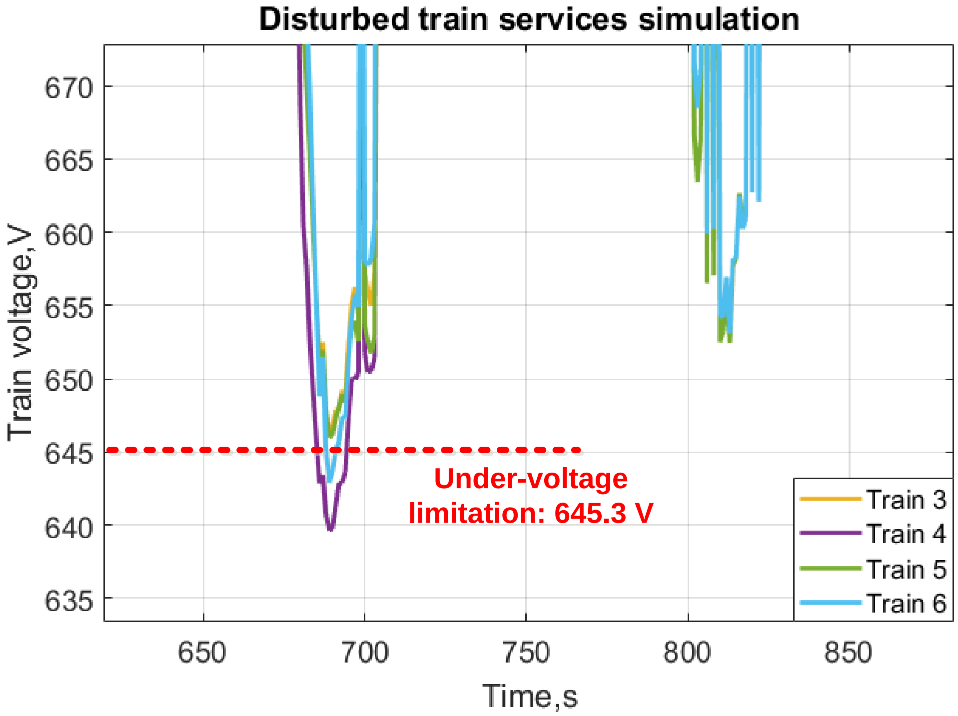


Figure 1. Trains operated at under-voltage

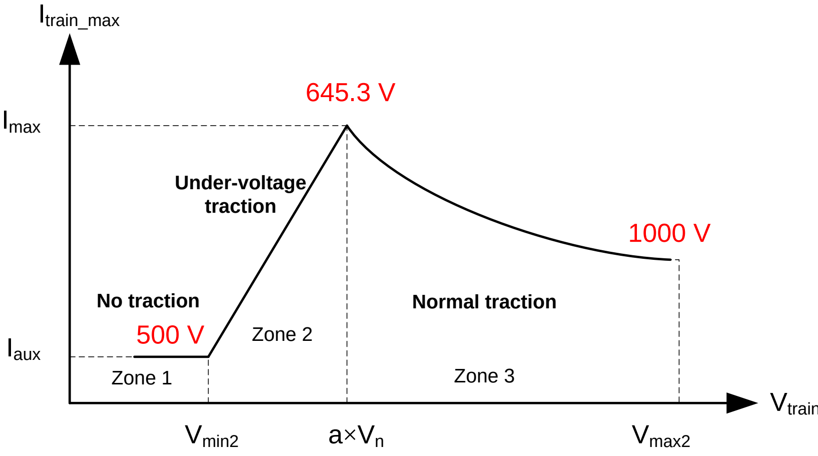


Figure 2. Current limitation of traction train

Shut Down a TPSS

- A traction power substation (TPSS) could be switched off when there is a fault current or in maintenance. The impact of TPSS outage on the network power consumption is evaluated in this section.
- Simulation findings:
  1. If one of TPSS is switched off, the energy consumption of this TPSS is zero. The energy consumption of TPSS around this fault TPSS increases.
  2. The amount of energy consumption changing of working TPSS depends on the distance from the fault TPSS. The maximum variation happens on the nearest working TPSS.
  3. If the fault TPSS supplied very large energy when it was on, the impact on the nearby TPSS will be significant when this fault TPSS is down.

Normal operation VS TPSS outage

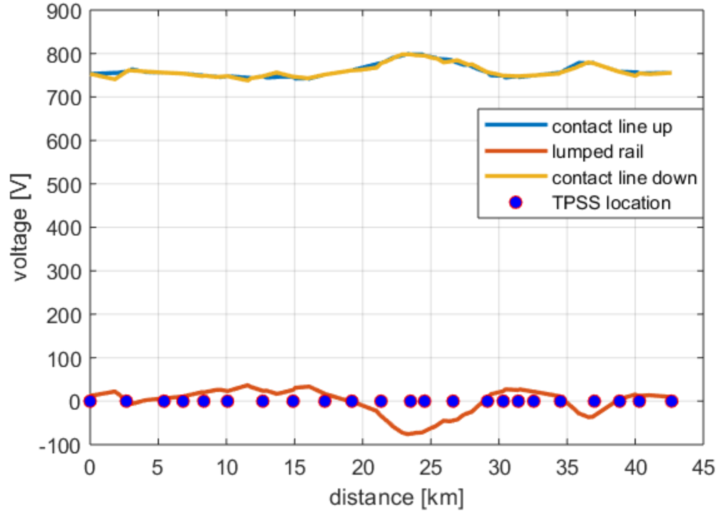
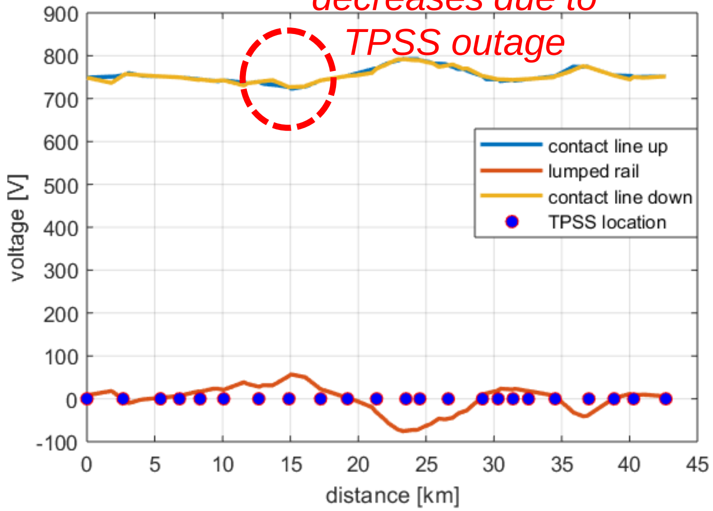


Figure 1 Network voltage against location



Network voltage decreases due to TPSS outage

Figure 3 Network voltage against location

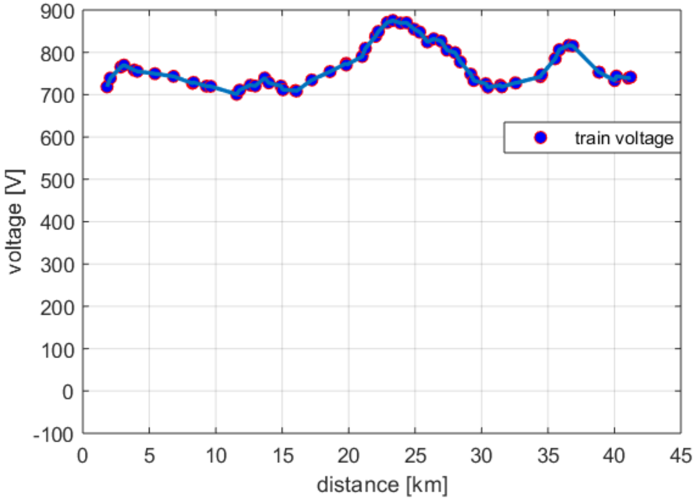


Figure 2 Train voltage against location

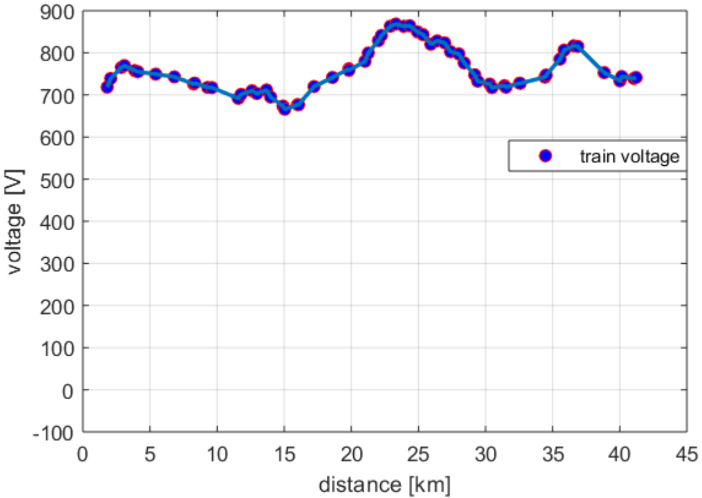


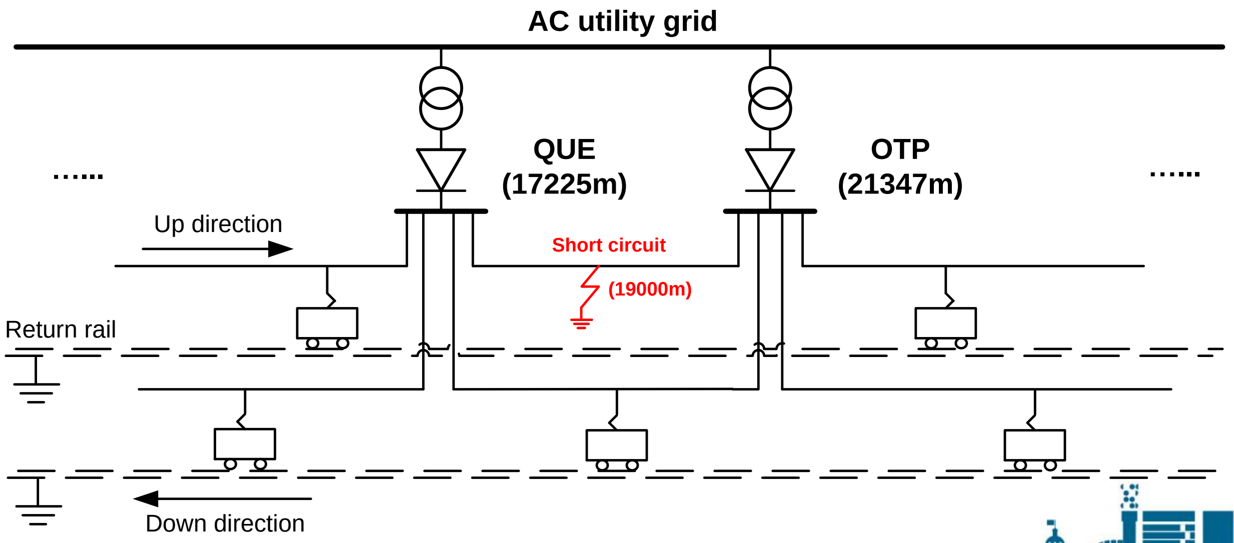
Figure 4 Train voltage against location

The energy consumed by each substation examples are shown in the table below. Case 1 shows a normal operation. Case 2 to Case 12 show the operation when a TTPS is shut down in [kWh]

	Station Code and Name	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12
1	JKN	1.16	0.00	2.10	1.25	1.18	1.17	1.16	1.16	1.16	1.16	1.16	1.16
2	PNR	1.75	2.70	0.00	2.22	1.87	1.79	1.77	1.76	1.76	1.75	1.75	1.75
3	LKS	1.30	1.47	1.99	0.00	1.78	1.46	1.36	1.32	1.31	1.30	1.30	1.30
4	CNG	1.11	1.15	1.33	1.71	0.00	1.51	1.26	1.16	1.12	1.11	1.11	1.11
5	JUR	1.07	1.09	1.15	1.27	1.48	0.00	1.58	1.22	1.11	1.08	1.07	1.07
6	SUO	1.16	1.17	1.19	1.23	1.29	1.58	0.00	1.67	1.28	1.19	1.17	1.16
7	CWO	1.38	1.38	1.39	1.40	1.41	1.48	1.80	0.00	1.97	1.53	1.43	1.39
8	BNV	1.44	1.44	1.44	1.44	1.45	1.47	1.55	2.06	0.00	2.01	1.61	1.49
9	QUE	1.55	1.55	1.55	1.55	1.55	1.56	1.58	1.70	2.10	0.00	2.23	1.75
10	DLO	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.70	1.80	2.29	0.00	2.33
11	OTP	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.72	1.75	1.88	2.34	0.00
12	RFP	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.32	1.35	1.46	1.90
13	CTH	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.15	1.16	1.21	1.40
14	LVR	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.39	1.39	1.39	1.40	1.45
15	ALJ	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.20
16	PYL	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.96
17	EUN	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
18	KEM	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
19	BDK	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
20	SBO	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
21	SIM	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23
22	TAM	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
23	PSR	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.8695	0.87

Short Circuit Case Study

- A 64P tripping occurred in SMRT on July 2017. In order to assist the understanding of short circuit fault, a simulation of short circuit fault are developed. The short circuit is assumed to occur between QUE 17225m) and OTP (21347m), between power supply network to earth.



Normal operation VS short circuit

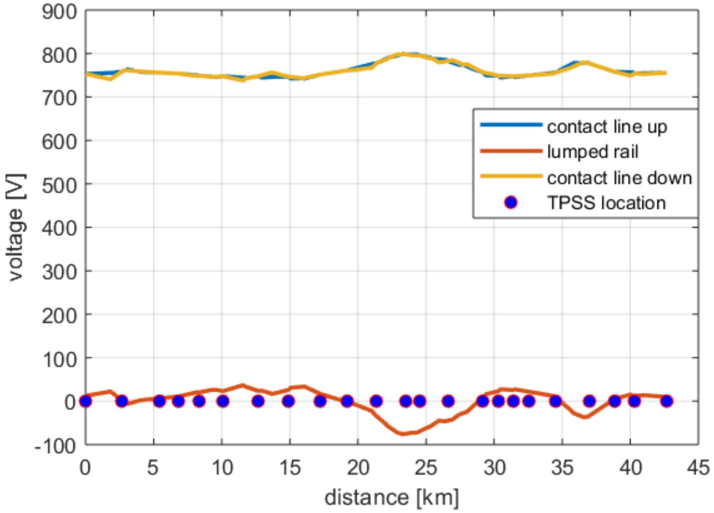


Figure 1 Network voltage against location

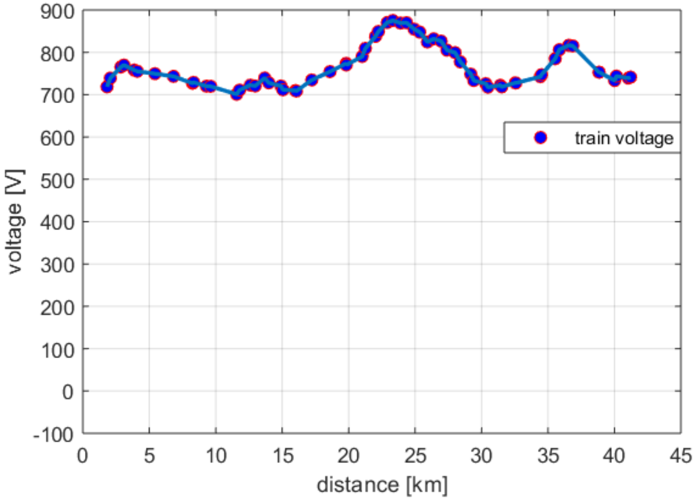
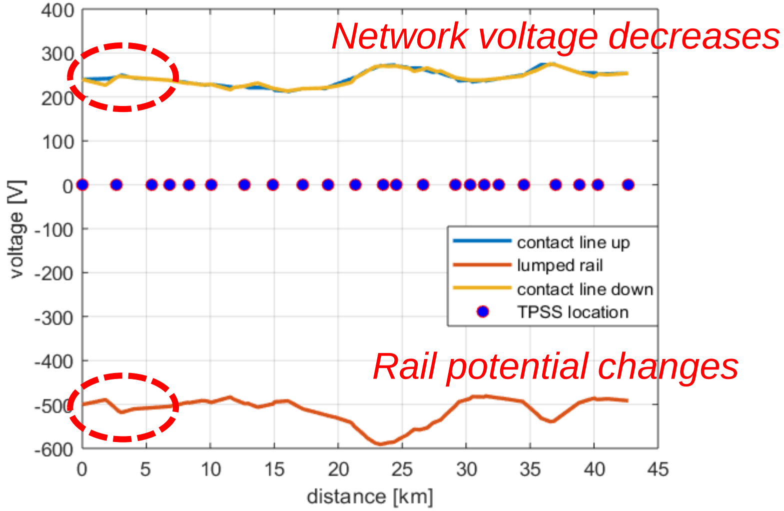


Figure 2 Train voltage against location



Network voltage decreases

Rail potential changes

Figure 3 Network voltage against location

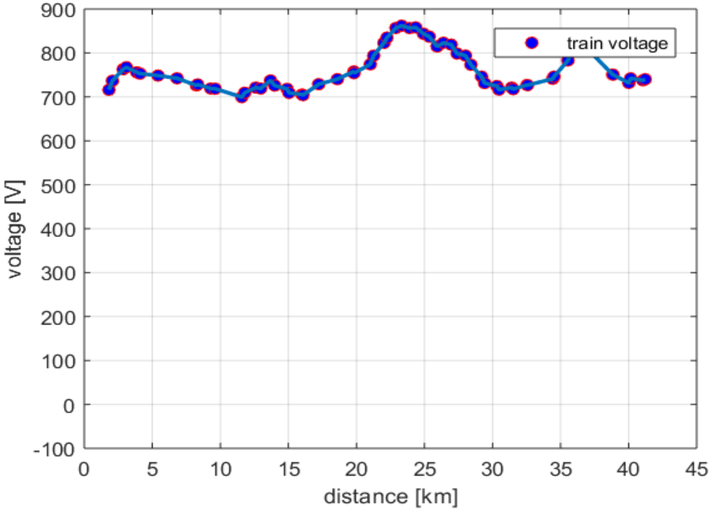
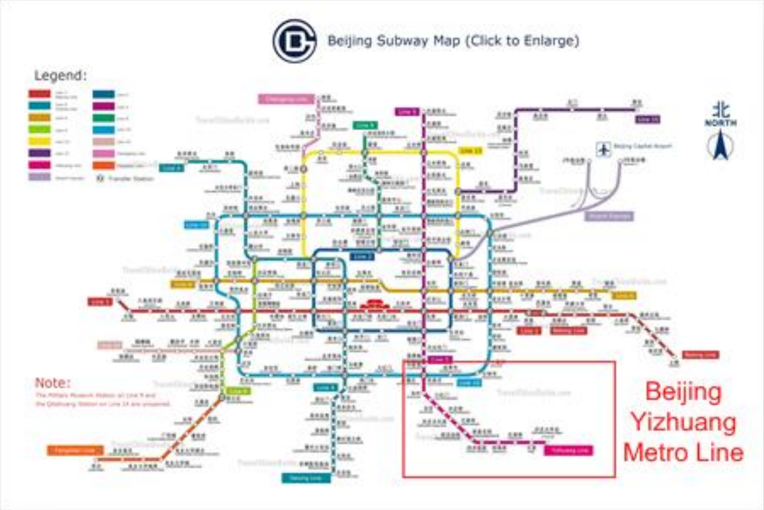


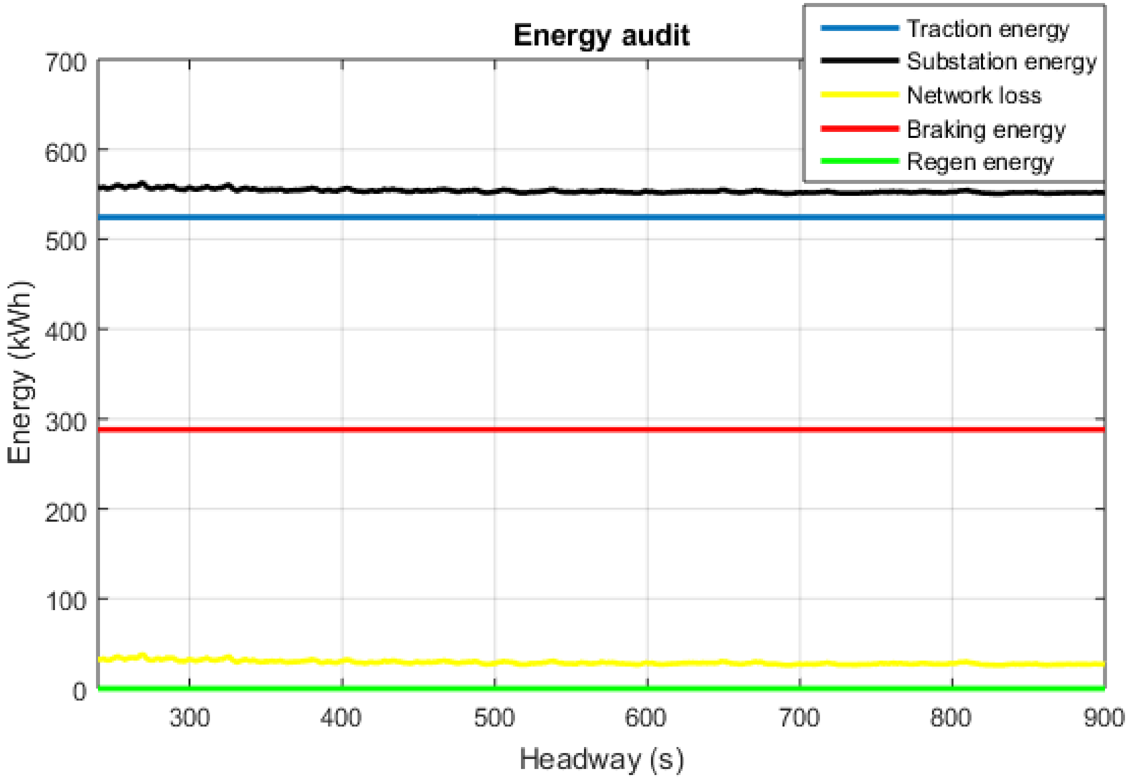
Figure 4 Train voltage against location

Beijing Yizhuang Subway Line- Optimisation



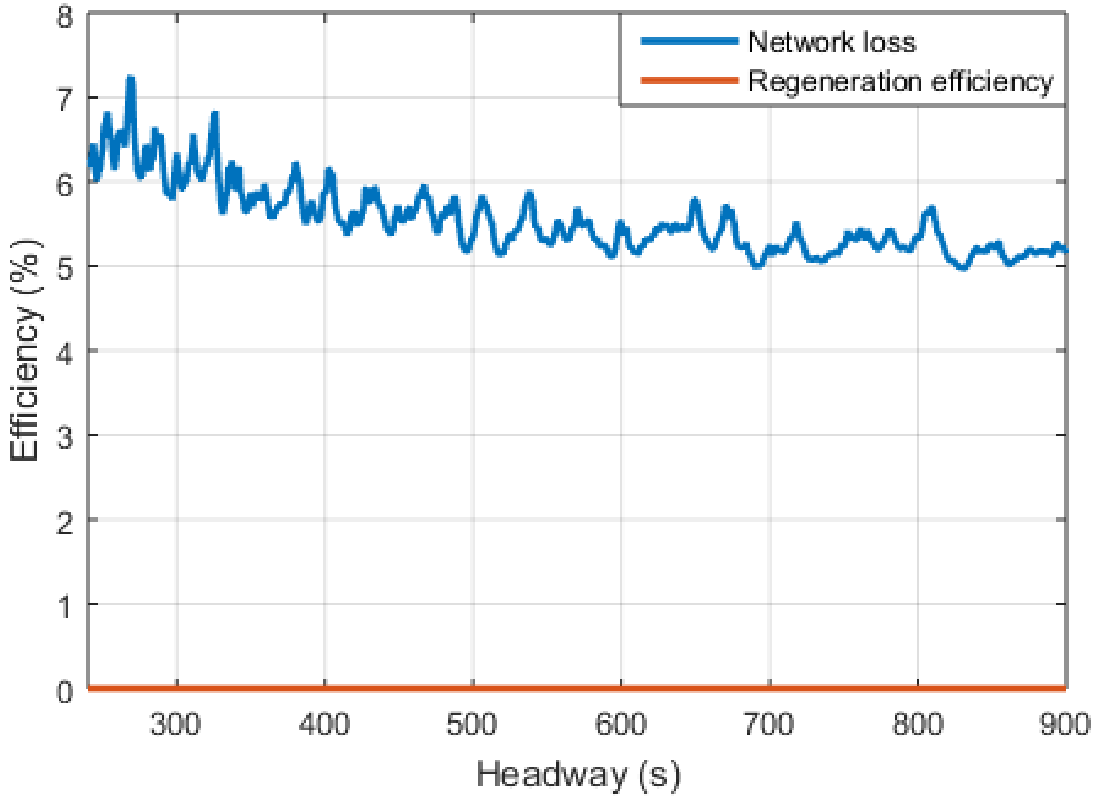
- Beijing Yizhuang Metro Line is a suburb commuter railway line equipped with CBTC systems;
- Connecting from Yizhuang Railway station to Songjiazhuang, total length 23km；
- Contains 14 stations and 12 rectifier substation with 750V third rail power supply system;
- Passenger flow 1.13 million passenger per day.

Energy consumption without regen



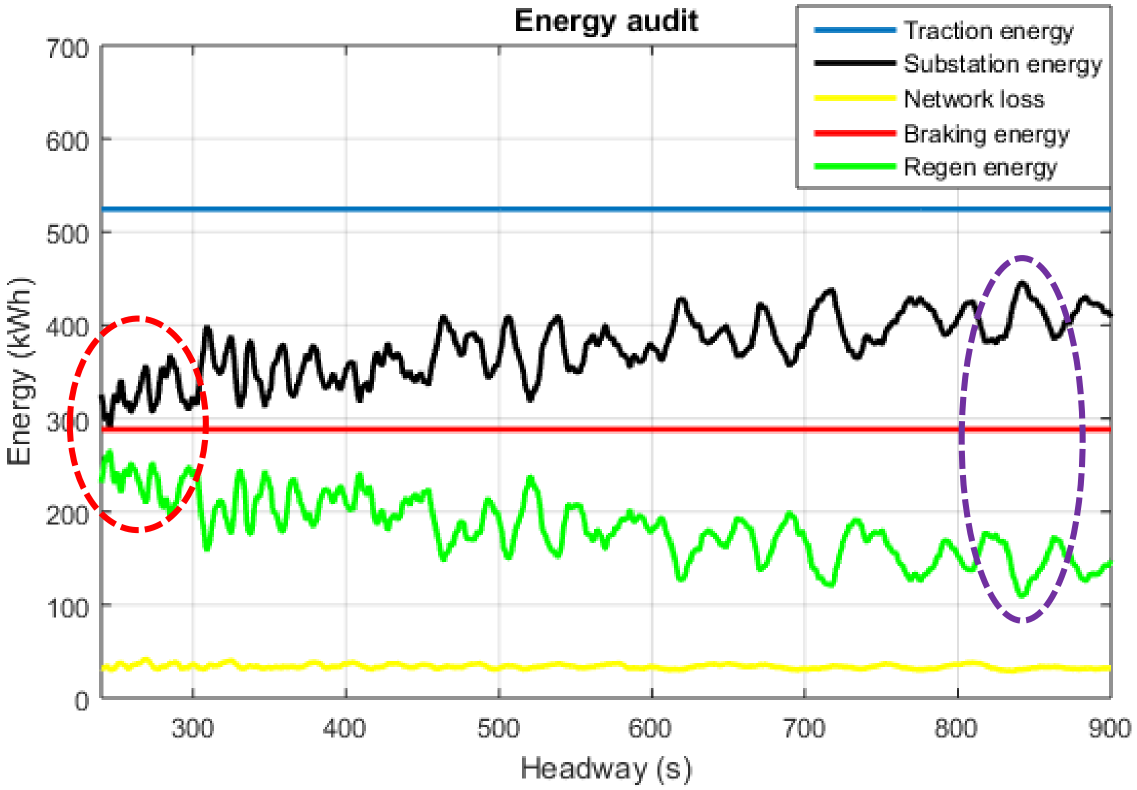
- Headway ranges from 240 to 900s;
- Traction and braking energy don’t change;
- Substation energy varies within 2%;
- No regenerative energy.

Energy consumption without regen



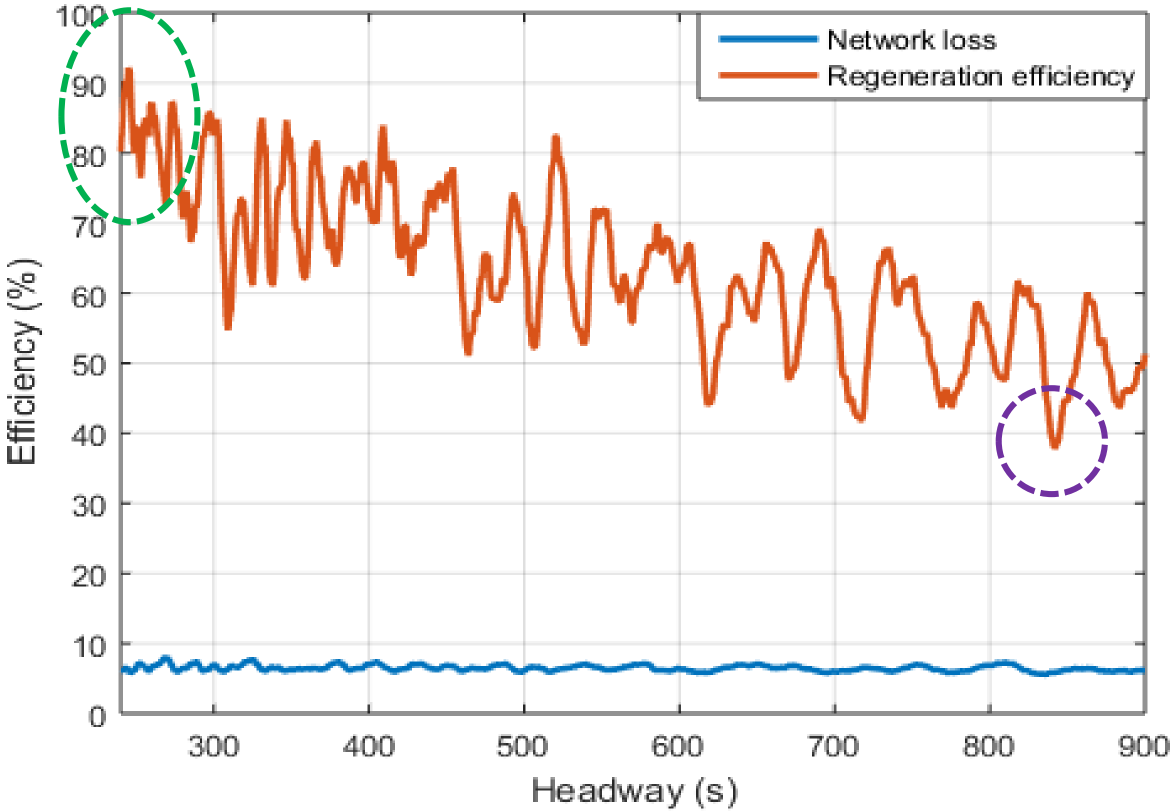
- Headway ranges from 240 to 900s;
- Regeneration efficiency is zero;
- Network loss coefficient ranges from 5% to 7%;
- Network loss decreases with the headway.

Energy consumption with regen



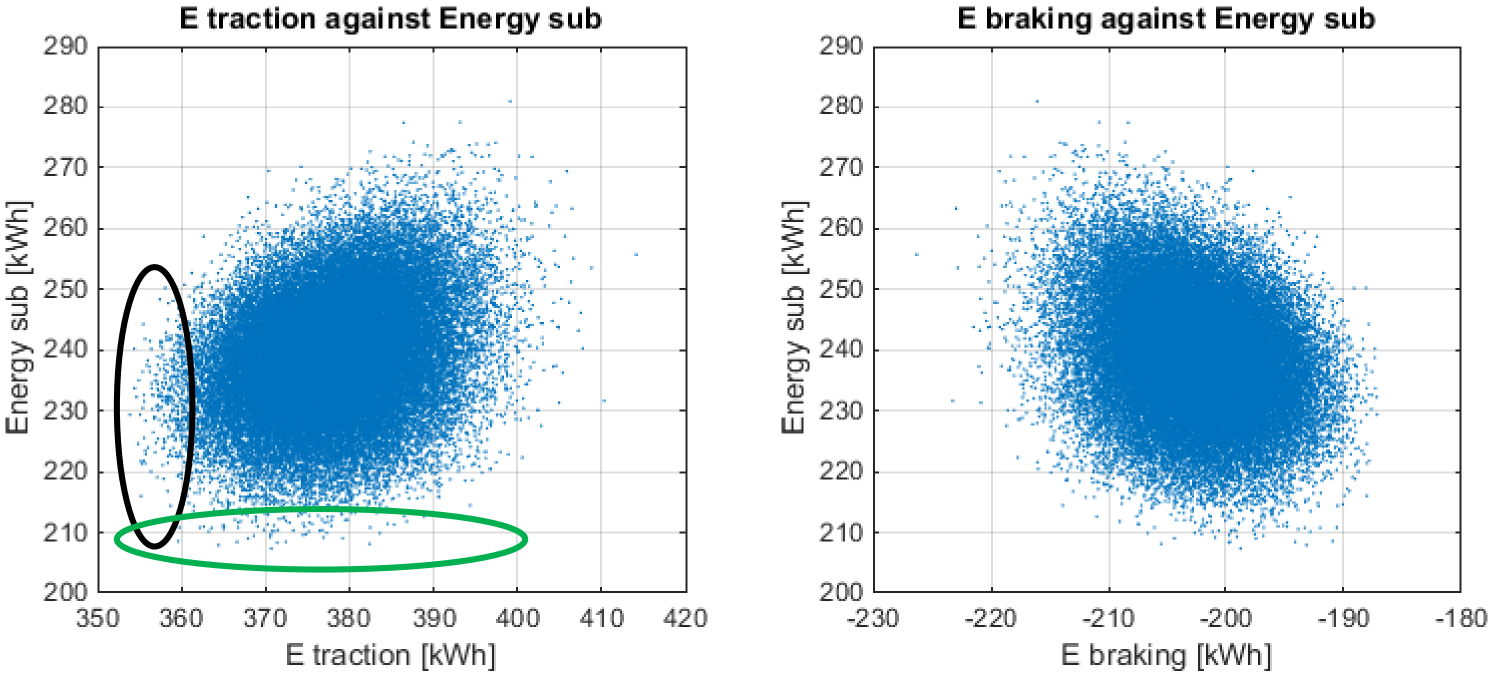
- Headway ranges from 240 to 900s;
- Traction and braking energy don’t change;
- Substation energy varies over 35%;
- Regenerative energy ranges from 109 kWh (at 842s) to 288 kWh (at 842 s).

Energy consumption with regen



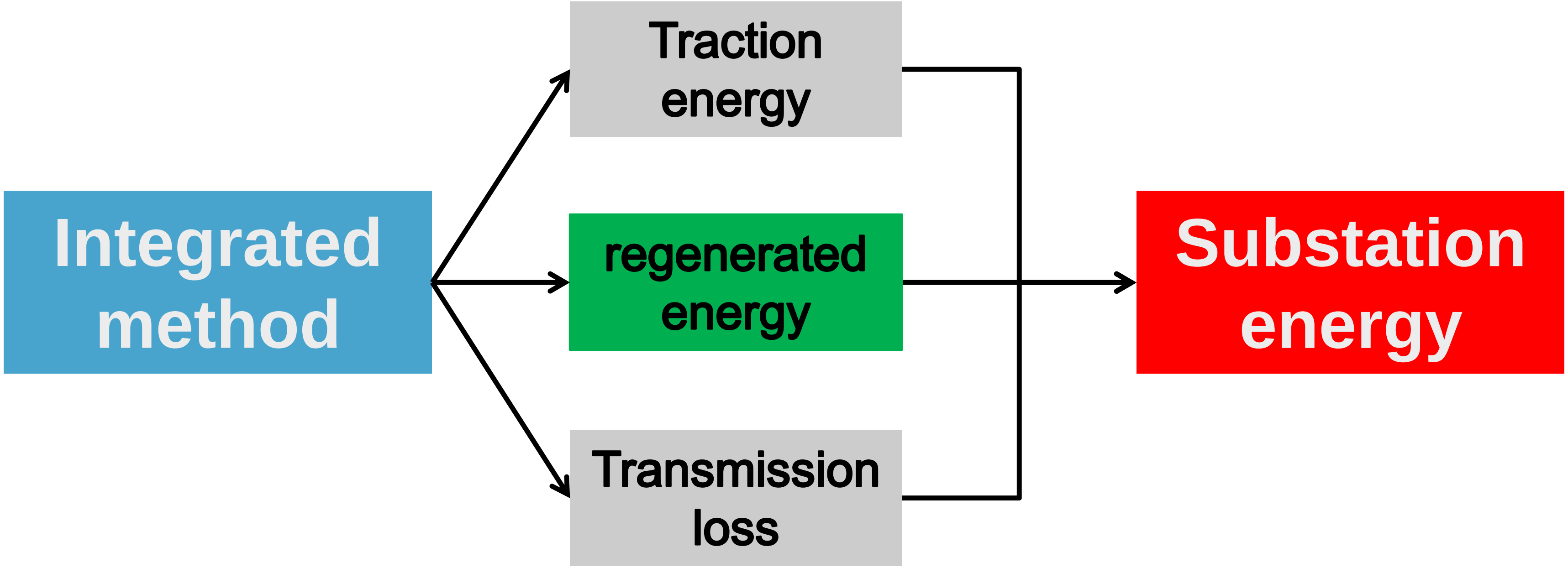
- Headway ranges from 240 to 900s;
- Regeneration efficiency ranges from 38% (at 842s) to 92% (at 842 s);
- Network loss coefficient ranges from 6% to 8%;
- Network loss is higher than the system without regeneration.

Understand system energy



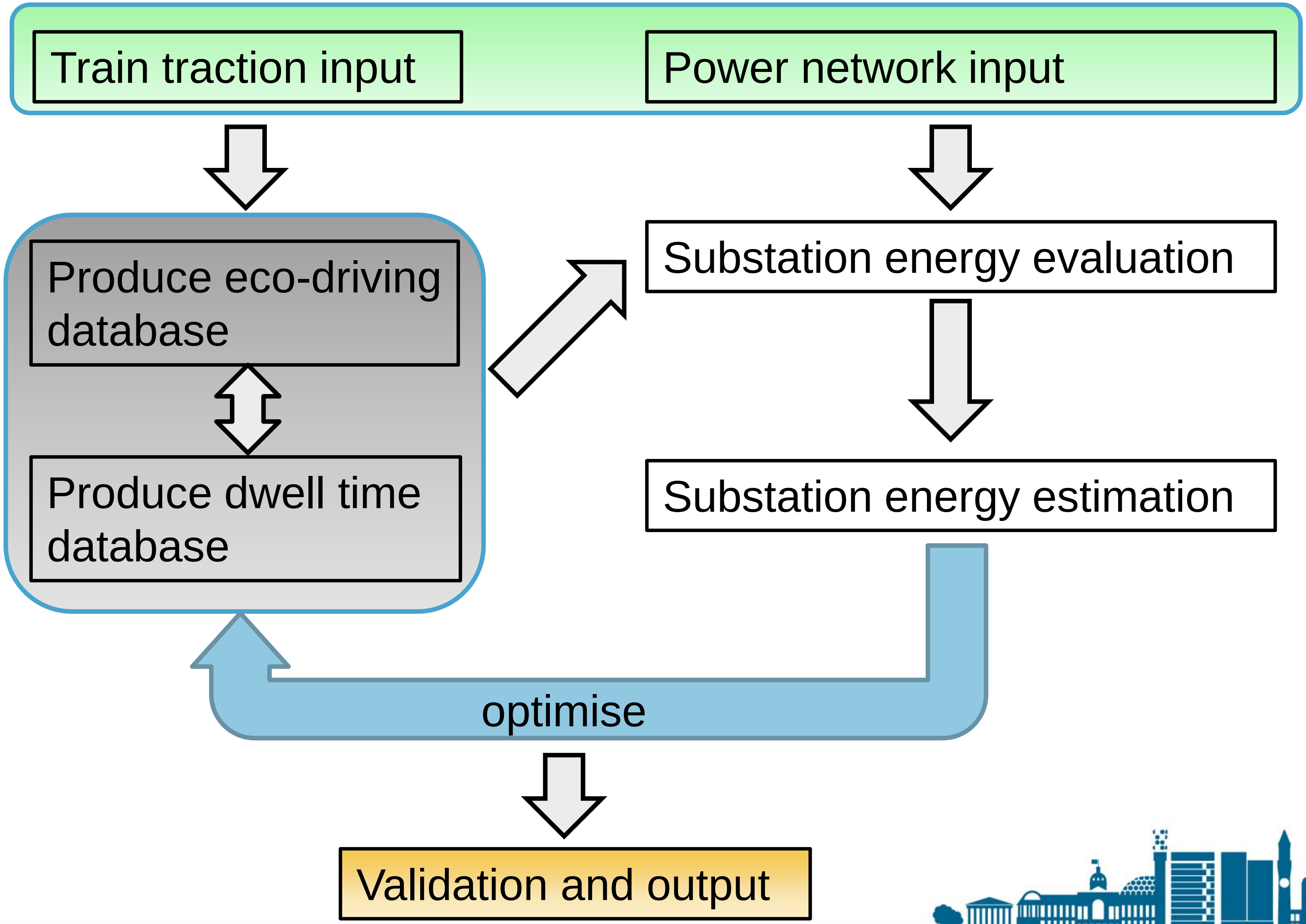
Traction energy saving is not the final objective!!!

System energy optimisation



- Interstation driving style and dwell time within constraints are treated as decision variables.
- Monte Carlo Simulation algorithm to reduce the comprehensive simulation calculation time.

Optimisation algorithm structure



Train traction input

Power network input

Produce eco-driving database

Produce dwell time database

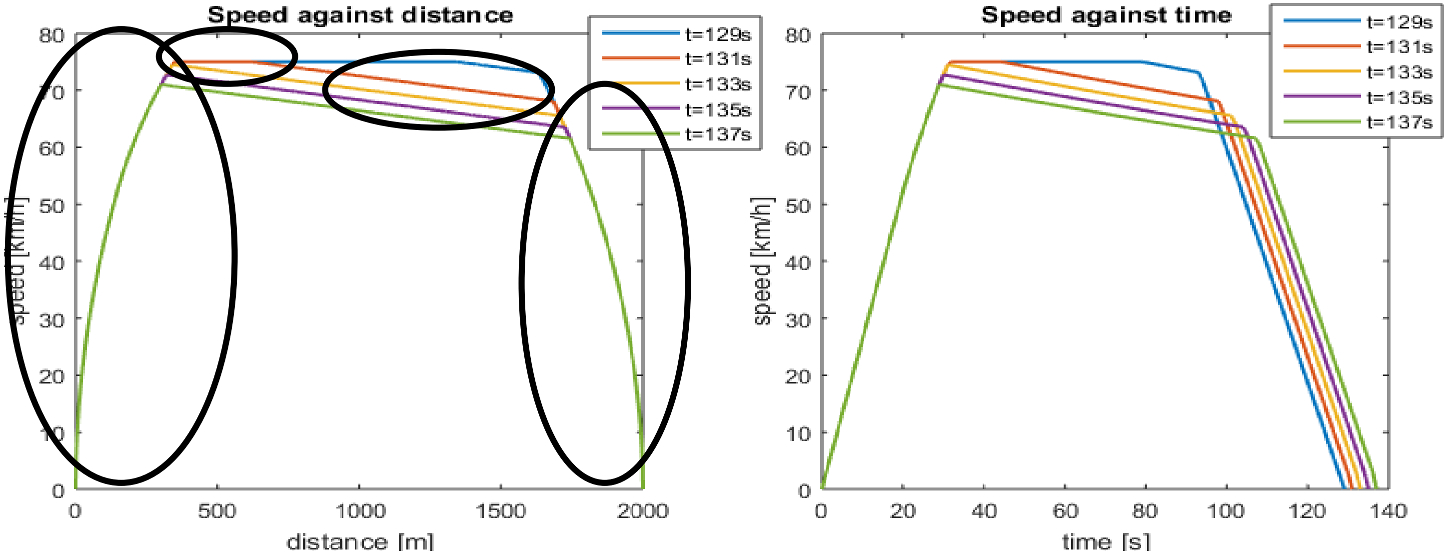
Substation energy evaluation

Substation energy estimation

optimise

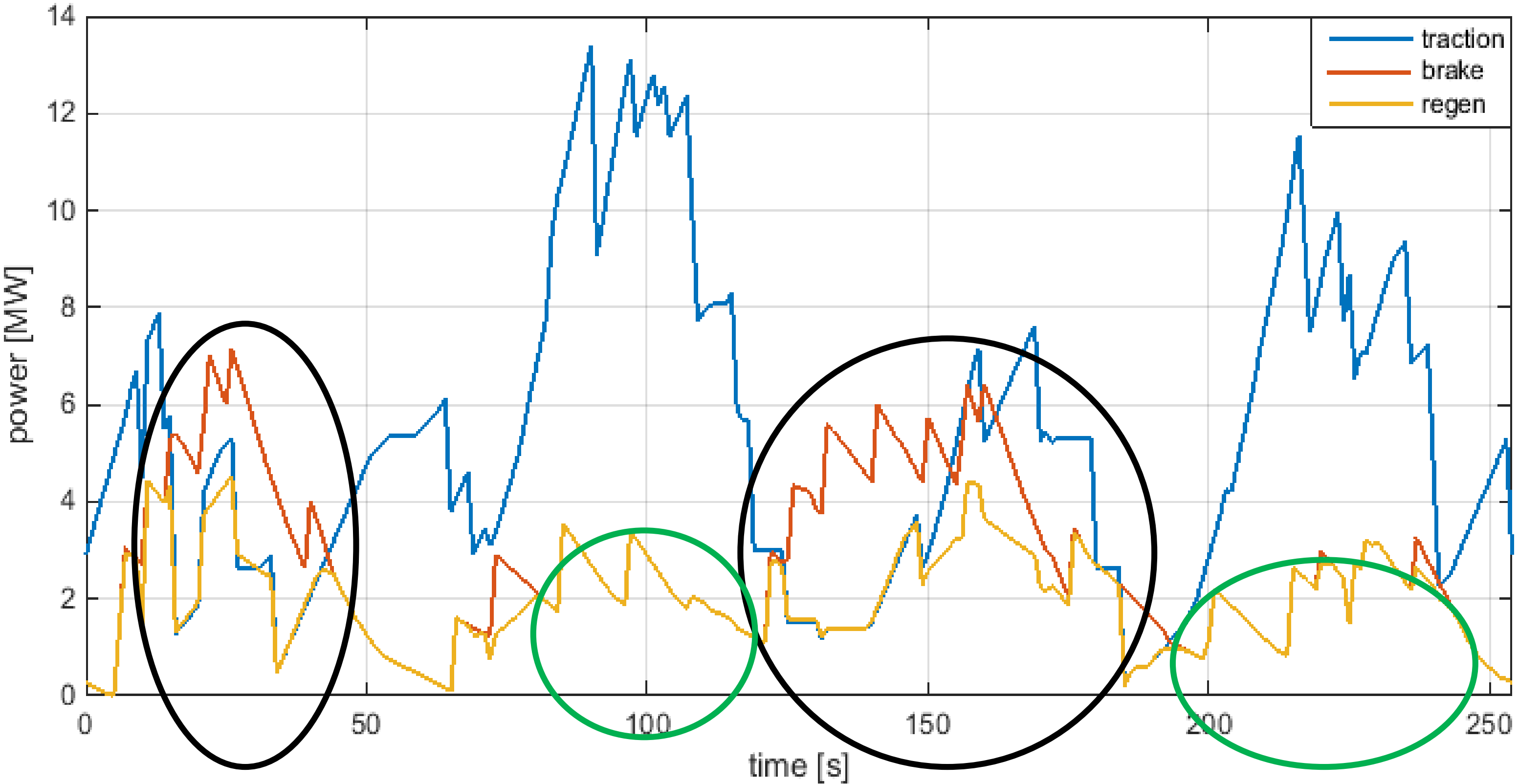
Validation and output

Energy-efficient driving



- ☐ The aim of the single train trajectory optimisation is to find the most appropriate train movement sequence to minimise energy usage within a constant total journey time;
- ☐ An Enhanced Brute Force algorithm was implemented in the optimisation. The algorithm is able to reduce the solution domain by calculating estimated solutions, thereby decreasing the computation time significantly.

Substation energy estimation



Power overlap ⇨ $$P_{overlap}(t) = min\left\{\sum_{n=1}^{N} P_{elec\_trac\_n}(t)\,,\sum_{n=1}^{N} P_{elec\_brake\_n}(t)\right\}$$

Substation energy estimation

- Substation energy consumption

$$E_{sub} = E_{elec\_trac} - \boxed{E_{regen}} + \boxed{E_{network\_loss}}$$

- Estimated substation energy consumption

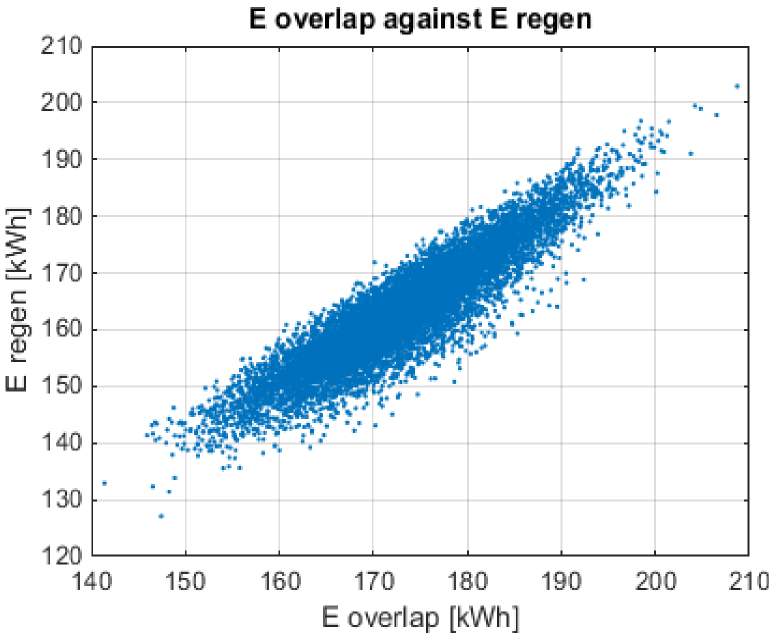
$$E_{sub\_est} = E_{elec\_trac} - \boxed{C_r \times E_{overlap}} + \boxed{C_n \times E_{sub\_est}}$$

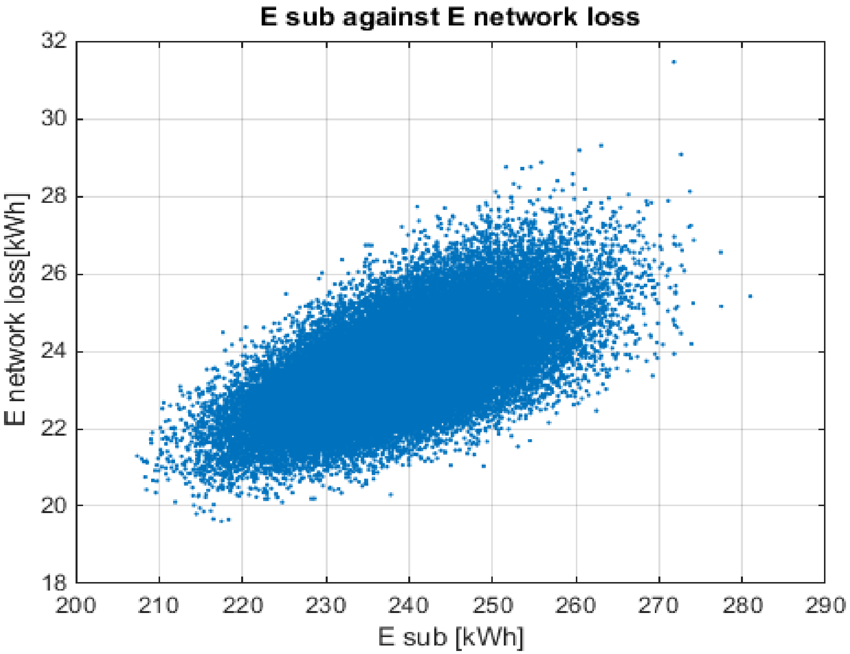
$$\begin{cases} \mathrm{E_{overlap}} = \int_0^{\mathrm{T}} \min\left\{\sum_{\mathrm{n=1}}^{\mathrm{N}} \mathrm{P_{elec\_trac\_n}(t)}, \sum_{\mathrm{n=1}}^{\mathrm{N}} \mathrm{P_{elec\_brake\_n}(t)}\right\} \mathrm{dt} \\ \mathrm{C_r, C_n} \text{ are two coefficients obtained based on the route} \end{cases}$$

$$E_{sub\_est} = \frac{1}{1 - C_n} \times \left(E_{elec\_trac} - C_r \times E_{overlap}\right)$$

Substation energy estimation

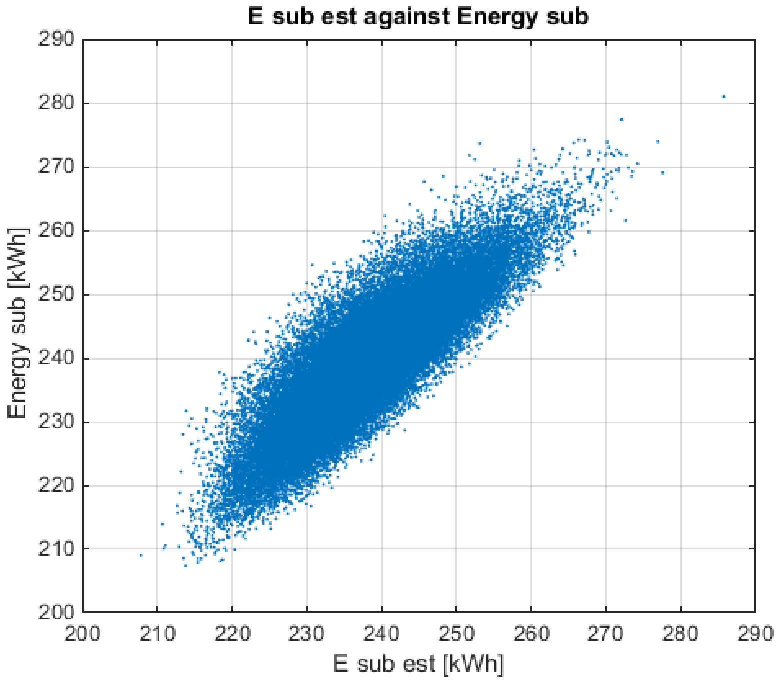
- The Pearson correlation coefficient is 0.917 between overlapping energy and regenerative energy and $\mathrm{C_r} = 0.944$
- The Pearson correlation coefficient is 0.6447 between substation energy and network loss and $\mathrm{C_n} = 0.0986$



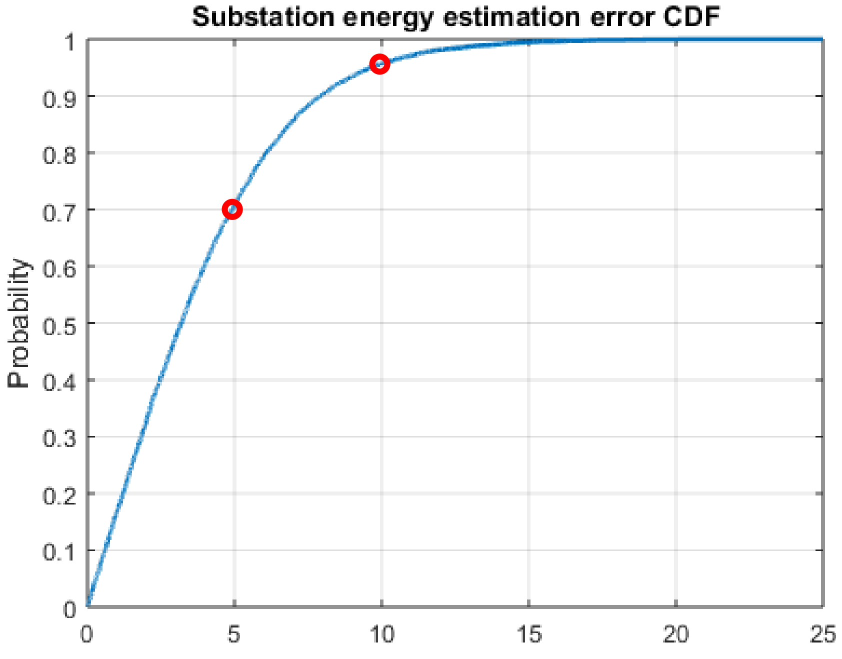


Monte Carlo Simulation

- ☐ The Pearson correlation coefficient is 0.862 between substation energy and the estimated substation energy.
- ☐ The probability that the absolute error is lower than 5 kWh is about 70%, becoming 95% when the absolute error is less than 10 kWh.



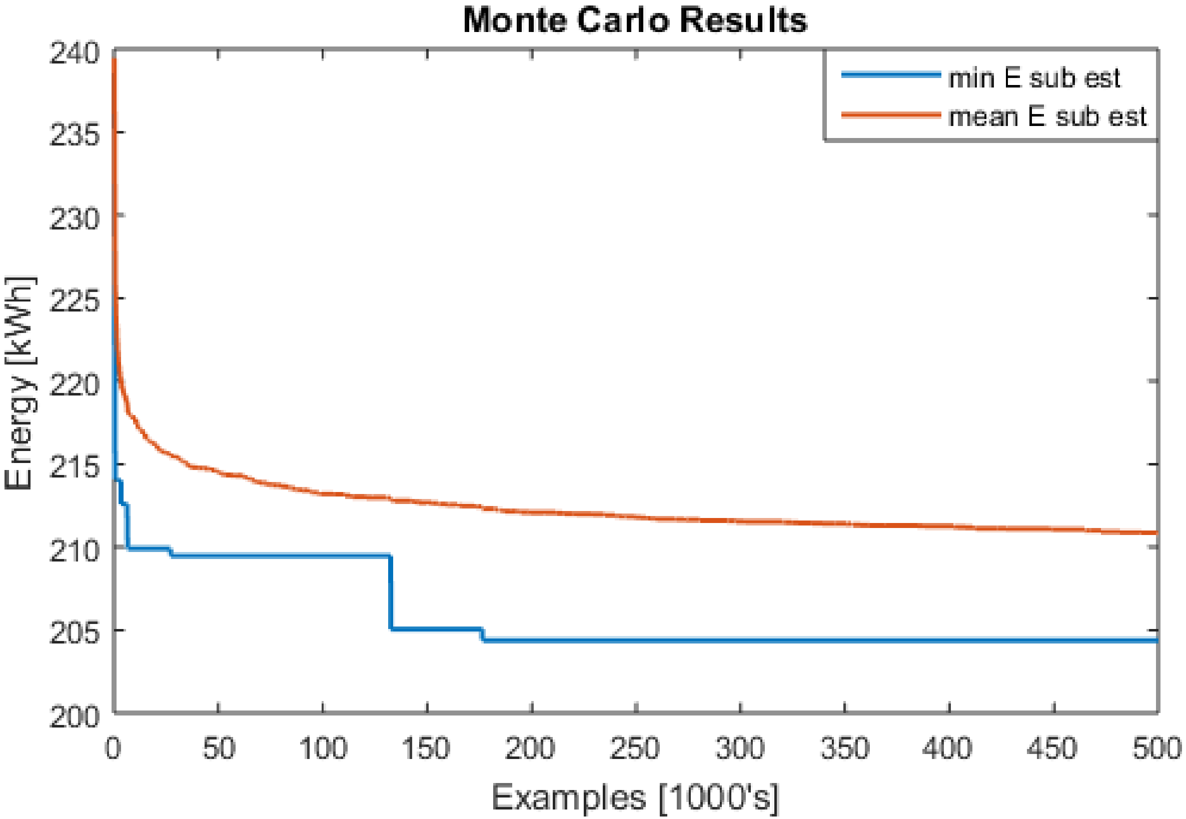
E sub est against Energy sub



Substation energy estimation error CDF

System energy optimisation results

- 500,000 random driving operation inputs are evaluated using 3 minutes.
- The best 100 cases with minimum estimated substation energy consumption are stored.



Top results from optimisation

- 500,000 random driving operation inputs are evaluated using 3 minutes.
- The best 100 cases with minimum estimated substation energy consumption are stored.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
T_{cycle} [s]	4248	4248	4289	4292	4291	4292	4290	4267
E_{sub}	203.37	203.95	204.72	204.88	205.50	205.73	205.75	206.35
$E_{sub\ loss}$	4.55	4.72	4.69	5.14	5.06	4.92	4.80	5.08
$E_{trans\ loss}$	16.18	15.44	15.90	16.44	16.42	16.50	16.41	15.67
$E_{traction}$	375.12	369.90	365.16	366.94	364.89	371.28	365.48	369.27
E_{elec_brake}	201.57	198.63	196.34	195.28	194.33	198.50	194.82	195.74
E_{regen}	192.48	186.12	181.04	183.64	180.88	186.96	180.94	183.66
η_{regen}	95.5%	93.7%	92.2%	94.0%	93.1%	94.2%	92.9%	93.8%

System energy optimisation results

	Current ATO operation	**Traction energy-saving operation***	**System energy-saving operation****
Cycle running time (s)	4281	4281	4287
Headway (s)	254	254	254
Substation energy (kWh)	331	232 **(-29.9%)**	203 **(-38.6%)**
Substation loss (kWh)	14	7	6
Transmission loss (kWh)	25	17	15
Traction energy (kWh)	526	372 **(-29.2%)**	375 **(-28.7%)**
Motion resistance (kWh)	106	82	82
Electro-braking energy (kWh)	290	199	201
Regenerative energy (kWh)	245	163	192
Regeneration efficiency	**80.6%**	**82.1%**	**95.5%**

**In traction energy-saving operation, each interstation time and dwell time are the same with current ATO operation, only interstation driving styles are optimised;*

***In system energy-saving operation, each interstation time, dwell time and driving styles are optimised together under the constrains.*

Results and contributions

- **Railway System Energy Simulator**
- **The main factors**
  - on energy consumption in railway systems
  - for upgrading existing routes or designing potential routes
- **Traction energy consumption**
  - using optimised driving strategies
  - reduced by **28%** in simulation
  - reduced by **16%** in field test = **£358 k** per year
- **Substation energy consumption**
  - using optimised driving strategy and timetable jointly
  - reduced by **38.6%**
- **Efficiency of regenerative braking energy**
  - improved from **80.6%** to **95.5%**

Thank you